# Full Equations Utilities (FEQUTL) Model for the Approximation of Hydraulic Characteristics of Open Channels and Control Structures During Unsteady Flow

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# Full Equations Utilities (FEQUTL) Model for the Approximation of Hydraulic Characteristics of Open Channels and Control Structures During Unsteady Flow

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## Abstract

The Full EQuations UTiLities (FEQUTL) model is a computer program for computation of tables that list the hydraulic characteristics of open channels and control structures as a function of upstream and downstream depths; these tables facilitate the simulation of unsteady flow in a stream system with the Full Equations (FEQ) model. Simulation of unsteady flow requires many iterations for each time period computed. Thus, computation of hydraulic characteristics during the simulations is impractical, and preparation of function tables and application of table look-up procedures facilitates simulation of unsteady flow.

Three general types of function tables are computed: one-dimensional tables that relate hydraulic characteristics to upstream flow depth, two-dimensional tables that relate flow through control structures to upstream and downstream flow depth, and three-dimensional tables that relate flow through gated structures to upstream and downstream flow depth and gate setting. For open-channel reaches, six types of one-dimensional function tables contain different combinations of the top width of flow, area, first moment of area with respect to the water surface, conveyance, flux coefficients, and correction coefficients for channel curvilinearity. For hydraulic control structures, one type of one-dimensional function table contains relations between flow and upstream depth, and two types of two-dimensional function tables contain relations among flow and upstream and downstream flow depths. For hydraulic control structures with gates, a three-dimensional function table lists the system of two-dimensional tables that contain the relations among flow and upstream and downstream flow depths that correspond to different gate openings. Hydraulic control structures for which function tables containing flow relations are prepared in FEQUTL include expansions, contractions, bridges, culverts, embankments, weirs, closed conduits (circular, rectangular, and pipe-arch shapes), dam failures, floodways, and underflow gates (sluice and tainter gates).

The theory for computation of the hydraulic characteristics is presented for open channels and for each hydraulic control structure. For the hydraulic control structures, the theory is developed from the results of experimental tests of flow through the structure for different upstream and downstream flow depths. These tests were done to describe flow hydraulics for a single, steady-flow design condition and, thus, do not provide complete information on flow transitions (for example, between free- and submerged-weir flow) that may result in simulation of unsteady flow. Therefore, new procedures are developed to approximate the hydraulics of flow transitions for culverts, embankments, weirs, and underflow gates.

# 1. INTRODUCTION

In unsteady flow, some aspect of the flow (velocity, depth, pressure, and others) is changing with time. Most flows of interest to hydraulic engineers, hydrologists, and planners are unsteady and may be considered one dimensional (that is, acceleration is substantial only in the longitudinal direction). In standard hydraulic-engineering practice, many problems involving one-dimensional, unsteady flows have been approximated by application of steady flows or piecewise-steady flows wherein storage-outflow relations are derived for channel reaches from a steady-flow hydraulic analysis [in the U.S. Army Corps of Engineers (1990a) Water Surface Profiles model HEC-2] and applied in simple hydrologic-routing methods [in the U.S. Army Corps of Engineers (1990b) Flood Hydrograph Package HEC-1]. Simulation of one-dimensional, unsteady flow in a complex stream system that contains many hydraulic structures is practicable with the recent increases in the computational speed and storage capabilities of computers.

The Full EQuations (FEQ) model (Franz and Melching, 1997) is a highly flexible and robust model for simulation of one-dimensional, unsteady flow in open channels and through control structures. An extensive description of the hydraulic characteristics of the stream system to be simulated is required in FEQ. At a minimum, the geometry of the stream channels must be described. In addition, the hydraulics of a variety of structures, including culverts, bridges, spillways, contractions, and expansions, either natural or constructed, may need to be described. The variety of structures that can be present in a stream system is practically unlimited. Some of these structures were designed and constructed thoughtfully, but many were not. Therefore, one of the major tasks of simulating the hydraulic behavior of a stream system is the description of the hydraulic characteristics of the various structures in that system. The utility program Full EQuations UTiLities (FEQUTL) has been developed to make the description of the hydraulic characteristics of the stream system easier. A variety of look-up tables are computed in FEQUTL to describe channel cross sections and hydraulic control structures to facilitate simulation of unsteady flow with FEQ.

Stream slopes are relatively flat and flood plains are relatively broad throughout Illinois. Further, the counties in the Chicago, Ill., metropolitan area are undergoing rapid urbanization. These factors have resulted in increased interest in application of unsteady-flow analysis for flood-plain delineation, flood warning, flood-control reservoir design and operation, and other applications in rapidly urbanizing counties in Illinois. Because a wide variety of hydraulic structures in the stream system could be simulated in FEQ, extensive testing and documentation were done by the U.S. Geological Survey (USGS) and cooperating agencies. The Illinois Department of Natural Resources, Office of Water Resources, and the County of Du Page, Department of Environmental Concerns, cooperated with the USGS and Linsley, Kraeger Associates Ltd. to document the procedures applied in FEQUTL to compute function tables that relate flow to upstream and downstream water-surface elevation for cross sections and hydraulic control structures in open-channel systems (streams) simulated with FEQ.

## 1.1 Purpose and Scope

The purpose of this report is to document the procedures applied in the Full EQuations UTiLities (FEQUTL) model to compute function tables that relate flow to upstream and downstream flow depth for cross sections and hydraulic control structures in open-channel systems (streams) simulated with the Full Equations (FEQ) model. The FEQUTL model and example inputs and outputs may be obtained by electronic retrieval from the World Wide Web (WWW) at http://water.usgs.gov/software/feq.html and by anonymous File Transfer Protocol (FTP) from water.usgs.gov in the pub/software/surface_water/feq directory. This report describes the procedures applied in FEQUTL to compute the hydraulic characteristics of channel cross sections, expansions, contractions, bridges, culverts, embankments, weirs, closed conduits (circular, rectangular, and pipe-arch shapes), dam failures, floodways, and underflow gates (sluice and tainter gates). The report begins with a description of the variety of function tables required to list the hydraulic characteristics of the stream features listed to facilitate simulation of unsteady flow with FEQ. The procedures applied to approximate the hydraulic characteristics of open channels (cross sections, expansions, and contractions) are discussed. The procedures applied to approximate the hydraulic characteristics of hydraulic control structures are developed.

Previous research on the hydraulics of control structures forms the basis of the procedures applied to approximate the hydraulics of control structures. This research was done to describe flow hydraulics for a single, steady-flow design condition and, thus, does not provide complete information on flow transitions (for example, between free- and submerged-weir flow) that may result in unsteady flow. Therefore, the procedures applied to approximate the hydraulics of flow transitions for culverts, embankments, weirs, and underflow gates are discussed in detail because these include new techniques that are not well known in the hydraulic literature but produce reasonable simulation results. Finally, the input for FEQUTL and the error messages and warnings issued in model computations are presented.

## 1.2 Look-up Tables

A look-up table in the context of FEQUTL computation is an organized collection of information that defines the important hydraulic characteristics of a cross section or control structure in the stream system simulated in FEQ. Look-up tables have been utilized for mathematical functions, such as the square root and the logarithm, for many years. Various forms of interpolation are utilized to determine values of these functions. The ready availability of these standard functions on calculators and in computer languages have made the use of table look-up procedures for standard mathematical functions rare.

For more complex mathematical functions, such as critical values for statistical tests, table look-up procedures are commonly included in computer programs. The shape and size of a stream cross section is normally not described by some simple, standard function. Approximation using polynomials or some other standard function is not practical because stream shapes greatly vary. Thus, carefully defined look-up tables are an efficient means for defining nonstandard functions. Utilization of look-up tables in FEQ simulation results in the generality of description needed in an unsteady-flow modeling system. In addition to the generality of description, look-up tables make computations in FEQ more efficient. Millions of calculations are involved in an unsteady-flow simulation. Therefore, superfluous computations must be eliminated for efficient simulation.

### 1.2.1 Look-up Tables for Channel Cross Sections

Cross sections of a stream usually are given in a series of horizontal distances from reference points, called offsets, and the elevation of points on the bed of the stream. The area of flow, the top width of the flow, the wetted perimeter of the flow, conveyance, and other characteristics can be computed given an elevation of the water surface. However, a review of the governing equations for unsteady flow (Franz and Melching, 1997) indicates that the details of which side is the right bank of a cross section and which side is the left bank of a cross section do not affect the computations if the left bank and right bank are defined consistently for curvilinear channels. All that is required to solve the governing equations is information on the variation with water-surface elevation of the key characteristics of the cross section, such as flow top width, area, square root of conveyance, correction coefficients for nonuniform flow, first moment of area about the water surface, and correction coefficients for channel curvilinearity. These characteristics can be computed from the basic cross-section description and stored in a look-up table. The hydraulic characteristics of open channels needed for flow simulation in FEQ are then readily available.

### 1.2.2 Look-up Tables for Hydraulic Control Structures

The application of look-up tables to describe the hydraulics of a variety of control structures eliminates superfluous computations of hydraulic characteristics of these structures during unsteady-flow simulation. Steady-flow relations are applied at these structures. Application of steady-flow relations is feasible because the change in the volume of water and in the momentum of the water in the control structure is small relative to the changes in the stream channels between structures. At a control structure, information on the relation between the flow through the structure and the water-surface elevation upstream and in some cases downstream from the structure are needed in flow simulation in FEQ, or any other similar model for unsteady-flow analysis. The detailed nature of the type of structure is irrelevant to the computations done in FEQ. Thus, in flow simulations done in FEQ, it is not important whether the structure is a bridge, a culvert, or a spillway. All that is needed for flow simulation is an adequate description of the relation between the flow through the structure, the water-surface elevation upstream from the structure, and the water-surface elevation downstream from the structure.

The description of the hydraulics of control structures is suited to application of look-up tables. The performance of the structure for a meaningful range of flows and water-surface elevations can be computed and the results placed in a look-up table. The look-up table is then accessed in FEQ simulations to complete the unsteady-flow computations. Thus, the computational burden of defining the flow through the structure need not be done in FEQ simulations. A major additional benefit of applying a look-up table is that the transitions in flow, such as the transition between partial and full flow in culverts, can be isolated and approximated before the unsteady-flow computations are done. This eliminates the difficulty of making a smooth transition between the flow patterns that can result in the structure as the computations proceed. Calculation of such transitions during the unsteady-flow computations is always difficult and sometimes nearly impossible. Computation of the transition flow conditions with steady-flow calculations in a utility program is feasible but may still be difficult.

### 1.2.3 Table Look-up Procedure

A look-up table contains one or more input arguments, the values utilized to do the look up, and one or more output items used in simulation. For a cross section the argument in FEQ is the maximum depth found in the section. The output items of interest are the cross-sectional characteristics, which are all functions of the maximum depth, such as top width, area, and conveyance. These are discussed at length in section 3. For flow through a culvert, two input arguments are utilized—the piezometric head upstream from the culvert and the piezometric head downstream from the culvert measured from the same datum—and the item of interest is the flow through the culvert.

Several components are needed in the development of a useful table look-up procedure. The tables must be patterned for efficient look up, an efficient searching scheme must be applied, and a set of rules must be established for defining values intermediate to those that are tabulated (rules for interpolation). The pattern of the tables is a programming detail that is outlined in the source code of FEQ and FEQUTL. The rules of interpolation are discussed in section 2. The search technique used for all tables in FEQ and FEQUTL is the simple linear search. This technique proves to be most efficient because the table look ups are most often repetitive at nearly the same value of the argument. The value determined in the last table look up and its location in the table are stored in FEQ and FEQUTL simulations, and the search for the function value at the next look-up time in the simulation begins at that point. Therefore, in most computations, the number of comparisons needed to find the point of interpolation for the current argument is minimal. Only occasionally is a long search required.

## 1.3 Procedure for Computation of Function Table for Use in Simulation of Unsteady Flow with the Full EQuations Model

The procedure for computation of function tables with FEQUTL for use in simulating unsteady flow in a system of open channels and control structures with FEQ is as follows.

1. The basic descriptive data for the stream system is measured or determined from available sources.
2. The data describing the cross sections for the stream are placed in one of the formats supported in FEQUTL. Each cross section is given a unique number as identification. This number becomes the identification number of the resulting look-up table.
3. The cross-section table is computed in FEQUTL from the description of the stream cross section. The cross-section tables are placed in one or more data files. These files are accessed later in FEQ flow simulation.
4. Steps 1-3 are followed to compute tables for culverts, bridges, and other structures. The resulting look-up tables are stored in files for later access.
5. Once all the tables are computed and the description and control input for FEQ are prepared, FEQ is run with references to the appropriate data files to access the look-up tables.

## 2. TABLE TYPES GENERATED IN THE FULL EQUATIONS UTILITIES MODEL

Several look-up tables are used in FEQ to represent the variety of functions required in unsteady-flow analyses. These tables are called function tables and are the basis of the look up and interpolation procedures applied in unsteady-flow computations. Some of these tables are computed in the utility program, FEQUTL, and others are prepared manually from other sources. The table origin does not affect FEQ computations if the table conforms to the expected structure and format. The table types that are generated in FEQUTL are described in this section. Table type 10 is used for input to FEQUTL but is neither generated in FEQUTL nor utilized in FEQ. Table type 10 is described in this report for completeness. The other table types are described in section 11 in the documentation report for the Full Equations model (Franz and Melching, 1997).

The three broad classes of function tables are called one dimensional, 1-D (having one argument), two dimensional, 2-D (having two arguments), and three dimensional, 3-D (having three arguments). Seven types of 1-D function tables, two types of 2-D function tables, and one type of 3-D function tables are computed in FEQUTL and are listed in table 1. The 1-D tables are the simplest and are presented first.

**Table 1.** Summary of function tables computed in the Full EQuations UTiLities model

[AMV, any meaningful value (for example stage, head, elevation); --, none; $T$, top width; $A$, cross-sectional area; $\sqrt{K}$, square root of conveyance; $\beta$, momentum-flux correction coefficient; $J$, first moment of area about the water surface; $\alpha$, energy-flux correction coefficient; $Q_C$, critical flow rate; $M_A$, area-correction coefficient for curvilinear channels; $M_Q$, discharge-correction coefficient for curvilinear channels; 1-D, one dimensional; 2-D, two dimensional; 3-D, three dimensional]

| Table type | Table dimension | First argument | Second argument | Values yielded |
|---|---|---|---|---|
| 2 | 1-D | AMV | -- | Function |
| 13 | 2-D | Head | Head | Flow |
| 14 | 2-D | Head | Flow | Head |
| 15 | 3-D | Gate setting | -- | 2-D table numbers |
| 20 | 1-D | Depth | -- | $T, A, \sqrt{K}, \beta$ |
| 21 | 1-D | Depth | -- | $T, A, \sqrt{K}, \beta, J$ |
| 22 | 1-D | Depth | -- | $T, A, \sqrt{K}, \beta, J, \alpha, Q_c$ |
| 23 | 1-D | Depth | -- | $T, A, \sqrt{K}, \beta, M_A, M_Q$ |
| 24 | 1-D | Depth | -- | $T, A, \sqrt{K}, \beta, J, M_A, M_Q$ |
| 25 | 1-D | Depth | -- | $T, A, \sqrt{K}, \beta, J, \alpha, Q_c, M_A, M_Q$ |

### 2.1 One-Dimensional Function Tables

Six of the seven types of 1-D function tables computed in FEQUTL list characteristics of stream cross sections, whereas the seventh type lists flow-rating curves. Complete descriptions of these function tables are given in the following sections.

#### 2.1.1 Type 2 Tables

Table type 2 lists a function of one argument. It is applied for simple rating curves for a variety of structures. Because there is only one argument, the rating is assumed to be unaffected by tail-water variations. This assumption must be considered when tables of type 2 are applied. In FEQUTL and FEQ computations, the variation of values between tabulated arguments is assumed to be linear. Thus, a piecewise-linear approximation of a function of one variable is represented in these tables. The piecewise-linear approximation is computed in FEQ as

$$\hat{f}_t(y_t) = f_{t_i} + \frac{(y_t - y_{t_i})}{(y_{t_{i+1}} - y_{t_i})}(f_{t_{i+1}} - f_{t_i}), \tag{1}$$

where

$\hat{f}_t(y_t)$ = the function value estimated from the table for argument value, $y_t$, of interest,

$f_{t_i}$ = the $i$th function value tabulated,

$y_{t_i}$ = the corresponding argument value, and $y_{t_i} \le y_t \le y_{t_{i+1}}$.

Enough data points should be included in the table so that straight-line interpolation between data points results in negligible error.

By proper selection of the tabulation interval and function values, the model user can represent a wide variety of functions with this type of table. These functions include rating curves, variation of spillway coefficients with head, and energy-loss coefficients. The following is an example of a portion of a type 2 table representing a rating curve at a gaging station as output from FEQUTL for input to FEQ.

```
TABLE#=   450
TYPE=    2
REFL=0.0
  HEAD  DISCHARGE
   0.0         0.
   0.1         8.
   0.5        51.
   1.0       114.
   2.0       258.
   3.0       415.
   4.0       582.
 -1.0
```

### 2.1.2 Cross-Section Function Tables

Six cross-section function tables are computed in FEQUTL and used in FEQ. The type numbers assigned are from 20 to 25. The cross-sectional characteristics are tabulated as a function of the water-surface height (equal to maximum depth) in the cross section in all tables. Therefore, these function tables are 1-D because only one argument is present. However, these function tables contain more than one function value for each argument value. The equations used to compute the cross-sectional characteristics listed in the various function tables are given in sections 3.1.1, 3.1.2, and 3.1.3.

All of the six table types list water-surface height, $y$; top width, $T$; cross-sectional area, $A$; square root of conveyance, $\sqrt{K}$; and the momentum-flux correction coefficient, $\beta$ (sections 3.1.1 and 3.1.2). The first moment of area about the water surface, $J$ (section 3.1.1), is added to table type 21. The first moment of area about the water surface, the energy-flux correction coefficient, $\alpha$, and critical flow rate, $Q_c$ (section 3.1.2), are added to table type 22. Table type 23 is similar to table type 20 with the addition of the weight factors to convert area to volume per unit length of channel, $M_A$, and to convert flow rate to momentum content per unit length of channel, $M_Q$, for curvilinear channels (section 3.1.3). In the same manner, table type 24 is similar to table type 21, and table type 25 is similar to table type 22. In terms of the defined symbols, the table types contain the cross-section characteristics as follows:

Type 20: $y, T, A, \sqrt{K}, \beta$
Type 21: $y, T, A, \sqrt{K}, \beta, J$
Type 22: $y, T, A, \sqrt{K}, \beta, J, \alpha, Q_c$
Type 23: $y, T, A, \sqrt{K}, \beta, M_A, M_Q$
Type 24: $y, T, A, \sqrt{K}, \beta, J, M_A, M_Q$
Type 25: $y, T, A, \sqrt{K}, \beta, J, \alpha, Q_c, M_A, M_Q$

Any cross-section table that contains the proper information can supply that information in FEQ simulation. Thus, tables of type 25 are applicable in all contexts. On the other hand, tables of type 20 are applicable in a more limited context. In FEQ simulation an error message results if a cross-section table does not contain the needed information.

The interpolation method for each of the cross-section characteristics is listed in table 2. In "integrated linear" interpolation, a linear function is integrated to find the interpolated value. Area is given by the integral of the top width. The top width is interpolated linearly between tabulated argument values. Therefore, the linear top-width variation is integrated to interpolate between the tabulated argument values. In the same way, the first moment of area is the integral of the area. The area is piecewise quadratic (an integral of a piecewise linear function). Thus, "integrated quadratic" interpolation is applied wherein the piecewise quadratic variation of area is integrated to interpolate for the first moment of area between tabulated argument values. Interpolation for the critical flow rate is done linearly for logarithmic transformed values ("linear in logarithms") because this yields exact values for many standard geometric shapes (Franz and Melching, 1997). Additional details are provided in sections 3, 4, and 11 in the documentation report for the Full Equations model (Franz and Melching, 1997).

**Table 2.** Cross-sectional characteristics computed and interpolation method applied in the Full EQuations UTiLities model

| Characteristic symbol | Definition | Interpolation method |
|---|---|---|
| $T$ | Top width | Linear |
| $A$ | Area | Integrated linear |
| $\sqrt{K}$ | Square root of conveyance | Linear |
| $\beta$ | Momentum-flux correction coefficient | Linear |
| $J$ | First moment of area about the water surface | Integrated quadratic |
| $\alpha$ | Energy-flux correction coefficient | Linear |
| $Q_c$ | Critical flow rate | Linear in logarithms |
| $M_A$ | Weight factor to convert area to volume per unit length of channel | Linear |
| $M_Q$ | Weight factor to convert flow rate to momentum content per unit length of channel | Linear |

The following is an example of a cross-section table of type 20 as output from FEQUTL for input to FEQ, where SQRT (CONV) is the square root of conveyance

```
TABLE#= 2020
TYPE=   20
STATION= 1.90000E-02
ELEVATION= 2.00000E+01
    DEPTH  TOP WIDTH          AREA   SQRT(CONV)     BETA
  0.00000      0.000  0.00000E+00  0.00000E+00  1.0669
  0.08000      0.607  2.42969E-02  2.03260E-01  1.0669
  1.00000      7.593  3.79626E+00  5.89644E+00  1.0669
  1.96154     11.154  1.28090E+01  1.41238E+01  1.0494
  2.92308     14.715  2.52460E+01  2.25344E+01  1.0549
  3.88461     18.276  4.11073E+01  3.13595E+01  1.0607
  4.84615     21.838  6.03930E+01  4.06248E+01  1.0649
  5.80769     25.399  8.31022E+01  5.03164E+01  1.0680
  6.76923     28.960  1.09236E+02  6.04121E+01  1.0701
  7.73077     32.521  1.38795E+02  7.08886E+01  1.0716
  8.69231     36.083  1.71778E+02  8.17243E+01  1.0728
  9.65384     39.644  2.08186E+02  9.28992E+01  1.0736
 10.61538     43.205  2.48017E+02  1.04396E+02  1.0742
 11.57692     46.766  2.91271E+02  1.16198E+02  1.0746
 12.53846     50.328  3.37951E+02  1.28293E+02  1.0750
 13.50000     53.889  3.88056E+02  1.40666E+02  1.0752
     -1.0
```

## 2.2 Two-Dimensional Function Tables

One-dimensional tables are limited to one argument. Therefore, 1-D tables can only represent a limited range of functions. Two cases for representing more complex functions with 2-D function tables are provided in FEQUTL. Thus, two types of function tables are computed in FEQUTL. The concepts underlying the two cases are presented in detail in section 11 in the documentation report for the Full Equations model (Franz and Melching, 1997). Only a brief outline is given here.

In the first case, represented with tables of type 13, a decrease (or drop) in piezometric head in the direction of flow always results across the control structure from the upstream, approach section to the downstream, departure section. In tables of type 13, the flow through the structure is listed as a function of piezometric head upstream from the structure in the approach section and the drop in piezometric head across the structure. Thus, in tables of type 13, flow is a function of upstream and downstream piezometric head (equal to the upstream piezometric head minus the drop) referenced to the stream-system datum. When this drop in piezometric head across the structure becomes large enough for a fixed upstream piezometric head (**HUP**), a critical control will result at some point in the structure. Further increases in the drop for the given upstream piezometric head will not increase the flow through the structure. The value of the drop in piezometric head across the structure at the point where further increases in drop have no effect is called the drop to free flow or just the free drop (**FDROP**). Free flow is the flow rate when the tail-water (downstream) piezometric head no longer affects the flow through the structure. Given the free drop for a specified upstream piezometric head, the flow for a range of drops that are smaller than the free drop, called partial free drops, is computed in FEQUTL. These partial free drops are further normalized by dividing by the drop to free flow, and the resulting normalized, partial free drop is abbreviated as **PFD**. Thus, a **PFD** of 0.0 implies that the flow is zero, and a **PFD** of 1.0 implies that the flow is equal to the free flow (the flow when the drop is the free drop).

The following is an example of a cross-section table of type 13 as output from FEQUTL for input to FEQ.

```
TABLE#=  300
TYPE=   13
LABEL=A-CRK1
NHUP=    7
NPFD=   10
  HUP    1000-4   1500-4   2000-4   4000-4   6000-4   8000-4   1000-3
FDROP    2482-4   2687-4   2916-4   3787-4   4598-4   5293-4   5958-4
  PFD    Flows for HUP and Proportion of FDROP
1000-5   3582-5   9038-5   1674-4   8882-4   2471-3   5298-3   9747-3
4000-5   6462-5   1701-4   3182-4   1706-3   4757-3   1023-2   1884-2
9000-5   8740-5   2332-4   4452-4   2428-3   6796-3   1469-2   2712-2
1600-4   9930-5   2809-4   5423-4   3014-3   8480-3   1849-2   3416-2
2500-4   1054-4   3080-4   6080-4   3447-3   9758-3   2150-2   3982-2
3600-4   1054-4   3211-4   6459-4   3734-3   1063-2   2399-2   4325-2
4900-4   1054-4   3275-4   6722-4   3925-3   1120-2   2519-2   4674-2
6400-4   1054-4   3275-4   6722-4   3925-3   1155-2   2600-2   4837-2
8100-4   1054-4   3275-4   6722-4   3999-3   1170-2   2635-2   4914-2
1000-3   1054-4   3275-4   6722-4   4005-3   1174-2   2643-2   4934-2
```

**NHUP** is the number of upstream piezometric heads and **NPFD** is the number of normalized, partial free drops. The values of the normalized, partial free drops considered are listed below the **PFD** in the example table. The values of the fixed upstream piezometric heads considered are listed in the row beginning with **HUP**. The values of the free drop for a fixed upstream piezometric head are listed in the row beginning with **FDROP** immediately below the corresponding upstream piezometric head. The drop is computed as the product of **PFD** and **FDROP**, and the downstream piezometric head is computed as **HUP – (PFD × FDROP)**. The numbers in the table are listed in a compact notation with the integer after the plus or minus sign giving the power of 10 to apply to the number that precedes the sign. For example, the maximum upstream piezometric head, the last number in the row that starts with **HUP**, is 1.0. The free flow at an upstream head of 0.8 appears at the bottom of the next to last column of the function table and is 26.43. The drop to free flow from this upstream piezometric head is in the second to the last entry in the row that starts with **FDROP** and is 0.5293. Values not tabulated are interpolated linearly during FEQ simulation as a function of upstream piezometric head and proportion of free drop. If the drop between the upstream piezometric head and the downstream piezometric head exceeds the free drop at the given upstream piezometric head, then the control structure is in a free-flow state and the flow is interpolated in terms of upstream piezometric head and free flow. The example table has been shortened relative to the table size normally used in FEQ simulation and illustrated in the example data files that may be obtained by electronic retrieval as described in section 1.1. In an application to a stream system, more upstream piezometric heads and more partial free drops would be computed so that linear interpolation would yield a better approximation to the variation of the flows.

In the second case, represented with tables of type 14, the downstream piezometric head is fixed and the upstream piezometric head is computed for a range of flows. Thus, in tables of type 14, upstream piezometric head is a function of flow and downstream piezometric head. When the flow is zero, the two piezometric heads are equal. As the flow increases from zero, the piezometric heads will differ. Eventually a flow will be reached for the fixed downstream piezometric head (**HDN**) that results in a critical control at some point in the structure. The upstream piezometric head at that point is at the free-flow limit. The upstream piezometric head for a series of partial free flows is then computed in FEQUTL. The flows are normalized by dividing by the free flow (**QFREE**) so that a partial free flow (**PFQ**) of 0.0 results in zero flow and a **PFQ** of 1.0 results in the free flow for the specified value of downstream piezometric head.

The following is an example of a table type 14 as output from FEQUTL for input to FEQ.

```
TABLE#=  960
TYPE=   14
LABEL=CONTRACTION INTO LEFT GAP
NHDN=  9
NPFQ= 19
 QFREE   4177-1  5076-1  5928-1  6999-1  8404-1  1015+0  1216+0  1444+0  1702+0
   HDN   9000-3  9200-3  9400-3  9600-3  9800-3  1000-2  1020-2  1040-2  1060-2
   PFQ   Upstream heads for HDN and Proportion of QFREE
 6746-5  9023-3  9225-3  9425-3  9626-3  9827-3  1003-2  1023-2  1043-2  1064-2
 1259-4  9078-3  9284-3  9485-3  9686-3  9890-3  1010-2  1030-2  1051-2  1072-2
 1813-4  9152-3  9363-3  9566-3  9769-3  9977-3  1019-2  1040-2  1062-2  1084-2
 2349-4  9239-3  9456-3  9662-3  9867-3  1008-2  1030-2  1052-2  1075-2  1097-2
 2872-4  9332-3  9557-3  9766-3  9974-3  1019-2  1042-2  1065-2  1089-2  1113-2
 3384-4  9430-3  9663-3  9875-3  1009-2  1031-2  1055-2  1079-2  1104-2  1129-2
 3887-4  9530-3  9770-3  9986-3  1020-2  1044-2  1068-2  1094-2  1119-2  1145-2
 4384-4  9630-3  9879-3  1010-2  1032-2  1056-2  1082-2  1108-2  1135-2  1162-2
 4874-4  9731-3  9989-3  1021-2  1044-2  1069-2  1095-2  1123-2  1150-2  1179-2
 5359-4  9832-3  1010-2  1033-2  1056-2  1081-2  1109-2  1137-2  1166-2  1195-2
 5839-4  9933-3  1032-2  1055-2  1079-2  1106-2  1136-2  1166-2  1198-2  1229-2
 6786-4  1013-2  1042-2  1067-2  1091-2  1119-2  1150-2  1181-2  1213-2  1246-2
 7254-4  1023-2  1053-2  1078-2  1103-2  1131-2  1163-2  1195-2  1229-2  1262-2
 7719-4  1033-2  1064-2  1089-2  1114-2  1144-2  1176-2  1210-2  1244-2  1279-2
 8181-4  1043-2  1075-2  1100-2  1126-2  1156-2  1190-2  1224-2  1260-2  1295-2
 8639-4  1053-2  1086-2  1111-2  1138-2  1168-2  1203-2  1238-2  1275-2  1312-2
 9095-4  1063-2  1096-2  1122-2  1149-2  1181-2  1216-2  1253-2  1290-2  1328-2
 9549-4  1073-2  1107-2  1133-2  1161-2  1193-2  1229-2  1267-2  1305-2  1344-2
 1000-3  1083-2  1118-2  1145-2  1172-2  1205-2  1243-2  1281-2  1321-2  1361-2
```

**NHDN** is the number of downstream piezometric heads, and **NPFQ** is the number of partial free flows listed in the table. The numbers in the line beginning with **QFREE** are the flow rate required to yield free flow at the downstream piezometric head listed immediately below in the line beginning with **HDN**. For a given downstream piezometric head, a flow greater than the **QFREE** value is a free flow, and in this case the relation between flow and upstream piezometric head must be applied in the interpolation. The upstream piezometric head for each of the values of **QFREE** appears in the last line of the table except at a **PFQ** of 1.00. For example, at a downstream piezometric head of 9.6, the upstream piezometric head at free flow is 11.72 and the free flow is 699.9. As an example, a downstream piezometric head of 9.6 and a flow of 840.4 are used. The flow would be computed as free in FEQ simulation because the value of the flow argument, 840.4, is larger than the critical flow at the free-flow limit for a downstream piezometric head of 9.6. The upstream piezometric head sequence at free flow and the free flow would be used to determine the upstream piezometric head for the given flow. As an example of table interpretation, if the downstream piezometric head is 9.60 and the flow is 237, a partial free flow of 0.3386 is obtained. For this flow and downstream piezometric head, the upstream piezometric head is 10.09.

A third type of 2-D table, applied only to supply parameters to FEQUTL for the CULVERT and UFGATE commands, is a table of type 10. This table represents an input parameter for the CULVERT or UFGATE command as a function of two arguments by tabulating the parameter values at the intersections of a rectangular grid defined by the two arguments. Linear interpolation is applied in both the row and column directions for computing values intermediate to the values listed in the table. The arguments and function values can be any value needed in FEQUTL calculations. The file, TYPE5.TAB, required as input to FEQUTL in the FTABIN command and available by electronic retrieval as described in section 1.1, contains 10 examples of this table type. One of these example tables of type 10 is given below.

```
TABLE#=10001
TYPE=  -10 '(10A8)' '(1X,10A8)' '(F8.0)' '(10F8.0)' '(1X,F8.4,9F8.4)'
LABEL= Ratios for lin spline interp of power functions
   POWER   0.001   0.005   0.010   0.020    0.030    0.050    0.075     0.100
  0.0500  1.5082  2.5192  3.7266  6.5955  10.4067  22.4071  51.6085  111.7321
  0.1000  1.3491  1.9530  2.5871  3.8771   5.3321   9.0005  15.6264   25.6329
  0.2500  1.2302  1.5888  1.9279  2.5420   3.1530   4.4714   6.4125    8.7968
  0.3333  1.2101  1.5302  1.8270  2.3541   2.8674   3.9451   5.4784    7.2987
  0.5000  1.1960  1.4930  1.7648  2.2406   2.6975   3.6406   4.9535    6.4791
  0.6667  1.2101  1.5302  1.8270  2.3541   2.8674   3.9451   5.4784    7.2987
  0.7500  1.2302  1.5888  1.9279  2.5420   3.1530   4.4714   6.4125    8.7968
  0.9000  1.3491  1.9530  2.5871  3.8771   5.3321   9.0005  15.6263   25.6333
  0.9500  1.5082  2.5192  3.7265  6.5955  10.4066  22.4072  51.6085  111.7912
    -1.0
```

The line of alphanumeric strings in quotes following the TYPE designation is the definition of an optional series of formats for processing the table. The first string is the format for the input of the column heading in the table. The second string is the format for the output of the column headings in the output from FEQUTL for checking purposes. The third string is the format for processing any numeric value in the column heading line. The fourth string is the format for processing a row of the table. The fifth and last string gives the format for the output of a row of the table in the output from FEQUTL. If this format information is omitted, each column in the table has six characters available on the row. In either case, the number of columns for function values is given by the parameter MCTD10 in the file ARSIZE.PRM associated with FEQUTL (appendix 2). The current value for MCTD10 is 9, which sets a maximum of 10 columns for the table including the argument value for each row of the table. The example table of type 10 lists the maximum ratio between successive arguments to a simple power function, $ax^b$, such that linear interpolation for the function between arguments will have a relative error less than the value given to the right of the column heading POWER. For example, if the power in the simple power function is 0.5 and the desired maximum relative error is 0.02, then the arguments at the end of the interpolation interval must have a ratio less than or equal to 2.2406. Linear interpolation in both the row and column argument is utilized for intermediate values. The value of -1 in the last line indicates the end of the table. All input for tables of type 10 is predefined, and user-generated input of this table type is not required. This information is provided so that users may examine the tables of type 10 included in TYPES5.TAB available by electronic retrieval, as described in section 1.1, in case problems result during simulation.

## 2.3 Three-Dimensional Function Tables

One type of 3-D table, type 15, is prepared with FEQUTL. An example of such a table is as follows.

```
TABLE#=  590
TYPE=   15
REFL=        0.0 LABEL=tainter gates at Lock and Dam 21
   OPENING   TAB#    H1FWULR      H4FWULR     H4SWSOMDR
    0.500    5901    1.495398     1.084812    1.040058
    1.000    5902    1.470118     1.144279    1.067500
    2.000    5903    1.438635     1.213044    1.101230
    4.000    5904    1.408617     1.265819    1.130807
    8.000    5905    1.385591     1.290136    1.146670
   12.000    5906    1.375924     1.294183    1.149444
   16.000    5907    1.370592     1.294341    1.149378
   24.000    5908    1.364875     1.292444    1.147601
   26.000    5909    1.363958     1.291904    1.147117
   32.000    5910    1.361857     1.290380    1.145769
   -1.000
```

This table is used to describe the flows through underflow gates, such as sluice gates and tainter gates, as a function of the gate opening, the piezometric head at the approach section to the gate, and the piezometric head at the departure section from the gate. The configuration, operation, and simulation of underflow gates are described in detail in section 4.8, and the computations for underflow gates are done in the UFGATE command (section 5.20). A table of type 15 lists for each gate opening, described by the vertical extent of the assumed rectangular opening, the table number of the 2-D table of type 13 that describes the flow for that gate setting. Three additional values are tabulated in the table for each gate opening. These values describe boundaries among flow conditions. H1FWULR is the ratio of the upstream piezometric head at section 1 (approach section) at the upper limit of free-weir flow to the gate opening; H4FWULR is the ratio of the piezometric head at section 4 (departure section) at the upper limit of free-weir flow to the gate opening; and H4SWSOMDR is the ratio of the piezometric head at section 4 at the boundary between submerged-weir flow and submerged-orifice flow for a head at section 1 midway between the head equal to the gate opening and the head equal to the upper limit of free-weir flow to the gate opening. Each of these variables is described in detail in section 4.8.

Interpolation within a table of type 15 is linear for all values except the table number. A look-up request in a table of type 15 returns five values: the pair of table numbers where the gate-opening heights bracket the current height of the gate opening and the three values used for defining boundaries between flow conditions. This only applies to one of the three arguments for the 3-D table. The other two arguments—the piezometric head at the approach section and the piezometric head at the departure section—are applied for table look up in the pair of 2-D tables determined in the table of type 15. The final interpolation, on gate opening, between the pair of 2-D tables is specific to the hydraulic characteristics of flow beneath underflow gates. This interpolation is described in section 4.8.

# 3. APPROXIMATION OF HYDRAULIC CHARACTERISTICS OF OPEN CHANNELS

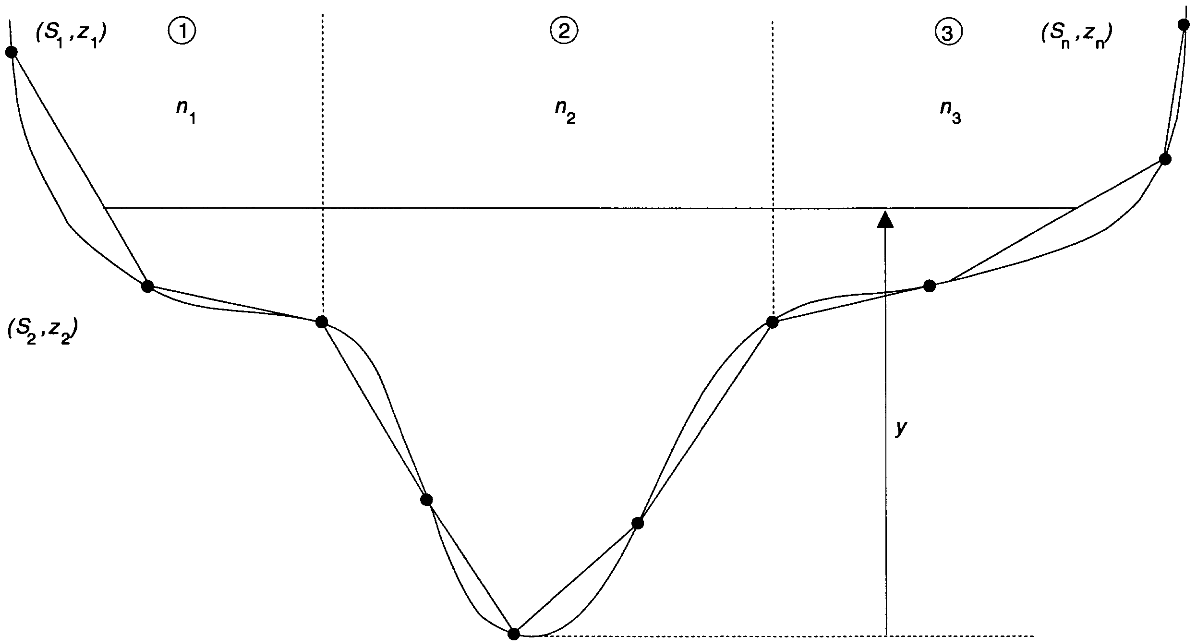
The hydraulic characteristics of open channels are divided between the description of the shape, size, and frictional resistance effects associated with the channel boundaries and the losses associated with abrupt expansions and contractions. Short channels, which allow high flows to bypass hydraulic structures in the stream, such as bridges and culverts, pose special problems that are discussed in this section. The description of the shape, size, and frictional resistance effects of channel boundaries are basic concepts and considered first in this section.

## 3.1 Characteristics of a Cross Section for a Branch

The definitions of the characteristics of a cross section given in section 4 in the documentation report for the Full Equations model (Franz and Melching, 1997) are rigorous and exact if the boundary of the cross section is known exactly. This only applies for design computations for artificial channels. It does not apply for artificial channels as constructed because variations (acceptable and otherwise) from the design computations are always present. Concrete and steel closed conduits also have manufacturing tolerances as large as 2 percent from the nominal dimensions. Therefore, the characteristics of a cross section are always approximate. An approach for definition of the characteristics for a cross section is needed so that the approximations will be convenient, consistent, and sufficiently accurate. Franz (1982) presented a discussion of errors in approximation for static cross-sectional characteristics.

Channels of regular shape, such as trapezoidal, rectangular, and circular, can be represented by simple formulas. However, cross sections with regular shapes appear infrequently in most stream systems (excluding storm sewers). Furthermore, it is convenient to represent all cross sections in the same way. This is done in FEQ by application of a look-up table for the cross-sectional characteristics. A carefully defined table is not only convenient but also consistent and accurate. The development of a carefully defined table begins with a definition of the practical boundary of a cross section.

An example cross-section boundary with selected points on the boundary marked and connected with straight lines is shown in figure 1. In practice, the boundary of a cross section is specified by measuring the horizontal distance to points on the boundary at which elevation is measured. These points should, in theory, be selected so that the variation of the boundary between points is approximately linear and the assumption of linear variation is accurate. In all subsequent discussion, the boundary of the cross section is assumed to be represented by the polygonal shape established by connecting the surveyed points by straight lines. The degree of approximation depends on the skill of the survey crew in selecting measurement locations and in making measurements and can only be estimated by making another more detailed survey of the cross section with more points. In FEQUTL, the value of Manning's *n* (roughness coefficient) may vary from subsection to subsection. The subsections should be defined primarily on the variation of shape and Manning's *n*. The goal of subsection delineation is for each subsection to be hydraulically compact so that the hydraulic radius properly represents the shape in Manning's formula and the subsection conveyance may be correctly approximated. If the FEQUTL command **FEQXEXT** (section 5.9) is applied, Manning's *n* can vary in three ways within a subsection: (1) Each line segment composing the boundary of the subsection can have a different value of Manning's *n*. This represents variations of roughness within a subsection that is compact and probably should not be further subdivided. If the Manning's *n* for a line segment is zero, that line segment is excluded from the calculation of the wetted perimeter. A line-segment-weighted average of Manning's *n* is applied in FEQUTL to compute the conveyance in the subsection; (2) The user can define variation of Manning's *n* in the vertical direction with the hydraulic depth in the subsection as the argument for the variation; (3) The user can define variation of Manning's *n* in the vertical direction with the water-surface height as the argument.




**EXPLANATION**

$S_i$ HORIZONTAL OFFSET FROM CONTROL POINT TO STATION $i$

$z_i$ ELEVATION OF STATION $i$ RELATIVE TO DATUM FOR THE STREAM SYSTEM

$n_j$ MANNING'S $n$ FOR SUBSECTION $j$ OF THE FLOW CROSS SECTION

$y$ WATER-SURFACE HEIGHT RELATIVE TO THE THALWEG OF THE CROSS SECTION

① SUBSECTION OF THE CROSS SECTION

**Figure 1.** Approximation of cross-section characteristics applied in the Full EQuations UTiLities model.

### 3.1.1 Static Characteristics and Simple Dynamic Characteristics

Points of subdivision that account for changes in shape or boundary roughness are shown in figure 1. The boundaries between the subsections must be measured points on the cross-section boundary. The cross-section characteristic values are computed in FEQUTL in the following sequence of steps.

1. The elevations, $\{z_i; i = 1,...,n_p\}$, are ranked from smallest to largest, repeated values are deleted, and the smallest value is subtracted from each distinct elevation to produce a sequence of ascending water-surface heights, $\{y_i; i = 1,...,n_p\}$. Here, $n_p$ is the number of points on the boundary.
2. The water-surface height sequence is reviewed and the near-zero-water-surface height value (**NRZERO**) given by the user (section 5.1) is inserted where needed. Additional water-surface height values also may be inserted to make the largest water-surface height interval less than or equal to the user-defined value of **DZLIM** (section 5.1). A water-surface height value near to zero water-surface height may not have been computed in the water-surface height sequence evaluated in item 1. This value is needed to improve the accuracy of the interpolation for conveyance at small water-surface heights. **DZLIM** gives the maximum water-surface height interval to be allowed in the table to improve the accuracy of the interpolation for conveyance.
3. For each water-surface height in the sequence established in item 2, the top width, $T_i$, wetted perimeter, $P_i$, area, $A_i$, and first moment of area, $J_i$, which is used to compute the hydrostatic-pressure force, are computed for

each of the $m$ subsections in the cross section where $i$ denotes the subsection number. This is done in FEQUTL by scanning the cross-section boundary from left to right and computing the hydraulic characteristic values for each line segment that would be partially or completely submerged if the cross section contained water at the specified height. The values for each line segment are added to totals maintained for each subsection. Each subsection must be assigned a unique number even if the roughnesses are the same. If this is not done, totally disjoint and disparate parts of the cross section may be combined into one subsection. This can lead to substantial errors in the conveyance. The user selects the procedure followed when one end of the cross section is lower than the other in the surveyed data available for that cross section. The low side of the section is extended with a frictionless, vertical wall so that its elevation matches the high side by application of the EXTEND option (section 5.1). The user also may request that no extension be applied so that the computed table will reach only the lowest elevation end of the cross section.

4. The hydraulic characteristic values are computed at each point in the water-surface height sequence. The following sequence of equations defines the hydraulic characteristics at the current depth in the depth sequence:

$$T = \sum_{i=1}^{m} T_i \tag{2}$$

$$A = \sum_{i=1}^{m} A_i \tag{3}$$

$$J = \sum_{i=1}^{m} J_i \tag{4}$$

$$K_i = \frac{c_u}{n_i} A_i \left( \frac{A_i}{P_i} \right)^{2/3} \tag{5}$$

$$K = \sum_{i=1}^{m} K_i \tag{6}$$

$$\alpha = \frac{A^2}{K^3} \sum_{i=1}^{m} \alpha_i \frac{K_i^3}{A_i^2} \tag{7}$$

$$\beta = \frac{A}{K^2} \sum_{i=1}^{m} \beta_i \frac{K_i^2}{A_i}, \tag{8}$$

where

$n_i$ is the Manning roughness coefficient for subsection $i$;
$c_u$ is the unit conversion for Manning's equation equal to 1.49 in English units and 1 in metric units;
$P_i$ is the wetted perimeter for subsection $i$; and
$K_i$ is the conveyance for subsection $i$.

The integrals of velocity squared and velocity cubed over the flow (cross section) are approximated in equations 7 and 8 by a summation in which it is assumed that the velocity in each subsection is given by $K_i S_f^{1/2} / A_i$, where $S_f$ is the friction slope, and that the average velocity for the cross section is given by $K S_f^{1/2} / A$. The friction slope is assumed to be the same for all subsections and, therefore, is not in the final relations.

The values of the momentum- and energy-flux correction coefficients in each subsection may be specified by the user or computed in FEQUTL. The method utilized in computing the momentum- and energy-flux correction coefficients, $\beta$ and $\alpha$, in the cross section is specified with the parameter **USGSBETA** (section 5.1). If **USGSBETA=NO**, then $\alpha = \beta = 1.0$ in each subsection of the cross section. If **USGSBETA=YES**, then the values of $\alpha_i$ and $\beta_i$ are calculated as $\alpha_i = 14.8n_i + 0.884$ and $\beta_i = 1 + 0.3467(\alpha_i - 1)$, where $n_i$ is the Manning's $n$ in the subsection. The relation for $\alpha$ was taken from Hulsing and others (1966). The relation between $\beta$ and $\alpha$ was computed by linear regression with unpublished data on $\beta$ from the USGS that was computed but did not appear in Hulsing and others (1966)[1]. Only the values for compact cross sections were used here. The first relation has considerable scatter relative to the data on $\alpha$, but its application greatly improves the computation of the value of $\alpha$ for the cross section. The second relation is well defined from the data with a correlation coefficient of 0.996 and a standard error of estimate of 0.0066 for 87 pairs of $\alpha$ and $\beta$ values computed from current-meter measurements in streams with approximately compact cross sections. **USGSBETA=YES** should be used with caution because it was developed on the basis of a limited data set, and it has not been verified computationally in detail. An alternative that may have better consistency is the **NEWBETA** option in FEQUTL, which is available for most nonconduit channels. The **NEWBETA** option is discussed in section 3.1.2.

5. The hydraulic characteristics are placed in a table for later use in either FEQ or FEQUTL. Tables of types 20 through 25 contain cross-sectional characteristics. The contents of these tables are as follows:

   Type 20: $y, T, A, \sqrt{K}, \beta$
   Type 21: $y, T, A, \sqrt{K}, \beta, J$
   Type 22: $y, T, A, \sqrt{K}, \beta, J, \alpha, Q_c$
   Type 23: $y, T, A, \sqrt{K}, \beta, M_A, M_Q$
   Type 24: $y, T, A, \sqrt{K}, \beta, J, M_A, M_Q$
   Type 25: $y, T, A, \sqrt{K}, \beta, J, \alpha, Q_c, M_A, M_Q$

   Tables of type 23 through 25 are similar to tables of type 20 through 22 with the corrections for channel curvilinearity added.

Once the table is complete, it can be utilized to find values of the hydraulic characteristics at any water-surface height in the range of the table. Only a finite number of water-surface height values are tabulated, and intermediate values are determined in FEQ simulation by interpolation as described in section 11 in the documentation report for the Full Equations model (Franz and Melching, 1997).

Critical flow also is listed in tables of type 22 or 25. Several options are available for computing critical flow. If **NEWBETA**, **NEWBETAM**, or **NEWBETAE** are not specified, the critical flow is computed and tabulated ignoring the effect of velocity distribution. However, if **NEWBETA**, **NEWBETAM**, or **NEWBETAE** is specified, problems arise when differentiating equations 7 and 8 for the rate of change of the flux coefficients with respect to water-surface height in the cross section. A discontinuity in the derivative results at every breakpoint on the boundary of the cross section because the rate of change of the wetted perimeter with respect to water-surface height changes at each breakpoint. Furthermore, ignoring or smoothing this discontinuity may still result in frequent computation of an undefined critical flow because the denominator becomes negative in the relevant equations, namely

[1]The values for $\beta$ were computed but not published. A copy of the results for $\beta$ was obtained from the U.S. Geological Survey in Menlo Park, California.

$$Q_E = A\sqrt{\frac{gA}{\alpha T - \frac{A}{2}\frac{d\alpha}{dy}}} \tag{9}$$

$$Q_M = A\sqrt{\frac{gA}{\beta T - A\frac{d\beta}{dy}}}, \tag{10}$$

where

$g$ is the acceleration of gravity,

$Q_E$ is the critical flow defined from specific energy, and

$Q_M$ is the critical flow defined from specific force (Chow, 1959, p. 54).

The use of subsection conveyance is too crude to define $\alpha$ and $\beta$ well enough for meaningful computation of critical flow.

### 3.1.2 Improved Flux Coefficients and Critical Flow

The options **NEWBETA, NEWBETAM,** and **NEWBETAE** are available in FEQUTL (sections 5.8 and 5.9) to include the effect of velocity distribution. Values are computed in the same manner in these options but different estimates of critical flow are tabulated. The inconsistencies between estimates of critical flow and the problems of determining critical flow indicate that a different method for estimating the flux coefficients should be developed. A first step in the development of a new method is an option for computing the flux coefficients for natural open channels available in FEQUTL. The new method is based on an approach suggested by Schönfeld (1951). In this approach, the depth-averaged velocities obtained by applying Manning's equation locally at each point across the cross section are integrated.

A typical line segment on the boundary of the cross section and the water surface above it are shown in figure 2. The boundary point on the left is denoted by the subscript $L$, and the boundary point on the right is denoted by the subscript $R$. These designations are used for any points of intersection between the boundary and the current water level. The slope of the boundary line, $m_s$, is defined as

$$m_s = \frac{z_R - z_L}{s_R - s_L}, \tag{11}$$

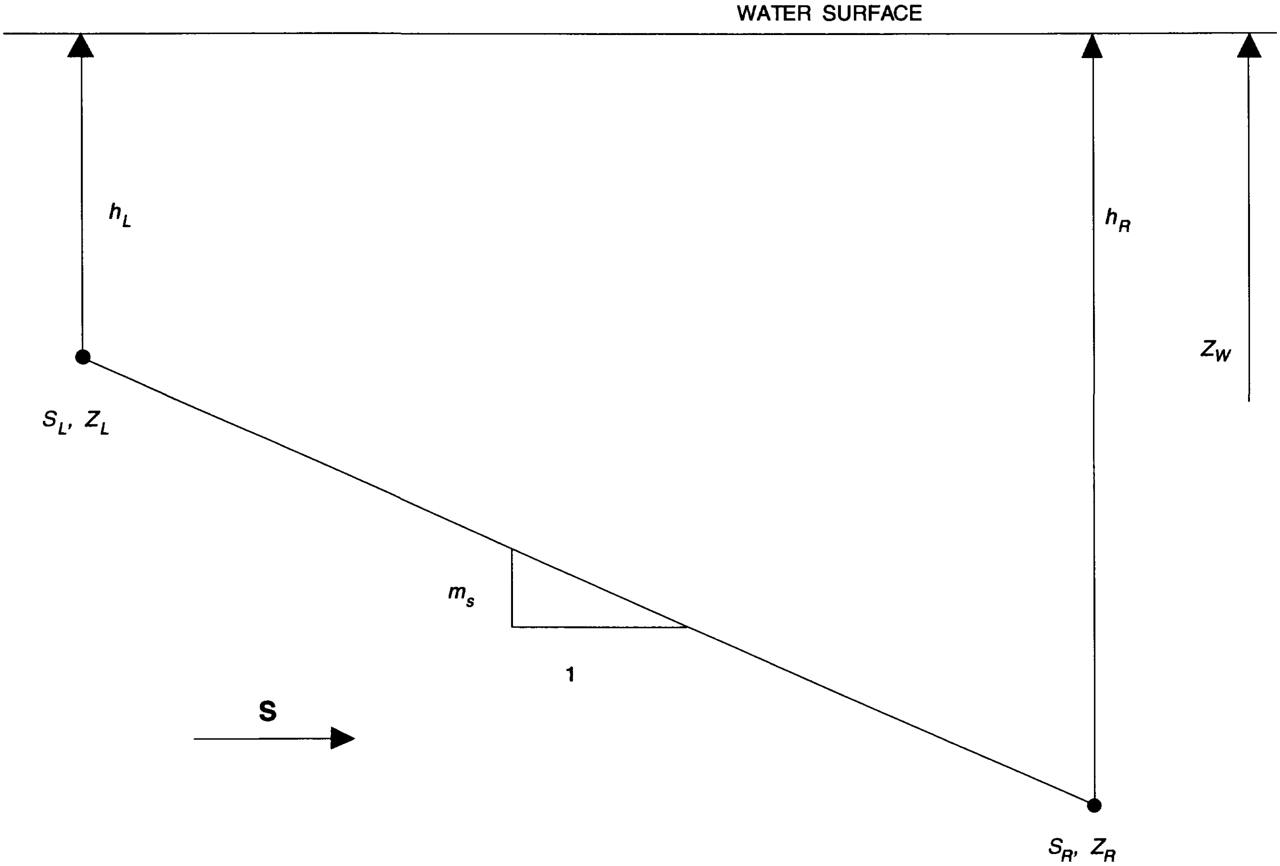
where $z$ denotes elevation and $s$ denotes lateral position (offset) in the cross section at the respective points $L$ and $R$. The elevation of a point on the boundary line at offset $s$ where $s_L \le s \le s_R$ is

$$z(s) = z_L + m_s(s - s_L), \tag{12}$$

and the local height of the water surface, $h$, is given by

$$h(s) = z_w - z(s) = h_L - m_s(s - s_L), \tag{13}$$

where $z_w$ is the elevation of the water surface. In each vertical denoted by $s$, it is assumed that the mean velocity, $v(s)$, is given by




**EXPLANATION**

| | |
|---|---|
| $S$ | HORIZONTAL OFFSET FROM CONTROL POINT |
| $Z$ | ELEVATION OF STATION RELATIVE TO THE DATUM FOR THE STREAM SYSTEM |
| $m_s$ | SLOPE OF THE CROSS-SECTION BOUNDARY IN THE LATERAL DIRECTION |
| $h$ | DEPTH FROM THE WATER SURFACE TO THE CHANNEL BOTTOM |
| $L$ | LEFT BOUNDARY OF SUBSECTION |
| $R$ | RIGHT BOUNDARY OF SUBSECTION |
| $Z_W$ | WATER-SURFACE HEIGHT |

**Figure 2.** Typical line segment for the **NEWBETA** option in the Full EQuations UTiLIties model.

$$V(s) = \frac{C_u}{n} R(s)^{2/3} S_A^{1/2}, \tag{14}$$

where $S_A$ is the appropriate slope (energy slope, $S_e$, or momentum slope, $S_f$) for the conservation principle considered, and the hydraulic radius is given by

$$R(s) = \frac{h(s)}{\sqrt{1+m_s^2}} . \tag{15}$$

The inclusion of the slope of the boundary line in equation 15 approximately represents the reduced velocity at shallow depths with sloping boundaries. For subsections with steep side slopes the hydraulic radius is substantially smaller than the depth when this approximation is applied. The friction or energy slope term does not appear in the final result for α and β because it is the same throughout the cross section and, thus, it is omitted from the following equations for notational convenience.

The following steps are applied in this method to estimate the flux coefficients and the critical-flow rate.

1. The flow rate above each line segment and below the water surface is computed by integrating the velocity given in equation 14 from $s_L$ to $s_R$. The sum of the flows for each line segment is computed to obtain the total flow for the cross section. The flow for a typical line segment, $Q_i$, is

$$Q_i = C\int_{s_L}^{s_R} [h_L - m_s(s-s_L)]^{5/3} ds , \tag{16}$$

where the subscript $i$ is omitted from the terms on the right-hand side to simplify the notation and

$$C_i = \frac{C_u}{n_i}\left(\frac{1}{\sqrt{1+m_{s_i}^2}}\right)^{2/3} . \tag{17}$$

If $m_s$ is not equal to zero, the integral in equation 16 is

$$Q_i = -\frac{3C}{8m_s}\left(h_R^{8/3} - h_L^{8/3}\right)s_A^{1/2} , \tag{18}$$

with a derivative of

$$\frac{dQ_i}{dz_w} = -\frac{C}{m_s}\left(h_R^{5/3} - h_L^{5/3}\right)s_A^{1/2} ; \tag{19}$$

whereas if $m_s$ equals zero (that is $h_L$ equals $h_R$), the integral of equation 16 is

$$Q_i = Ch_L^{5/3}(s_R - s_L) , \tag{20}$$

with a derivative of

$$\frac{dQ_i}{dz_w} = \frac{5C}{3}h_L^{2/3}(s_R - s_L) . \tag{21}$$

The total flow for the cross section, $Q$, then becomes

$$Q = \sum_{i=1}^{n_s} Q_i, \qquad (22)$$

with a derivative of

$$\frac{dQ}{dz_w} = \sum_{i=1}^{n_s} \frac{dQ_i}{dz_w}, \qquad (23)$$

where $n_s$ is the number of line segments below the water surface. This flow estimate is applied only for the estimation of the flux coefficients, and it is never applied for estimation of the conveyance of the cross section.

2. The flux of kinetic energy above each line segment and below the water surface is computed by integrating the local flux, and the fluxes are summed for each line segment to get the flux for the cross section. To simplify the notation, the factor of 1/2 has been dropped from the kinetic energy. The flux of kinetic energy, $F_{E_i}$, for a typical line segment is

$$F_{E_i} = \int_{S_L}^{S_R} h(s)\, V(s)^3 ds, \qquad (24)$$

where $V(s)$ is the flow velocity at offset s in the cross section.
Substituting for the water-surface height and velocity from equations 13 and 14 yields

$$F_{E_i} = C^3 \int_{S_L}^{S_R} [h_L - m_s(s - s_L)]^3 ds. \qquad (25)$$

If $m_s$ is not equal to zero, equation 25 simplifies to

$$F_{E_i} = -\frac{C^3}{4m_s}\left(h_R^4 - h_L^4\right), \qquad (26)$$

with a derivative of

$$\frac{dF_{E_i}}{dz_w} = -\frac{C^3}{m_s}\left(h_R^3 - h_L^3\right); \qquad (27)$$

whereas if $m_s$ equals zero, equation 25 simplifies to

$$F_{E_i} = C^3 h_L^3 (s_R - s_L), \qquad (28)$$

with a derivative of

$$\frac{dF_{E_i}}{dz_w} = 3C^3 h_L^2 (s_R - s_L) . \tag{29}$$

The total flux of kinetic energy for the cross section is

$$F_E = \sum_{i=1}^{n_s} F_{E_i}, \tag{30}$$

with a derivative of

$$\frac{dF_E}{dz_w} = \sum_{i=1}^{n_s} \frac{dF_{E_i}}{dz_w}. \tag{31}$$

3. The momentum flux is computed for each line segment and the fluxes are summed to obtain the total momentum flux for the cross section. The flux of momentum, $F_{M_i}$, for a typical line segment is

$$F_{M_i} = \int_{S_L}^{S_R} h(s) V(s)^2 ds. \tag{32}$$

Substituting for the depth and velocity from equations 13 and 14 yields

$$F_{M_i} = C^2 \int_{S_L}^{S_R} [h_L - m_s (s - s_L)]^{7/3} ds. \tag{33}$$

If $m_s$ is not equal to zero, equation 33 simplifies to

$$F_{M_i} = -\frac{3C^2}{10m_s}\left(h_R^{10/3} - h_L^{10/3}\right), \tag{34}$$

with a derivative of

$$\frac{dF_{M_i}}{dz_w} = -\frac{C^2}{m_s}\left(h_R^{7/3} - h_L^{7/3}\right); \tag{35}$$

whereas if $m_s$ equals zero, equation 33 simplifies to

$$F_{M_i} = C^2 h_L^{7/3} (s_R - s_L) , \tag{36}$$

with a derivative of

$$\frac{dF_{M_i}}{dz_w} = \frac{7C^2}{3} h_L^{4/3} (s_R - s_L) . \qquad (37)$$

The total flux of momentum for the cross section is

$$F_M = \sum_{i=1}^{n_s} F_{M_i}, \qquad (38)$$

with a derivative of

$$\frac{dF_M}{dz_w} = \sum_{i=1}^{n_s} \frac{dF_{M_i}}{dz_w}. \qquad (39)$$

4. The estimates of the flux coefficients and their derivatives are computed as

$$\alpha = \frac{A^2}{Q^3} F_E \qquad (40)$$

$$\beta = \frac{A}{Q^2} F_M \qquad (41)$$

$$\frac{d\alpha}{dz_w} = \frac{2ATF_E}{Q^3} - \frac{3A^2 F_E}{Q^4} \frac{dQ}{dz_w} + \frac{A^2}{Q^3} \frac{dF_E}{dz_w} \qquad (42)$$

$$\frac{d\beta}{dz_w} = \frac{TF_M}{Q^2} - \frac{2AF_M}{Q^3} \frac{dQ}{dz_w} + \frac{A}{Q^2} \frac{dF_M}{dz_w}. \qquad (43)$$

5. The critical flow rate is computed with equations 9 and 10. If the **NEWBETA** (sections 5.8 and 5.9) option is applied, the geometric mean of the values computed with equations 9 and 10 is determined if both values are defined. That is, the tabulated critical flow in table types 22 and 25 is $\sqrt{Q_M Q_E}$. If either of these critical-flow estimates is undefined, $Q_c$ is defined as

$$Q_c = \sqrt{\frac{gA^3}{T}} = A\sqrt{gA/T}. \qquad (44)$$

If the **NEWBETAE** (sections 5.8 and 5.9) option is applied, $Q_E$ is tabulated. If the **NEWBETAM** (sections 5.8 and 5.9) option is applied, $Q_M$ is tabulated.

An undefined critical flow has not been encountered in application of this method to more than 300 natural cross sections. The method can still be improved because the two estimates of critical flow can be substantially different and the computed values of the flux coefficients are constant for some channel shapes. The local flux coefficient for each vertical is assumed to be one in the current version (1997) of the method.

### 3.1.3 Correction Coefficients for Channel Curvilinearity

The static and dynamic characteristics described previously depend only on variation at a cross section. The correction coefficients for channel curvilinearity are weights to apply to integrands to compensate for the effects of stream curvature, and values of these coefficients depend on the variation of flow-line lengths between cross sections as well as variations at the cross sections. Dynamic characteristics affected by flow curvilinearity are the conveyance and the flux coefficients. The effect of curvilinearity on the cross-section hydraulic characteristics is outlined here. In typical applications of unsteady-flow analysis to curvilinear streams, the effects of channel curvilinearity are small, unless the channel meander loops are substantial. For example, through laboratory experiments Miller and Chaudhry (1989) found curved channels with compact cross sections and no overbank flow may be simulated with the conservation of momentum principle ignoring changes in direction. Thus, for practical simulation of unsteady-open-channel flow, if the cross sections are selected such that their hydraulic characteristics are representative of the reaches between cross sections, reasonably reliable simulations will be obtained. It is standard hydraulic-engineering practice to measure a cross section near the centroid of each bend to represent the hydraulic geometry of the meandering stream. Further discussion of the effects of channel curvilinearity are given in section 4.2 of the documentation report for the Full Equations model (Franz and Melching, 1997).

The correction coefficients for channel curvilinearity, $M_A$ and $M_Q$, are defined in equations 4 and 6 in Franz and Melching (1997) in terms of a limit involving the true volume of a slice of the channel. The equations defining $M_A$ and $M_Q$ are repeated here for convenient reference as

$$M_A(x, y_0) = \lim_{\Delta x \to 0} \frac{S_h(x - \Delta x/2, x + \Delta x/2)}{A(x, y_0)\,\Delta x} \tag{45}$$

$$M_Q(x, y_0) = \lim_{\Delta x \to 0} \frac{S_q(x - \Delta x/2, x + \Delta x/2)}{Q(x, y_0)\,\Delta x}, \tag{46}$$

where $S_h(x_1, x_2)$ is the correct volume of water between cross section at locations $x_1$ and $x_2$ for a given water-surface height, $y_0$, and $S_q(x_1, x_2)$ is the correct momentum content of the flow between cross sections at locations $x_1$ and $x_2$ for a given water-surface height, $y_0$. This slice of the channel is defined by placing cross sections at a distance of $\Delta x/2$ upstream and downstream from a point $x$ on the distance axis, where $\Delta x$ is the distance between cross sections. Every offset in a section has a flow line passing through it, and by definition each flow line is orthogonal to each cross section. Thus, $\Delta L(s)$ is defined as the distance between the two cross sections at the upstream and downstream faces of the slice at offset $s$. This incremental distance is dependent on the offset and varies with the offset but is independent of the local water-surface height, $h(s)$. The true volume of this slice becomes

$$S_h(x - \Delta x/2, x + \Delta x/2) = \int_{s_B}^{s_E} \Delta L(s)\,\bar{h}(s)\,ds, \tag{47}$$

where an implicit water-surface elevation, $z_w$, with a water-surface height of $y(x)$, is assumed, $\bar{h}(s)$ is the average local water-surface height in the two sections, and $s_B$ and $s_E$ are the starting and ending points for the top width in the section at $y(x)$. To include the possibility that the cross-section boundary is above the water surface at some point within the inundated limits, the local depth, $h(s) = z_w - z(s)$, becomes zero whenever $z(s) \geq z_w$. Substitution of the volume in equation 47 into the definition for $M_A$ in equation 45 yields

$$M_A[x, y(x)] = \lim_{\Delta x \to 0} \frac{1}{A[x, y(x)]} \int_{s_B}^{s_E} \frac{\Delta L(s)}{\Delta x} \bar{h}(s)\, ds. \tag{48}$$

In the limit $\bar{h}(s)$ approaches $h(s)$ . The term $\Delta L(s)/\Delta x$ is the ratio of an incremental distance along a flow line to the corresponding incremental distance along the axis. In the limit $\Delta L(s)/\Delta x$ becomes the derivative of flow line distance to axis distance. This derivative is the sinuosity of the channel and it may be denoted by $\sigma(s)$. As an example, a sinuosity of 2.0 for a flow line means that at that point the distance between adjacent cross sections will be twice the distance between adjacent cross sections at the axis. Substitution of these limits into equation 48 yields

$$M_A[x, y(x)] = \frac{1}{A[x, y(x)]} \int_{s_B}^{s_E} \sigma(s)\, h(s)\, ds, \tag{49}$$

where $h(s)ds$ is a differential of area, $dA$. Also, the integral in equation 49 encompasses the entire wetted area of the cross section. Therefore, equation 49 can be expressed as

$$M_A = \frac{1}{A} \int_A \sigma dA, \tag{50}$$

where integration is over area and the arguments for all the functions are dropped. Equation 50 is the same result as developed by DeLong (1989).

These same operations applied to equation 46 result in

$$M_Q[x, y(x)] = \frac{\int_{s_B}^{s_E} \sigma(s)\, q(s)\, ds}{\int_{s_B}^{s_E} q(s)\, ds}, \tag{51}$$

and

$$M_Q = \frac{1}{Q} \int_Q \sigma(s)\, dQ, \tag{52}$$

where $q(s)ds$ is the differential for the total flow, $dQ$. Equation 52 also is the same result as developed by DeLong (1989).

In order to compute $M_Q$, the local flow rate, $q(s)$, must be defined. It is estimated using the local conveyance function, $k(s)$, and the assumption that the decline in total energy-line elevation is constant along all flow lines that join two cross sections. The differential increment in the total energy-line elevation is $dz_e$. Further, if the differential increment of distance on the axis is $dx$ and the increment of distance on an arbitrary flow line is $dx^{(i)}$, then along an arbitrary flow line the local flow rate estimated in this manner is

$$q(s) = k(s) \sqrt{\frac{-dz_e}{dx^{(i)}}}. \tag{53}$$

Application of $M_Q$ requires knowledge of $q$ for a given location in the cross section and for a given decline of the elevation of the total-energy line as measured along the axis; not along some arbitrary flow line. Thus, the sinuosity is introduced by equating $dx^{(i)}$ to $\sigma(s)dx$, and substituting $\sigma(s)dx$ for $dx^{(i)}$ in equation 53 yields

$$q(s) = \frac{k(s)}{\sqrt{\sigma(s)}}\sqrt{\frac{-dz_e}{dx}} = \frac{k(s)}{\sqrt{\sigma(s)}}\sqrt{S_e}, \tag{54}$$

where $S_e$ is the energy slope as measured along the axis. Substitution of this definition of $q(s)$ into equation 51 then defines the correction coefficient for channel curvilinearity effects on momentum content as

$$M_Q[x, y(x)] = \frac{\int_{s_B}^{s_E} \sqrt{\sigma(s)}\, k(s)\, ds}{\int_{s_B}^{s_E} q(s)\, ds}. \tag{55}$$

The correction coefficients for channel curvilinearity and all the other hydraulic characteristics in the cross-section tables are computed in the CHANNEL command (section 5.2) in FEQUTL. $M_A$ and $M_Q$ are listed in tables of types 23, 24, and 25. In order to compute these characteristics for tabulation in a cross-section table, the sinuosity must be defined. Once sinuosity is defined for each cross section, equations 50 and 55 can be applied to compute the correction coefficients for any water-surface height desired. Two forms for the sinuosity are applied in FEQUTL: sinuosity that is piecewise constant (**PWC**) over one or more subsections of a cross section, and sinuosity that is piecewise linear (**PWL**) between flow lines. **PWC** sinuosity is utilized to represent the sinuosity in cross sections derived from the Hydraulic Engineering Center Water Surface Profiles model, HEC-2, (U.S. Army Corps of Engineers, 1990a) data files and other sources that provide two or more distances between adjacent cross sections. These distances are defined as the mean flow distance, for example, on the left overbank, in the main channel, and on the right overbank. Thus, a flow line is not defined but rather an average distance is defined that represents the effect of all the flow-line distances between successive parts of adjacent cross sections. **PWL** sinuosity is utilized when specific flow lines are given and it is reasonable to assume that the sinuosity varies linearly between flow lines in a cross section. For **PWC** sinuosity, the mean flow lengths are treated as if measured from a line that is continuous through all cross sections. The computation of sinuosity is the same for both **PWC** and **PWL** variation with this interpretation; only the interpretation of the final values differs. For **PWC** variation, the sinuosity is the constant value that applies to the part of the cross section containing the mean flow line. For **PWL** variation, the sinuosity applies only at the intersection between the flow line and the cross section. Values of sinuosity for the cross section between flow lines are determined by linear interpolation.

Information is required in FEQUTL on two or more flow lines that pass through the cross sections for which function tables are being computed. The cumulative distance along each flow line to each cross section is input to or computed in FEQUTL from data supplied by the user. The cumulative distance along the *i*th flow line at the *j*th cross section is denoted as $L_{ij}$. One of the flow lines will be the selected distance axis, which is specified by the user. The index for the axis is denoted by the subscript $a$ in place of the index $i$; that is, $L_{aj}$ is the distance to the *j*th cross section on the distance axis. For a given flow line, the distance to successive cross sections is considered as a function of the distance to these same cross sections on the axis. This is the flow-line distance function. The sinuosity is the first derivative or slope of the flow-line distance function. Therefore, computation of the sinuosity is equivalent to computation of the first derivative of this function at each cross section. Thus, the sinuosity at the *j*th cross section on the *i*th flow line is

$$\sigma_{ij} = \frac{dL_{ij}}{dL_{aj}}. \tag{56}$$

Computation of derivatives from crude numerical data, such as flow-line distances, can result in special problems. Four options are available in FEQUTL to define the sinuosity and give the user a large measure of control in the computation. These options are listed below.

1. A value of sinuosity is input by the user for one or more cross sections.
2. The sinuosity is computed from the first derivative of a cubic spline fitted to the points on the flow-line distance function in $L_{ij}$ for a given $i \neq a$. The sinuosity of the axis flow line is always 1.0. An end condition is needed for the cubic spline. The user can supply the sinuosity as an end condition, or the end condition will be taken as a zero value for the rate of change of sinuosity with distance along the flow line. The second derivative of the flow-line distance function is made zero at that point.
3. The sinuosity is computed by fitting a parabola to three consecutive points on the flow-line distance function and taking the derivative of this fitted parabola as an estimate of the sinuosity at the central point.
4. The sinuosity is computed by fitting a straight line between adjacent points on the flow-line distance function. This gives two estimates of sinuosity at each section on the interior of the stream segment considered, that is, for $j = 2,..., n_c - 1$ where $n_c$ is the number of cross sections. At these points, the sinuosity is computed as the arithmetic average of the two sinuosities. Special options also are available to set the sinuosity to be one of the two values. These options are sometimes needed when the cubic-spline option is utilized to force special sinuosity values in linear parts of the channel.

The options can be mixed so that, for example, the linear and parabolic options can define the end conditions for the cubic spline. Standard numerical techniques for the operations outlined are applied to compute the sinuosity as a derivative of the flow-line distance function. Details of these numerical techniques are not given here. The methods utilized for the cubic splines are described in the monograph by Ahlberg and others (1967, p. 9-16), and the definition of the cubic splines in terms of first derivatives is applied because it fits with the goal of computing the sinuosity.

Once the sinuosities at each flow line and cross-section intersection are computed, the sinuosity function at each cross section, either **PWC** or **PWL**, must be defined. For computation, offsets for the boundaries of the subsections for the **PWC** variation and offsets at each flow line for **PWL** variation are required. These offsets are specified by the user. Extrapolation is applied if needed to extend the definition of sinuosity to whatever offset is required in the computations.

Any hydraulic characteristic that involves the distribution of the flow across the section will be affected by the sinuosity through $q(s)$. This includes the conveyance and the flux-correction coefficients. The following adjustments apply if the sinuosity is **PWC**. Considering the effects of sinuosity, equations 6, 7, and 8 become

$$K = \sum_{i=1}^{m} \frac{K_i}{\sqrt{\sigma_i}} \qquad (57)$$

$$\alpha = \frac{A^2}{K^3} \sum_{i=1}^{m} \alpha_i \frac{K_i^3}{A_i^2 \sigma_i^{3/2}} \qquad (58)$$

$$\beta = \frac{A}{K^2} \sum_{i=1}^{m} \beta_i \frac{K_i^2}{A_i \sigma_i}, \qquad (59)$$

where $\sigma_i$ is the sinuousity applicable to the $i$th subsection in the cross section. The only change in these equations from equations 6, 7, and 8 is the inclusion of the proper power of the sinuosity to reflect the change in flow-rate distribution.

The equations for computing the correction factors for curvilinear elements are then

$$M_A = \frac{1}{A} \sum_{i=1}^{m} \sigma_i A_i, \tag{60}$$

and

$$M_Q = \frac{1}{K} \sum_{i=1}^{m} \sigma_i K_i. \tag{61}$$

The integrals in the case of **PWL** sinuosity are more complex, and closed-form expressions are long and complicated. Therefore, numerical integration is applied in FEQUTL for the integrals involved. The approach is similar to that used for **NEWBETA**. In this case, however, the boundary points input by the user are augmented with the points on the boundary of the cross section wherever a flow line is placed. This augmented list is then placed in ascending order of offsets with all duplicate points deleted. This process results in a series of distinct coordinate points on the boundary of the section. Over the interval defined by consecutive points in this series, both the local water-surface height, $h(s)$, and the sinuosity, $\sigma(s)$, are piecewise linear functions of cross-section offset, $s$. With the modification that the subscripts $L$ and $R$ refer to the augmented boundary point series, equations 11, 12, and 13 give the slope of the boundary, the boundary elevation, and the local water-surface height, respectively, for any point on any submerged line segment. As previously discussed, the meaning of the subscripts $L$ and $R$ is extended to include the intersection point for the water surface with the boundary.

The slope of the sinuosity for a submerged line segment, $\mu$, on the cross-section boundary is defined as

$$\mu = \frac{\sigma_R - \sigma_L}{s_R - s_L}, \tag{62}$$

and

$$\sigma(s) = \sigma_L + \mu(s - s_L). \tag{63}$$

In terms of the constant, $C$, defined in equation 17, the local conveyance is

$$k(s) = Ch(s)^{5/3} = C[h_L - m_s(s - s_L)]^{5/3}, \tag{64}$$

and the local flow rate $q(s)$ is

$$q(s) = \frac{k(s)}{\sqrt{\sigma(s)}} \sqrt{S_f}. \tag{65}$$

The local velocity $V(s)$ is given by $q(s)/h(s)$.

The functions for the local sinuosity, conveyance, flow rate, and velocity are defined and continuous over any nonvertical, submerged line segment of the cross-section boundary that faces upward. Cross sections with converging sides are not permitted in these computations, and any vertical line segments are skipped because their lengths are not considered in the computed values. Three different functions and three different integrands are required in **NEWBETA** and related options. These functions define the flow rate, the flux of kinetic energy, and the flux of momentum above each submerged line segment; and, when combined with the derivatives of these functions with respect to the water-surface elevation, the information required in **NEWBETA** and related options is complete. The flows and fluxes as shown here do not contain the friction slope because it is a common factor to both the denominator and numerator of the final ratios of interest. Thus, the flows and fluxes are directly proportional to the same power of the friction slope with the power depending on the equation involved. The notation is the same as in equations 16, 24, and 32. The integrands and integrals involved are the following.

1. Flow above the line segment:

$$Q_i = \int_{S_L}^{S_R} q(s)\,ds \tag{66}$$

$$\frac{dQ_i}{dz_w} = \frac{5}{3}\int_{S_L}^{S_R} v(s)\,dx \tag{67}$$

2. Kinetic-energy flux above the line segment:

$$F_{E_i} = \int_{S_L}^{S_R} h(s)\,v(s)^3\,ds \tag{68}$$

$$\frac{dF_{E_i}}{dz_w} = 3\int_{S_L}^{S_R} v(s)^3\,ds. \tag{69}$$

3. Momentum flux above the line segment:

$$F_{M_i} = \int_{S_L}^{S_R} h(s)\,v(s)^2\,ds \tag{70}$$

$$\frac{dF_{M_i}}{dz_w} = \frac{7}{3}\int_{S_L}^{S_R} v(s)^2\,ds. \tag{71}$$

The values for each line segment are summed using equations 22, 23, 30, 31, 38, and 39 and the section values are computed with equations 40 through 43.

The numerical integration is done on the basis of a low-order Gauss rule. The same rule is applied for all the integrals so that each flux and its derivative are consistent. The correction factors for channel curvilinearity also are computed from equations 49 and 55 with the same Gauss rule.

If the **NEWBETA** options and **PWL** sinuosity are requested, no segmentwide value of sinuosity is available to adjust the subsection conveyance as required in equation 57. A local-conveyance-weighted mean of $1/\sqrt{\sigma(s)}$ within each subsection is computed and applied to adjust the subsection conveyance for the effect of sinuosity to make this adjustment consistent with the other values as defined under **NEWBETA**.

### 3.1.4 Interpolation of Cross Sections

Cross-section measurements are not always made where cross-section information is needed. Therefore, interpolation of cross-section characteristics at points between measured cross sections may be done in FEQUTL and FEQ. An intermediate cross-section boundary for the **FLOWLINE** option could be computed in FEQUTL. This could be done for the boundary shape and size by linearly interpolating along flow lines. However, problems result in interpolation of the subsections and roughness in each subsection. A smooth variation in hydraulic characteristics between cross sections is desired. Subsections are discrete units and fractional subsections are not possible. In order to define a meaningful intermediate cross section by direct interpolation for points on the boundary, some new method for describing the distribution of roughness and subsequent computation of local conveyance must be developed because of the limits imposed by the crude methods available for description of the frictional characteristics of natural open channels. Until such a method is developed, direct interpolation for the boundary of an intermediate cross section is not reasonable.

A different approach can be utilized for the direct interpolation of the hydraulic characteristics of intermediate cross sections. The hydraulic characteristics may be interpolated in the cross-section table and without interpolation of the cross-section boundary. This permits the conveyance and other values that depend on the subsection boundaries to vary smoothly between measured cross sections. In the interpolation of intermediate cross-section tables in FEQUTL and FEQ the following rules are applied.

1. The elevations along the distance axis (the profile of the minimum elevation in the cross sections) vary linearly with distance between cross sections.
2. The top width varies linearly with distance between cross sections when the water-surface height is held constant. This also means that the area and first moment of area vary linearly with distance between cross sections.
3. The square root of conveyance, the momentum-flux correction coefficient, $\beta$, the energy-flux correction coefficient, $\alpha$, the critical flow, and the correction coefficients for channel curvilinearity vary linearly with distance between cross sections when the water-surface height is held constant.

If possible, the locations of measured cross sections should be selected such that these rules of interpolation are appropriate.

The tabulated water-surface-height values in the interpolated tables consist of the merged series of water-surface heights in the defining cross-section tables. In this way, no additional approximations are introduced in the intermediate cross sections. In FEQ simulation, the interpolation is restricted to be within the boundaries of a single branch, whereas in FEQUTL computation, the interpolation is restricted only to the confines given in the **XSINTERP** command (section 5.24) and is not limited to a single branch. Therefore, it is possible to define an interpolated cross section in FEQUTL computation to serve as the originating or terminating cross section for a branch in FEQ simulation.

## 3.2 Channel Expansions and Contractions

The expansions and contractions considered in this section are large enough that critical controls may be present or are located at a junction among branches. The eddy losses at minor variations in channel shape and size can be represented within a branch (see section 5.5.3 in the documentation report for the Full Equations model (Franz and Melching, 1997)). The expansions and contractions considered here may result from both natural and constructed changes of channel cross-sectional shape.

A 2-D table of type 14 is computed in the **EXPCON** command (section 5.7) in FEQUTL to approximate the flow through a transition in channel cross-sectional shape. The transition is defined by an upstream cross section, a downstream cross section, the respective bottom elevations, the distance between the cross sections, and parameters related to the computation of friction and shock losses. Flow through a channel transition is a complex phenomenon, and evaluation of losses is difficult. The shock losses are approximated in **EXPCON** by a constant fraction of the difference in the true velocity heads where the constant differs for contracting and expanding flows.

This approximation has been frequently used in hydraulic engineering, and most handbooks have recommended ranges for the loss coefficients. The approximation is crude, but no suitable replacement is readily available.

The principal difficulty with flows in transitions is that the velocity distribution changes from section to section in a manner only slightly affected by the channel boundary. This is especially true of expanding flows with possible channel-wall-separation effects and the attendant, inherent instability in the velocity distribution. This unpredictable variation in velocity distribution makes estimation of the losses difficult. Simplifying assumptions are made in the **EXPCON** command so that flow computation is possible. Some of the major assumptions are given below.

1. The velocity-head (energy-flux) correction factor, $\alpha$, for both the upstream and downstream sections, is a function of depth in the section and is computed in the cross-section table commands in FEQUTL. This means the velocity distribution is determined by the boundary geometry alone. This is only approximately correct and may be substantially incorrect if the transition is an expansion. However, little other choice is available for reasonably determining flow through the transition without making each transition a research project.
2. The pressure distribution at both the upstream and downstream cross sections is hydrostatic. This should be satisfied so long as the sections are away from regions with pronounced vertical or horizontal curvature (or acceleration).
3. The losses resulting from boundary friction can be estimated by a mean friction slope multiplied by the distance between the two sections. Several options are available for computing the mean friction slope. The user also may request that boundary-friction losses be ignored in the computations. Given the uncertainties of the loss estimation, ignoring the boundary-friction losses is often a reasonable option.
4. Control by critical depth will be located at either the upstream section or the downstream section. The possibility that the control is at some intermediate point is ignored. Determination of the location of the actual control point in a transition is difficult, and again the uncertainties inherent in the calculation of flows in transitions do not justify the additional effort and assumptions required to determine the location of a control at an intermediate point. In any case, it is unlikely that the control would remain at an intermediate point over more than a narrow range of flows. Thus, although such a control is possible, it is unlikely to practically affect flows at the level of detail of interest in applications of FEQ.
5. Critical flow is as defined in the cross-section tables computed in FEQUTL. The critical-flow value is affected by the choice of parameters when the cross-section table is computed. Application of the **NEWBETA** option (sections 5.8 and 5.9) will produce results that differ from those produced without its application. A critical-flow value that reflects the effect of velocity distribution is computed in the **NEWBETA** option. In all other cases, critical flow is computed as if the velocity distribution were uniform across the cross section and $\alpha = \beta = 1$. Thus, if the channels under consideration are not compact, then **NEWBETA** should be applied. The critical flow in closed conduits with flow transitions must be limited by application of the **QCLIMIT** command (section 5.18) before the **EXPCON** command is invoked.
6. Critical flow is meaningful in a flow transition, and the water-surface curvature introduced may invalidate the assumption of hydrostatic pressure distribution. However, the transitions often are short and the often-substantial water-surface curvature resulting from critical flow in the transition may not affect the computations in FEQUTL. A further problem is that critical flow may result at the downstream section even though the flow is expanding in a situation where the flow area at the critical section is larger than the flow area upstream. If the cross-section shapes were the same, then this situation would not be possible. However, changes in cross-section shape also may be simulated in **EXPCON**. When the cross-section shape changes in the transition, critical flow can result at the section with the larger area in FEQUTL computations.
7. Computation of the losses in the transition in channel cross-sectional shape as a fraction of the difference in velocity heads between upstream and downstream sections applies in the limit as flow becomes critical. The formula of head loss as a function of velocity-head difference was derived for subcritical flows not close to critical because most designs of transitions in cross-sectional shape avoid flows near critical.
8. The loss formula can be smoothed to represent losses when the flow areas are nearly the same but the cross-section shapes are not. The uncorrected formula results in a zero loss at that point. Some losses must result because the change in shape can be large even though the flow areas are the same. This illustrates a deficiency

of applying any formula that depends on velocity or velocity head differences alone. Again, little alternative is available to this approach, and smoothing over this region as outlined in the following section results in losses that are consistent with the simple loss formula.

### 3.2.1 Governing Equations for Expansions and Contractions

The principal equation used to estimate the flows in a transition is

$$y_1 + z_{m_1} + \frac{\alpha_1 Q^2}{2gA_1^2} = y_2 + z_{m_2} + \frac{\alpha_2 Q^2}{2gA_2^2} + (x_2 - x_1)\frac{Q^2}{\bar{K}^2} + k_{ec}\left|\frac{\alpha_2 Q^2}{2gA_2^2} - \frac{\alpha_1 Q^2}{2gA_2^2}\right|, \tag{72}$$

where $z_m$ is the elevation of the minimum point, $\bar{K}$ is the mean conveyance, $x$ is the location of the section along the channel, and $k_{ec}$ is the loss factor depending on the sense of the transition. The sense of the transition denotes whether the flow is expanding or contracting. Another convenient and perhaps preferable description is to define the flow in the transition as either accelerating or decelerating. The flow is accelerating in a contraction and decelerating otherwise. The subscripts denote the section with section 1 the upstream section and section 2 the downstream section of the transition.

Equation 72 is applied to critical flow despite the potential problems outlined previously. The need to compute critical flow results primarily from the requirement for a consistent flow in FEQ simulations. Therefore, the flow relations must include the possibility of critical control even though the user believes such flow will not result. The purpose of modeling is to understand the behavior of a proposed or real stream system and to make reasoned estimates for conditions for which no data are available (for example, design conditions and extreme conditions for planning scenarios). Simulation of these conditions may unintentionally impose flows and depths that result in critical control at one or more locations where such a control is possible. If FEQ does not include that possibility, the computations either will fail for some unknown reason or will yield an unreasonable result because the control present in the structure is not simulated. Furthermore, if such a control appears unavoidable, some change in the physical structure should be made so that critical flow can be estimated more accurately. If this is not possible, a physical model must be constructed to define the flow and its characteristics at that location in the stream.

Consistent and reasonable estimates of critical flow, within the bounds of 1-D analysis, are required. For those cases in which critical flow is difficult to define, assumptions must be made as needed to produce consistent relations for the flow through the transition. The assumptions applied in FEQUTL computations of flow in transitions have been described in this section.

### 3.2.2 Expansion-Contraction Losses

The computation of expansion-contraction losses (eddy losses or shock losses) is approximate and uncertain. In general, the loss fraction for expanding flows commonly is considerably larger than for contracting flows. No problems result if the sense of the transition never changes. However, when the sense of the transition changes, patterns of flow may result such that the velocity head change is small, but the flow undergoes a major change in section shape. A computational point may result in the flow simulation where the velocity heads on each side of the transition are the same and no energy loss will be estimated with equation 72. The user has the option of requesting smoothing of the loss formula near this point to provide some loss at this point.

The loss term can be exactly computed as

$$k_{ec}\left|\frac{\alpha_2 Q^2}{2gA_2^2} - \frac{\alpha_1 Q^2}{2gA_2^2}\right| = f_{ec}\left(\sqrt{\alpha_2}V_2 - \sqrt{\alpha_1}V_1\right)\frac{\sqrt{\alpha_2}V_2 + \sqrt{\alpha_1}V_1}{2g}, \tag{73}$$

where $V$ is the average velocity in the cross section (=$Q/A$). The function, $f_{ec}(X)$, is defined as $Xk_A$ when $X \geq 0$ and as $-Xk_D$ when $X < 0$, where $k_A$ is the loss coefficient for accelerating (contracting) flows, $k_D$ is the loss coefficient for decelerating (expanding) flows, and $X$ is the difference in the product of the velocity and the energy-flux correction coefficient from the downstream section to the upstream section (difference in the rescaled velocities). For equation 73 to be valid for both transition senses, $f_{ec}(X)$ must be greater than or equal to zero. No information is available on the loss coefficients when the kinetic-energy-flux correction factor is large. In equation 73, it is assumed that the loss should be proportional to the difference in the true velocity head and not in the nominal velocity head. The sense of the loss is assumed to change at the zero difference point between the rescaled velocities, the argument to the function $f_{ec}$. Smoothing this function when the argument is near zero will result in a loss when the difference in velocity heads is zero.

A small, positive value of velocity difference, denoted by $\Delta V$, is specified by the user to define an interval, $[-\Delta V, \Delta V]$. Over this interval, a cubic polynomial is fitted such that the value of the function and its derivative is matched by the polynomial and its derivative at the ends of the interval. Under these conditions, the coefficient on the cubic term in the polynomial vanishes and a parabolic transition over the interval is obtained, yielding

$$f_{ec}(X) = \Delta V\left[(k_D + k_A)\left(\frac{X + \Delta V}{2\Delta V}\right)^2 - k_D\frac{X + \Delta V}{\Delta V} + k_D\right]. \tag{74}$$

This smoothing procedure yields a function with a continuous first derivative over the entire range. Without smoothing, the derivative of $f_{ec}$ is discontinuous at the origin. At the origin, the point of zero loss without smoothing, the smoothed function yields

$$\Delta V\frac{k_D + k_A}{4}.$$

This means that, when the velocity difference is zero, the loss is estimated to be the same as the loss that would result from a velocity difference of $\Delta V$ and a loss coefficient that is one-half the average of the two loss coefficients.

### 3.2.3 Mean Conveyance for the Expansion or Contraction

The friction losses defined in equation 72 depend on the method for computing a mean conveyance. The mean conveyance is defined as a function of an averaging parameter, $a$, as

$$\bar{K}(a) = \left[\frac{K_1^a + K_2^a}{2}\right]^{1/a}. \tag{75}$$

The generalized mean for two values is given by equation 75. The mean values obtained as $a$ varies over its range are

$$\lim_{a \to \infty} \bar{K}(a) = \max(K_1, K_2) \tag{76}$$

$$\bar{K}(1) = \frac{1}{2}(K_1 + K_2) \tag{77}$$

$$\lim_{a \to 0} \bar{K}(a) = \sqrt{K_1 K_2} \tag{78}$$

$$\bar{K}(-1) = \frac{2(K_1 + K_2)}{K_1 K_2} \tag{79}$$

$$\lim_{a \to -\infty} \bar{K}(a) = \min(K_1, K_2) \ . \tag{80}$$

Equation 77 gives the arithmetic mean, equation 78 gives the geometric mean, and equation 79 gives the harmonic mean of the two end-point conveyances. No established rules are available regarding which mean value to apply. The geometric mean is preferred in many cases and may be a reasonable first approximation.

### 3.2.4 Outline of Solution Process for Expansions and Contractions

The user specifies a series of downstream piezometric heads to define the 2-D table of type 14. The head is measured from the maximum of the two bottom elevations for the cross sections at each end of the transition. For each downstream head, the upstream piezometric head resulting in critical flow at either cross section must be computed with the **EXPCON** command (section 5.7). This defines the smallest critical flow that can result for the given downstream head. The upstream piezometric head is computed as a function of downstream head and partial free flow for a series of partial free flows (critical flow is the free flow) until the partial free flow is zero. When the partial free flow is zero the two heads are equal. Each stage of the computations involves an iterative solution.

A control may result at either cross section and the control may shift as the flow levels change. An extensive search is made in **EXPCON** computations for a control at each of the cross sections, if necessary. The validity of this control is checked in **EXPCON** computations. For a control to be valid, the flow must be critical at one section and subcritical at the other section. It may be that no control can be found. Normally, this problem can be solved by adjustment of the friction losses. In some cases, the addition of a small friction loss allows a control to be found in the computations. In other cases, the reduction or elimination of friction loss allows a control to be found in the computations.

Special care must be applied if a closed conduit is present in the flow transition; for example, a stream directed underground through a long, closed conduit of substantially different cross-sectional area. Critical flow is undefined when a closed conduit is flowing full. The introduction of a hypothetical slot in the top of the conduit allows a hypothetical, equivalent free surface to be simulated to account for pressurized flow, but leads to a critical flow, which commonly is many times larger than any flow that may result in the conduit. This results in unrealistic upstream heads in the computations. These large heads cause only a small part of the table to be utilized in FEQ simulations. To avoid this unrealistic outcome, the **QCLIMIT** command (section 5.18) should be applied to the closed-conduit cross section or cross sections before **EXPCON** is invoked for those sections. The critical flows tabulated in the cross-section table are modified in **QCLIMIT** so that the maximum value is more realistic, although arbitrary. For accurate and reliable simulation, the maximum flow assigned to the critical flow when the closed conduit is full must be somewhat larger than the maximum flow likely to result in the conduit.

## 3.3 Channel Ratings for Bypass Channels

Flow at a bridge or a culvert often involves multiple flow paths when the water levels are high enough to overflow the bridge. Water may flow through the structure, over the structure, and (or) around the structure in the flood plain of the stream. If the flood plain is crossed by an embankment leading to a road crossing of the stream (culvert of bridge), then this embankment serves as a broad-crested weir. The flow over the road can be included in the flow table, but if the flow in the flood plain is large, multiple flow paths should be simulated. Studies of friction losses for flow through bridges and culverts have shown that an important factor is the degree of contraction that results for the water flowing through the structure opening. This may be only a small part of the water in the stream at flood stage. Therefore, careful division of the flow into (1) the flow through and directly over the structure and (2) the flow around the structure through the flood plain increases the reliability of the estimates of friction losses resulting at the structure.

The FEQUTL command, **EMBANKQ** (section 5.6), may be applied to compute the flow over a roadway or an embankment. This is discussed in section 4.3. In some cases, however, the approaches to the road crossing are essentially at the same level as the surrounding terrain. This often is true in parks and golf courses. The roadway then does not form a meaningful weir. In this case, the flow in the flood plain is flow in a wide open channel with the roadway constituting part of the boundary roughness, and the slope of this channel is typically mild, zero, or adverse. If the slope of the short bypass channel was steep, then the roadway could be simulated as an embankment weir. The **CHANRAT** command (section 5.3) in FEQUTL is designed to compute a flow relation for application in FEQ in this case. A 2-D table of type 13 is computed in **CHANRAT** for the flow in a short, prismatic channel with a mild, zero, or adverse slope. The rating for the flow through the channel, as a function of the upstream water-surface elevation and the difference in water-surface elevation, is given in this type 13 table. The flow is assumed to be subcritical at all levels. Furthermore, the table is only computed for one flow direction. If bidirectional flow might result, then two separate **CHANRAT** commands are needed to compute the two tables required to represent the bidirectional flows.

### 3.3.1 Governing Equation for Channel Ratings

The bottom slope, channel length, and cross-section table number are specified by the user, and the flow and steady-flow profile through the channel are computed in **CHANRAT** for each of a series of user-supplied upstream water-surface elevations for a range of downstream water-surface elevations specified as partial free drops. The equation governing the steady-flow profiles is

$$\frac{dx}{dy} = \frac{1 - \boldsymbol{F}^2}{S_0 - S_f}, \qquad (81)$$

where $\boldsymbol{F}$ is the Froude number and $S_0$ is the slope of the bottom with a drop in the $x$-direction taken as positive.

### 3.3.2 Outline of Solution Process for Channel Ratings

The governing equation is integrated numerically in **CHANRAT** by utilizing an adaptive Simpson's rule routine. The integral is computed to a user-supplied error tolerance such that the length of the water-surface profile between two depths on the profile is accurately determined. The solution process is as follows.

1. The free flow and the drop to free flow are computed for the given upstream head. The free flow is critical flow at the downstream end of the channel and the drop to free flow is the difference between the water-surface elevations at the upstream and downstream ends of the channel when the flow is critical at the downstream end. The secant method is applied to make the computed length of the profile nearly match the length of the channel, assuming that the flow is critical at the unknown downstream water-surface height.
2. The submerged flow is computed for each of a series of downstream water-surface heights that are greater than critical depth. In this case, the upstream and downstream heads are fixed and the flow is unknown. The secant method is applied to determine the flow for which the computed profile length closely matches the length of the channel.

In these computations of free and submerged flow, flow conditions close to normal depth should not be computed because the derivative, $dx/dy$, becomes unbounded. The vertical slope at critical depth is substituted for a vertical slope at normal depth in direct integration. Two input parameters, **NDDABS** and **NDDREL**, are used in **CHANRAT** to control how close the computations may approach to normal depth. The first parameter is the allowable absolute deviation from normal depth and the second is the allowable relative deviation from normal depth. The parameter value resulting in the closest approach to normal depth is applied in the computations. For a channel with mild slope, the stopping water-surface height, $y_s$, for the computation of the profile length in **CHANRAT** is computed as

$$y_s = y_n \pm \min(\textbf{\textit{NDDABS}}, [1 - \textbf{\textit{NDDREL}}]\, y_n) , \tag{82}$$

where $y_n$ is the normal depth (water-surface height) for the given flow, and the plus sign is applied if the current profile is above normal depth, and the minus sign is applied if the current profile is below normal depth.

The flow will be computed as normal flow if the computed profile length between the water-surface height at the downstream end and the stopping water-surface height when the flow is normal is less than the length of the channel. This can result for small upstream heads. These complications are not considered if normal depth cannot result. Thus, the computations proceed more rapidly if the bottom slope is zero or adverse and normal depth cannot result.

# 4. APPROXIMATION OF HYDRAULIC CHARACTERISTICS OF CONTROL STRUCTURES

Function tables that describe the hydraulic characteristics of a variety of control structures are computed in FEQUTL. The following sections outline the methods used in computing these characteristics.

## 4.1 Bridges

The Water-Surface Profile Computations (WSPRO) computer model described in Shearman (1990) and Shearman and others (1986) is applied in FEQUTL to compute a description of the hydraulics of bridges. A set of commands is provided in FEQUTL to assist the user in creating a 2-D table of type 14 in which the head upstream from the bridge is a function of the downstream head and partial free flow through the bridge for application in FEQ simulation. Head is the water-surface elevation less the elevation of the datum for the bridge. This approach was taken to avoid the extensive effort required to include the WSPRO methods in FEQUTL. WSPRO, FEQUTL, and FEQ must be applied and preferably well known by the user to simulate flow through bridges. WSPRO software is widely distributed and is in use by several organizations.

WSPRO is applied to compute multiple water-surface profiles through the structure to define the range of flows and downstream and upstream heads expected during unsteady-flow simulation. This means that 100 to 400 profiles may be required to properly define the table of type 14. Three commands are provided in FEQUTL to make the process of defining these profiles easier.

Application of the WSPROX command (section 5.23) results in extraction of cross-section data from a WSPRO input file and reorganization of these data into FEQXEXT format (section 5.9) for later computation in FEQUTL. The user also can request that the cross-section tables be computed in FEQUTL directly without the intermediate step of placement in the FEQXEXT format. The WSPROX command is used to extract cross sections from available WSPRO input. The cross sections of interest are those required in both WSPRO and FEQ to represent the hydraulics of bridges. The approach and exit sections for the bridge are required in both WSPRO and FEQ. The approach section is usually one bridge-opening width upstream from the bridge. If spur dikes are present, the approach section is one spur-dike-opening width upstream from the opening of the spur dikes. The exit section from the bridge is about one bridge-opening width downstream from the bridge and not at the downstream face of the bridge. Shearman (1990) provided details on the selection of the approach and exit sections. The approach section will be at the downstream end of the branch upstream from the bridge and the exit section will be at the upstream end of the branch downstream from the bridge in the stream-network schematization applied in FEQ. In general applications of FEQUTL, WSPROX may be used to convert all cross-section data from a WSPRO input file into function tables for use in FEQ simulation.

The cross sections between the approach and exit section required in WSPRO are not used in the FEQ model. The effects of those cross sections are implicit in the type 14 function table describing the hydraulics of the bridge. This table must describe the relations among three quantities: the water-surface elevation in the approach section, the water-surface elevation in the exit section, and the flow between these two cross sections. Flow through bridge openings, flow through culverts, and flow over the roadway are calculated in WSPRO. Any of these flow paths can appear in the WSPRO description of the structure. The resulting function table will list the information required in FEQ to simulate the hydraulics between the approach and exit sections of the bridge.

WSPRO is applied to compute the water-surface elevation in the approach section given a series of flows and water-surface elevations in the exit section. These water-surface elevations and flows are placed in a 2-D table of type 14. The water-surface elevation at the approach section for a range of flows must be computed in WSPRO, for each water-surface elevation in the exit section. The flow range must include all flows expected for each exit-section water-surface elevation. The range of flows that must be defined depends on the nature of the flows at the bridge. For example, if the bridge is not subject to backwater effects, the range of flows can be narrow, only including the possible range of flows at a given elevation resulting from variations in water-surface slope as a flood wave passes. Conversely, if the bridge is subject to substantial backwater effects, such as resulting from a gated spillway on a dam, the range of flows must be large. The maximum flow of the range of flows is treated in FEQ simulation as a free flow (free of backwater effects). This will not be true in general because the free-flow limit for the structure cannot be defined in WSPRO computations. This means that the maximum flow in the table for each exit-section water-surface elevation must be larger than any flow that may be computed for that elevation during the unsteady-flow simulation. If a larger flow is computed during simulation than is in the table, flow through the bridge will be simulated as free flow and the water-surface elevations in the table describing the hydraulics of the bridge will be erroneous. The range of flows needed for each exit-section water-surface elevation must be established by the user with careful consideration of these requirements. The user must carefully check the computed downstream heads and flow rates at bridges to ensure that the maximum flow tabulated for each exit-section water-surface elevation was not exceeded.

The WSPROQZ command (section 5.21) can be used for setting the range of flows for a series of exit-section (downstream) water-surface elevations. The user provides the series of downstream water-surface elevations as well as information that defines the maximum flow rate for each elevation. This information can be a flow value, a normal-depth rating computed using the exit cross section and a user-supplied friction slope, or a critical-flow cross section. The user also supplies the smallest partial free flow to compute in the table. By selecting a friction slope larger than is possible for the bridge location, the user can force the maximum flow to be large. However, if the maximum flow is too large, the flow in the bridge opening will become supercritical and the computations in WSPRO may fail. The bridge-opening cross section can be given as the critical-flow cross section, at least when the opening is flowing part full, to limit the maximum flow defined by a friction slope. Additional details are provided in section 5.21.

The flow and water-surface-elevation input lines and WSPRO comment and output-specification lines are prepared when the WSPROQZ command is applied. All other WSPRO information, such as cross-section geometry and flow-resistance and head-loss coefficients, must be prepared by the user in accordance with the formats given in Sherman (1990). The WSPRO input lines prepared in WSPROQZ are then transferred by the user to the manually prepared input file for the WSPRO description of the bridge. A series of water-surface profiles is computed with WSPRO as specified in the input lines prepared in WSPROQZ. The output-specification lines prepared in WSPROQZ result in a WSPRO output format that may be converted to a table of type 14 in FEQUTL. More than one run of WSPRO may be required because of profile storage limitations of the particular executable version of WSPRO.

The printer-output file or files computed with WSPRO are accessed and a 2-D function table is prepared with the WSPROT14 command (section 5.22). The partial free flows from a value of 1.0 to the minimum given by the user plus a value at a partial free flow of 0.0 are placed in the table. The user must ensure that the flow range is adequate and that linear interpolation between tabulated values is acceptably accurate.

## 4.2 Culverts

The flows through culverts are computed in FEQUTL by using peak-flow estimation methods developed by the USGS as outlined in Bodhaine (1968). The principles given by Bodhaine for the routing technique are applied in the CULVERT command (section 5.5) to compute 2-D tables of type 13 for a culvert with or without flow over the roadway. The cross-section locations used in the routing analysis are shown in figure 3. The approach section, section 1 in figure 3, is at least one culvert-opening width upstream from the entrance to the culvert. Section 2 is the cross section of the culvert barrel at the culvert-barrel entrance. Section 3 is the cross section of the culvert barrel at the culvert-barrel exit. The departure section, section 4, is usually located where the distribution of velocity in the stream has essentially returned to the distribution resulting if the culvert were not present. This location shifts with changes in flow and is a complex function of poorly understood factors. Therefore, in practical terms, the section represents the shape of the stream one opening width or more downstream from the culvert-barrel exit. In FEQ simulation, section 1 is the cross section at the downstream end of the branch upstream from the culvert, and section 4 is the cross section at the upstream end of the branch downstream from the culvert. Thus, the flow through the culvert is computed in the CULVERT command in FEQUTL for a range of water-surface elevations at section 1 and section 4. The other sections are applied only in FEQUTL computations and are not applied in FEQ simulation. In FEQUTL applications, the length of stream between sections 1 and 2 is called the approach reach and the length of stream between sections 3 and 4 is called the departure reach.

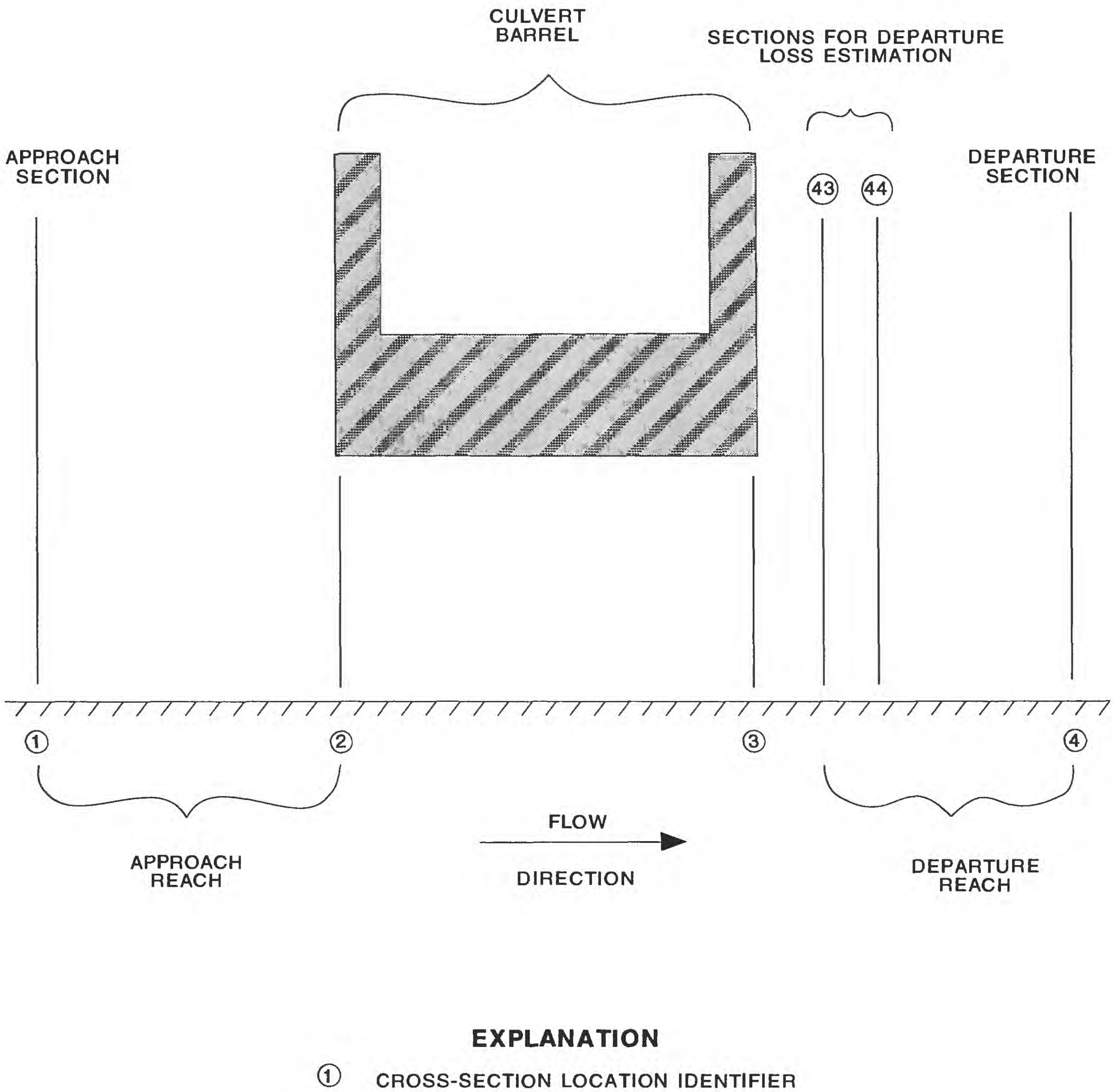



**Figure 3.** Locations of cross sections for culvert analysis in the Full EQuations UTiLities model.

### 4.2.1 Additional Flow Types

Flow through culverts is one of the more complex steady-flow phenomena encountered in the application of one-dimensional flow techniques. Bodhaine (1968) defined six flow types for flow through culverts, summarized in table 3, to determine peak discharges at culverts on the basis of high-water marks and culvert geometry. Three of these flow types (1, 2, and 3) are for low-head flow, two are for high-head flow (5 and 6), and one is for the case where both the culvert inlet and exit are submerged (4).

Bodhaine (1968) defined the boundary between high-head and low-head flow as $(z_{w_1} - z_{ci})/D = 1.5$, where $z_{w_1}$ is the water-surface elevation in the approach section (section 1 in fig. 3), $z_{ci}$ is the elevation of the culvert invert at the downstream end, and $D$ is the maximum inside vertical dimension of the culvert barrel. Chow (1959, p. 493) noted that the change between high-head and low-head flow (culvert entrance submerged or not submerged) may result for $(z_{w_1} - z_{ci})/D$ as small as 1.2 depending on the geometry, barrel characteristics, and approach condition. Chow states that for preliminary analysis $(z_{w_1} - z_{ci})/D \le 1.5$ may be used because computations have shown that, where submergence was uncertain, greater accuracy can be obtained by assuming that the entrance is not submerged (low-head flow). However, for routing of unsteady flow through the culvert, a more explicit consideration of the transition region is necessary. As a specific example, Bodhaine (1968, p. 47) noted that, for a range of approach water-surface elevations, the designation of the flow as low head (flow type 1) or high head (flow type 5) is unstable. Laboratory data indicate that the unstable condition begins at $(z_{w_1} - z_{ci})/D = 1.2$, where the flow is usually low head, and ends at $(z_{w_1} - z_{ci})/D = 1.5$, where the flow usually becomes high head. Bodhaine (1968) recommended that the culvert discharge rating in this range of approach water-surface elevations between flow types 1 and 5 be represented by a straight line between the discharge computed with low-head methods at a ratio of 1.2 and the discharge computed with high-head methods at a ratio of 1.5.

Tables of type 13 are computed with FEQUTL to represent the flow through culverts and to be applied as internal boundary conditions in the unsteady-flow simulation in FEQ. Tables of type 13 contain flow rate as a function of upstream and downstream water-surface elevations. These tables are computed as follows. Initially the upstream and downstream water-surface elevations are identical and no flow results. Then the downstream water-surface elevation is lowered (as per a user-specified series of partial free drops) and at the same time the flow rate is increased from the initial zero flow so that the upstream water-surface elevation is maintained. As the downstream water-surface elevation continues to lower, the flow increases to maintain the upstream water-surface elevation. This computational procedure precludes the use of the method recommended by Bodhaine (1968) because in his method the flow rates for $(z_{w_1} - z_{ci})/D$ equal to 1.5 and 1.2 are computed for a fixed downstream water-surface elevation. Then the linear interpolation is applied on the flow rate for the actual value of $(z_{w_1} - z_{ci})/D$, whereas flow rates are computed for fixed, upstream water-surface elevation and variable, downstream water-surface elevation in FEQUTL. Thus, special additional flow types [relative to the six flow types identified by Bodhaine (1968)] must be defined and used in FEQUTL to simulate flow in the range of upstream water-surface elevations between flow types 1 and 5.

The need for special additional flow types to simulate the flow between low-head and high-head flow types 1 and 5 results from physical oscillations for a range of upstream water-surface elevations. Other special additional flow types are needed to approximate flow in the vicinity of changes between high-head flow types, low-head and high-head flow types, and submerged flow (type 4) and low-head or high-head flow. These special flow types do not necessarily result in a real stream system, but rather these flow types may be needed to circumvent computational problems at transitions between flow types in FEQ simulation of unsteady flow. For example, as flows in culverts change between free-surface and pressurized conditions, a discontinuity in the flow results. The numerical methods applied in FEQ to route unsteady flows through the stream system may not be capable of obtaining a solution for flows or water-surface heights at an internal boundary condition if a large discontinuity in the flow rating is present. Therefore, special flow types are included in FEQUTL to circumvent discontinuities in the internal boundary conditions at culverts. The flow conditions described with the additional flow types may be present only for short periods as a flood wave passes through the culvert or backwater extends from downstream locations. As detailed in later sections, not all transitions between flow types involve substantial flow discontinuities; thus, not all changes between flow types are considered in FEQUTL. The actual transition between flow types as upstream and downstream water-surface elevations change during unsteady flow are simulated in FEQ by look-up among the tables of type 13 representing the various upstream and downstream water-surface elevations.

Special additional flow types also are needed because simulation of unsteady flow in streams requires flow to be defined for a wide range of flows, from small to large, and not just the large design flows considered by Bodhaine (1968).

The additional flow types defined in FEQUTL to describe a wider range of flow conditions than included in the six flow types defined by Bodhaine (1968) are designated flow types 0, 31, 41, 42, 51, 52, 61, 62, and 7. These are described in table 3 and illustrated in figures 4-11. The designations of entrance and exit in table 3 refer to the direction water is flowing, not the direction that is the predominant or expected direction. The nature of flow in the culvert is described as free or submerged in table 3. Submerged indicates that no critical control is present in the structure because it is drowned by backwater effects. For example, flow type 4, defined by Bodhaine (1968), is obviously submerged because both ends of the culvert are underwater. Flow type 3, defined by Bodhaine (1968), also is submerged because the downstream water-surface elevation is greater than the elevation of critical depth in the culvert. Each of the other flow types defined by Bodhaine (1968) is free flow. This designation is less explicit than Bodhaine's (1968) designation of flow in culverts as critical, subcritical, supercritical, and full barrel or critical, tranquil, rapid, and full barrel because some of the special additional flow types are intermediate conditions between subcritical and supercritical flows and may be either type of flow, depending on hydraulic and geometric conditions of the culvert. For the computations in FEQUTL, a more precise definition of flow regime is not necessary. Further, this designation is consistent with that for free and submerged weir and orifice flow for underflow gates (section 4.8).

At large flows, culverts almost always cause a contraction of the flow at the entrance and an expansion of flow at the exit. This is the standard assumption for analysis of culverts. However, at low to moderate flows, culverts can provide an expansion of flow at the entrance and a contraction of flow at the exit. Such conditions are considered in flow types 0 and 7. In flow type 0, the control is the approach section. At a given upstream water-surface elevation (upstream head), the capacity of the culvert is such that critical flow is present at the approach section. In flow type 7, the control is at the departure section so that critical control is present such as may result from a riffle in the stream channel downstream from the culvert during low flow. Flow type 31 results when flow types 1 or 2 in long culverts are submerged. In this case the exit can be submerged but the entrance has a free surface.

A flow of type 6 results in a piezometric surface at the culvert exit that is below the soffit (the highest point in the culvert at a given location) of the culvert at that point. When the piezometric surface in the departure reach for flow type 6 is drowned but the soffit is under free-flow conditions (that is, not submerged) the flow is designated as type 42 in FEQUTL. This could result from submergence of the control for flow types 6 or 62. Flow type 61 only results for flow against an adverse slope. For this flow type, the culvert is flowing full at the inlet but is flowing partially full at critical depth at the outlet. Submergence of flow type 61 can result in flow type 41. Flow type 41 also is a transition between flow types 3 and 4. Flow type 62 is transitional and is used to smooth the transition between the low-head flow types 1 and 2 and the high-head flow type 6. Flow type 62 also is used as a transitional flow type between flow types 61 and 6. Flow types 51 and 52 provide transitions between flow types 1 and 5 and flow types 2 and 5, respectively. Typical flow profiles for the additional flow types are shown in figures 4-11.

### 4.2.2 General Routing Methodology for Culvert Flow

The routing methodology defined by Bodhaine (1968) starts at a control point or at a known water-surface elevation, and a steady-flow energy-conservation equation from that point is applied to define the unknown flow and elevation values. The equations that result fall into three groups: flow type 1, flow types 2 and 3, and flow types 4 and 6.

For culvert-flow type 1, the control is at the culvert entrance (section 2). The coefficient of discharge, $C_d$, in this case does not represent appreciable energy losses because the flow is contracting into the culvert entrance. The loss of energy is caused by subsequent expansion in the culvert barrel that results downstream from section 2. Therefore, the coefficient of discharge may be determined by applying

**Table 3.** Culvert flow types in the Full EQuations UTiLities model

[--, not applicable]

| Flow type | Flow regime | Control at section | Intermediate between flow types | Culvert entrance condition | Culvert flow condition | Culvert exit soffit underwater? | Nature of flow in culvert |
|---|---|---|---|---|---|---|---|
| 0 | -- | Approach | -- | Part full | Part full | No | Free |
| 1 | Low head | Culvert entrance | -- | Part full | Part full | No | Free |
| 2 | Low head | Culvert exit | -- | Part full | Part full | No | Free |
| 3 | Low head | -- | -- | Part full | Part full | No | Submerged |
| 31 | -- | -- | 1, 2, or 3 and 4 | Part full | Full | Yes | Submerged |
| 4 | Submerged culvert | -- | -- | Full | Full | Yes | Submerged |
| 41 | -- | -- | 3 and 4; 61 and 4 | Full | Part full | No | Submerged |
| 42 | -- | -- | 6 and 4; 62 and 4 | Full | Full | No | Submerged |
| 5 | High head | Culvert entrance | -- | Full | Part full | No | Free |
| 51 | -- | Culvert entrance | 1 and 5 | Full | Part full | No | -- |
| 52 | -- | Culvert entrance | 2 and 5 | Full | Part full | No | -- |
| 6 | High head | Culvert exit | -- | Full | Full | No | Free |
| 61 | Adverse slope | Culvert exit | -- | Full | Part full | No | Free |
| 62 | -- | Culvert exit | 1 or 2 and 6 | Full | Full | No | -- |
| 7 | -- | Departure | -- | -- | -- | -- | -- |

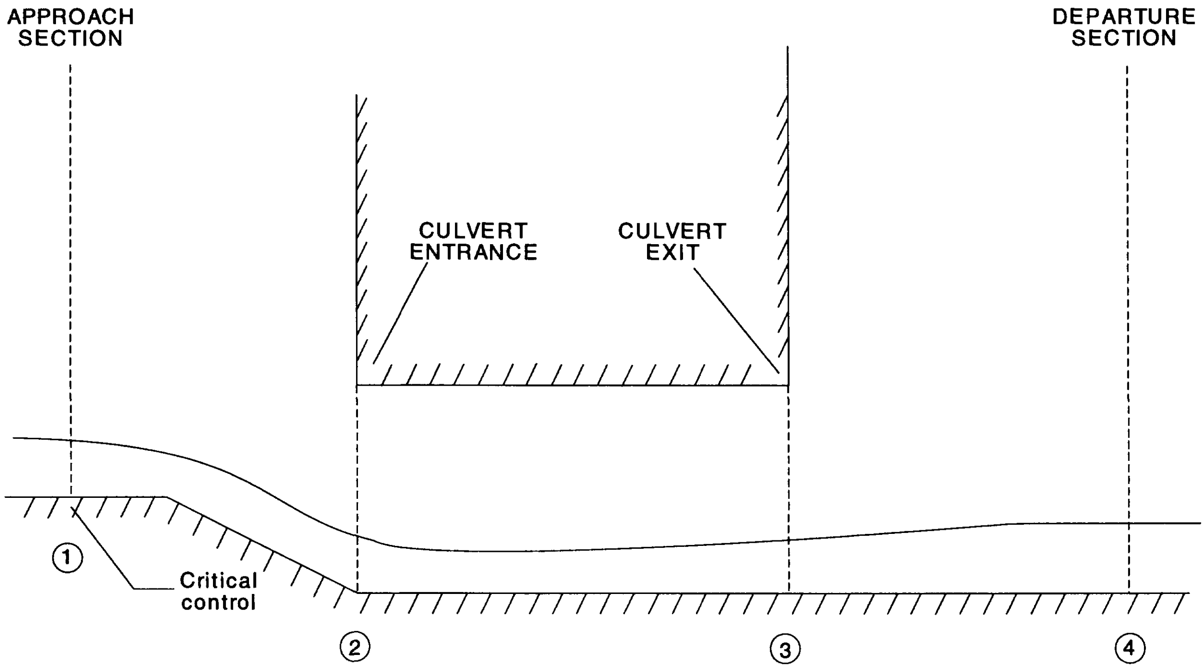



**Figure 4.** Typical flow profile for culvert-flow type 0 considered in the Full EQuations UTiLities model computations of two-dimensional culvert-rating tables.

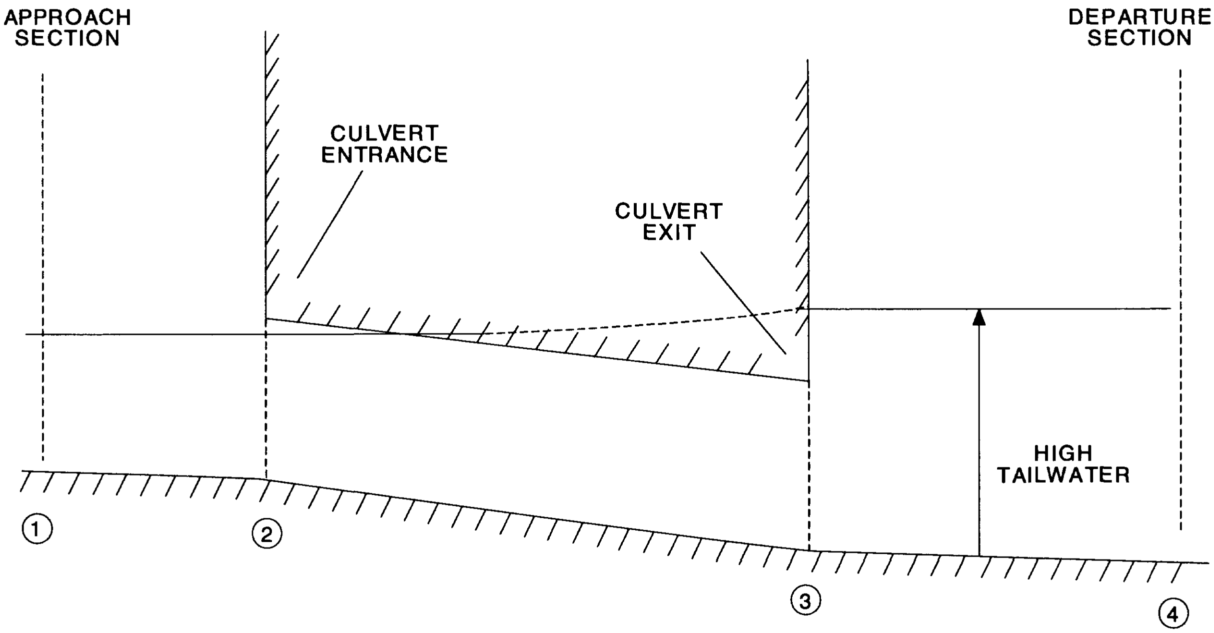



**Figure 5.** Typical flow profile for culvert-flow type 31 considered in the Full EQuations UTiLities model computations of two-dimensional culvert-rating tables.

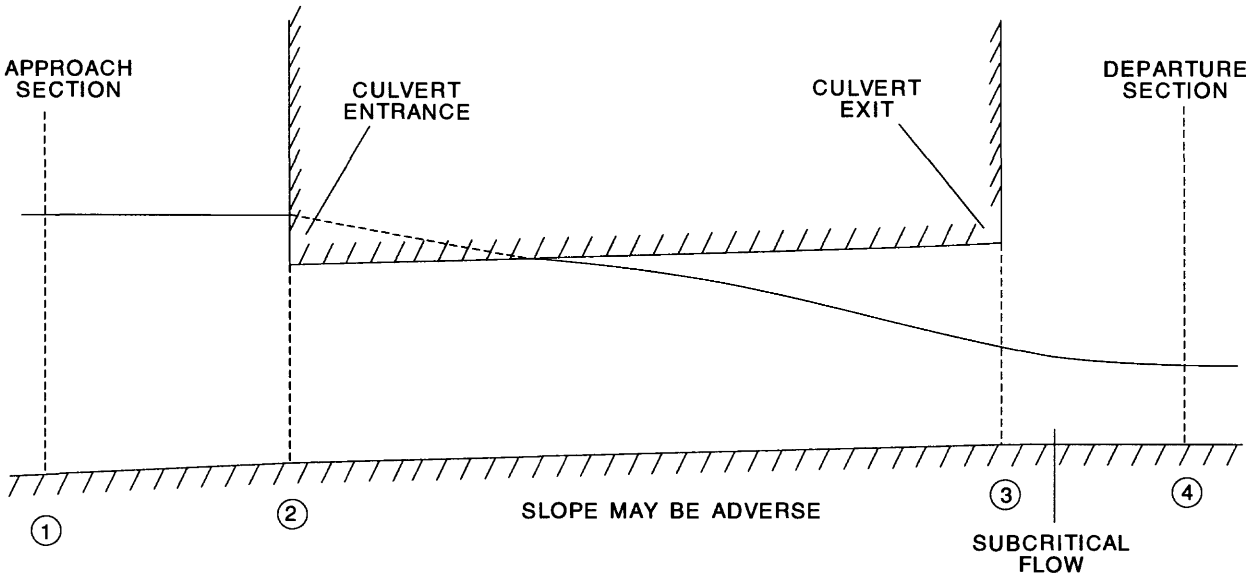



**Figure 6.** Typical flow profile for culvert-flow type 41 considered in the Full EQuations UTiLities model computations of two-dimensional culvert-rating tables.

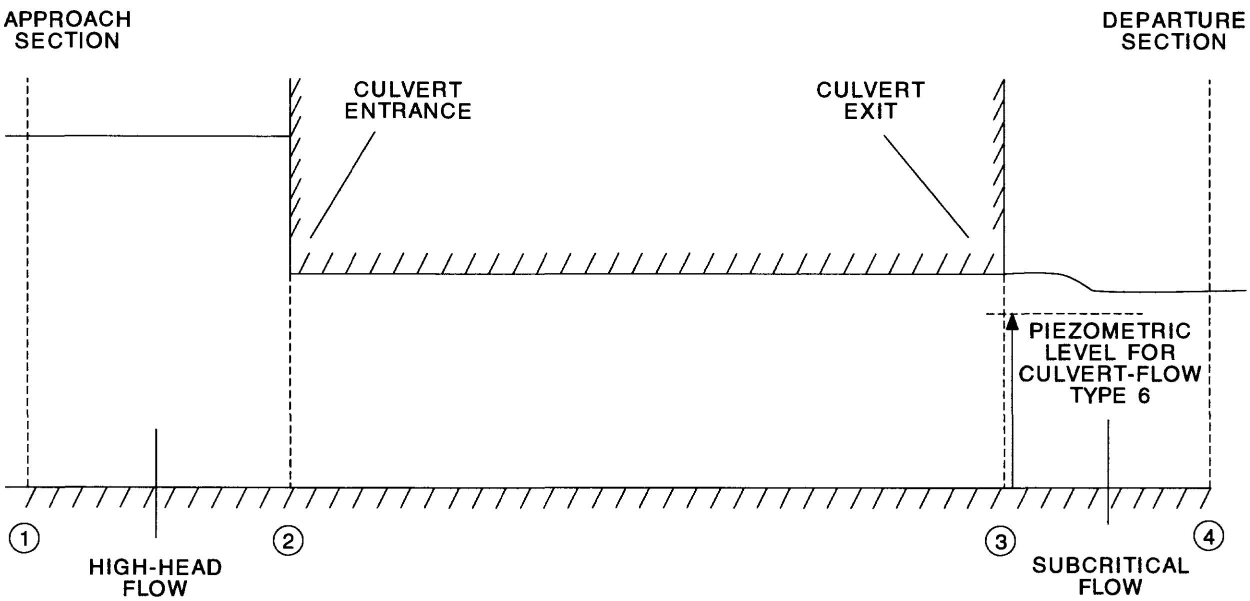



**Figure 7.** Typical flow profile for culvert-flow type 42 considered in the Full EQuations UTiLities model computations of two-dimensional culvert-rating tables.

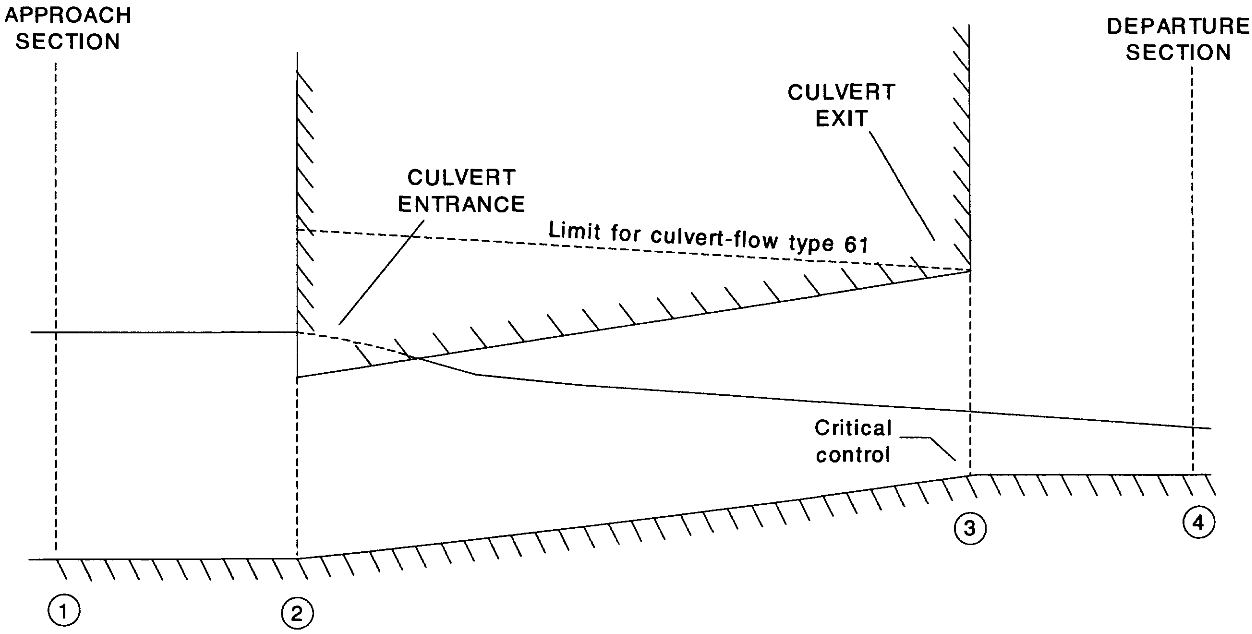



**Figure 8.** Typical flow profile for culvert-flow type 61 considered in the Full EQuations UTiLities model computations of two-dimensional culvert-rating tables.

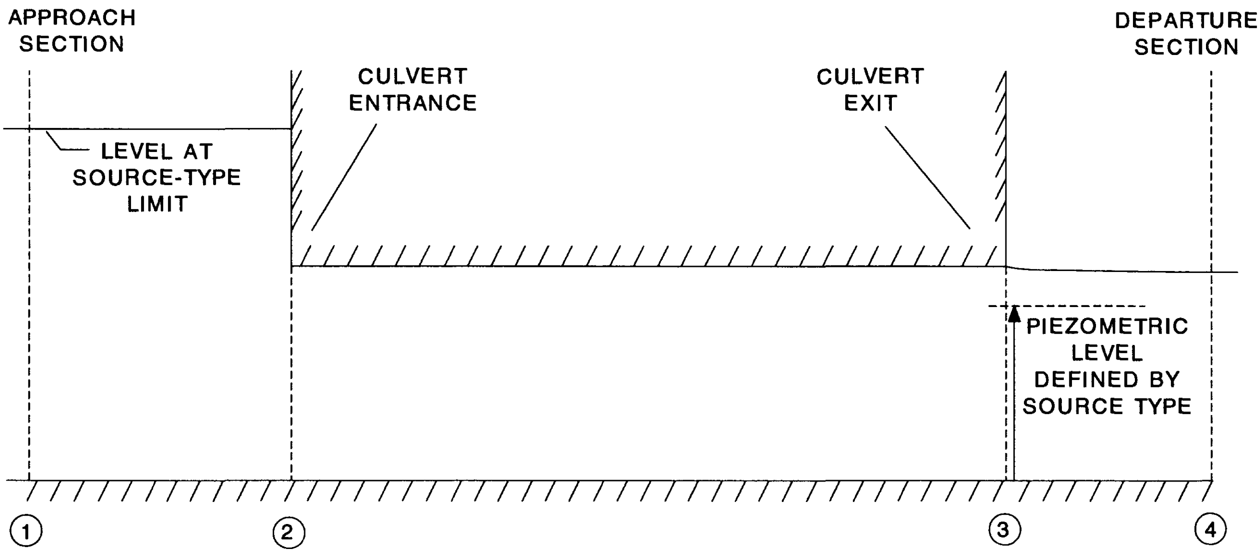



**Figure 9.** Typical flow profile for culvert-flow type 62 considered in the Full EQuations UTiLities model computations of two-dimensional culvert-rating tables.

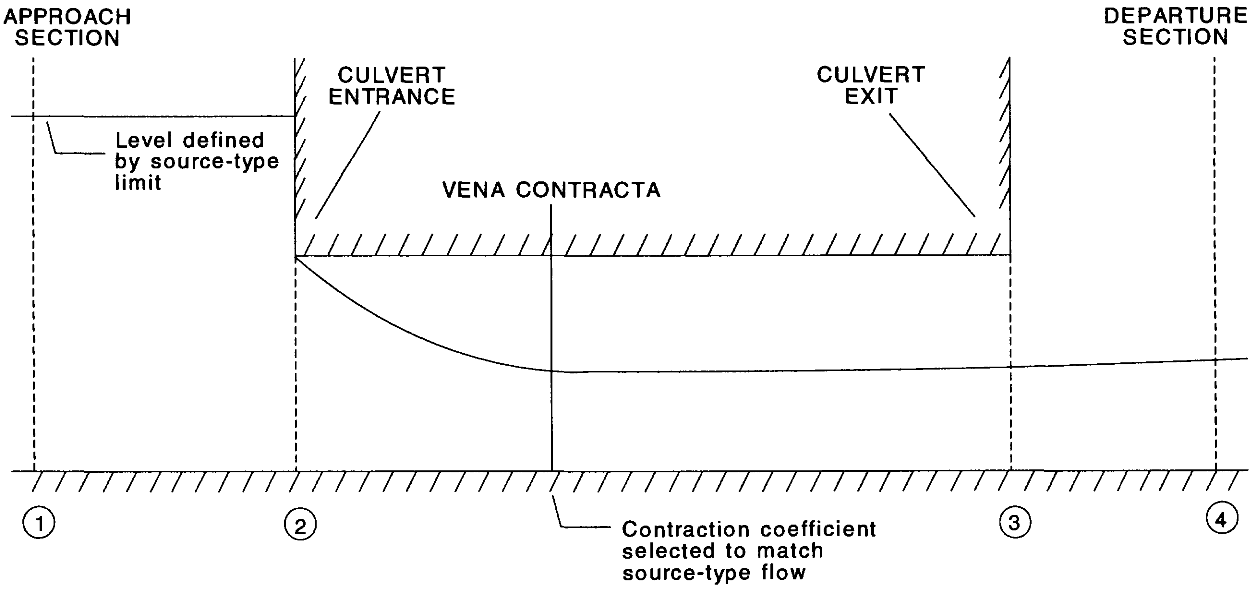



**Figure 10.** Typical flow profile for culvert-flow type 51 and 52 considered in the Full EQuations UTiLities model computations of two-dimensional culvert-rating tables.

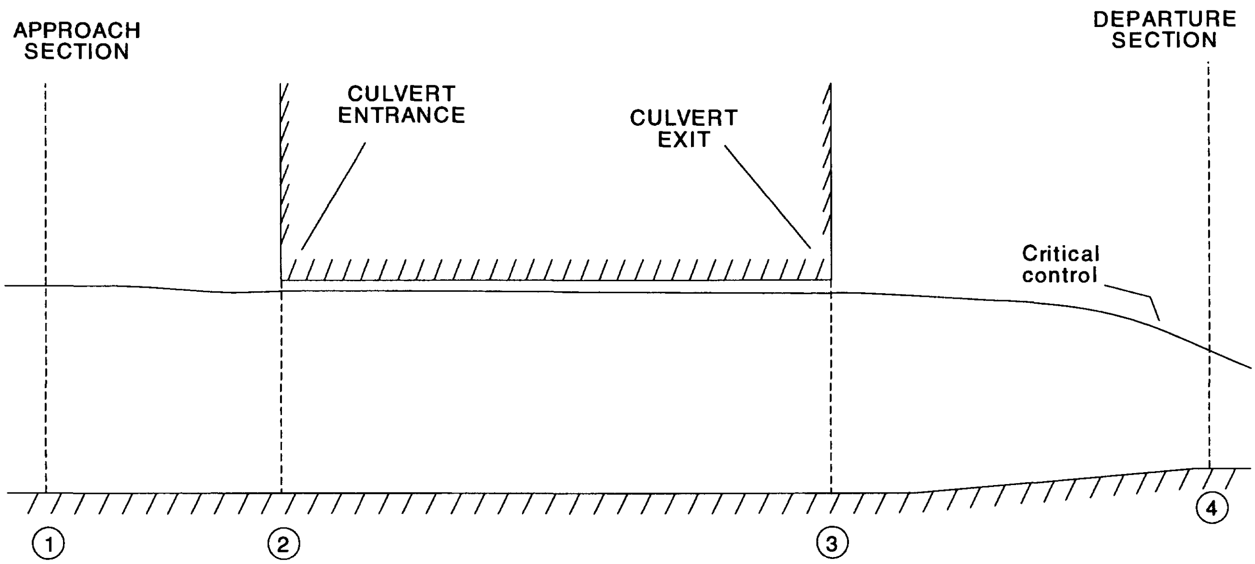



**Figure 11.** Typical flow profile for culvert-flow type 7 considered in the Full EQuations UTiLities model computations of two-dimensional culvert-rating tables.

$$\alpha_1 \frac{(Q_B+Q_r)^2}{2gA_1^2} + z_{w_1} = \frac{Q_B^2}{2gA_2^2} + z_{w_2} + \left(\frac{1}{C_d^2} - 1\right)\frac{Q_B^2}{2gA_2^2} + \Delta x_{12}\frac{Q_B(Q_B+Q_r)}{K_1K_2}, \tag{83}$$

where

$\alpha_1$ is the kinetic-energy flux correction coefficient at section 1 (the approach section);
$Q_B$ is the flow in the culvert barrel;
$Q_r$ is the flow over the roadway;
$g$ is acceleration due to gravity;
$A_i$ is the flow area at section $i$;
$z_{w_i}$ is the water-surface elevation at section $i$;
$\Delta x_{12}$ is the distance between sections 1 and 2;
$K_i$ is the conveyance at section $i$; and
the critical flow at section 2 is given by $Q_B = A_2\sqrt{g(A_2/T_2)}$.

The flow rate at section 2 is critical with the water-surface elevation at section 2, $z_{w_2}$, being the water-surface elevation at critical flow. This equation is solved iteratively starting with an initial estimate of the critical depth at section 2. The iteration continues until the known elevation at section 1, $z_{w_1}$, is matched to an acceptable tolerance criterion.

For culvert-flow types 2 and 3 the energy equation is

$$\alpha_1 \frac{(Q_B+Q_r)^2}{2gA_1^2} + z_1 = \frac{Q_B^2}{2gA_3^2} + z_{w_3} + \left(\frac{1}{C_d^2} - 1\right)\frac{Q_B^2}{2gA_3^2} + \Delta x_{12}\frac{Q_B(Q_B+Q_r)}{K_1K_2} + \Delta x_{23}\frac{Q_B^2}{K_{23}^2}, \tag{84}$$

where $\Delta x_{23}$ is the length of the culvert and $K_{23}$ is the average value of conveyance for the culvert that gives the correct barrel-friction loss computed in the steady-flow profile computations. The barrel friction loss and the conditions at section 2 are estimated by computing a steady-flow water-surface profile in the culvert barrel. The entrance losses, $\left(1/C_d^2 - 1\right)Q^2/2gA_3^2$, are assigned to the barrel so that the estimated water-surface elevation at section 2 reflects the expansion losses that take place in the barrel downstream from the entrance. These losses may not be fully realized if the barrel is short. This refinement is not included in the CULVERT command because the factors involved are not well defined. Therefore, a warning message is given if the culvert is clearly too short, usually defined as a length less than six times the maximum inside the vertical dimension, $D$.

For culvert-flow type 2, the flow at the outlet of the conduit (section 3) is critical, but for culvert-flow type 3, the flow is subcritical throughout the conduit. Equation 84 is solved iteratively for the water-surface elevation at section 1 given either that the flow at section 2 is critical or given a water-surface elevation at the culvert exit (section 3), $z_{w_3}$.

For culvert-flow types 4 and 6, the energy equation is

$$\alpha_1 \frac{(Q_B + Q_r)^2}{2gA_1^2} + z_{w_1} = \frac{Q_B^2}{2gA_{3f}^2} + z_{3p} + \left(\frac{1}{C_d^2} - 1\right)\frac{Q_B^2}{2gA_{3f}^2} + \Delta x_{12}\frac{Q_B(Q_B + Q_r)}{K_1 K_{2f}} + \Delta x_{23}\frac{Q_B^2}{K_f^2}, \tag{85}$$

where $z_{3p}$ is the elevation of the piezometric surface at section 3 and the $f$ in subscripts denotes the full-flow value for the culvert barrel. This equation must be solved iteratively for culvert-flow type 6 because the piezometric level at section 3 is a function of the flow in the culvert barrel as shown in figure 18 in Bodhaine (1968). For culvert-flow type 4, equation 85 may be solved directly for the flow because in this case the piezometric level at section 3 is given. This direct solution is only possible if no flow over the road results. If flow over the road results, iteration is required.

The flow over the road is defined by the water-surface elevation at section 1, the upstream water level for weir flow over the road. The downstream water-surface elevation for the flow over the road is taken at section 43 (fig. 3). The downstream water-surface elevation for flow through the culvert also is defined at section 43. Under submerged flow conditions (flow type 4) the piezometric levels at sections 3 and 43 are identical. The flow over the road is computed using the same methods as for embankments and other weirs (section 4.3). The effect of approach velocity head on the flow over a weir is included on a local basis. The approach conditions for the flow at a point on the weir crest are estimated upstream from that point and not for the approach of the entire cross section. This is done because flows over a road commonly take place during floods, and the approach conditions to the road are usually on the flood plain of the stream. The velocity head on the flood plain can be substantially different from the velocity head in the stream channel at the culvert or bridge. Flow over the road directly above the culvert is normally a small part of the total flow over the road. Often, guard rails or other obstructions to flow above the culvert further reduce the effectiveness of the flow path directly above the culvert. Furthermore, no laboratory or field data are available on the nature of the interaction between flow through the culvert opening and flow over the road directly above the culvert. Consequently, in the CULVERT command the velocity head induced at section 1 by the flow through the culvert is assumed to have a negligible effect on the flow over the road. Therefore, the flow over the road, for free-flow conditions, is computed from the water-surface elevation at section 1, independently of the flow through the culvert.

Transitional-flow profiles are computed with variations on equations 83-85. For example, culvert-flow type 61 is computed with an equation like that for culvert-flow type 2 (equation 84), except that the entrance flows full, the culvert barrel is full along part of its length, and the coefficient of discharge differs from that for type 2. The Preissmann (1961) slot technique is applied in the CULVERT command to represent pressurized flows as free-surface flows. Water-surface profiles in the barrel that are a combination of full flow and part-full flow are computed by allowing the section to flow full with the water level in the slot giving the piezometric level in the full-flow part of the barrel. The other nonstandard flow types (41, 51, 52, and 62) are computed in a similar manner.

### 4.2.3 Routing Methodology for Culvert-Flow Type 5

The representation for flow type 5 in Bodhaine (1968) does not permit the application of a routing methodology. This cannot be applied in the CULVERT command. All culvert-flow types can be submerged given sufficient downstream water-surface elevations. Therefore, culvert-flow type 5 must be computed so that it can be merged with the other culvert-flow types.

Type 5 flow is analogous to free flow under a sluice gate. The entrance to the culvert is flowing full, but the water surface becomes free of the culvert soffit and an air space is present above the water surface from the entrance to the exit. The nature of the rounding and beveling of the culvert has a marked effect on type 5 flow. The flow in the culvert barrel contracts to a minimum area (vena contracta) at about three vertical diameters from the entrance (Portland Cement Association, 1964, p. 111). Downstream from the vena contracta, flow expansion takes place with losses similar to those for full-barrel flow for the same entrance condition. The discharge coefficients for culvert-flow type 5 relate primarily to the reduction in area and not the loss of energy. The loss of energy, as in culvert-flow type 1, takes place downstream from the vena contracta. The flow at the vena contracta is supercritical.

The depth downstream from the vena contracta may increase or decrease, depending on the slope and roughness of the barrel.

Submergence of type 5 flow cannot be separated from the transition to full-barrel flow. For the part-full flow to persist during flow transitions, an adequate flow of air into the space above the water surface must be present. The high velocities normally present in culvert-flow type 5 are quite effective in moving and entraining air. If the barrel is long enough and the water level or velocity is high enough, the air stream entering the culvert along the soffit will encounter enough resistance to reduce the pressure in the space above the water surface close to the inlet, resulting in full flow at the culvert entrance. Once initiated, the full-flow region will rapidly fill the remainder of the culvert. The flow rate immediately increases, and this increase may lead to air entrainment through vortices at the culvert inlet. Part-full flow may then result because of the entrained air. The flow will oscillate between part-full and full flow until the water level at the entrance rises too high for sufficient air to be entrained by the vortices.

The ventilation of the culvert barrel can also be reduced by a rising tail-water level that results in a hydraulic jump in the barrel exit. Eventually, the face of the jump will come close enough to the exit soffit to restrict the air flow sufficiently to result in full flow. This full-flow value is assumed to be a submerged flow value in FEQUTL. It may be possible that submergence of a culvert-flow type 5 may result in a culvert-flow type 6 that is unsubmerged. Insufficient data are available to determine under what conditions an unsubmerged culvert-flow type 6 could result from submergence of culvert-flow type 5.

A hydraulic jump commonly will start in the culvert barrel and end at some point in the departure reach. A sketch of the location of the jump and the sections is shown in figure 12. As the water-surface elevation at the departure section and the section at the end of the jump (sections 4 and 44) increases, the jump moves farther into the barrel. To estimate the water-surface elevation at sections 4 and 44 that results in full flow in the barrel, a modified, simple momentum balance is utilized. The hydrostatic, piezometric level at section 43 is sought. The pressure distribution at section 43 is not hydrostatic because parts of section 43 are in a hydraulic jump. However, the pressure on the downstream face of a hypothetical head wall at the culvert outlet would be approximately hydrostatic. Thus, the full-flow-inducing depth is defined in terms of hydrostatic, piezometric head because it is not possible to compute any other level by applying simple equations. The modified momentum balance equation for the departure reach is

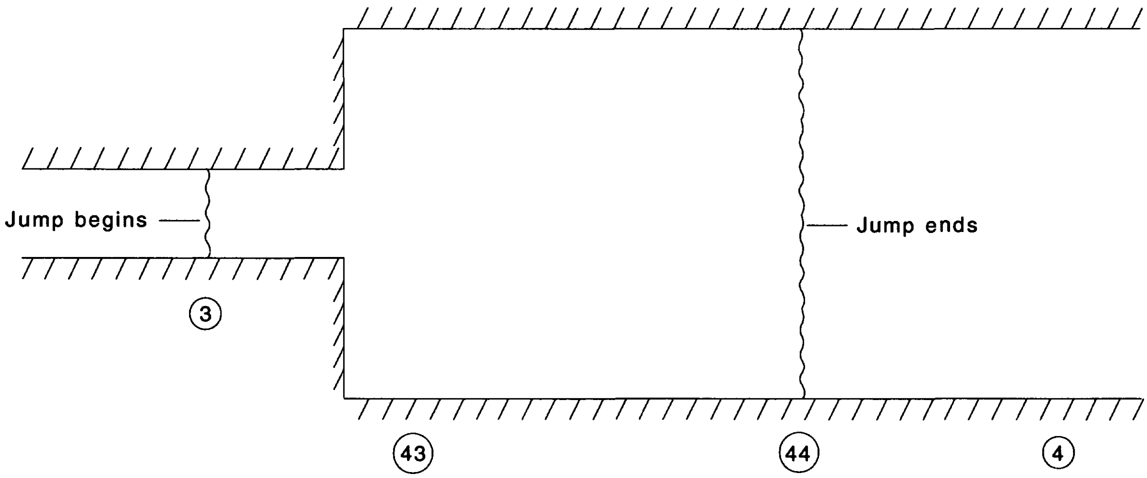
$$\beta_3 \frac{Q_B^2}{A_3} + g\left[J_3(y_3) + J_{43}\left(z_{w_{43}} - z_{b_{43}}\right) - J_3\left(z_{w_{43}} - z_{b_3}\right)\right] + M_r = \beta_4 \frac{(Q_B + Q_r)^2}{A_{44}} + gJ_{44}(y_{44}) \,, \qquad (86)$$

where $M_r$ is the momentum flux over the roadway and the subscript $b$ denotes the invert elevation at the given section, and $J(X_f)$ indicates that the first moment of area with respect to the water surface is a function of $X_f$. The flow at section 3 is supercritical, so the depth and flow there are known from the computations of culvert-flow type 5.

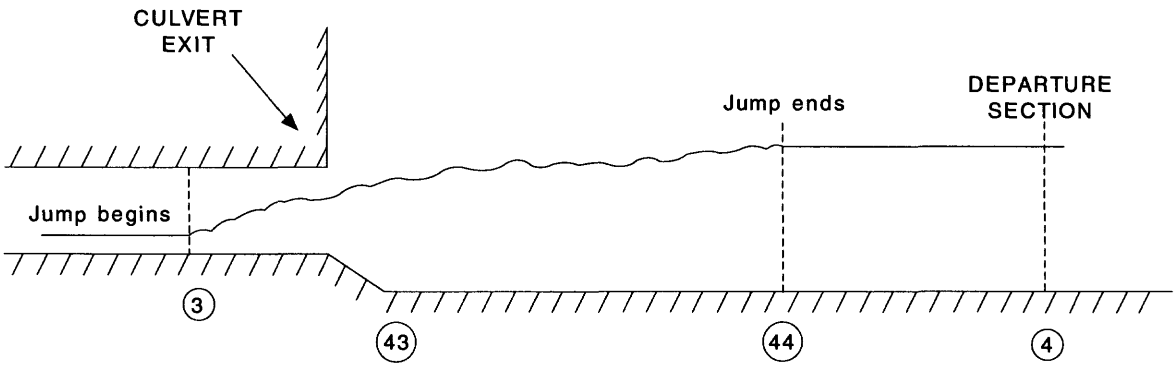
The downstream water-surface elevation resulting in full flow for culvert-flow type 5 and that resulting in submergence of culvert-flow type 5 are taken to be identical. Thus, the submergence can be defined if the flow and depth at section 3 can be estimated. The discharge equation for culvert-flow type 5, given in Bodhaine (1968), is

$$Q_B = C_d A_{2f} \sqrt{2g\left(z_{w_1} - z_{b_2}\right)} \,. \qquad (87)$$

The velocity head of approach is assumed to be negligible in equation 87. This may be reasonable because culvert-flow type 5 under high-head conditions is not efficient. Friction losses in the approach reach are also not considered in equation 87. The details of the location and size of the vena contracta are implicit in equation 87. An energy equation between section 1 and the vena contracta can be written as




(A) Plan view of departure reach.




(B) Elevation view of departure reach.

**EXPLANATION**

(3) CROSS-SECTION LOCATION IDENTIFIER

**Figure 12.** Plan and elevation views for culvert-departure reach with a hydraulic jump in the culvert-barrel exit.

$$\frac{Q_B^{\ 2}}{2gA_1^2} + z_{w_1} = \frac{Q_B^{\ 2}}{2g(A_{2f}C_c)^2} + f_c(C_c)D_2 + z_{b_{vc}}, \tag{88}$$

where

$C_c$ is the contraction coefficient on the full barrel area giving the flow area at the vena contracta;

$f_c(C_c)$ is the piezometric depth ratio to the maximum vertical dimension as a function of the contraction coefficient; and

$z_{b_{vc}}$ is the invert elevation at the vena contracta.

A simple way to define the function $f_c$ is to assume that the piezometric depth is the same as the depth to vertical diameter ratio that defines the contracted area. This function is then determined once the barrel cross-sectional shape is defined. For example, if $C_c$ is 0.5, then for a circular culvert, the depth ratio is also the same. In a box culvert, the partial-depth ratio and the partial-area ratio are the same. The partial-depth ratio and partial-area ratio deviate from each other for other shapes. The assumption that this applies to the piezometric depth is only approximate. The contraction at the entrance is predominantly from the soffit, but there also are contractions from the sides of the culvert entrance. The effective flow area at the vena contracta is probably less than the area of water at the vena contracta. The simple assumption applied in FEQUTL is that the effective flow area and the area containing water are the same.

The contraction coefficient is defined by requiring that the flow in equations 87 and 88 be the same. These two equations define a contraction coefficient for a given water-surface elevation at section 1 and a given discharge coefficient for culvert-flow type 5. A contraction coefficient for culvert-flow type 5 is determined in the CULVERT command whenever required. Once the contraction coefficient is defined, it is applied in an equation without the assumptions made for equation 87. The equation for culvert-flow type 5 then becomes

$$\alpha_1 \frac{(Q_B + Q_r)^2}{2gA_1^2} + z_{w_1} = \frac{Q_B^{\ 2}}{2g(C_cA_2)^2} + D_{vc}f_c(C_c) + z_{b_{vc}} + \Delta x_{12}\frac{Q_B(Q_B + Q_r)}{K_1K_{2f}}, \tag{89}$$

where $D_{vc}$ is the maximum inside vertical dimension of a culvert barrel at the vena contracta. This equation yields slightly different results than the defining equation (equation 87), but the differences are small when both equations are applicable.

Most of the expansion losses in part-full flow take place close to the vena contracta. These losses are assumed to be the same as for culvert-flow type 6 at the same flow rate but at full flow. It is further assumed that the losses are realized over a distance of three culvert diameters downstream from the vena contracta, which is located three culvert diameters downstream from the culvert entrance. Experience with FEQUTL has indicated that application of the full culvert-flow type 6 losses sometimes result in failure of supercritical-profile computations when no physical reason for failure is present. In these cases, the estimated losses are reduced iteratively by 0.95 until the losses are small enough to permit computation of the supercritical profile.

During computation of a 2-D culvert-rating table in FEQUTL, a procedure must be specified to determine which high-head culvert-flow type, 5 or 6, is present. The slope, length, roughness, and entrance condition of the culvert are all factors that affect the presence of culvert-flow type 5 or 6. Bodhaine (1968) prepared two figures to aid in the determination of whether high-head culvert-flow is type 5 or type 6. Bodhaine's figure for pipe or box culverts with a smooth surface (concrete or similar material) is presented in figure 13, and his figure for pipe culverts with rough barrels is presented in figure 14. The first estimate of the culvert-flow type for high-head flow is given in these figures. If the culvert-flow type selected is type 6, computations for culvert-flow type 6 proceed. However, if the culvert-flow type selected is type 5, further checking of flow conditions is done in FEQUTL.

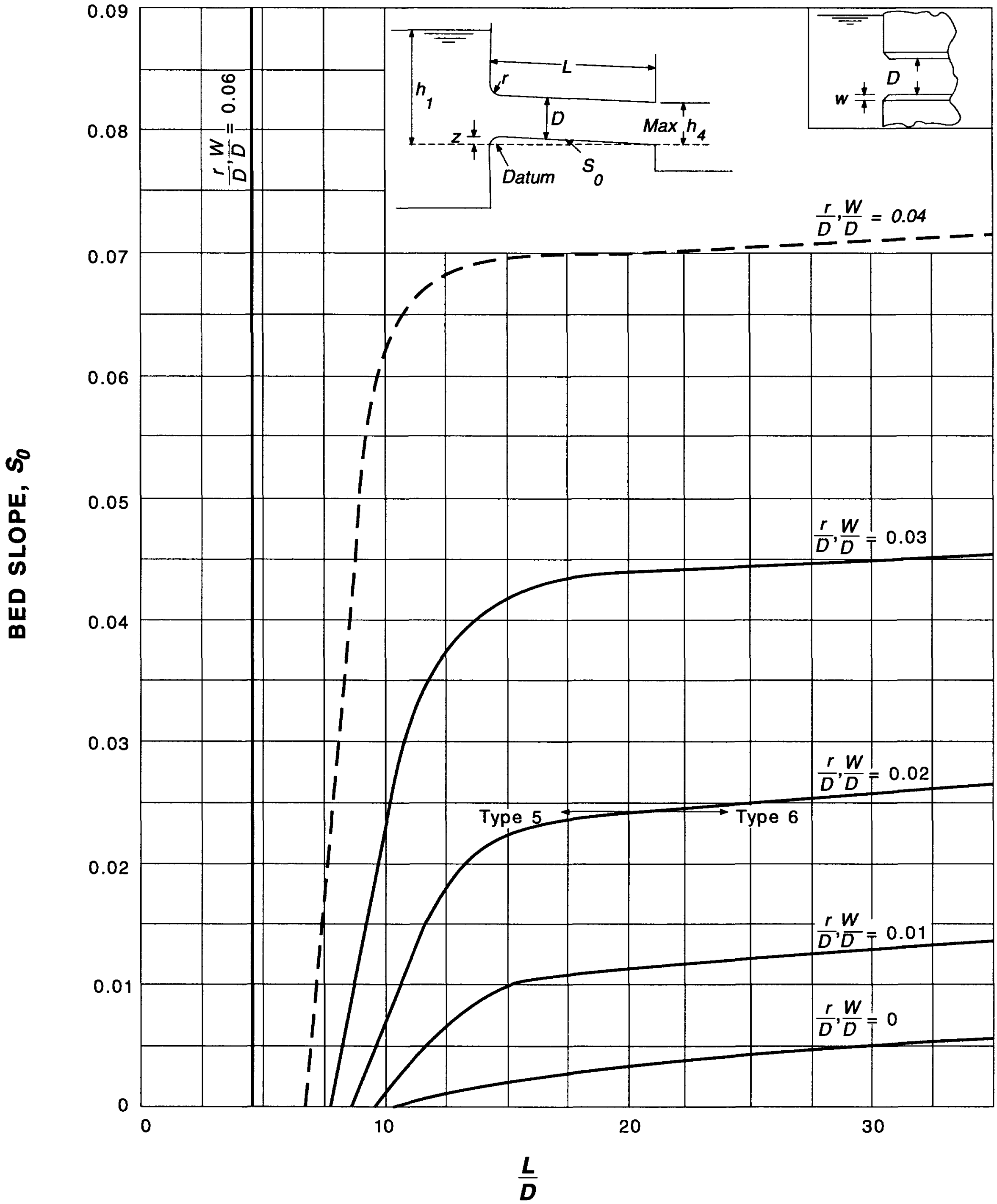



**Figure 13.** Criterion for classifying culvert-flow types 5 and 6 in box and pipe culvert with concrete barrels and square, rounded, or beveled entrances, either with or without wingwalls.

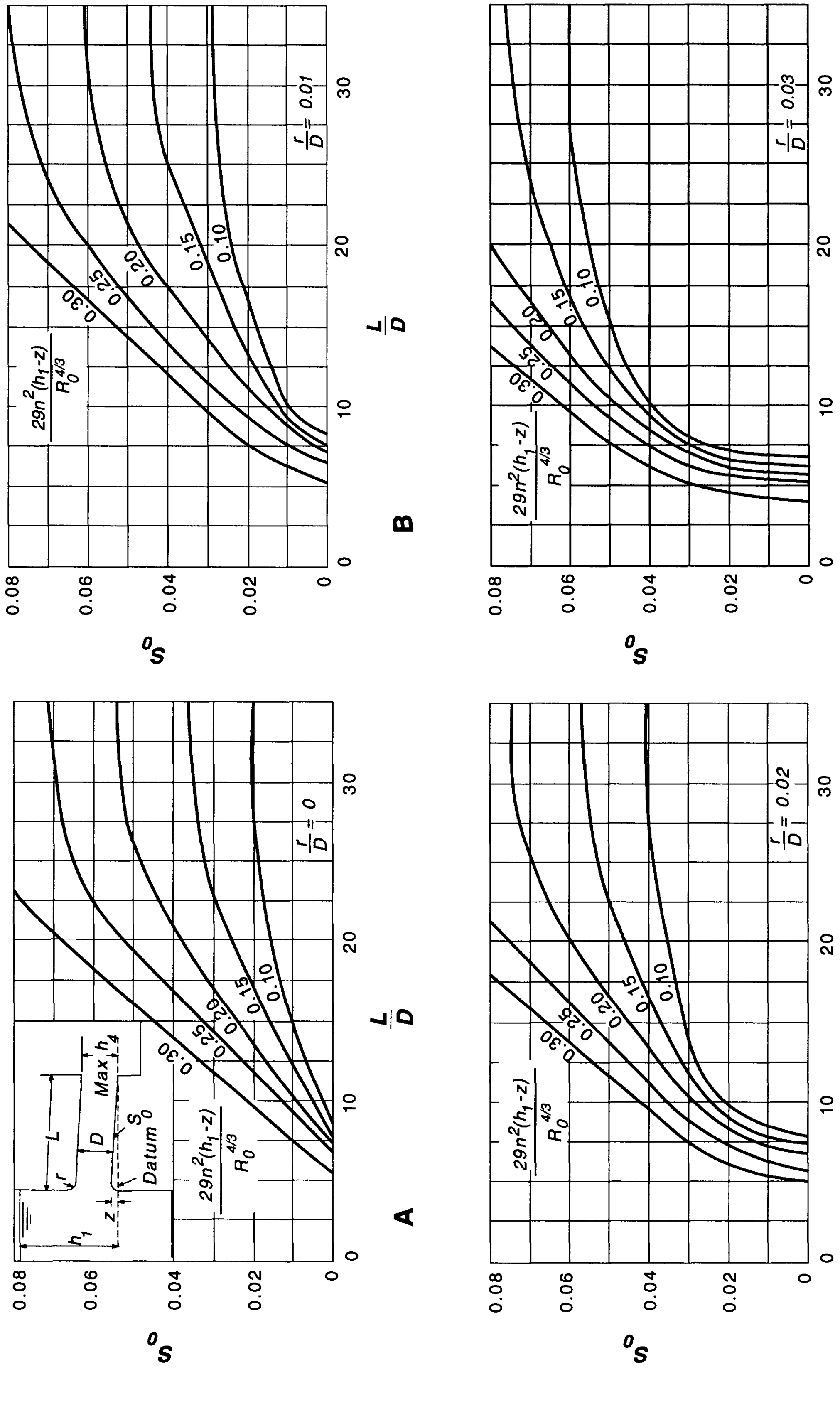



**Figure 14.** Criterion for classifying culvert-flow types 5 and 6 in pipe culverts with rough barrels.

Culvert flow type 5 must be verified and a full-flow-inducing depth must be assigned at the culvert exit. Verification is important because the classification of culvert-flow types in figures 13 and 14 is only approximate and many culverts fall outside the range of the figures. The tables in FEQUTL that represent these figures have been extended to accommodate a larger range of culverts. However, this extension is an extrapolation and does not involve any new data or computations. Furthermore, culverts have a tendency to flow full, as discussed in Portland Cement Association (1964, p. 98-99). Therefore, the decision rules programmed in FEQUTL result in culvert-flow type 6 more often than culvert-flow type 5.

The following steps are completed in FEQUTL to verify culvert-flow type 5.

1. Starting at the vena contracta, a supercritical flow profile is computed to the culvert exit. If the culvert is shorter than three culvert diameters, then the vena contracta is treated as if it is at the entrance. This profile may not extend to the exit because a hydraulic jump forms at some point in the barrel.
2. A subcritical profile is computed from the culvert exit to the vena contracta starting at critical depth for culvert-flow type 5. This profile may not result, may result part way, or may extend to the vena contracta.
3. A simple momentum balance is applied between the subcritical and supercritical profiles to locate any hydraulic jump. If no jump is present and supercritical flow is present throughout the culvert, then culvert-flow type 5 is applied. If subcritical flow is present throughout the culvert, then culvert-flow type 5 is rejected.
4. If a jump is present, culvert-flow type 5 is rejected if the estimated depth of flow on the downstream side of the jump is more than 0.8 D. Hydraulic jumps in these cases would probably have substantial waves on the subcritical side. Thus, any close approach to the barrel soffit would effectively seal the air space and culvert-flow type 5 would not result.

A full-flow-inducing depth value at the exit of the culvert barrel is assigned in FEQUTL as follows. This value is computed to determine what flow conditions must be present to establish a transition from culvert-flow type 5 to type 6. The goal of completing the following eight steps is to define a full-flow-inducing depth that is consistent with the culvert-flow type 5. If this is not done, the results will be in error or the computations that follow might fail.

1. The value of rounding/beveling necessary so that the culvert would be on the boundary between flow types in figures 13 and 14 is computed. If the rounding or beveling is already at or above the maximum value given in those figures, a user-assigned parameter defining the ratio of the full-flow-inducing depth at the exit to D at the exit, TY5SBF, is applied. The default value of TY5SBF determined from engineering judgment is 0.75.
2. The discharge coefficient corresponding to the enhanced rounding/beveling, determined in step 1, is determined from table 6 in Bodhaine (1968), which is included in the TYPE5.TAB input file for FEQUTL. Utilizing this discharge coefficient the type 5 flow for the enhanced rounding/beveling is computed.
3. The computations for verification of the culvert-flow type 5, outlined above, are done to define the nature of the water-surface profile resulting for the flow computed for the enhanced rounding/beveling.
4. If the prevailing profile at the flow computed for the enhanced rounding/beveling is subcritical or includes a hydraulic jump that has a downstream depth greater than 0.8 D, the enhanced rounding/beveling is reduced and the value for flow computed for the new enhanced rounding/beveling is reduced. This is done in steps of one-eighth of the difference between the enhanced rounding/beveling and the actual rounding/beveling value in FEQUTL. If no meaningful flow profile corresponding to the enhanced rounding/beveling can be found in this process, type 5 flow is rejected. An acceptable enhanced profile must have a rounding/beveling value greater than the actual rounding/beveling value and must result in supercritical flow or a hydraulic jump in the culvert with a downstream depth less than 0.8 D.
5. If both the actual profile and the profile corresponding to the flow computed for the enhanced rounding/beveling are supercritical and extend through the length of the culvert, then the end depth from the enhanced profile is taken as the full-flow-inducing depth.
6. If the actual profile includes a hydraulic jump and the profile corresponding to the flow computed for the enhanced rounding/beveling is supercritical, then the end depth of the supercritical profile is taken as the full-flow-inducing depth if it is larger than the end depth of the actual profile. If the enhanced profile end depth is not larger, then TY5SBF is applied to define the full-flow-inducing depth.

7. If the profile corresponding to the flow computed for the enhanced rounding/beveling includes a hydraulic jump, and the actual profile includes a hydraulic jump, and the actual jump is higher than the other jump, then type 5 flow is rejected.
8. If the profile corresponding to the flow computed for the enhanced rounding/beveling includes a hydraulic jump and the actual profile does not include a hydraulic jump or includes a hydraulic jump too small to cause type 5 flow to be rejected in step 7, the exit depth of the actual profile is varied above critical depth until a hydraulic jump results, or the calculated hydraulic jump is increased, to match the downstream depth of the jump in the profile corresponding to the flow computed for the enhanced rounding/beveling.

This process extracts the maximum amount of information, perhaps more information than is available, from figures 13 and 14. The basis for these figures is not revealed in Bodhaine (1968) or Carter (1957). Figures 13 and 14 are primarily based on laboratory experiments done at the Georgia Institute of Technology by Jack Davidian. In the laboratory, the transition between flow types 5 and 6, and between flow types 1,2, or 3 and 5 or 6 could be accurately determined. Thus, the figures and table available in Bodhaine (1968) should be reasonably reliable in defining the boundaries between flow types (Lamar Sanders, U.S. Geological Survey, written commun., 1995).

#### 4.2.4 Transitions Between Flow Types

The development of tables of type 13 involves computation of 100 or more distinct flow profiles. Some of these profiles will likely fall into a transition region between culvert-flow types. As the water level at section 1 increases, the free flow will pass from one culvert-flow type to another with some transition between them. Sometimes the transition is smooth, and sometimes it is not. For example, a pipe culvert at small, upstream head levels could be in culvert-flow type 2. As the upstream head increases, the culvert-flow could become type 1. As the upstream head continues to increase, the culvert-flow type could shift back to type 2 because the converging side walls cause the critical flow to increase rapidly. Eventually, the culvert-flow type could become type 5 or type 6, or both, depending on the slope, length, and roughness of the culvert barrel. Some of the computational transitions between flow types are reasonably smooth because of the equations utilized. For example, the transition between types 1 and 2 is computationally smooth because of the nature of the governing equations. Thus, no special treatment is implemented for this transition. In the following discussion the concern is with the **computed flows** and not the actual flows in the transition. The actual flow may be quite unstable and oscillatory in some transitions, and an approach must be developed in which these features of the actual flow are ignored but for which accurate routing of flows through the culvert is obtained.

The approach taken for defining equations for the transitions is as follows.

1. Limits for the various culvert-flow types are computed. The limit is the water-surface elevation (upstream head) at section 1 at which the equation for a given culvert-flow type no longer applies or is no longer permitted to apply. For example, the limit for culvert-flow type 2 is defined as the flow with a water level at section 2, computed ignoring flow-contraction effects at the entrance but including the expansion losses downstream from section 2, just in contact with the soffit of the culvert at the entrance. The water-surface elevation at section 1 for this condition is then the type 2 flow limit. If the water-surface elevation at section 1 is above this limit, the flow is no longer type 2. The limits are summarized in table 4. A natural limit for culvert-flow type 1 results from the geometry of box culverts that is in a reasonable range. However, the converging side walls in culverts of other shapes cause critical flow to increase without bound as flow depth approaches the culvert soffit. Consequently, a limit on culvert-flow type 1 controlled by the depth at section 2 may result in a water-surface elevation at section 1 that is above the value observed to normally induce full flow at the entrance to the culvert. The default value of the maximum water-surface height at section 2 for culvert-flow type 1, $y_{2max}$, is $0.95D_2$, and the default value of the maximum water-surface elevation at section 1 for culvert-flow type 1, $z_{w_{1MAX}}$, is $z_{b_2} + 1.4D_2$ in FEQUTL computations. These defaults can be overridden by

optional user input in the CULVERT command. The input parameters are TY1YTD and TY1HTD. Complete input details for these parameters are provided in section 5.5. The upper limits for culvert-flow types 1 and 2 are set lower than the lower limits for culvert-flow types 5 and 6 to allow transitional flow to be computed.

**Table 4.** Free-flow limits for the culvert-flow types simulated in the Full EQuations UTiLities model

[$S_0$, the slope of the culvert invert with a decline in elevation in the downstream direction taken as positive; $S_c$, the critical slope in the culvert barrel; $y_i$, the water-surface height at section $i$; $D_i$, maximum inside vertical dimension of the culvert barrel at section i; $z_{b_i}$, invert elevation at section $i$; $y_{2max}$, the maximum water-surface height at section 2 allowed for type 1 flow; $z_{w_1}$, water-surface elevation at section 1; and $z_{w_{1MAX}}$, the maximum water-surface elevation permitted at section 1 for type 1 flow; ≤ less than or equal to; max (a, b), a function that selects the maximum value between the arguments a and b; section 1 is the culvert approach section one culvert-opening width upstream; section 2 is the culvert entrance; section 3 is the culvert exit]

| Flow type | Limit | Conditions defining the limit |
|---|---|---|
| 1 | Lower | Minimum $y_2$ at $S_o = S_c$ |
| 1 | Upper | $S_o = S_c$ and $y_2 \leq y_{2max}$ and $z_{w_1} \leq z_{w_{1MAX}}$ |
| 2 | Upper | $y_2 = D_2$ and $z_{w_1} \leq z_{w_{1MAX}}$ |
| 61 | Lower | Same as type 2 upper limit |
| 61 | Upper | $y_2 = z_{b_3} + D_3 - z_{b_2}$ |
| 5 | Lower | $\mathrm{Max}(1.5D_2 + z_{b_2}, 1.5D_3 + z_{b_3})$ |
| 6 | Lower | $\mathrm{Max}(1.5D_2 + z_{b_2}, 1.5D_3 + z_{b_3})$ |

2. The transitional flow types are utilized between the upper limits of the low-head culvert-flow types (1 and 2) and the lower limits of the high-head culvert-flow types (5 and 6). The equation for the high-head flow type is forced to match the flow and downstream water-surface-elevation limit of the low-head flow type. This is accomplished by computing a discharge coefficient for culvert-flow type 6 or a contraction coefficient for culvert-flow type 5 that will match the flow for the corresponding low-head culvert-flow. If this is not possible, no transition is computed and the user must adjust the resulting function table of type 13 manually if one or more transitions are too abrupt. The downstream water-surface-elevation limit is the tail-water elevation at which free flow ends and submerged flow begins. For example, for culvert-flow type 2, the downstream water-surface-elevation limit is critical depth in the culvert barrel.
3. For any water-surface elevation at section 1 in a transition region, the downstream condition and the discharge or contraction coefficient are varied linearly with elevation at section 1 between the values at the lower and upper limits of the transition region. For example, the upper limit for a culvert flow of type 2 in a given culvert might be 8.4 ft with a critical depth at the culvert exit (section 3) of 4.5 ft and a discharge coefficient of 0.95. For this same culvert, the lower limit for a culvert-flow of type 6 might be 10.5 ft with a piezometric level at the culvert exit of 4.8 ft and a discharge coefficient of 0.84. Assuming that the discharge, upstream water-surface elevation, and downstream (section 3) piezometric level corresponding to the upper limit for culvert-flow type 2 are applied in equation 85 describing culvert-flow type 6, the discharge coefficient for culvert-flow type 6 would be 0.78. For an upstream water-surface elevation of 9.45 ft, at the middle of the transition region, the discharge coefficient for culvert-flow type 6 would be 0.81 and the piezometric level at the culvert exit would be 4.65 ft. Physical realism is sacrificed for transitional smoothness in this approximation. Both the piezometric level at the culvert exit and the discharge coefficient may be physically unrealistic or unattainable in any real flow. Such unrealistic conditions are not important in model simulation; the transitional flow that results in the physical system cannot be computed because it is physically unstable. All that

is required for computational accuracy is that the transitional flows be in a reasonable range. Flow types 51, 52, and 62 are the corresponding transitional types.

4. Culvert flow type 61 is transitional and may be stable. At its upper limit, the discharge coefficient is taken as if the culvert-flow were type 6. Its lower limit is the upper limit of culvert-flow type 2. Critical flow results at the culvert exit for both culvert-flow types 2 and 61. Thus, only the discharge coefficient is varied between the lower limit and upper limit of culvert-flow type 61. The transition between culvert-flow types 61 and 6 is treated the same as in item 3 with culvert-flow type 61 defining the conditions that the equation describing culvert-flow type 6 (equation 85) must match.

Transitions between free-flow types and submerged flow types as well as between submerged flow types must be considered. Some transitions, such as between culvert-flow types 6 and 4 are smooth, as long as culvert-flow type 42 is recognized. The transition between culvert-flow types 3 and 4 can be abrupt. However, considerable uncertainty results regarding the details of the transition from part-full flow to full flow for the culvert. Thus, the transition from culvert-flow type 3 to culvert-flow type 4 is usually accomplished through culvert-flow type 41. The conditions that cause the barrel to flow full are not explicitly determined. Whether the barrel is flowing full is determined by the water level at section 43. The transition from culvert-flow type 3 to type 4 is smoothed with culvert-flow type 41 without an explicit identification of the transition.

The transition from free-flow, culvert-flow type 5 to full-pipe flow is not smooth. Culvert-flow type 5 is unstable in that adequate ventilation of the free space above the water in the barrel must be available. When this ventilation is restricted by the friction of the air flow in the barrel or by a hydraulic jump in the barrel or at the exit of the barrel, the barrel will abruptly switch from part-full flow to full flow. This transition is marked by an increase in the flow as the barrel is used more efficiently. This change in discharge can be 30 percent or more. This transition is unstable because the increase in discharge may induce air entrainment at the entrance through one or more vortices. The entrainment of this air may allow the flow to momentarily be part full. Thus, the flow surges and oscillates until the upstream water-surface elevation rises enough to prevent substantial entrainment of air at the culvert entrance. During this time, the value for flow in the culvert is probably between the culvert-flow type 5 value and the value when the barrel is flowing full throughout (culvert-flow type 4). Therefore, a special discharge coefficient for the equation describing culvert-flow type 5 is computed in the CULVERT command such that the culvert-flow type 4 matches the culvert-flow type 5 at its limit. This coefficient is then varied linearly between the culvert-flow type 5 submergence (full-flow inducing) level and the current downstream water-surface elevation. This interpolation continues until the current downstream water-surface elevation is at or above the exit soffit. Then the culvert-flow becomes type 4. The transitional culvert flow is denoted 42 because it is full flow and the piezometric level at the culvert exit is below the culvert soffit.

### 4.2.5 Departure-Reach Losses

Bodhaine (1968) took the departure reach losses to equal complete loss of the velocity-head difference between the culvert exit and the departure section. In general, this loss is too large. The cumulative effect of using this simple loss on a sequence of culverts along a stream in an urban area could substantially bias the computed water-surface elevations. Therefore, a simple momentum balance in the departure reach is applied in FEQUTL following Henderson (1966, p. 208–210). This approach or variations have been applied and described by Schneider and others (1977).

In Bodhaine (1968), the losses at the exit of the culvert are estimated using the complete loss of velocity-head difference between the exit of the culvert, section 3, and the departure reach, section 4. This would seem to imply that this loss method must be used for consistency in the selection and application of discharge coefficients. However, this implication is incorrect as described in the following discussion.

Culvert-flow types 3 and 4 in Bodhaine (1968) are the only flow types that can be affected by exit losses. The other culvert-flow types are free of tail-water effects by definition and, therefore, the discharge coefficients are independent of any assumptions made about the losses in the departure reach. The only effect of exit-loss assumptions on culvert-flow types 1, 2, 5, and 6 involve the conditions that must be present at section 4 for these flow types to be valid.

The discharge coefficients for culvert-flow types 4 and 6 are identical in Bodhaine (1968). These culvert-flow types only differ in the conditions in the departure reach, with the exit of the culvert submerged in type 4 flow so that tail water affects the flow. Bodhaine (1968) points out that the piezometric level at section 3 is below the soffit of the culvert, but no statement is given on submergence-level effects below the soffit. In FEQUTL, additional culvert-flow types have been included in the CULVERT command to represent submergence of type 6 flow when the tail water is above the exit piezometric level but below the soffit. The deviation of the discharge coefficient from the ideal value of unity for these flow types is a reflection of the energy losses incurred at the contraction and expansion of the flow near the culvert entrance. These contraction and expansion effects are identical in both culvert-flow types 4 and 6. Consequently, the assumptions regarding the exit losses cannot have a significant effect on the model experiments that yielded the discharge coefficients for culvert-flow type 4. Otherwise, the computed discharge coefficients would have differed significantly from those found for culvert-flow type 6. Therefore, in both culvert-flow types 6 and 4, the piezometric level at the exit is the proper value for computing the flows with the discharge coefficients. The only difference is that for culvert-flow types 6 and 4, the piezometric level is below the water surface and at the water surface, respectively.

Culvert-flow type 3 is similar to culvert-flow types 1 and 2 except that tail water affects the type 3 flow. However, Bodhaine (1968) gives the discharge coefficients for all three flow types using the same relation. Bodhaine (1968) gives the base discharge coefficient for pipe culverts in figures 20 and 25 and the discharge coefficient for box culverts in figure 23. Culvert-flow types 1 and 2 are independent of the treatment of losses in the departure reach. Again, if the culvert-flow type 3 discharge coefficients in the model experiments were greatly affected by the treatment of the departure reach losses, it seems unreasonable to expect that the discharge coefficients would follow the same relation. Therefore, the proper value of the water-surface elevation for culvert-flow type 3 is the water-surface elevation at section 3.

The unpublished details and raw results of the laboratory model study utilized to develop Bodhaine (1968) have been lost since the experiments were completed about 40 years ago. Therefore, the sizes of the model approach section and departure section relative to the model culvert barrel is unknown. Nevertheless, considering the goal of the study, peak-flow estimation, and the need to reduce computational effort, it seems logical that the model would have a departure reach much larger in flow area than the area of the culvert barrel. In this case, the water-surface elevation at section 3 approaches that at section 4 as shown by a simple momentum balance. The equivalence of water-surface elevations in sections 3 and 4 is a close approximation of the conditions most likely to be found in the field in natural channels at flood stage. If the departure-reach flow area is large enough relative to culvert flow area, then the assumption of an exit loss given by the difference in velocity heads is valid. It is reasonable to assume that the model departure reach was sized so that this was the case. This avoids the tedious calculations of the momentum balance in the departure reach before the common availability of digital computers.

In summary, the application of the momentum balance for the departure reach losses is consistent with the discharge coefficients in Bodhaine (1968), and it results in more reasonable losses for culvert-departure conditions that violate the assumptions implicit in application of the difference in velocity heads as the estimate of the energy loss in the departure reach. Assumption of complete loss of the difference in velocity heads in the culvert departure reach often results in an overestimation of the losses and, in some cases, a gross overestimation of the losses. The simple momentum balance provides a reasonable alternative that maintains basic validity to the limit of a departure reach with the same width as the culvert exit. In that limit, the simple momentum balance gives results for a submerged hydraulic jump in a rectangular channel. Assuming complete loss of the velocity-head difference can lead to an underestimate of the culvert discharge when the departure reach has a flow area only a few times larger than the culvert exit. This underestimation is corrected by using a simple momentum balance to estimate the conditions at section 3 from the conditions at section 4.

In applying a simple momentum balance, it is assumed that the departure reach is horizontal, prismatic, and frictionless. The simple momentum balance is calculated for sections 3, 43, 44, and 4 shown in figure 3. Section 43, the cross section of the stream channel a short distance downstream from the culvert exit, represents the upstream end of the control volume for the simple momentum balance. Section 44 represents the downstream end of the control volume for the simple momentum balance. The distance between these two sections is not considered in the computations because friction and bottom slope are ignored. The geometry of section 44 is always the same as section 43 because a prismatic channel is assumed in the simple momentum balance. Different designations are applied because the water-surface elevation and water-surface height in these sections will differ. If the departure reach is prismatic and horizontal, the geometry of section 4 will be the same as sections 44 and 43 with the same water-surface elevation as section 44.

If the departure reach is not horizontal or prismatic, then the geometry of section 4 will differ from section 43. However, section 44 will still be the same as section 43, defining a horizontal and prismatic subreach in the departure reach. This is needed for the simple momentum balance. A simple momentum balance is used to estimate the losses in this case because the application of the momentum balance to a nonhorizontal or nonprismatic control volume requires knowledge of the water-surface profile in the control volume. Simple assumptions regarding this profile may introduce errors so large that the results become useless. This is analogous to the representation of a hydraulic jump. A simple momentum balance produces a close match to measurements if the jump is in a prismatic, nearly horizontal channel. If the channel is nonprismatic or nonhorizontal, simple estimation of the gravity force or of the downstream component of the pressure forces on the sides of the channel fails to produce good results, and laboratory measurements must be made. No such measurements are available for the departure reaches of culverts, and only a limited number of measurements are available for hydraulic jumps.

The simple energy balance between sections 44 and 4 is

$$z_{w_{44}} + \alpha_{44}\frac{Q_{44}^2}{2gA_{44}(y_{44})^2} = z_{w_4} + \alpha_4\frac{Q_4^2}{2gA_4(y_4)^2}, \tag{90}$$

where $Q_{44} = Q_4 = Q_B + Q_r$. The water-surface elevation at section 4 is transferred to section 44 by applying equation 90 and assuming no energy losses. The assumption of no energy loss resulting from friction is reasonable because of the short distance between sections 44 and 4. The simple momentum balance becomes

$$M_r + \beta_3\frac{Q_3^2}{A_3(y_3)} + gJ_{43}(y_{43}) = \beta_{44}\frac{Q_{44}^2}{A_{44}(y_{44})} + gJ_{44}(y_{44}) \,. \tag{91}$$

Equations 90 and 91 give the relations for the departure reach once the culvert and roadway flows and momentum fluxes are known.

### 4.2.6 Outline of Solution Process for Culvert Flow

The solution process for culvert-flow proceeds in the following major steps for each upstream head given by the user. The datum for head is the maximum value of the elevations of the minimum points at sections 1–4.

1. The free flow over the roadway, if any, is determined. The drop to free flow for the flow over the roadway (that is, the difference in elevation between the water surface at sections 1 and 43 at incipient submergence of the free flow) also is computed in this step.
2. The free flow and the flow type for the culvert are determined. All free-flow type transitions are included in this step as is the computation of the free-flow limits.
3. The departure reach for the free flow is computed. The conditions at section 3 and section 43 are known. The flow and momentum flux for the roadway are known. Equation 91 is solved for the water-surface height and, therefore, the elevation at section 44. Equation 90 is then solved for the water-surface height at section 4. The drop to free flow for the 2-D table is then given by the difference in water-surface elevations between sections 1 and 4. A case may result where no solution is possible. This indicates the control is at section 4, and the free-flow type is type 7. Free drop and the free flow must be computed at a later step (see step 9).
4. The drop between the water-surface elevation at section 1 and the piezometric level at section 3 corresponding to the free flow determined in step 2 is computed. A series of tail-water elevations at section 43 is computed

covering the range from the minimum, the free-flow piezometric level, to the maximum, the water-surface elevation at section 1. The distribution of partial drops specified by the user defines the series of downstream water-surface elevations to be evaluated in the CULVERT command. The drop from section 1 to section 43 must be distinguished from the drop from section 1 to section 4.

5. The flow in the culvert and the flow over the roadway are computed for each downstream water-surface elevation determined in step 4 above the minimum elevation for free flow. The flow in the culvert will be submerged. The water-surface elevations at sections 1 and 43 are known, so the only unknown is the flow in the culvert. The flow over the roadway is computed first because it can affect the flow in the culvert through the velocity head at section 1. The square root of the drop in water-surface elevation from section 1 to section 43 is then computed.
6. A function relating the sequence of culvert-flows and the associated square root of drop is determined. A variation-limited cubic spline is fitted to these values with flow taken as a function of square root of drop. The points defining the fit are called knots. Thus, the knots in this case are the values of square root of drop at which the culvert-flow was computed. An interior knot is any knot that is not at the beginning or end of the sequence of knots. A cubic spline is a piecewise cubic polynomial with the function value, first derivative, and second derivative being continuous at each interior knot. A variation-limited cubic spline is a cubic spline in which the variation of the spline between adjacent knots is monotonic; that is, the first derivative always has the same sign. The purpose of requiring that the first derivative be monotonic is to prevent introducing new extreme values by interpolation between knots. If this is not done, the fit of the cubic spline or other nonlinear function could result in new extremes that are invalid. Because the spline is variation limited, extreme values not already present at the knots will not be produced by interpolation. In some cases, the spline is not variation limited. The computed first derivatives at the knots are then adjusted in FEQUTL to force the piecewise cubic polynomial to have monotonic variation. This no longer results in a cubic spline because the adjustment of the first derivative causes the second derivative at the adjusted knot to be discontinuous. However, the simulated model fit to the data may still be excellent. Once the function is defined, it is stored in a function table for later use.
7. A function that gives the flow-defining area at the culvert exit as a function of the water-surface elevation at section 43 is determined. The culvert can be flowing full or part full. The function will have a unique value for each water-surface elevation at section 43 for a given upstream water-surface elevation. A piecewise linear function is adequate to define the water-surface elevation at the culvert exit. This function is stored in a function table of type 2 for later use. If the water-surface elevation at the culvert exit is known, the flow area can be computed for the culvert exit. If the flow area and the flow are known, the momentum flux for the flow at the culvert exit can be computed.
8. The flow and the momentum flux over the road are easily computed as needed, so special tables are not used. These values are always computed from basic definitions. This is efficient because submergence of flows over embankment-shaped weirs is affected by downstream water-surface elevation only when that elevation is higher than about 70 percent or more of the approach head. Usually, the flows computed for the last few downstream water-surface elevations as the upstream water-surface elevation is approached deviate from the free-flow values.
9. If the freeflow corresponds to culvert-flow type 7, the free flow and the drop to free flow are calculated. Culvert-flow type 7 is a submerged flow in the culvert because the control at section 4 drowns all other controls. The following steps are applied to calculate the free flow and drop to free flow.
    - 9.1. A water-surface height at section 43, $y_{43}$, is selected. This water-surface height defines the flow in the culvert with the associated momentum flux by using the special tables developed in steps 6 and 7. The flow and momentum flux over the roadway are computed. The water-surface height, $y_{43}$, defines all cross-sectional characteristics needed at section 43.
    - 9.2. The flows are now known, so critical water-surface height at section 4 may be computed. This defines all other values at section 4. Equation 90 is solved for the flow and water-surface height at section 44. This defines all cross-sectional characteristics needed at section 44.

9.3. Flow and water-surface-height values at section 43 and section 44 are defined. These values are applied in equation 91 to compute the left-hand side and the right-hand side of the equation. If the two sides are in close agreement, the solution for free flow is found. If not, a new depth is selected at section 43 that will improve the agreement and steps 9.1–9.3 are repeated.

10. The partial free drops between sections 1 and 4 are computed. These are not the same as the drops between sections 1 and 43. From these drops the corresponding water-surface elevations at section 4 are computed, starting at the minimum elevation at free flow and ending at an elevation equal to the elevation at section 1.

11. For each elevation computed in item 10, the submerged flow is determined utilizing the departure-reach equations, 90 and 91. The process is as follows.

11.1. A water-surface height at section 43, $y_{43}$, is selected. This water-surface height defines the flow in the culvert with the associated momentum flux by utilizing the special tables developed in steps 6 and 7. The flow and momentum flux over the roadway are computed. The water-surface height, $y_{43}$, defines all cross-sectional characteristics needed at section 43.

11.2. The flows are now known, so flow and water-surface-height values at section 4 are known. Equation 90 is solved for the flow and water-surface-height values at section 44. This defines all cross-sectional characteristics needed at section 44.

11.3. Flow and water-surface height-values at section 43 and section 44 are defined. These values are applied in equation 91. If the two sides of equation 91 are in close agreement, the solution for flow and water-surface height is found. If not, a new water-surface height is selected at section 43 that will improve the agreement and steps 11.1–11.3 are repeated.

### 4.2.7 Momentum Flux for Flow Over the Roadway

The momentum flux over the roadway enters into the simple momentum balance for the departure reach. It is assumed that the horizontal momentum flux over the roadway enters the channel unaffected by gravitational acceleration or flow resistance down the roadway embankment. When the flow over the roadway becomes a large part of the total flow, the momentum flux must be considered. For moderate depths of flow over a roadway, the depth is approximately critical depth when the flow is free of downstream effects. Assuming that the flow over the roadway is critical results in the depth as

$$y = \left(\frac{C_{wr}^2 H^3}{g}\right)^{1/3}, \tag{92}$$

where $C_{wr}$ is the weir coefficient and $H$ is the head on the roadway (depth of flow relative to the minimum point on the roadway embankment) utilized to compute the weir flow. The estimated momentum flux per unit width of roadway, $q_r^2/y$, becomes

$$\frac{q_r^2}{y} = g^{1/3} C_{wr}^{5/3} H^2, \tag{93}$$

where $q_r$ is the flow per unit width of roadway. The weir coefficient includes the effects of friction losses in the approach and other factors. The flux per unit width is integrated along the roadway crest as the flow per unit width. Additional details are provided in section 4.3.

When the flow over the roadway is submerged, equations 92 and 93 are not valid. The flow is no longer approximately critical, and the flow is reduced from that given by the unit-width weir equation (equation 93). The crest depth for submerged flow is estimated in FEQUTL assuming that the loss of energy from section 1 to the roadway crest will be in the same proportion to the loss of energy from section 1 to section 43 as for incipient submergence. In equation form this assumption becomes

$$\Delta E_{1s} = \Delta E_{143s} \frac{\Delta E_{1f}}{\Delta E_{143i}}, \quad (94)$$

where

$\Delta E_{1s}$ is the energy loss from section 1 to the roadway crest when the flow over the roadway is submerged;

$\Delta E_{143s}$ is the energy loss from section 1 and 43 when the flow over the roadway is submerged;

$\Delta E_{1f}$ is the energy loss from section 1 to the roadway crest when the flow over the roadway is free; and

$\Delta E_{143i}$ is the energy loss from section 1 to section 43 at incipient submergence of the free flow.

The loss ratio at incipient submergence is assumed to remain the same for submerged conditions in FEQUTL computations. The specific energy at the roadway crest for submerged flow is computed and inverted to find the crest depth for submerged flow. This crest depth is then used to estimate the momentum flux for submerged flow.

Assuming critical flow on the crest, the energy loss from section 1 to the roadway crest at free flow is

$$\Delta E_{1f} = H - 1.5y. \quad (95)$$

Assuming that the roadway embankment height, $P_e$, above the approach reach is about the same as its height above the departure reach, the loss from section 1 to section 4 at incipient submergence is estimated from

$$\Delta E_{143i} = H - \frac{q_r^2}{2g(h_I + P_e)^2} - h_I, \quad (96)$$

where $h_I$ is the piezometric downstream head at incipient submergence measured from the roadway crest. The energy loss from section 1 to section 43, $\Delta E_{143s}$, is given by equation 96 with $h_I$, the downstream head at incipient submergence, replaced by $h_t$, the downstream head causing submergence.

Several checks on the results for the submerged crest depth are performed in FEQUTL computations. The loss ratio is given a minimum value of 0.005. Also, the crest depth computed for submerged flow is not permitted to be less than the crest depth for free flow at the given upstream head.

The momentum flux over the roadway crest may not be a good estimate of the effective flux that enters the control volume of the departure reach for the simple momentum balance. The pathway of flow over the roadway entering the departure reach should be considered. Many rural and suburban roads do not have curbs and gutters. Ditches adjacent to the roadway serve as drainage channels. A portion of the water flowing over a roadway at a culvert crossing may be intercepted by the ditch on the downstream side of the road. This water is then delivered to the departure reach of the culvert. This water enters the departure reach at approximately a right angle. Therefore, the effective momentum flux in the downstream direction from the flow over the roadway is much smaller than the momentum flux computed for the flow over the roadway. A fixed factor is included in FEQUTL as a multiplier on the estimated momentum flux over the roadway to better estimate the effective flux for the simple momentum balance used in the departure reach.

### 4.2.8 Special Losses

Culverts commonly are placed in a stream in a manner that departs markedly from the placement assumed in the laboratory tests on which the loss estimates are based. For example, for reasons of simplicity, economy, or physical restrictions, culverts commonly are placed so that the stream approaches the culvert perpendicular to the barrel and makes a sharp right-angled bend immediately upstream from the culvert entrance. An input value, APPLOS, is included in FEQUTL and is taken as a factor on the approach velocity head to represent additional losses. When the flow entering the culvert undergoes an expansion, the loss coefficients determined in laboratory tests do not apply. The input value, APPEXP, is then applied as a factor on the velocity-head difference between sections 1 and 2.

### 4.2.9 Summary of the CULVERT Command

This discussion of the CULVERT command contains a simplified outline of the steps in the solution process. Many special conditions must be detected and addressed. One of the more difficult problems is convergence failure at some point in the solution process. The process has many iterative solutions: steady-flow profiles, critical depth, normal depth, inversion of specific energy, inversion of specific force, and others. A failure to converge could arise from a user error, a program error, or an incorrectly selected path. Tests are included in the program code to distinguish these causes of convergence failure, but sometimes these causes cannot be determined in the tests. Only a subset of all possible culverts can be computed with the CULVERT command.

Two common cases result in computational failure in the CULVERT command. One case where problems arise is in computation of culvert-flow type 0. This flow type only should result at low flows when the culvert barrel has a greater capacity than does the low-flow channel in the approach section. No transitions for type 0 flow are provided in FEQUTL. If type 0 flow results for moderate to high flows, it is likely that the approach section is invalid.

A related condition arises with flow over the road. All the flow in the culvert and over the roadway must pass through the approach section. If the length of overflow for the roadway is too wide, culvert-flow type 0 will result. Critical control at section 1 is assumed in culvert-flow type 0. For computation of flow over the roadway it is assumed that critical control cannot result at section 1. These two assumptions conflict, and computational failure or problems will result. The flow over the roadway is computed, if possible, as long as the flow is less than or equal to the critical flow in section 1. This is done only to provide a result that can be interpreted. Flow over the road and culvert-flow type 0 are not compatible. If culvert-flow type 0 results at moderate to high flows or with flow over the road, then the representation of the culvert must be changed. Two alternative representations of the culvert are possible.

The flow over the road can be computed separately from the flow in the culvert by applying the EMBANKQ command (section 5.6). Calculation of the flow over the road with the CULVERT command is suppressed by specifying a high value for the elevation of the roadway crest. Two flow tables will be computed in FEQUTL: one for flow over the road and the other for flow through the culvert barrel. These flow tables are then used in parallel in FEQ to represent the culvert. Some of the interaction between the two flow paths is lost. However, this may be applied if the flow over the road is at a distance from the culvert or if the flow over the road is large relative to the flow through the culvert.

The other alternative for computing flow over the road and through the culvert is introduction of an explicit expansion upstream from the culvert applying the EXPCON command (section 5.7). The approach section, which is smaller than the culvert opening, is utilized as the upstream cross section for the expansion. A new approach section, made large enough that the flow always contracts as it enters the culvert, is then utilized for the approach section for the culvert and as the downstream section for the expansion. In the FEQ model, the expansion is connected to the culvert with a short branch, usually only 1 or 2 ft long, with the new approach section of the culvert defining the cross section for the branch.

Neither of these alternatives account for the lack of knowledge of the physics of flows expanding at a culvert. However, these alternatives account for the problem of computational failure. Only a careful field check of the cross sections can reveal if they are properly measured. Unless the culvert opening is partially blocked, a cross section must be available that is larger than the culvert opening. If the culvert opening is partially blocked, then the barrel cross section utilized is incorrect.

## 4.3 Embankments and Weirs

Flow over embankment-shaped weirs as well as weirs of other shapes is computed in the FEQUTL command EMBANKQ (section 5.6). The computations follow the principles developed and outlined in Hulsing (1967, p. 26-27). The principles described in Hulsing are based on research reported by Kindsvater (1964). The procedure applied in FEQUTL divides embankment-shaped weirs into two classes: weirs with paved surfaces and weirs with gravel surfaces. The variation of the weir coefficient with flow conditions in each of these classes is further subdivided into high-head and low-head cases. The boundary between high-head and low-head cases was set at 0.15 of the crest width of the embankment. The high-head weir coefficients vary with the ratio of piezometric head to crest width, whereas the low-head weir coefficients vary with the piezometric head. In both cases, the piezometric head is used in the weir equation. The work by Kindsvater (1964) indicated that the effect of embankment height was rendered negligible if the piezometric head was used in the weir equation. Submergence-reduction factors for both paved- and gravel-surface weirs are applied in FEQUTL. These factors are applied as functions of the ratio of the piezometric tail-water head to the piezometric head on the crest.

Six tables, which may be electronically retrieved with FEQUTL as described in section 1.1, are included in a file named EMBWEIR.TAB to represent embankment-shaped weirs. These tables contain the weir coefficients for high-head and low-head flow and the submergence-reduction factors for weirs with paved surfaces and with gravel surfaces. The values included in these tables were derived from the information in Hulsing (1967) and Kindsvater (1964). The physical dimensions of the embankment-shaped weir are input by the user, and the appropriate coefficient tables are accessed to compute 2-D tables of types 6 and 13 for a user-specified range of upstream heads and partial free drops.

The six tables described are listed as default table numbers in the input description for the EMBANKQ command (section 5.6). If 2-D tables for other types of weirs (sharp crested, broad crested, or ogee shaped) are to be computed, the user must input tables containing the weir coefficients for high-head and low-head flow and the submergence-reduction factor using the FTABIN command (section 5.13). These tables are referenced in the EMBANKQ command (section 5.6).

The weir crest is assumed to be level in the typical weir equation. This is rarely true for the profile of a roadway crest as illustrated in figure 18 (in section 5.6). Integration of the unit-width weir equation is applied in EMBANKQ to account for the possibility that the weir crest is not horizontal. Horton (1907, p. 57), in his summary of weir formulas and coefficients, recommended this procedure. Brater and King (1976, p. 5-16) showed that the equation resulting from the integration of the unit-width weir equation gives a close approximation to the flow for a triangular, sharp-crested weir (V-notch weir). A single equation represents a wide range of experiments and angles of notch within 5 percent. Therefore, integration along an embankment crest much less sharply inclined than a V-notch weir should produce useful results.

The user must specify the elevation of the crest, the width of the crest in the direction of flow, the elevation of the approach surface to the weir, and the nature of the crest surface (PAVED or GRAVEL) for each of a series of locations along the weir crest perpendicular to the flow as shown in figure 18 and described in detail in sections 5.5 and 5.6. These values are then a function of the offset distance, $s$, along the weir crest measured from some convenient reference point. The elevation of the approach surface is needed to define the height of the weir crest to compute the velocity head of approach.

The unit-width discharge over a weir, $q_w$, is computed in the EMBANKQ command as

$$q_w(s) = f_{CH}[h_w(s)/W(s)]H(s)^{1.5}f_s\left[\frac{h_t(s)}{H(s)}\right] \tag{97}$$

for the high-head range, and

$$q_w(s) = f_{CL}[H(s)]H(s)^{1.5}f_s\left[\frac{h_t(s)}{H(s)}\right] \tag{98}$$

for the low-head range,
where

$W(s)$ is the crest width represented at the local offset $s$;
$f_{CL}$ is the function that gives the weir discharge coefficient for low-head flow;
$f_{CH}()$ is the function that gives the weir discharge coefficient for high-head flow;
$H$ is the piezometric head on the weir;
$h_w$ is the piezometric head on the weir;
$h_t$ is the downstream head causing flow submergence at a weir; and
$f_s()$ is the submergence function.

The total flow at a given upstream water-surface elevation, $Q_w(z_w)$, is

$$Q_w(z_w) = \int_{s_L(z)}^{s_R(z)} q_w(s)\,ds\,, \tag{99}$$

where $s_L$ and $s_R$ give the limits of integration that depend on the water-surface elevation, $z_w$. Equation 99 does not include the case of two or more separate paths for flow over the roadway, but the generalization to that case is straightforward. Equation 99 can be applied to each path and the results summed to obtain the total flow. Hulsing (1967) indicated that the width to use for defining flow over the roadway is difficult to define and recommended that five-sixths of the maximum piezometric head be used to define the level that establishes the limits of flow. This approximation is not applied in the EMBANKQ command. Instead, the water-surface elevation is projected to the weir crest to define the limits of integration. This approach produces good results for V-notch weirs up to a central angle of 120 degrees. No data are available to check the results for smaller slopes. It is clear that the wetted width of the roadway will be narrower than the width obtained by projecting the upstream water-surface elevation to the crest. However, it is not clear what the limits of integration should be. Careful measurements on large-scale inclined weirs are needed to draw conclusions on this matter. The typical slopes along roads are small. Although the difference in integration widths obtained from the two assumptions may be substantial, the differences in flow may not be substaintial. The piezometric head on the weir crest in the region where the integration limits differ will be relatively small. Thus, the total contribution of flow from these regions of the crest to total flow will be small.

The integral in equation 99 is approximated on the basis of Simpson's Rule. Simpson's Rule is applied to each line segment defined by the successive points along the weir crest. The weir crest is assumed to vary linearly between adjacent points. Thus, for each line segment, the flow per unit width is computed at three points: at each end and at the midpoint. The velocity head of approach is computed for each point and results from the unit width of flow over the weir at that point alone. This deviates from the typical practice for flow over weirs wherein a global velocity head is used. This means that the velocity head is not a constant along the weir crest and may vary from point to point. This gives a more realistic representation of the flow field approaching the weir when flow over the flood plain is present than the constant-velocity-head approximation. If a crest segment is very long with a large change in elevation between the two ends, it may be necessary to subdivide this segment for computational accuracy in Simpson's Rule.

The free flow and a range of submerged flows are computed for a series of upstream maximum piezometric heads defined by the user. The maximum piezometric head is computed from the water-surface elevation to the point of minimum crest elevation. Given these values and the six function tables defining the weir characteristics, the following steps are applied to compute the values.

1. The upstream water-surface elevation is computed for the current maximum piezometric head.
2. The line segments that compose the weir crest are scanned.
3. For each line segment completely submerged, the unit-width flow rate is computed as defined above for the particular head range and surface class for each end and for the midpoint of the segment. If culvert computations are involved, the various flux terms also are computed applying the same rule for integration.
4. For each partly submerged line segment, the intersection point with the water surface is located, and the flux terms defined in step 3 are computed for the truncated line segment.

5. Simpson's Rule is applied to approximate the integral in equation 99 over the line segment.
6. The line-segment values are summed to obtain the free-flow values at the given upstream water-surface elevation.
7. The drop to the downstream water-surface elevation at the free-flow limit is computed if the submergence functions have been given. If not, the free-flow result is placed in a function table of type 2, and the next maximum upstream piezometric head given by the user is evaluated.
8. For each of a series of partial free drops defined by user-input values, the submerged flows over the weir are computed in a manner analogous to that for free flow.
9. The results are placed in a 2-D table of type 13, and the next maximum upstream piezometric head given by the user is evaluated.

## 4.4 Closed Conduits

Closed conduits for large storm sewers or culverts that are too long to simulate with the CULVERT command must be simulated in FEQ. The equations governing the flow change when the free surface in the conduit disappears as the conduit flows full. To circumvent this problem, a hypothetical slot is introduced at the top of the closed conduit in FEQ simulation, as in many other unsteady-flow modeling systems. This is called the Preissmann (1961) slot. Pressurized flow may then be represented by a hypothetical free-surface flow in the slotted pipe. The cross section then resembles a thermometer bulb with the stem of the thermometer being very narrow relative to the size of the bulb. The slot is made as high as needed to prevent water from flowing out of the slot.

A free surface is maintained at all times in this hypothetical slot. Consequently, the governing equations for unsteady flow can remain the same as for flow in a branch. Furthermore, the small width of the slot causes the wave celerity to increase to a large value. For rigorous analysis the slot could be sized to approximate the speed of an abrupt pressure wave in the conduit. However, this is rarely needed; in any case, the estimation of the speed of a water-hammer wave in a storm sewer is difficult. The width should be made small so that the area of flow is not greatly increased for the expected surcharge levels. High levels of surcharge in small conduits should be avoided. The approximations inherent in this approach to flow in closed conduits are not meant for the pressures encountered in a typical water-distribution network. However, substantial levels of surcharge can probably be represented for large storm sewers.

Details of the hydraulic characteristics of a closed conduit are not directly utilized in FEQ simulation because only cross-section function tables are required in FEQ simulation. Therefore, three commands for computing cross-section function tables representing closed conduits are provided in FEQUTL. In the simplest command, SEWER (section 5.19), a cross-section function table is computed for a single circular pipe. In the next most simple command, MULPIPES (section 5.17), a cross-section function table is computed for one or more circular conduits. Finally, in the most general command, MULCON (section 5.16), a cross-section function table is computed for one or more circular, elliptical, pipe-arch, or box-shaped conduits. For two or more conduits, the hydraulic characteristics at a given water-surface elevation are aggregated in MULPIPES and MULCON.

In the commands for computing cross-section function tables for closed conduits, the basic definition of the shape is utilized to compute a polygonal approximation to that shape. In the SEWER and MULPIPES commands, the user specifies the number of sides utilized in the polygon. The number of sides in the polygonal approximations in MULCON is fixed in FEQUTL. The polygon is computed such that the full flow area of the shape is matched. The polygonal description then becomes the same in form as that used in the commands FEQX or FEQXEXT described in section 3. The internally generated description is then processed in the same way as a polygonal description given by the user. A polygon of 20 or more sides approximates the shape of the conduit more precisely than the manufacturing tolerances allowed for the shape. Therefore, the use of a polygonal approximation introduces no additional errors.

The combination of conduits or culvert barrels of different shapes and sizes into a single cross-section function table should be done with care. If the sizes differ too much or if the invert elevations are significantly different, then the conduits should not be combined into one function table. Two or more flow paths should be utilized to represent the flow in such a conduit system. Each flow path would then consist of a set of conduits comparable in size and invert elevation. If this is not done, a major distortion of the flow in the conduit system may result.

The commands for computing cross-section function tables for closed conduits are applied to compute the descriptions of culvert barrels as well as for storm sewers. Relatively large amounts of sediment may accumulate in the bottom of a culvert barrel. In some cases, this sediment remains even during floodflows. Therefore, an optional specification of a mud line in a conduit is provided in FEQUTL. This mud line can have a roughness value that differs from the wall of the conduit. A wetted-perimeter averaged roughness is computed for each conduit. For multiple conduits, the conveyance for each conduit is computed separately and then the total conveyance corresponding to a given water-surface elevation is summed for all conduits.

## 4.5 Generalized Ritter Dam-Break Solution

A generalization of the Ritter (1892) solution for the peak outflow following the instantaneous failure of a dam is computed with the GRITTER command (section 5.14). The reservoir cross section is assumed to be prismatic, horizontal, and frictionless. Furthermore, there can be an initial flow in the reservoir, and the cross section of the failure site need not match the cross section of the reservoir. Although restrictive, the assumptions for the generalized solution allow reasonable estimates to be made of the peak flows that are physically possible as a result of a variety of failures. These estimates can be used to assess the reasonableness of the results obtained through solution of the dam-break problem using the options available in FEQ.

The generalization to a nonrectangular channel cross section involves the introduction of the Escoffier stage variable, $\omega$, defined as

$$\omega(y) = \int_0^y \frac{g}{c(y_1)} dy_1 , \tag{100}$$

where

$c(y_1)$ is the flood-wave celerity at height $y_1$, $\sqrt{gA(y_1)/T(y_1)}$ ;
$A(y_1)$ is the flow area at height $y_1$; and
$T(y_1)$ is the top width of the water surface at height $y_1$.

The Escoffier stage variable transforms the characteristic form of the governing equations into a convenient form for solution. The details of this transformation and a derivation of the solution are presented in Franz (1977). The solution for the relation between the water-surface height and velocity at the dam site after the failure is

$$V_D + \omega = V_{D_1} + \omega_1 , \tag{101}$$

where

$V_D$ is the velocity at the dam site after the failure;
$\omega$ is the Escoffier stage variable at the dam site after the failure; and
the subscript 1 denotes the corresponding values at the dam site before the failure.

Equation 101 contains two unknowns: water-surface height and water velocity at the dam site after the failure. If the dam fails completely and the cross section at the dam is identical to the cross section in the reservoir, the Ritter solution indicates that the flow at the dam site is critical. Thus, it is reasonable, as confirmed by test results, to assume that the flow at the dam site will be critical for a partial failure with perhaps some allowance made for the associated contraction losses. The critical-flow relation at the dam site for the dam breach provides another equation relating the velocity to water-surface height at the dam site in the reservoir cross section. Thus, a function, $f_{DB}(y)$, is defined that yields the flow through the breach for each water-surface height in the reservoir. The water-surface height in the reservoir is not the same as the water-surface height in the breach if the breach is partial. Therefore, $f_{DB}(y)$ gives the critical flow in the breach for the corresponding water-surface heights in the reservoir.

In these calculations, it is assumed that the distance between the breach and the upstream point in the reservoir is a small part of the length of the reservoir and that the application of a steady-flow relation will not appreciably affect the results.

The depth and velocity in the reservoir at the dam site must be the same for both equation 101 and for $f_{DB}(y)$. Therefore, $f_{DB}(y)/A(y)$ is substituted for $V_D$ in equation 101 to yield the governing equation for the generalized Ritter solution as

$$\frac{f_{DB}(y)}{A(y)} + \omega(y) = V_{D_1} + \omega_1 . \tag{102}$$

A modified false-position technique is applied to solve equation 102.

The command CRITQ (section 5.4) is designed to compute the function $f_{DB}(y)$, consistent with equations 100–102. The Escoffier stage variable is internally computed and interpolated in GRITTER by applying the following approximation to the integral in equation 100 over each tabulation interval in the cross-section table for the approach section

$$\int_a^b \frac{g}{c(y_1)} dy_1 \approx \frac{2g(b_i - a_i)}{c(a_i) + c(b_i)} , \tag{103}$$

where $a_i$ and $b_i$ represent the limits of a tabulation interval in the cross-section table. This approximation is exact for rectangular, triangular, and parabolic cross sections as well as for any cross section that has a linear variation of hydraulic depth ($A/T$) with the maximum depth in the cross section.

### 4.6 Critical-Flow Function

A critical-flow function is computed for the GRITTER command (section 5.14) or for a critical-flow boundary in FEQ with the CRITQ (section 5.4) command. The critical-flow function needed for the GRITTER command must be computed assuming that the velocity distribution in a cross section is uniform to be consistent with the governing equations applied in the generalized Ritter solution to the dam-break problem. This is obtained by using cross-section tables with no critical-flow tabulations. If critical flow is tabulated in the table, the tabulated critical flow will be utilized in CRITQ. However, in most cases, the tabulated critical flow in the table will include the effect of nonuniform velocity distribution. This is inconsistent with the governing equation applied in the generalized Ritter dam-break solution.

Two cross sections are given for the computation of the critical-flow function. One is the cross section of the stream channel upstream from a constricted cross section. This section is called the approach section. The constricted cross section, the second cross section included in CRITQ, must have a bottom elevation that is equal to or greater than the bottom elevation of the approach cross section. Also, the constricted section must be no larger than the approach cross section at any point. The water-surface height in the approach cross section corresponding to critical flow in the constricted cross section is computed for each tabulated water-surface height in the constricted cross section. The user assigns a discharge coefficient as an estimate of the contraction losses that may result in the flow through the constriction.

The flow and head in the critical-flow table are computed as follows. For each nonzero water-surface height in the cross-section table for the constricted section, the critical-flow rate is selected from the table if tabulated, or is computed if not tabulated applying

$$Q_c = A_c\sqrt{\frac{gA_c}{T_c}}, \tag{104}$$

where

$Q_c$ is the critical-flow rate at critical depth, $y_c$;
$A_c$ is the flow area at critical depth; and
$T_c$ is the top width of the water surface at critical depth.

Given the critical-flow rate at each water-surface height in the constricted section, the water-surface height in the approach cross section required to produce this flow is computed by applying an energy balance between the approach section and the constricted section, and the following equation is solved for $y_a$ as

$$z_{m_a} + y_a + \alpha_a \frac{Q_c^2}{2gA_a^2} = z_{m_c} + y_c + \alpha_c \frac{Q_c^2}{2gC_{dc}^2 A_c^2}, \tag{105}$$

where $z_{m_a}$ and $z_{m_c}$ are the bottom elevations of the approach and constricted section, respectively. The coefficient of discharge, $C_{dc}$, is 1.0 if no losses result. A coefficient of discharge less than 1.0 implies a loss $\left(1/C_{dc}^2 - 1\right)$ of the velocity head in the constriction. Values of $C_{dc}$ close to 1.0 are reasonable because the losses in contracting flows are generally small. The approaching flow must be subcritical for a meaningful solution to result. A subcritical solution is sought and an error is reported in FEQUTL if a subcritical solution cannot be calculated. A subcritical solution will result if the constricted section is restrictive at all depths. The tabulation interval in the constricted cross-section table should be small, especially at small depths, if accurate interpolation is to be obtained in the resulting critical-flow table. The DZLIM (section 5.1) value in FEQUTL can be used to force a small interval for this table.

The maximum water-surface elevation in the approach cross-section table must be higher than the maximum water-surface elevation in the constricted cross-section table. The water-surface elevation and the corresponding water-surface height in the approach section are computed for assumed critical flow at each nonzero water-surface height tabulated in the cross-section table for the constricted section. Because the flow is contracting, the water-surface elevation in the approach section will always be equal to or greater than the water-surface elevation in the constricted section.

## 4.7 Floodway Delineation

Determining the boundaries of a regulatory floodway is difficult because, although the floodway definition is simple, the floodway may be established in many ways. The floodway is that portion of the available flow cross section that cannot be obstructed without causing an increase in the water-surface elevations resulting from a flood with a 100-year average return period of more than a given amount. The Federal Emergency Management Agency (1995, p. 5-3) establishes the amount to be 1.0 ft, but States can require a smaller amount of increase and, as an example, the State of Illinois requires that the increase be 0.1 ft or less. This definition allows great freedom in the establishment of the actual boundaries of the floodway.

Various auxiliary requirements have been imposed in FEQUTL to more closely define the floodway. The main flow channel, if such can be defined, is generally required to be in the floodway. Thus, the hypothetical obstruction must not affect the lower flows in the stream. Furthermore, the obstruction usually is allocated between the left and right banks of the flood plain so as to reduce the hydraulic capacity of each by about the same amount.

Cases can result where only one streambank includes a flood plain, and then all the obstruction must be placed on only one side of the main channel. In other cases, the total capacity of one side of the flood plain may be inadequate for the planned reduction in capacity, and the other side must then have a greater reduction. A mixture of hydraulics and regulatory convenience combine to provide the tools and rules for establishing the boundaries of a regulatory floodway.

The loss of capacity for flow is computed in terms of conveyance, but a hydraulic problem is immediately encountered. Conveyance is an aggregate quantity that can only be computed meaningfully for complete channels or subdivisions of a channel with a shape such that the hydraulic radius properly reflects the frictional characteristics of the channel boundary. Thus, for the typical natural channel with a flood plain on the right and left, three subchannels are present: left overbank, main channel, and right overbank. A value of conveyance may be computed for each subchannel, and then the three subchannel conveyances are added to estimate the conveyance of the entire cross section. The manner in which the subchannels are defined is subject to some uncertainty, as is the best way to treat the interactions across the hypothetical boundaries between the main channel and the flood-plain channels. The hypothetical boundaries are assumed to be vertical and frictionless in most steady-flow and unsteady-flow models. Thus, no interaction is computed between the flow in the main channel and the flood-plain channels. Flow interaction does happen in nature, but the approximation is simple and no convenient, well-established alternative is available. More complex assumptions have been developed from laboratory studies, but too few field studies have been completed to make conclusions concerning the validity of the assumptions.

To compute a trial floodway, a rule of equal reduction of conveyance on the left and right of the channel is applied in FEQUTL by using the following steps.

1. For the water-surface elevation corresponding to the 100-year flood, the conveyance in the current cross section is computed. This is the reference conveyance.
2. A target conveyance for the cross section is computed for the placement of the right-hand encroachment. For example, if the total reduction in conveyance is set at 10 percent, then 5 percent of the conveyance will be removed on the right-hand side of the cross section. This means that 95 percent of the reference capacity will be available after the right-hand encroachment is in place when the water surface is at the 100-year flood elevation.
3. A vertical frictional wall is placed on the right-hand flood plain such that the target capacity of the remaining channel is obtained. The Manning's *n* of the boundary of the cross section where the wall is located is assigned to the wall. In the present example, this wall would be placed so that the conveyance in the cross section, when encroached only from the right, would be 95 percent of the reference conveyance.
4. A vertical frictional wall is placed on the left-hand flood plain such that the cross section has the desired target capacity. In the present example, the conveyance of the cross section, as encroached upon from both left and right flood plains, is 90 percent of the reference conveyance.

In some cases, the introduction of the vertical wall may lead to a slight increase in the conveyance because, for the shallow flows on the flood plain, it is possible to reduce the wetted perimeter more rapidly than the area, resulting in an increase in the conveyance. However, as the wall encroaches more and more of the cross section, the conveyance will be reduced. Also, the conveyance of the parts of the channel that have been cut off by the encroaching wall will not be the same on each side of the channel, nor will they be exactly the desired value. This problem cannot be remedied because conveyance is really an aggregate quantity, and estimates of the conveyance of a small part of the cross section are only rough approximations.

Another type of problem in the determination of a floodway is that the concept of a floodway, at least as implemented in practice, is unequivocally a steady-flow concept. A floodway is defined in terms of the reduction in flow capacity only, and any changes in storage are ignored. This greatly simplifies the analysis and may be adequate in many cases. The true efficacy of this simplification is unknown because no detailed study of the effects of storage change has been completed. The steady-flow concept is simple because a unique meaning can be assigned to the average 100-year return-period flow, and all that is required for a steady-flow analysis is a flow rate. However, for unsteady-flow analysis, further requirements include one or more hydrographs to determine the water-surface elevation that will be exceeded on the average only once in 100 years. In principle, no single hydrograph can be utilized to determine the 100-year water-surface elevations everywhere in the watershed. The assumption made in the steady-flow analysis is that the flows used represent all possible flow interactions; therefore, a simple analysis can be made. The problem in unsteady-flow analysis is that it is unlikely that an observed hydrograph is available for which the peak or volume approaches a reasonable range for the 100-year flood level.

The logistical aspects of applying FEQUTL and FEQ to define a floodway are now considered. The shape of the cross section is not considered in FEQ. The shape and size of the cross section are only considered in FEQUTL. Only a table of the cross-sectional characteristics for the entire section as a function of the maximum depth in the section is considered in FEQ simulation. Thus, an encroachment into the channel can only be defined with any precision in FEQUTL. Two sets of function tables must be input to FEQ: one set for the stream channel without a floodway and another set for the stream channel with a floodway. Furthermore, FEQUTL must be run for each change in the floodway. Therefore, the user should develop a structure of files that will simplify these operations.

All function tables that do not represent cross sections should be placed in one or more files distinct from the cross-section tables. Also, all the bridge and culvert definitions and the associated cross sections should be in distinct files so they can be run separately. Finally, the remaining cross sections not related to bridges should be in a distinct file. Any closed-conduit sections should also be in distinct files because these will not be involved in floodway changes. Thus, five or six files of input to FEQUTL and the same number of output files containing the function tables for use as input to FEQ may be needed. A well-thought-out naming convention should be established to keep track of the various files. Directory structure also is important for keeping track of the files.

The floodway specification, described in section 5.12, was designed to eliminate the need for making changes to the cross-section descriptions. Thus, the floodway specification consists of a table, with one line in the table used for each cross section to be modified, giving (1) a description of the method to apply in defining the floodway and (2) key items of information required to implement that method. The table number of the cross-section description is utilized to associate the floodway information with the cross-section description. If no floodway information is given in the floodway table for a cross section that appears in the subsequent input, then the cross-section table is computed unchanged. Conversely, floodway information given in the floodway table for a cross section not in the subsequent input is read in FEQUTL but not used. Thus, only those tables for which floodway information is given and that also appear in the subsequent input are changed. However, the complete input should always be processed to simplify the bookkeeping for files because the time taken in FEQUTL computations of the function tables is minimal.

The floodway table is stored in a distinct file and is referenced with the FLOODWAY command. In this way, only one copy of the floodway table is needed for a stream system. This reduces errors and helps maintain consistency. Only two lines must be added to the input files for FEQUTL to invoke the floodway option. Details for the floodway table and the FLOODWAY command are given in section 5.12.

Once the modified set of cross-section tables has been computed and the input to FEQ modified to reference the file containing the modified tables, FEQ can be run with the flood hydrograph or hydrographs selected for defining the floodway. It is unlikely that the first trial to determine floodway limits will be successful. The maximum values for water-surface elevation from FEQ simulation need to be reviewed, and adjustments should be made in the floodway table accordingly. A revised set of modified cross-section tables are then computed and the process is repeated. The process is usually started with a floodway defined in steady-flow analysis. This gives an immediate indication of the significance of the loss in flood-plain storage because steady-flow analysis does not include storage effects, whereas the initial unsteady-flow simulation includes storage effects.

If the cross sections close to bridges and culverts are extensively modified, the flow tables for these structures may need to be recomputed. This complication results because in FEQ simulation the hydraulic characteristics of certain structures must be precomputed to avoid the time and the potential for computational failure of computing them "on the fly" together with the flow computations in the branches. The large number of culverts and bridges in streams in urban areas requires that they be represented carefully to develop a meaningful and useful model of the stream system. The effect of these structures and their mutual interaction on the floodway may be more important than the representation of the branches.

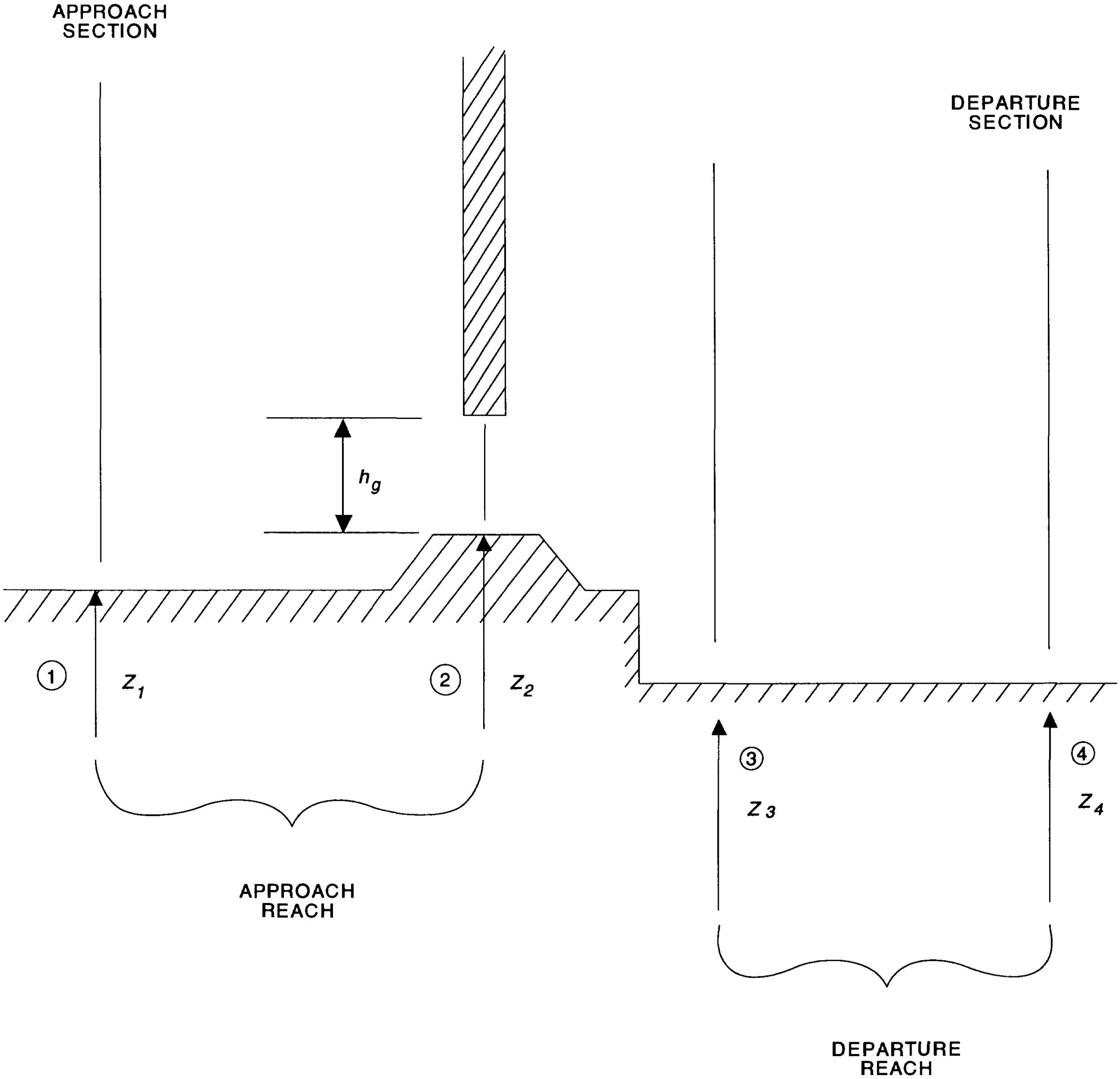
## 4.8 Underflow Gates

The flows through a sluice gate or a tainter gate are approximated in FEQUTL by computing a series of 2-D tables: one table for each of a series of gate openings. When the gate opening is fixed, the flow is defined for given upstream and downstream water-surface elevations. The 2-D tables are of type 13. This requires that a drop is present from the upstream water surface to the downstream water surface. This should be applicable in most cases. These tables are computed in the UFGATE command (section 5.20). A 1-D table of type 15 is used to store the gate openings and the corresponding table numbers for the 2-D tables. Thus, a 3-D table look-up is done in FEQ simulation to define the hydraulics of a sluice or tainter gate.

A sketch of the cross sections used to define the gate and its approach and departure channels is shown in figure 15. A sketch of the various flow conditions that may result for an underflow gate at a fixed gate opening is shown in figure 16. The flow through the gate is zero when the piezometric head at section 1 is the same as the piezometric head at section 4. The flow is grouped into four classes or conditions as identified in Fisk (1988): free and submerged orifice and weir flows. Free-orifice flow (FO) results when flow in contact with the gate lip is unaffected by downstream water level. Free-weir flow (FW) results whenever the gate lip is free of the water surface and the flow is unaffected by downstream water levels. The transition between the two flow conditions results when the upstream piezometric head at section 1 exceeds the gate-lip elevation enough to raise the water at section 2 to the gate lip. The boundary between these two flow conditions is shown as a vertical dashed line in figure 16. If the piezometric head at section 1 is held at a fixed value and the downstream water-surface elevation at section 4 is increased enough, the flow through the gate will be submerged. If the gate lip is in contact with the water, the flow condition is denoted as submerged orifice (SO). If the gate lip is free and subcritical flow is present at the weir, the flow condition is denoted as submerged weir (SW). The regions for these flow conditions are shown in figure 16 with the boundaries between regions represented by dashed lines. The assumptions made in the analysis applied in FEQUTL result in the transitions as shown in figure 16. The boundaries between the four regions meet at a single point.

The key assumptions, not including the 1-D flow assumption, made in the analysis of underflow gates are as follows.

1. The departure channel, from section 3 to section 4 in figure 15, is assumed to be horizontal and prismatic so that a simple momentum balance can be used to estimate the submergence of the flow through the gate openings. This assumption has been used with reasonable success by Henry (1950) and Rao and Rajaratnam (1963).
2. At least a small contraction in the flow area between the approach section (section 1) and the gate openings is always present. Generally, the appurtenances needed for the mounting and movement of the gates make this necessary. This means that the flow is contracting as it moves from section 1 to section 2 even if the gates are raised to the maximum position and are not in contact with the water.
3. The floor of the departure reach is at or below the floor of the approach reach. If a step is present, it is as shown in figure 15.
4. Submergence of the flow through the gate begins as soon as the estimated depth at the point of minimum contraction of the emerging jet is exceeded by the water-surface elevation at section 3. Sections 2 and 3 are taken at essentially the same point with section 2 describing the emerging jet and section 3 describing the conditions at the upstream end of the departure reach.
5. The size of the emerging jet is approximately the same in both free-flow and submerged-flow conditions. For cases of orifice flow, the jet size is given by $C_{co}h_g$, where $C_{co}$ is a contraction coefficient and $h_g$ is the gate opening. This is not always true, but utilization of this assumption for underflow gates by Henry (1950), Toch (1955), and Elevatorski (1958) produced good results.
6. FW flow is computed assuming that critical flow results in the gate opening. This avoids the need for estimating a weir coefficient for this condition.
7. The submergence of the flow for both FO and FW conditions is computed based on a simple momentum balance. Smooth transitions between different flow conditions may be obtained with a simple momentum balance.
8. The coefficient of contraction for sluice gates is a function of the ratio of the gate opening to the approach piezometric head, called the gate-opening ratio. The coefficient of contraction for tainter (radial) gates is



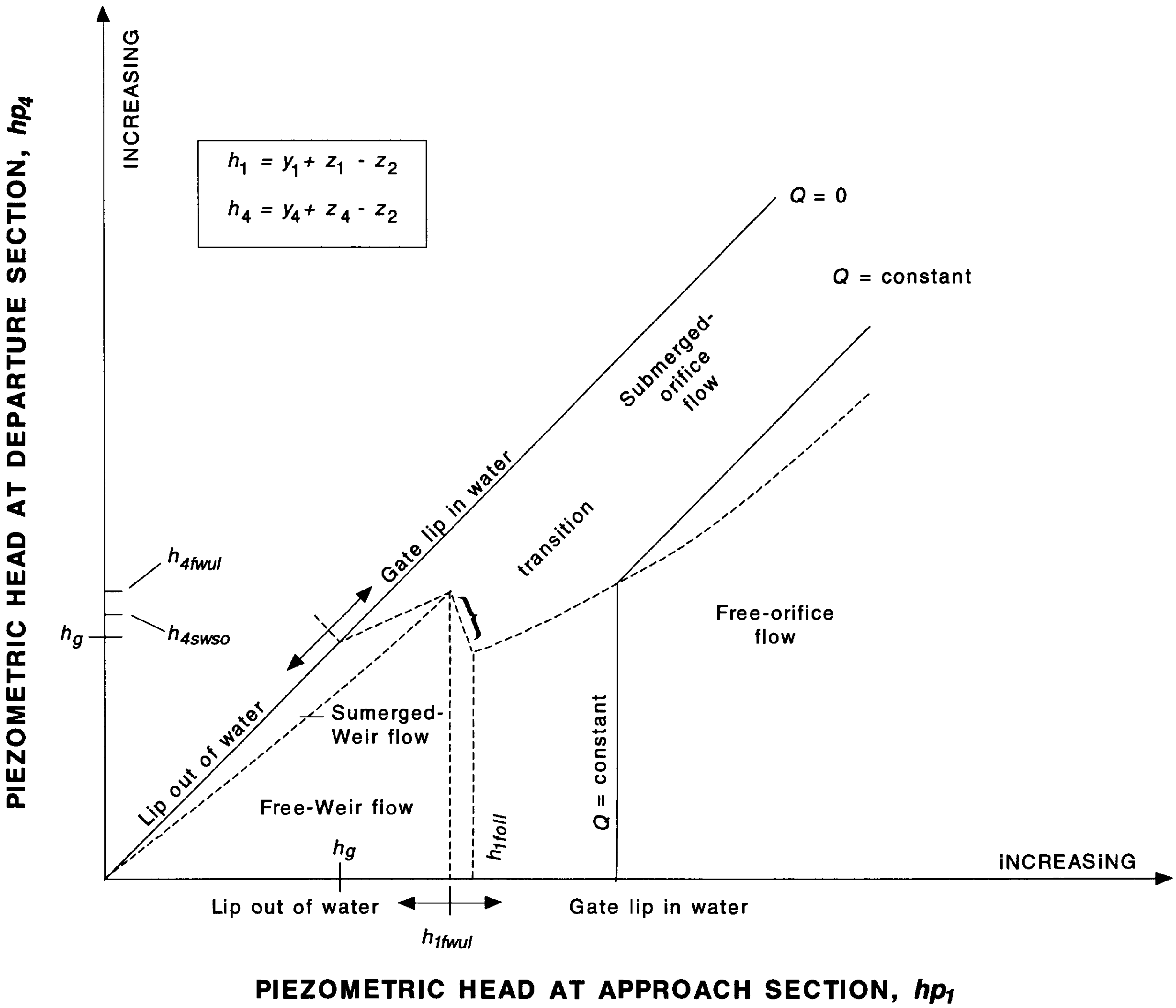

**EXPLANATION**

$Z_j$ BOTTOM ELEVATION AT SECTION $j$ RELATIVE TO THE DATUM FOR THE STREAM SYSTEM

$h_g$ GATE-OPENING HEIGHT

(1) CROSS-SECTION LOCATION IDENTIFIER

**Figure 15.** Location of cross sections for sluice-gate analysis in the Full EQuations UTiLities model.




## EXPLANATION

| | |
|---|---|
| $Q$ | DISCHARGE |
| $h_g$ | FIXED GATE-OPENING HEIGHT FOR THIS EXAMPLE |
| $z_i$ | BOTTOM ELEVATION AT SECTION $i$ RELATIVE TO THE DATUM FOR THE STREAM SYSTEM |
| $y_i$ | WATER-SURFACE HEIGHT AT SECTION $i$ |
| $h_{1fwul}$ | UPPER LIMIT FOR PIEZOMETRIC HEAD AT SECTION 1 FOR FREE-WEIR FLOW |
| $h_{1foll}$ | LOWER LIMIT FOR PIEZOMETRIC HEAD AT SECTION 1 FOR FREE-ORIFICE FLOW |
| $h_{4fwul}$ | UPPER LIMIT FOR PIEZOMETRIC HEAD AT SECTION 4 FOR FREE-WEIR FLOW |
| $h_{4swso}$ | PIEZOMETRIC HEAD AT SECTION 4 ON THE BOUNDARY BETWEEN SEBMERGED-WEIR AND SUBMERGED-ORIFICE FLOW FOR THE PIEZOMETRIC HEAD AT SECTION 1 MIDWAY BETWEEN $h_g$ AND $h_{1fwul}$ |

**Figure 16.** Flow-condition definition for sluice gates as simulated in the Full EQuations UTiLities model.

taken to be a function of the angle that the upstream face of the gate lip makes with the horizontal plane (Toch, 1955).

9. Transitions between the flow classes are smoothed by varying the contraction coefficient from the value of 1.0 at the weir-flow (FW or SW) limit when the water just touches the gate lip to the contraction-coefficient value for orifice flow (FO or SO). The smoothing takes place over the interval $h_{1fwul}$ to $h_{1fwul} + R_{hg}h_g = h_{1foll}$, where $h_{1fwul}$ gives the upper limit for piezometric head at section 1 for FW flow; $h_{1foll}$ gives the lower limit of FO flow with a standard coefficient of contraction; and $R_{hg}$ is the fraction of the gate opening width over which the transition in contraction coefficient is applied. The variation is taken to be linear as a function of the head at section 1. In addition, $C_{co}$ is 1.0 for the small region of SO flow that is above the SW flow region between $h_{p_1} = h_g$ and $h_{p_1} = h_{1fwul}$ in figure 16. The user controls the abruptness of the transition by selection of the value of $R_{hg}$.

### 4.8.1 Free-Orifice Flow

Utilizing a simple energy relation between sections 1 and 2 and allowing for some loss of energy with a discharge coefficient, $C_{dfo}$, yields the governing equation for FO flow

$$z_1 + y_1 + \alpha_1 \frac{Q^2}{2gA_1^2} = z_2 + C_{co}h_g + \frac{Q^2}{2g(C_{co}B_g h_g C_{dfo})^2}, \tag{106}$$

where $B_g$ is the width of the gate opening; and $z_j$ is the elevation of the channel bottom at a section $j$. The arguments for area, contraction coefficient, and other factors have been omitted to simplify the notation. Solution of equation 106 for the flow gives

$$Q = C_{dfo}C_{co}B_g h_g \sqrt{\frac{2g(z_1 + y_1 - z_2 - C_{co}h_g)}{1 - \alpha_1 (C_{dfo}C_{co}B_g h_g / A_1)^2}}, \tag{107}$$

as the definition of FO flow.

### 4.8.2 Free-Weir Flow

In order to maintain a smooth transition between FO flow and FW flow, an equation similar to equation 106 is applied with the assumption of critical flow at section 2 to define FW flow as

$$z_1 + y_1 + \alpha_1 \frac{Q^2}{2gA_1^2} = z_2 + y_2 + \frac{Q^2}{2g(y_2 B_g C_{dfw})^2} \tag{108}$$

and

$$Q = y_2 B_g \sqrt{g y_2}, \tag{109}$$

where $C_{dfw}$ is the discharge coefficient for FW flow. Substituting for flow in equation 108 with that from equation 109 gives

$$z_1 + y_1 - z_2 - y_2\left(1 + \frac{0.5}{C_{dfw}^2}\right) + \alpha_1 \frac{y_2^3 B_g^2}{2A_1^2} = 0, \tag{110}$$

as the nonlinear equation in the unknown water-surface height at section 2. Equation 110 is solved iteratively for $y_2$ and then the flow through the sluice opening is defined by equation 109.

### 4.8.3 Submerged-Orifice Flow

Two equations are required to define SO flow: an energy equation analogous to equation 106 and a simple momentum balance. The energy equation is

$$z_1 + y_1 + \alpha_1 \frac{Q^2}{2gA_1^2} = z_3 + y_3 + \frac{Q^2}{2g\,(C_{co} h_g B_g C_{dso})^2}, \tag{111}$$

where $C_{dso}$ is the discharge coefficient for SO flow. The water-surface height at section 3 replaces the piezometric level for the emerging jet, but the velocity head is given by the velocity of the jet, assuming it is close to the value that would have resulted had the jet not been submerged. The simple momentum balance is

$$gJ_4(y_3) + \frac{Q^2}{C_{co} h_g B_g} = gJ_4(y_4) + \beta_4 \frac{Q^2}{A_4}, \tag{112}$$

where the arguments of the first moment of area about the water surface, $J$, have been shown explicitly. This equation is applied for two purposes. In the first application, the drop between sections 1 and 4 at the free-flow limit for FO flow is defined. In this application, there is only one unknown, $y_4$. The flow is defined in the FO equation for the given upstream water-surface elevation at section 1. In the second application, equations 111 and 112 are solved simultaneously to define the flow and the submergence level, $y_3$, when the flows for partial free drops are computed for a given value of $y_1$.

### 4.8.4 Submerged-Weir Flow

The energy equation for SW flow is

$$z_1 + y_1 + \alpha_1 \frac{Q^2}{2gA_1^2} = z_3 + y_3 + \frac{Q^2}{2g\,[\,(y_3 + \Delta z)\,B_g C_{dsw}]^2}, \tag{113}$$

where $\Delta z$ is $z_3 - z_2$, and $C_{dsw}$ is the discharge coefficient for SW flow. The corresponding momentum equation is

$$gJ_4(y_3) + \frac{Q^2}{(y_3 + \Delta z)\,B_g} = gJ_4(y_4) + \beta_4 \frac{Q^2}{A_4}. \tag{114}$$

Equation 114 also is applied for the same two purposes as equation 112 in the case of SO flow.

### 4.8.5 Outline of Solution Process for Underflow Gates

For each of a given series of gate openings, the free and submerged flows must be computed for user-specified series of upstream water-surface elevations and partial free drops (that specify the downstream water-surface elevations). For a given gate opening, the following steps summarize the solution process.

1. The limiting upstream water-surface height for FW flow, $y_{1fw}$, is determined for the gate opening. The FW flow is assumed to just touch the gate lip, that is, $y_2 = h_g$. The upstream water level required to produce the FW flow is computed from equation 108. The right-hand side (RHS) of equation 108 is known if $y_2 = h_g$. Thus, the specific energy on the left-hand side may be used to compute the subcritical value of upstream water-surface height, $y_{1fw}$. This water-surface height at section 1 defines $h_{1fwul}$. The lower limit for FO flow, $h_{1foll}$, is computed from $h_{1fwul}$ and $h_g$. If all gate openings have been evaluated, the computations are complete.
2. The free flow for the current upstream water-surface height, $y_1$, is determined if any upstream water-surface heights must still be evaluated. If $y_1 \leq y_{1fw}$, the FW flow is computed for that level. If not, the FO flow is computed for the current upstream water-surface height. The free weir or orifice flow is denoted as $Q_f$. If no upstream water levels remain to be evaluated, the procedure returns to step 1.
    - 2.1. If the upstream water-surface elevation exceeds the elevation of the gate lip ($y_1 + z_1 > h_g + z_2$), SW flow will transition to SO flow. At the limiting downstream water-surface-height level for SW flow, $y_{4sw}$, the water just touches the gate lip from downstream. The flow rate for this condition is computed with equation 113 with $y_3 = h_g + z_2 - z_3$.
    - 2.2. The limiting downstream water-surface height for SW flow, $y_{4sw}$, is calculated by solving equation 114 for the tail-water level, applying the value of $y_3$ and flow determined in step 2.1.
3. The downstream water-surface height at the free-flow limit, $y_{4f}$, is determined. If the flow is FW, then equation 114 is applied to find $y_{4f}$ when the flow is $Q_f$ and the water-surface elevation at section 3 matches the water-surface elevation at critical flow at section 2. Otherwise, $y_{4f}$ is computed with equation 112 under the same conditions of matching water levels at sections 2 and 3.
4. The next downstream water-surface height, $y_4$, for submerged flow is computed. This is done on the basis of distributing the partial free drops according to parameters supplied by the user. The downstream water-surface height varies from the free-flow limit to equality with the water-surface elevation at section 1.
5. If the flow is FO, the solution procedure moves to step 7; otherwise, this step is done. For FW flow, the submerged flow may be SW but may transition to SO if the current upstream water-surface elevation is above the gate opening. If $y_1 + z_1 > h_g + z_2$, then steps 5.1 and 5.2 are done; otherwise, step 6 is done.
    - 5.1 If $y_4 > y_{4sw}$, the submerged flow is SO. The SO flow is computed applying equations 111 and 112. $C_{co}$ is interpolated as needed to make the transition at the boundary smooth.
    - 5.2 If $y_4 \leq y_{4sw}$, the submerged flow is SW. The SW flow is computed applying equations 113 and 114. The procedure returns to step 4 for the next downstream water-surface height and the computations continue.
6. For this case, the FW flow can only transition to SW flow for a constant upstream water-surface elevation. The SW flow is computed applying equations 113 and 114. The procedure returns to step 4 for the next downstream water-surface height and the computations continue.
7. FO flow can only transition to SO flow for a constant upstream water-surface elevation. The SO flow is computed applying equations 111 and 112. The procedure returns to step 4 for the next downstream water-surface height and the computations continue.

This outline of the solution process suppresses the details of storing the flows and the proper water-surface elevations in the 2-D tables. The computations are extensive, and many of the equations must be solved using an iterative process such as Newton's method or the method of false position. If 5 gate openings and 15 upstream water-surface elevations are considered, and 15 flows are computed for each upstream water-surface elevation, then 1,125 values of flow must be computed with the UFGATE command (section 5.20).

Precise definitions of the point of transition between the flow regions in figure 16 are used in the solution procedure. These transitions are not precise when observed in the field. The level of submergence of the emerging jet required to affect the flow during FO flow is unclear. The pressure distribution at small levels of submergence of the jet is not hydrostatic. If accurate field measurements are available to define this transition, then the procedure can be modified to more accurately define the point of transition. It also is assumed in the transitions from weir flow that the critical depth, as computed from 1-D flow theory, defines the contact with the gate lip. This probably is not true. Streamline curvature as the water approaches the gate opening will cause the pressure distribution in the flow to deviate from hydrostatic. The water surface will be strongly curved, and detailed knowledge of the gate arrangement is needed to define the actual point of contact. It also is possible that the point of transition from FW to FO may differ from the point of transition from FO to FW. The point of transition may depend on the direction of movement of the water surface. Only careful measurements in the laboratory or field can refine the assumptions applied here.

### 4.8.6 Interpolation for Flows at Nontabulated Gate Openings

Interpolation between tables of type 13 must be done to define the flows at gate openings that fall between the gate openings selected for the 2-D tables placed in the table of type 15. Straightforward linear interpolation on the gate opening results in large errors when the flow class changes within the interval of interpolation. As an example, if tables of type 13 have been computed at gate openings of 2 and 3 ft, it is possible that interpolation at an opening of 2.5 ft would indicate FO flow in the table for the 2-ft opening and FW flow in the table for the 3-ft opening. A means to develop, conceptually at least, an intermediate table complete with flow boundaries, computed from the tables below it and above it in gate-opening sequence, is needed.

The approach for this interpolation is developed from a special case of the governing equations. In this special case the bottom elevation at all the key sections is the same ($z_1 = z_2 = z_3 = z_4$). Further, it is assumed that the approach and departure sections are rectangular, that the contraction coefficient is at most a function of the piezometric head at section 1 relative to the gate opening, and that $\alpha_1 = \beta_4 = 1$. The gate-opening Froude number for orifice flow, $\mathbf{F_g}$, is approximated as

$$\mathbf{F}_{\mathbf{g}}^2 = \frac{Q^2}{g h_g^3 B_g^2}. \tag{115}$$

Applying this Froude number to describe the flow transforms the governing equation for FO flow to

$$\mathbf{F}_{\mathbf{g}} = C_{dfo} C_{co} \sqrt{\frac{2\left(\tilde{h}_1 - C_{co}\right)}{1 - \left(C_{dfo} C_{co} / \tilde{h}_1 \tilde{B}_1\right)^2}}, \tag{116}$$

where $\tilde{h}_1 = h_{p_1}/h_g$, $\tilde{B}_1 = B_1/B_g$, and $B_1$ is the channel width at section 1. In this form, the gate-opening Froude number is constant if the gate-relative head at section 1 is a constant.

The conservation of energy equation for SO flow then becomes

$$\tilde{h}_1 + \frac{F_g^2}{2(\tilde{h}_1 \tilde{B}_1)^2} = \tilde{h}_3 + \frac{F_g^2}{2(C_{co} C_{dso})^2} \tag{117}$$

and the conservation of momentum equation becomes

$$\frac{\tilde{h}_3^2 \tilde{B}_4}{2} + \frac{F_g^2}{C_{co}} = \frac{\tilde{h}_4^2 \tilde{B}_4}{2} + \frac{F_g^2}{\tilde{h}_4 \tilde{B}_4} . \tag{118}$$

The symbols with the tilde are taken relative to the corresponding dimension of the gate opening. These equations indicate that the gate-opening Froude number is a constant if the gate-opening relative heads at sections 1 and 4 are held fixed.

If all sluice gates were accurately described with the simplifying assumptions, then only one table of type 13 would be needed to represent the flows for all nonzero gate openings. This also implies that the boundaries between different flow classes, expressed relative to the gate opening, would be constant. Most sluice gates only approximately satisfy these simplifying assumptions. The approach and departure sections are only approximately rectangular. Also, the bottom elevations are frequently not all the same. A gate sill may be used to raise the gate opening above the bottom of the approach channel. Furthermore, it is often true that the bottom of the departure channel may be below the gate opening to help stabilize the hydraulic jump. These deviations from the simplifying assumptions cause (1) the gate-opening Froude number to vary slightly even when the gate-opening relative heads are held constant, and (2) the boundaries between the flow regions to vary with gate opening. The simplifying assumptions are even less appropriate for tainter gates because, in addition to the problems at sluice gates of varying bottom elevations for the approach and departure sections and nonrectangular approach and departure sections, the flow contraction coefficient varies with the lip angle for tainter gates.

Because the simplifying assumptions previously described only approximately apply to sluice gates and tainter gates, linear interpolation is used on gate-opening relative values to approximate the variations with gate opening in FEQ and FEQUTL. In addition to the 2-D table number for each gate opening, type 15 tables contain three values that define key points on the boundaries between the flow classes. These are the head at section 1 at the upper limit of FW flow, the head at section 4 at the upper limit of FW flow, and the head at section 4 on the boundary between SW and SO flow midway between heads at section 1 of $h_g$ and $h_{1fwul}$. These heads are all expressed relative to the gate opening.

The look-up procedure is as follows.

1. The interval in the type 15 table that contains the current gate opening, $h_g$, is determined. The table with a gate opening less than $h_g$, $h_{gL}$, is the left-hand table, and the table with a gate opening greater than or equal to $h_g$, $h_{gR}$ is the right-hand table.
2. The three key points on the boundaries between flow regions are interpolated with respect to gate opening. The interpolated gate-opening ratios are then multiplied by $h_g$ to obtain the actual values of $h_{1fwul}$, $h_{4fwul}$, and $h_{4swso}$.
3. If $h_{p_1}$ and $h_{p_4}$ are in the weir-flow region, defined in figure 16, the weir-flow values from the right-hand table are applied. Otherwise, the procedure continues to step 4.
4. If this step is applied, the flow is orifice flow. The heads used for interpolation in the tables are computed. The heads at sections 1 and 4 for the left-hand table are $h_{p_{1L}} = h_{gL} h_{p_1} / h_g$ and $h_{p_{4L}} = h_{gL} h_{p_4} / h_g$, respectively. The heads for the right-hand table are computed in a similar manner for the right-hand gate opening.
5. The flow rate is determined from each table, and the gate-opening Froude number is computed for the left- and right-hand tables. The gate width is taken as 1.0 for this purpose. The actual width is not important.
6. Linear interpolation on gate opening is applied to compute the gate-opening Froude number for $h_g$. The flow for the gate opening is then computed.

This approach for interpolating flow values for nontabulated gate openings is more complex than simple linear interpolation on gate opening, but errors resulting from simple linear interpolation across the weir-flow and orifice-flow boundary are avoided with few exceptions. The exceptions result because linear interpolation for the boundary-point ratios are not exact. Some mixed interpolations for orifice flow also may result where one of the tables indicates SO flow and the other indicates FO flow. This results close to the boundary and is caused by the inexactness of linear interpolation in the tables. However, the effect of these exceptions should be small if the flows of interest are away from the boundaries between flow classes.

# 5. INPUT DESCRIPTION FOR THE FULL EQUATIONS UTILITIES MODEL: VERSION 4.0

The input to FEQUTL consists of a block of lines, called the standard header, followed by one or more blocks of lines, called command blocks. A command block starts with a command and may be followed with additional lines of information required by the command. A command is a sequence of predefined alphanumeric characters read in FEQUTL defining which computations are to be done. The input blocks used to compute the hydraulic characteristics of open channels and control structures are listed in table 5.

Each of the input blocks listed in table 5 is described in detail in subsequent sections except the BRIDGE command. The BRIDGE command should not be used in new applications of FEQ and FEQUTL, and the Bureau of Public Roads (Bradley, 1970) procedure is not described here. The BRIDGE command is retained in FEQUTL for support of stream-system models developed previous to FEQUTL version 4.0. The commands WSPROX, WSPROQZ, and WSPROT14 should be used with the WSPRO software to represent bridges for any new applications of FEQ and FEQUTL.

**Table 5.** Summary of input blocks for the Full EQuations UTiLities model

| Block name | Summary of block |
|---|---|
| Bridge | Bridge hydraulics computed with the Bureau of Public Roads procedure (Bradley, 1970). |
| Channel | Sinuosity is computed for a series of flow lines and combined with FEQX, FEQXLST, or FEQXEXT to compute cross-section function tables that include corrections coefficients for channel curvilinearity. |
| Channel rating | Flows are computed for short, prismatic bypass channels (for example, overland flow around culverts). |
| Critical flow | Critical flow is computed in a given cross section assuming that the cross section represents a constriction to the flow; most often used with the GRITTER command for the generalized Ritter (1892) solution to an instantaneous dam failure. |
| Culvert | Flows through culverts and over the associated roadway are computed. |
| Embankments and weirs | Flows over weirs, embankments, and other weir-like structures are computed. |
| Expansion/Contraction | Flow through an expansion or contraction is computed. |
| FEQX | Hydraulic characteristics of a cross section are computed from data in a fixed format. |
| FEQX extension | Hydraulic characteristics of a cross section are computed. The computations are extended to consider frictionless line segments and roughness values that vary with water-surface height. |
| FEQX list | Hydraulic characteristics of a cross section are computed from data in a list format. |
| Finish | The files are closed and execution of FEQUTL is terminated. |
| Floodway | A table of values is input to be used later in FEQX and FEQXLST in defining the cross-section hydraulic characteristics for a floodway analysis. |
| Function table input | One or more function tables in the format used in FEQ simulation are input. |
| Generalized Ritter dam-break method | The generalized Ritter (1892) dam-break method for estimating the flood-peak stage at a dam site is computed. |
| HEC2X | Cross-section input for the HEC-2 water-surface profiles model (U.S. Army Corps of Engineers, 1990a) is transformed to a format suitable for the CHANNEL command or FEQX command or for direct use in FEQ. |
| Multiple conduits | The hydraulic characteristics are computed for one or more conduits that may be circular, rectangular, true elliptical, nominal elliptical, reinforced-concrete pipe arch, or corrugated-metal arch. |
| Multiple pipes | The hydraulic characteristics are computed for one or more circular sections. |
| Critical-flow limit | A limit on the critical-flow rate in a closed conduit is set so that EXPCON computations will be suitable with one or both cross sections as a closed conduit. |
| Sewer pipe | The hydraulic charcteristics are computed for a single circular section. |
| Underflow gates | Flow through underflow gates (sluice and tainter gates) with variable gate settings is computed. |
| WSPROQZ | Input lines for the WSPRO (Shearman, 1990) steady-flow water-surface profile model are prepared to define the flows and elevations for multiple water-surface profiles required to define the hydraulics of a bridge. |
| WSPROT14 | A two-dimensional table of type 14 is prepared using the water-surface profiles computed with WSPRO (Shearman, 1990) as defined by the WSPROQZ command. |
| WSPROX | Cross-section input for the WSPRO water-surface profile model (Shearman, 1990) is transformed to a format suitable for the CHANNEL command or FEQXEXT command or for direct use in FEQ. |
| Cross-section interpolation | One or more cross-section tables are interpolated from information in two specified cross-section tables. |

Each command must begin in column 1 of a line. The first eight columns of the command line are reserved for the command, but the remainder of the line may contain a comment. The input associated with a command begins on the line following the command line. The lines of input are numbered from the first line of input and not the command line in the descriptions given in this section. The null command, consisting of all blanks in the first eight columns of a line, may be used to add comments and blank lines to the input. Comments entered with the null command cannot appear within the input for any command. These comment lines can only appear between the end of the input for a command and the subsequent command. Blank lines may be inserted anywhere in the FEQUTL input. Comments that can appear anywhere in the input are lines that begin with either a semicolon (;) or an asterisk (*). If the line begins with a semicolon, the line is not read in FEQUTL. However, if the line begins with an asterisk, the line is read and placed in the output file for FEQUTL.

Three standard files are used in FEQUTL operation. The first standard file is the input file containing the standard header block and the command blocks prepared by the user. The contents of this file are described in this section. The second standard file is called the output file. This file contains information read from the input file with annotations, error and warning messages to the user, and summaries of results from some of the commands. The third standard file, called the function table file, or just the table file, contains the function tables computed in FEQUTL in a format suitable for access in FEQ.

## 5.1 Standard Header Block

The standard header block must always appear first in the input to FEQUTL. It defines the command names used in FEQUTL to process the subsequent input. Some values and options that control command processing in FEQUTL also are defined. The command names are changed infrequently, usually only when a new version of the software is released. Therefore, the common practice is to copy the standard header block from an available input file.

The number to the right of each command name in the standard header block is an internal control number for FEQUTL. The number must not be changed. The number is used to access the part of FEQUTL that completes the operations defined by the command. Changing the name of the command is inconsequential, but changing the internal control number changes the command drastically.

The lines in the standard header block are as follows.

```
UNITS=   ENGLISH     (or METRIC) Selects measurement units.
NCMD=   24           Number of commands present in standard header block
FEQX            1
FLOODWAY        2
BRIDGE          3
CULVERT         4
FINISH          5
FEQXLST         8
SEWER          10
MULPIPES       11
FTABIN         12
EMBANKQ        13
CRITQ          15
GRITTER        16
MULCON         18
CHANRAT        19
EXPCON         20
HEC2X          21
QCLIMIT        22
XSINTERP       23
FEQXEXT        25
CHANNEL        26
WSPROX         27
WSPROQZ        28
WSPROT14       29
UFGATE         30
DZLIM= 1.0           Minimum water-surface height increment in output table; must be > 0
```

```
NRZERO= 0.08         Minimum nonzero water-surface height in the table; must be > 0
USGSBETA=NO          Selection of computation of α and β
EPSARG=4.E-5         Convergence criterion for CULVERT, EXPCON
EPSF=1.E-4           Convergence criterion for CULVERT, EXPCON
EXTEND=NO            Cross-section extension option.
```

Explanation:

DZLIM and NRZERO are used to control the spacing of the water-surface heights argument values in cross-section tables. The list of water-surface heights in a cross-section table is first developed from the unique water-surface heights values defined by the breakpoints along the boundary of the cross section. This list is then checked for an argument near zero. If no argument near zero is available, the value given by NRZERO is inserted as an argument. The list of arguments also is checked to ensure that the interval between successive arguments in the table is never greater than DZLIM. Both of these parameters are provided to help control the errors of interpolation in conveyance for the cross section. The near-zero point is needed because the conveyance varies rapidly near zero water-surface height, and linear interpolation in the square root of conveyance at small water-surface heights is inaccurate if a near-zero argument is not in the table.

USGSBETA defines the method utilized in computing the momentum correction coefficient, $\beta$, and the energy-flux correction coefficient, $\alpha$, in a cross section. If USGSBETA=NO, then $\beta = 1.0$ and $\alpha = 1.0$ in each subsection of the cross section. If USGSBETA=YES, then the value of $\beta$ and $\alpha$ in each subsection are computed with the USGS method given in section 3.I.I.

EXTEND defines the procedure for extending or adjusting the channel boundary if the first and last point of a cross-section description are either not at the same elevation or are not the maximum elevation in the section. If EXTEND=YES, then a frictionless vertical extension of the channel boundary at either the first or last point, or both, is applied to match the maximum elevation found at any point in the cross section. The size of the extension is given in a warning message. If EXTEND=NO, then no extension is applied and the table is computed to the minimum of the elevations of the first and last point given on the boundary.

If one side of the cross section is extended in FEQUTL and then a water-surface elevation above the low side of the cross section is computed in FEQ, a warning message cannot be issued in FEQ simulation because only the cross-section table and not the cross section is considered in the FEQ computations. If the extension is large, the results from FEQ may be in error because a large part of the cross section is unknown. It is best to use EXTEND=NO and to manually adjust cross sections that have an inadequate vertical extent as determined in subsequent computations in FEQUTL or FEQ.

Examples of most commands and options for FEQUTL appear in the example input file FEQUTL.EXM. This file may be obtained by electronic retrieval from the World Wide Web (WWW) at http://water.usgs.gov/software/feq.html and by anonymous File Transfer Protocol (FTP) from water.usgs.gov in the pub/software/surface_water/feq directory.

## 5.2 CHANNEL Command

Purpose: The means to compute the hydraulic properties of a cross section including the correction factors for curvilinearity are provided in the CHANNEL command.

Notes: In the commands FEQX, FEQXLST, and FEQXEXT, the sinuosity is assumed to be zero unless a sinuosity value is specified in a CHANNEL command. Consequently, the input for the CHANNEL command is divided into two parts: the sinuosity-definition block, which defines the sinuosities for a series of cross sections, and the cross-section function-table definition block, which consists of a series of FEQX, FEQXLST, or FEQXEXT commands, one for each cross section involved in the sinuosity-definition block. An example CHANNEL command for a curved reach in a prismatic channel is the following.

```
CHANNEL
SINDEF=LINEAR
HEAD  LFP     AXIS    RFP

STAT  0.000   0.000   0.000
OFFS  0.000   10.00   20.00

STAT  1.500   1.000   0.500
OFFS  0.000   10.00   20.00

STAT  3.000   2.000   1.000
OFFS  0.000   10.00   20.00

END

FEQX
TABLE#=  900 OUT25
STATION=0.000
          :
TABLE#=  902 OUT25
STATION=1.000
          :
TABLE#=  904 OUT25
STATION=2.000
          :
ENDCHAN
```

The sinuosity-definition block starts with the input item SINDEF and ends with the END item. Then after the sinuosity-definition block, only the first two lines of input for the FEQX commands are shown in the example. The input for FEQX, FEQXLST, or FEQXEXT is unchanged if these commands appear within a CHANNEL command. The stations for the cross-section function tables in the FEQX commands are the stations along the axis of the sinuosity-definition block. The CHANNEL command ends with the ENDCHAN Line.

Each flow line in the sinuosity-definition block is given a name on the HEAD Line. Points along each of the named flow lines are defined by subsequent lines of input. Each of these input lines starts with a four-character identifier giving the nature of the data items on that line. The line identifiers are: HEAD—defining the names for the flow lines; OFFS–defining the offsets of the flow lines; STAT–defining the station for each flow line for a cross section; SINU–defining the numeric value of the sinuosity for a flow line at a cross section or defining how the sinuosity is computed; LENG–gives the incremental length along each flow line from the previous cross section; and END–signals end of the sinuosity definition table. These identifiers must begin in column 1 of the line. The identifiers and their order in the input are discussed in the line-by-line input description that follows.

In the FEQX, FEQXLST, or FEQXEXT commands within a CHANNEL command, the output of a table type that tabulates the correction factors for curvilinearity must be specified if these factors are to appear in the cross-section function tables computed. These factors are tabulated in table types 23, 24, and 25. The stations given for these tables in the cross-section computation commands must match the stations given for the longitudinal axis in the sinuosity-definition block.

Most of the input for the CHANNEL command is format free and the requested values need not appear in any particular columns. The exceptions are the standard line names, the SINDEF Line, and the FEQX, FEQXLST, or FEQXEXT command specifications that follow the sinuosity definitions. However, the input on a line that is format free is still order dependent, and some restrictions are placed on the order of the lines. Items on a line must be separated by one or more spaces, and all items for a line must appear on a single line. The items listed below for a given line cannot be split between two or more lines of input. Even though the format of much of the data is free of column restrictions, orderly columns should be utilized as shown in the previous example. Orderly columns make reading and checking the input much easier.

LINE 1

Variable: SINDEF

Format: 7X, A8

Example: SINDEF=LINEAR

Explanation:

SINDEF is the global value of the method to be used in computing the sinuosity of each nonaxis flow line at each cross section. This must be the first line of input after the CHANNEL command is specified. The sinuosity is the derivative of the flow-line length relative to the length along the axis. An example of a flow-line distance function is shown in figure 17. The variation in flow-line length relative to the length along the distance axis also is shown in figure 17. Typically, the flow-line distance function will oscillate about the line of constant sinuosity (sinuosity=1.0). Three different options for approximating the derivative of the flow-line distance function are available in the CHANNEL command. These options are LINEAR, PARABOLA, and CUBIC.

The derivative at a point like point *M* in figure 17 is computed as the arithmetic average of the slope of the piecewise-linear approximation to the flow-line distance function in the LINEAR option. The slope (sinuosity) of the line segment to the left of point *M* is

$$\sigma_{i_{ML}} = \frac{(L_{iM} - L_{iL})}{(L_{aM} - L_{aL})}, \tag{119}$$

and the slope of the line segment to the right of point *M* is

$$\sigma_{i_{MR}} = \frac{(L_{iR} - L_{iM})}{(L_{aR} - L_{aM})}, \tag{120}$$

where

$L_{ij}$ is the distance along flow line *i* at point *j*;

$L_{aj}$ is the distance along the axis at point *j*; and

$\sigma_{i_{Mj}}$ is the sinuosity of flow line *i* between points *M* and *j*.

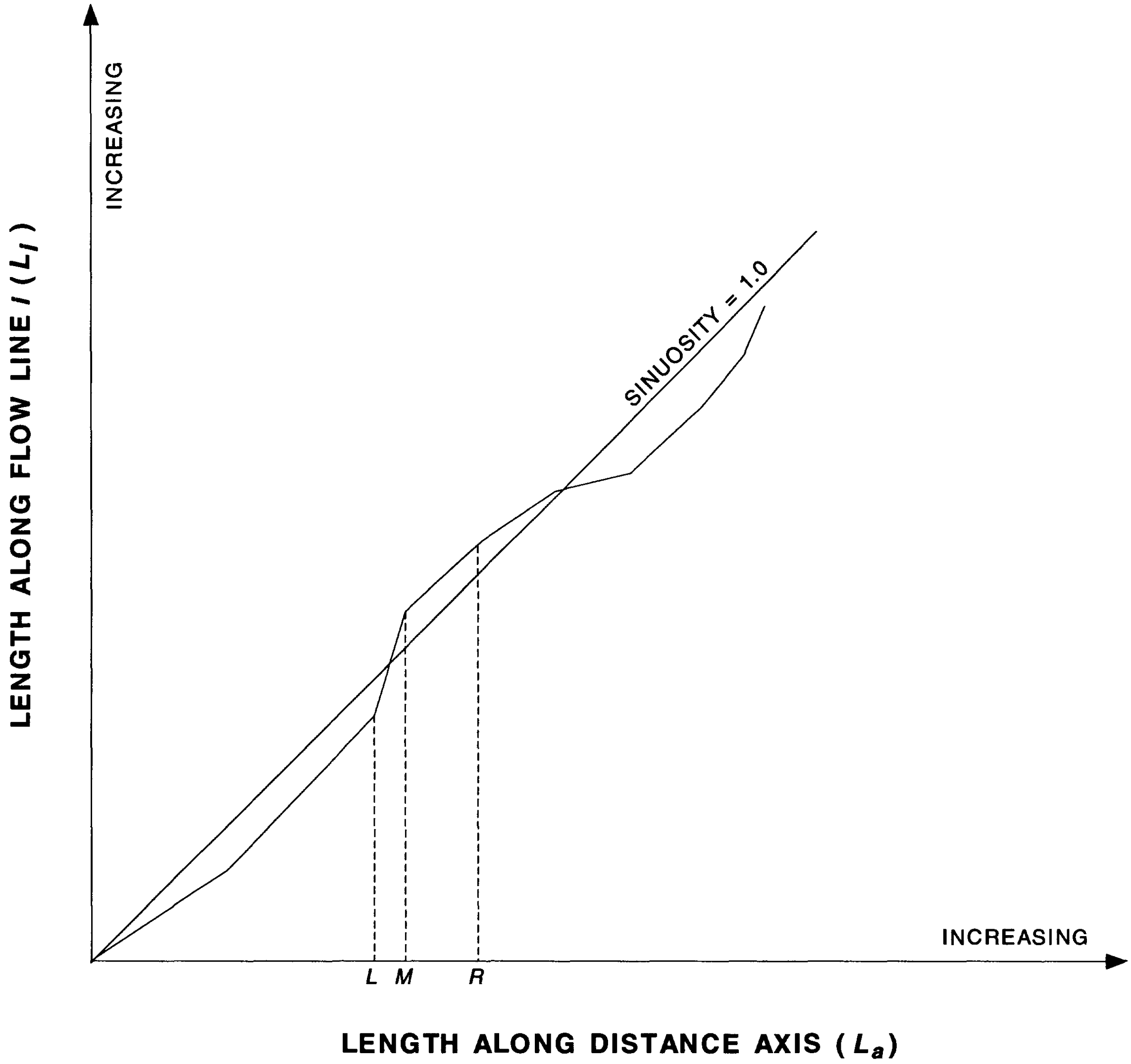
The sinuosity at point *M* along flow line *i* computed in the LINEAR option is

$$\sigma_{i_M} = \frac{\left(\sigma_{i_{ML}} + \sigma_{i_{MR}}\right)}{2}. \tag{121}$$

This approximation is reasonable only at interior points such as *M* in figure 17. At the first cross section, the slope of the line to the right of the point, $\sigma_{i_{MR}}$, must be applied, and at the last cross section, the slope of the line to the left of the point, $\sigma_{i_{ML}}$, must be applied.

The derivative at a point such as *M* is computed as the derivative of the parabola fitted to the three points *L*, *M*, and *R* in the PARABOLA option. Again, at the first and last cross section, the derivative must be taken at the beginning or ending point of the parabolic segment.

The derivative at a point is computed as the derivative of a cubic spline fitted to three or more consecutive points on the flow-line distance function in the CUBIC option. Computation of a cubic spline requires specified end-point conditions. The default option for the end conditions is to force the second derivative to be zero. This




**EXPLANATION**

*M* POINT ALONG DISTANCE AXIS AT WHICH SINUOSITY IS EVALUATED

*L* POINT ALONG DISTANCE AXIS IMMEDIATELY UPSTREAM OF *M*, LOCATION UTILIZED TO DETERMINE SINUOSITY AT *M*

*R* POINT ALONG DISTANCE AXIS IMMEDIATELY DOWNSTREAM OF *M*, LOCATION UTILIZED TO DETERMINE SINUOSITY AT *M*

**Figure 17.** Example of the flow-line distance function applied in the description of channel curvilinearity computed in the channel command of the Full EQuations UTiLities model.

implies that the cubic function should approach linear variation as the end points are approached. The default end condition may be changed with the SINU input line.

LINE 2

Variables: CRDNAM, VALUES (*)

Format: A4, free

Example: HEAD LFP AXIS RFP

Explanation: The names for the flow lines that will be defined on subsequent lines of input are specified on this line.

CRDNAM must be "HEAD" in the first four characters of the first line of input after the SINDEF value is given.

VALUES are the labels for flow lines. One of the flow lines must be labeled AXIS or axis to identify the flow line that will be used as the distance axis. The other flow lines must be given a valid name of eight or less alphanumeric characters with the first character required to be alphabetic. The number of flow lines is defined by the number of flow-line names that appear on the HEAD Line.

LINE 3 (Repeated in combination with Lines 4 and 5 as a group until the curvilinear portion of the channel is input. The STAT or LENG Line must be the first line for each cross section or incremental distance for each flow line.)

Variables: CRDNAM, VALUES (*)

Format: A4, free

Example 1: STAT 0.0 0.0 0.0

Example 2: LENG 125.0 115.0 110.0

Explanation:

CRDNAM defines whether the station of a cross section or the incremental distance from the previous cross section are specified on this line. The STAT Line must be given for the first cross section in a sequence because the first cross section has no previous cross section from which to define the incremental distance values for the LENG Line.

VALUES are the values of station or incremental distance for each flow line. The units of the station or incremental distance must be the same for all cross sections in the CHANNEL command. The same units must be used for the station values given in the FEQX, FEQXLST, or FEQXEXT commands that follow the definition of the sinuosity. The order of the values is the same as the order of the flow-line names. The STAT or LENG Line must be the first line for each cross section in the sinuosity-definition block of the CHANNEL command.

LINE 4 (Repeated in combination with Lines 3 and 5 as a group until the curvilinear portion of the channel is input. This line must be specified for each cross section in the sinuosity-definition block.)

Variable: CRDNAM, VALUES (*)

Format: A4, free

Example: OFFS 0.0 10.0 20.0

Explanation:

CRDNAM must be OFFS to indicate that the offsets of the flow lines in a cross section are specified on this line. This line must be specified for each cross section in the sinuosity-definition block.

VALUES are the values of the offsets for each flow line. The order of the values is the same as the order on the HEAD Line. The units must be the same as the units for the offsets in the cross sections used in the FEQX, FEQXLST, or FEQXEXT commands that follow the sinuosity-definition block.

The number of offsets relative to the number of flow-line names determines the sinuosity variation as piecewise constant (PWC) or piecewise linear (PWL). If the number of offsets matches the number of flow-line names, then the sinuosity variation is PWL. If the number of offsets is one less than the number of flow-line names, then the sinuosity variation is PWC. Any other number of offsets is an error. Also, the sinuosity variation cannot change once specified.

LINE 5 (Repeated in combination with Lines 3 and 4 as a group until the curvilinear portion of the channel is input. This line of input is optional.)

Variable: CRDNAM, VALUES

Format: A4, free

Example 1: SINU linearu 1.0 1.05

Example 2: SINU * * linearu

Example 3: SINU cubic

Explanation:

CRDNAM must be SINU to indicate input of either a local option for computing the sinuosity or a local value of sinuosity.

VALUES are the values that are sufficient to define the sinuosity for the flow line or lines of interest. The sinuosity for the axis flow line is always 1.0, and any other value given is ignored. In the first example, a local option for computing the sinuosity is specified. The second example illustrates how a local sinuosity-definition option may be specified for one of the flow lines while the global option is applied for the other flow lines. The asterisk denotes the default value for the sinuosity definition. In the third example, the sinuosity definition is assigned to the first flow line given in the HEAD Line. Subsequent flow lines will take the global value from SINDEF. If the linearu option is specified, the slope of the line segment to the left (upstream) of the current cross section is used to define the sinuosity at this cross section. This option may be specified as linearu, LINEARU, linu, and LINU. The slope of the line segment to the right (downstream) of the current cross section is selected by application of lineard, LINEARD, lind, or LIND as the local option. Local options for a parabolic definition of the derivative are parabola, PARABOLA, parab, PARAB, paraboli, and PARABOLI. Local options for a cubic-spline definition of the derivative are cubic, CUBIC, cspline, and CSPLINE. If no local sinuosity-definition option is specified and no numeric sinuosity value is specified, then the sinuosity definition given by SINDEF is applied. Any values on the SINU Line are assigned in left to right order to the flow lines named in the HEAD Line.

LINE 6

Variable: CRDNAM

Format: A4

Example 1: END

Example 2: ENDCHAN

Explanation:

CRDNAM equals END terminates the sinuosity-definition block, whereas CRDNAM equals ENDCHAN terminates the entire CHANNEL command.

The following example of a CHANNEL command is presented below to illustrate some of the options not previously discussed.

```
CHANNEL
SINDEF=CUBIC
HEAD   LOB                 AXIS                ROB

STAT   0.0000000           0.0000000           0.0000000
OFFS              75.00               153.00
SINU   1.0                 1.0

STAT   0.0606061           0.0700758           0.0833333
OFFS              138.30              164.20

STAT   0.1496212           0.1553030           0.1666667
OFFS              92.70               168.70

STAT   0.1560606           0.1617424           0.1731061
OFFS              103.40              236.40

STAT   0.1655303           0.1712121           0.1825758
OFFS              142.80              210.80

SINU   LINU                1.0                 LINU

END

FEQX
TABLE#= 700 OUT23
STATION= 0.0000000
         :
FEQX
TABLE#= 698 OUT23
STATION= 0.0700758
         :
FEQX
TABLE#= 696 OUT23
STATION= 0.1553030
         :
FEQX
TABLE#= 694 OUT23
STATION= 0.1617424
         :
FEQX
TABLE#= 692 OUT23
STATION= 0.1712121
         :
ENDCHAN
```

This example of the CHANNEL command is adapted from one created in the CHANNEL option in the HEC2X command (section 5.15). In the HEC2X command, a HEC-2 input file is processed, the cross sections are extracted, and a sinuosity-definition table is computed with the data in the HEC-2 input file on the flow distances in the left overbank (LOB), the main channel (AXIS), and the right overbank (ROB). In this case, only two offsets result even though there are three flow lines. Thus, PWC variation is selected for sinuosity across a section. The offset values in this case give the offsets at the banks of the stream. The computation option CUBIC has been selected in the global sinuosity-definition option, SINDEF. A SINU line has been added for the first and last cross section. These lines override the default end condition of the cubic spline fit computed in the CUBIC option. At the first section, the sinuosity has been defined as 1.0 for all flow lines. This is appropriate if the stream channel at that point becomes essentially linear. The default end condition of the second derivative equal to zero may not produce appropriate values in this case. At the last section, the sinuosity has been defined by the average sinuosity in the last flow-line segment.

## 5.3 CHANRAT Command

Purpose: A 2-D table for flows through a short, prismatic channel that simulates the overbank flow bypassing a culvert or bridge opening is computed with the CHANRAT command. The rating for the flow through the channel resulting from the differences in water-surface elevation across it is given in the table. Additional discussion of this command is presented in section 3.3.

Notes: The results for each upstream head and partial free drop are printed out with the CHANRAT command. Also printed is a column of values headed by QDRERR, which is the same as the integration error tolerance so long as no special problems result during computation. If the value of QDRERR becomes large, this indicates that the stopping depth tolerances are too small or that there is some error in the program.

LINE 1

Variable: TABLE

Format: 7X, I5

Example: TABLE#= 9900

Explanation:

TABLE gives table number for the table to be computed in FEQUTL.

LINE 2

Variables: TABTYP, ERRKND, INTHOW, EPSINT, NDDABS, NDDREL

Format: A4,1X,I5,5A5

Example: TYPE= 13

Explanation:

TABTYP gives the type of 2-D table to produce. Currently, tables of type 6 and of type 13 can be computed in the CHANRAT command.

ERRKND specifies the error measure to apply in the adaptive integration. An absolute error is selected if ERRKND = 0, and a relative error is selected if ERRKND = 1. An absolute error criterion is the default option.

INTHOW is the method utilized for integration. Simpson adaptive integration is selected if INTHOW = 1. Simpson adaptive integration is the only option available. Others may be added in the future.

EPSINT is the tolerance value for the adaptive integration and has a default value of 0.1. This default value means that the estimated integration error must be less than 0.1 ft before computations are completed in the adaptive routine for numerical integration.

NDDABS is the absolute deviation from normal depth used to control the integration near the singularity in the governing equation at normal depth. The default value for NDDABS is 0.005 ft.

NDDREL is the relative deviation from normal depth used to control the integration near the singularity in the governing equation at normal depth. The default value for NDDREL is 0.005.

Variables other than type are given default values if omitted. These default values should be applied and changed only when necessary. These defaults should be changed only with caution.

LINE 3

Variable: LABEL

Format: A5,1X,A50

Example: LABEL=Overbank flow at Golf Course Bridge on Dinky Creek.

Explanation:

LABEL gives a user-defined label to identify the resulting table.

LINE 4

Variable: XSTAB

Format: A6,1X,I5

Example: XSTAB#= 100

Explanation:

XSTAB gives the table number of the cross-section table defining the shape of the channel. This table must contain critical flow. Therefore, it must be type 22 or type 25.

LINE 5

Variable: BOTSLP

Format: A6,1X,F10.0

Example: BOTSLP= 0.005

Explanation:

BOTSLP gives the bottom slope of the channel with decline downstream taken as positive. The bottom slope may be negative or zero. The flow must be subcritical. If a flow is supercritical in CHANRAT, an error message will be issued and the rating table will not be computed.

LINE 6

Variable: LENGTH, ELEV

Format: A6,1X,F10.0, 1X, 8X,F10.0

Example: LENGTH= 30.0 MIDELEV= 256.00

Explanation:

LENGTH gives the length of the channel, which must be > 0.

ELEV gives the elevation of the midpoint. The elevation of the midpoint is used to compute the elevation for head to be stored in the table for later checking with the value given for elevation for head in FEQ when this table is used. The elevation for head is computed in FEQUTL as the maximum of the two end-point elevations computed from the given slope and one-half the length. In the current example, if the bottom slope was 0.005, the elevation for head would be 256.075.

LINE 7

Variable: HEAD

Format: A80

Example: HEAD SEQUENCE FOR TABLE

Explanation:

HEAD gives a descriptive label for subsequent input.

LINE 8

Variable: NFRAC

Format: 6X,I5

Example: NFRAC= 21

Explanation:

NFRAC gives the number of partial free-drop fractions to use in computing the tail-water heads. A complete discussion of partial free-drop fractions for computation of 2-D function tables is given in section 11.2 of the documentation report for the Full Equations model (Franz and Melching, 1997).

LINE 9

Variable: POWER

Format: 6X,F10.0

Example: POWER= 2.0

Explanation:

POWER gives the power used to distribute the partial free drops from 0 to 1. The proportion of free drop is given by

$$P_i = \left(\frac{i-1}{NFRAC-1}\right)^{POWER}$$

for $i = 1, \ldots, NFRAC$.

LINE 10 (Repeated as needed to give the ascending sequence of upstream heads.)

Variable: HUVEC(I)

Format: F10.0

Explanation:

HUVEC gives the upstream heads to use in computing the 2-D table. The input of the list is terminated when a negative head is encountered. Head is measured from the end of the channel with the higher elevation. A nonzero head must result in a nonzero flow. Thus, if the bottom slope is positive, the datum for head is the upstream end of the channel; and if negative, the datum for head is the downstream end of the channel.

## 5.4 CRITQ Command

Purpose: The critical flow in a constricted section as a function of the depth of water in an approach section is computed in this command. The resulting flow table contains the flow as defined by critical flow at the constriction, but the height of the water in the approach section is used as the argument. This command is most often used with the GRITTER command for the generalized Ritter (1892) solution to an instantaneous dam failure.

LINE 1

Variables: TABLE, SAVEIT

Format: 7X, I5, 1X, A4

Example: TABLE#= 9900 SAVE

Explanation:

TABLE gives the table number for the table to be computed in FEQUTL.

SAVEIT indicates that the resulting table is saved internally within FEQUTL by entering SAVE so that the table can be referenced for use in later commands. If the SAVE option is omitted, the table is not saved and it cannot be referenced in later commands. For example, a critical-flow table must be given for the GRITTER command (section 5.14). Application of the SAVE option retains that table so that it is available when the GRITTER command is applied.

LINE 2

Variables: NAME, APPTAB

Format: A8, I5

Example: APPTAB#= 25

Explanation:

NAME must be APPTAB#=.

APPTAB gives the table number for the cross-section table describing the shape of the channel conveying water to the critical section. This is called the approach cross section or just the approach section. The bottom elevation of the approach cross section cannot be higher than the bottom elevation of the critical section. The elevations of the bottom of each cross section are taken from the elevation entry in the cross-section table.

LINE 3

Variables: NAME, CONTAB

Format: A8, I5

Example: CONTAB#= 29

Explanation:

NAME must be CONTAB#=.

CONTAB gives the table number for the cross-section table defining the cross section at which critical flow is assumed to be present. The bottom of the constricted cross section must be at or above the elevation of the approach section. The elevations are taken from the elevation entry in the heading of the cross-section table. The constricted cross section must not be larger than the approach cross section. However, it can be the same shape and size.

If the same table number is used for both the approach and the constricted section, an error message that the cross section is not high enough will be issued. This results because an entry in the critical-flow table is computed in FEQUTL for each entry in the constricted section. The water-surface elevation required in the approach section to produce critical flow in the constricted section is always higher than the water-surface elevation in the constricted section. Therefore, the computations for the depth in the approach section must overtop the cross-section table when computing the larger depth values in the critical section. Extending the cross-section table does not solve the problem of tabulated cross section overtopping because this also causes the computations for critical flow to go to larger depths. The solution is to copy the cross-section table in the input to the FTABIN command (section 5.13) and change the table number and then extend this copied table to a value large enough to avoid the problem of tabulated cross-section overtopping.

LINE 4

Variables: NAME, CD

Format: A8, I5

Example: DISCOEF= 0.95

Explanation:

NAME must be DISCOEF=.

CD gives the discharge coefficient for the opening. The discharge coefficient applies to the flow in the constricted section.

LINE 5

Variable: LABEL

Format: A50

Example: Flow at partial failure of Upper Baker Dam.

Explanation:

LABEL gives up to a 50-character label that will appear to the left of the column headings in the constricted-flow table produced in CRITQ.

## 5.5 CULVERT Command

Purpose: Flows through culverts and over an associated roadway are computed in this command by use of methods outlined in section 4.2. A 2-D table of type 13 is computed in this command. Only standard culverts and small deviations from standard culverts can be represented with the CULVERT command. Culverts with drop inlets or other special structural features that are uncommon in practice cannot be analyzed with the CULVERT command.

LINE 1

Variable: TABLE

Format: 7X, I5

Example: TABLE#= 9900

Explanation:

TABLE gives table number of the 2-D function table computed for the flows through the culvert.

LINE 2

Variable: CHAR4, TABTYP

Format: A4, 1X, I5

Example: TYPE= 13

Explanation:

CHAR4 must be TYPE.

TABTYP specifies the table type. Types 6 and 13 are currently supported in the FEQ model. Both table types contain the same information, but type 13 is more compact, takes less table-storage space, and is easier to read. Type 13 should be used unless type 6 is more appropriate for a specific application.

LINE 3

Variable: CHAR6, LABEL

Format: A5, 1X, A50

Example: LABEL= Twin-barrel 54-inch [illegible] Monte Road

Explanation:

CHAR[illegible]

LABEL [illegible] ill appear in the table for identification purposes.

LINE 4

Variable: HEAD

Format: A80

Example: Approach-section data

Explanation:

HEAD gives a subheading to break the input into logical components. The subheading may be any text, but should describe the data that follow.

LINE 5

Variable: CHAR6, APPTAB

Format: A6, 2X, I5

Example: APPTAB#= 342

Explanation:

CHAR6 must be APPTAB.

APPTAB gives the table number for the cross-section table of the approach section for the culvert. This table must have been input with the FTABIN command (section 5.13) or have been computed with the SAVE option in the FEQX, FEQXEXT, or FEQXLST commands (sections 5.8-5.10). Furthermore, the approach cross-section table must be of type 22 or 25 because values of critical flow are required in the CULVERT command.

LINE 6

Variable: CHAR6, APPELV

Format: A6, 1X, F10.0

Example: APPELV= 723.10

Explanation:

CHAR6 must be APPELV.

APPELV supplies the elevation of the minimum point of the cross section specified in APPTAB. This elevation should match the bottom-profile elevation at the downstream end of the branch upstream from the culvert in the FEQ input.

LINE 7

Variable: CHAR6, APPLEN

Format: A6, 1X, F10.0

Example: APPLEN= 24.0

Explanation:

CHAR6 must be APPLEN.

APPLEN gives the distance between the approach cross section and the entrance to the culvert. This distance should be about the same as the opening width of the culvert or the sum of the opening widths of multiple culverts. This value must be > 0.

LINE 8

Variable: CHAR6, APPLOS

Format: A6, 1X, F10.0

Example: APPLOS= 0.1

Explanation:

CHAR6 must be APPLOS.

APPLOS gives the hydraulic-energy loss resulting from special approach conditions in terms of the fraction of the velocity head in the approach cross section. Normally this loss is 0, but it can be used to approximate the losses resulting from trash racks, right-angle bends upstream from the culvert entrance, and other entrance conditions. This value should be between 0 and 1.

LINE 9

Variable: CHAR6, APPEXP

Format: A6, 1X, F10.0

Example: APPEXP= 0.5

Explanation:

CHAR 6 must be APPEXP.

APPEXP gives a coefficient to be applied to the difference between the approach-velocity head and the velocity head in the culvert entrance if the culvert is an expansion in flow area instead of a contraction in flow area. The discharge coefficient for the entrance loss for the culvert is set to the maximum value for no contraction of 0.98 (Bodhaine, 1968) if the flow is expanding instead of contracting. This value should be between 0 and 1.

LINE 10

Variable: HEAD

Format: A80

Example: Culvert Description

Explanation:

HEAD provides a subheading for the culvert cross section, elevation, and length description.

LINE 11

Variables: CHAR6, NODEID

Format: A6, 1X, A4

Example: NODEID=YES

Explanation:

CHAR 6 must be NODEID.

NODEID indicates whether an identifying string for each node along the culvert is included in the input. If NODEID is YES, then identifying strings are present; otherwise, they are omitted. At a minimum, each culvert will have two nodes: the entrance and the exit of the culvert. More nodes may be needed, however, if the shape or slope of the culvert is changed. Also, additional nodes may be needed to compute the flow through the culvert.

LINE 12

Variable: CHAR4, SFAC

Format: A4, 1X, F10.0

Example: SFAC= 1.0

Explanation:

CHAR4 must be SFAC.

SFAC gives the multiplying factor that converts the stations in the input to distances required in FEQUTL. The required distances are in feet for the ENGLISH unit option and in meters for the METRIC units option.

LINE 13

Variable: HEAD

Format: A80

Example: NODE XNUM STATION ELEVATION

Explanation:

HEAD gives user-defined heading that describes the information on subsequent lines.

LINE 14 (Repeated as needed for each node on the culvert.)

If NODEID=NO then

Variables: NODE, XTAB, X, Z, KA, KD

Format: 2I5, 2F10.0, 2F5.0

If NODEID=YES then

Variables: NODE, NAME, XTAB, X, Z, KA, KD

Format: I5, 1X, A8, 1X, I5, 2F10.0, 2F5.0

Explanation: The values describing each node on a culvert barrel are given on this line.

NODE is the node number on the current culvert. The end of a culvert-barrel description is indicated by a negative value of the NODE entry. The remainder of the line containing the terminating node number may be blank. The number for the first node on each branch must be given. The NODE column may be left blank for the other nodes and the node number will be computed in FEQUTL. If node numbers are given, they must be consecutive and increasing. The entrance to the culvert is the first node in the table.

NAME is the identification string for the node.

XTAB is the number of the cross-section table computed with the SEWER (section 5.19), MULPIPES (section 5.17), or MULCON (section 5.16) command.

X is the station of the node.

Z is the elevation of the minimum point in the stream at the node.

KA is the loss coefficient to apply to the difference in velocity head when the velocity is increasing in the direction of flow—that is, when the flow is accelerating.

KD is the loss coefficient to apply to the difference in velocity head when the velocity is decreasing in the direction of flow—that is, when the flow is decelerating.

A culvert may be too long to compute a steady-flow profile by use of cross sections at its entrance and exit only. Thus, additional nodes and cross sections must be added. This will be done in FEQUTL computations, overriding user data if there are at most two cross-section tables specified to describe the culvert barrel and if only two elevations are specified to define the slope of the invert. This means that only two nodes are needed for culvert computations. Only the initial node and the final node on the culvert barrel are needed in FEQUTL computations. Values of KA and KD specified on the line for the final node are used for all other nodes added to the barrel. Internal criteria are used in FEQUTL to define the node spacing so that the steady-flow profile computations will not result in convergence problems.

If the culvert-barrel size and shape change in a manner that cannot be described with just two cross sections, then the user must assign the intermediate nodes. Two methods are available for adding intermediate cross sections. The first method is simple propagation of the last known cross section at equal station intervals and with linear interpolation for the profile elevation. This method is selected by one or more blank lines in the input. A line of complete cross-sectional information above the blank lines and a line of complete cross-sectional information below the blank lines must be specified. The upstream table number is assigned to each blank line, and the stations and elevations are distributed uniformly between the two lines of known values. Linear interpolation of cross-section characteristics between two known cross sections is utilized in the second method. This method is selected by assigning a negative table number for the cross-section table or, more conveniently, by merely assigning a minus sign in the rightmost column of the field for the table number. An available table number is then supplied at the proper time in the FEQUTL computations. This prevents the problem of the user having to remember which table numbers are available for interpolated cross sections. If the station and elevation values are given, they will be utilized in the interpolation. If they are omitted, the station values will be distributed uniformly and the elevation will be linearly interpolated. The first method should only be applied if the conduit is prismatic over the interval of additional cross sections. The second method should be applied when the conduit characteristics vary over the interval between the known cross sections.

All cross sections given in the culvert-barrel description must be of table type 22 or 25 and must have a vertical slot so that a hypothetical free surface can be computed. The intermediate nodes close to the entrance and the exit should have small spacing less than one inlet maximum vertical dimension between them. Conditions change rapidly near these points, and the distance increment for profile computation should be relatively small.

To compute type 5 flow, there must be one node that is three times the inlet maximum vertical dimension from the inlet and one node that is six times the inlet maximum vertical dimension from the inlet. These locations are needed because the flow contracts to a minimum area (vena contracta) at a length of about three times the maximum vertical culvert dimension from the entrance, and in FEQUTL it is assumed that most of the expansion losses result within a distance of three times the maximum vertical culvert dimension downstream from the vena contracta (section 4.2.3).

LINE 15

Variable: CHAR6, CULCLS

Format: A6, 1X, A8

Example: CULCLS= BOX

Explanation:

CHAR6 must be CULCLS.

CULCLS gives the general class of the culvert for selection of the discharge coefficient. The culvert class does not determine the shape of the culvert. Thus, if an irregular-shaped culvert is judged to be best described as a box culvert for determination of the hydraulic characteristics, then the culvert class should be specified as BOX even though the culvert is not strictly a box culvert. The available options are: BOX–box culverts, PIPE–circular, elliptical, and arch pipes; MITER–mitered entrance for pipe culverts, RCPTG–reinforced-concrete pipe with machine tongue-and-groove construction and also pipes with commercially flared entrances.

LINE 16

Variable: HEAD

Format: A80

Example: Departure section description

Explanation:

HEAD gives a subheading for the departure section data that follow.

LINE 17

Variable: CHAR6, DEPTAB, BEGTAB, RMFFAC

Format: A6, 2X, I5, A5, A5

Example: DEPTAB#= 341

Explanation:

CHAR6 must be DEPTAB.

DEPTAB gives the table number of the cross-section table of the departure section for the culvert. This section represents the stream cross section where the flow concentration caused by the culvert in the downstream flow has essentially dissipated.

BEGTAB specifies an optional table number for the cross-section table describing the departure reach at the exit from the culvert.

RMFFAC is an optional entry that specifies a multiplying factor on the estimated momentum flux over the roadway. If RMFFAC is omitted, the default value is 1. This value must be $> 0$ and $\leq 1$.

LINE 18

Variable: CHAR6, DEPELV, BEGELV, DSFFAC, WIDFAC

Format: A6, 1X, F10.0, A10, A5, A5

Example: DEPELV= 629.05

Explanation:

CHAR6 must be DEPELV.

DEPELV gives the elevation of the bottom of the departure section. This elevation should match the elevation of the bottom profile of the upstream end of the branch downstream from the culvert in the FEQ input.

BEGELV is the elevation of the bottom of the beginning cross section for the departure reach. The beginning elevation, if omitted, is set as follows. If DEPELV is greater than the culvert-exit invert elevation, then BEGELV is set to the culvert-exit invert elevation; otherwise, BEGELV is set to the same elevation as DEPELV.

DSFFAC is reserved for potential future expansion of FEQUTL and is not used. The default value for DSFFAC is 0.

WIDFAC is a width factor for checking the beginning cross section of the departure reach. The default value for WIDFAC is 1.02.

The validity of BEGTAB may be checked with WIDFAC. BEGTAB represents the cross section of the departure reach at the culvert exit and must always be at least WIDFAC wider than the culvert exit. This width increase is checked at each tabulated water-surface height in the cross-section table for the culvert barrel, and if the test fails at any tabulated water-surface height, the cross section in BEGTAB is rejected. A height-by-height report on the widths of the two cross sections is output in FEQUTL computations. A cross section for BEGTAB must be input that will not obstruct any part of the exit cross section for the culvert barrel. If the obstruction is present and not just an artifact of the manner in which BEGTAB was defined, then the cross section of the culvert barrel at the exit should be modified to reflect the obstruction.

LINE 19

Variable: CHAR6, LOSOPT

Format: A6, 1X, A8, F10.0

Example: LOSOPT=MOMENTUM

Explanation:

CHAR6 must be LOSOPT.

LOSOPT gives the loss option for the expansion of the flow into the departure reach. The procedure for culvert flow in Bodhaine (1968) includes losses resulting from contraction at the culvert entrance and subsequent expansion in the culvert barrel. The loss caused by the expansion of the flow in the departure reach must be computed separately. One loss option, denoted by MOMENTUM, is available in the CULVERT command. A simple momentum balance in the departure reach is applied to estimate the losses in the expanding flow in this option. Complete details are given in section 4.2.5.

LINE 20

Explanation: Line 20 is not currently used in FEQUTL, but it is reserved for future expansion of the loss options in the departure reach. This line is retained to maintain the line number sequence.

LINE 21

Variable: HEAD

Format: A80

Example: Discharge coefficient data

Explanation:

HEAD gives the subheading for discharge-coefficient information.
The selection of the discharge coefficient involves several factors. Some of these factors are purely geometric and are not changed by the depth or flow of water in the culvert. Some of the factors are hydraulic and depend on the depth or flow of water. Consequently, some discharge coefficients are determined by geometric factors alone, and some are determined by a combination of geometric and hydraulic factors. In order to allow for the greatest flexibility in model simulation and to simplify the input for the CULVERT command, the discharge coefficients dependent on hydraulic factors are determined internally in FEQUTL computations. Discharge factors and adjustment factors that depend on geometry only must be supplied in the input. However, the values defined by geometry only may be determined by table look up in FEQUTL computations if requested by the user. Determination of the values by table look up is the preferred method. However, the ability to provide explicit values is retained to maintain maximum flexibility. The values that may be determined by table look up are: the multiplying factor to adjust the base-discharge coefficient for flow types 1, 2, and 3 for the effect of rounding or beveling of the entrance to the culvert, KRB; the adjustment factor for the effect of wingwalls on the discharge coefficient for flow types 1, 2, and 3 when the wingwalls are present for box culverts, KWING; the adjustment factor for the effect for projecting entrances for flow types 1, 2, and 3, KPROJ; and the discharge coefficient for type 4 and 6 flow, C46. To request look up, these four variables are given the value of 0.0 (in Lines 22-25, respectively). If a nonzero value for these variables is specified, that value will be applied, and no look up will be done. The special file TYPE5.TAB (which may be retrieved electronically as described in section 5.1) must be input using FTABIN (section 5.13) if look up is requested. This file contains both flow-type 5 related tables and tables defining KRB, KWING, KPROJ, and C46. If look up is requested for any one of these values, the optional input for the flow-type 5 parameters, Line 25–1, must be given. The input for flow-type 5 parameters has been expanded to include the geometric variables required to define KRB, KWING, KPROJ, and C46.

LINE 22

Variable: CHAR3, KRB

Format: A3, 1X, F10.0

Example: KRB= 1.05

Explanation:

CHAR3 must be KRB.

KRB gives the multiplying factor to adjust the base discharge coefficient for flow types 1, 2, and 3 for the effect of rounding or beveling of the entrance to the culvert. The value should be between 1 and 1.5. The base coefficient is selected on the basis of the culvert class. Bodhaine (1968) presented a series of figures that may be used to estimate the multiplying factor for culverts corresponding to the PIPE and BOX input descriptions. For sharp-edged entrance conditions, figure 20 in Bodhaine should be used with the PIPE designation and figure 23 should be used with the BOX designation. For culverts with rounded entrances, the value determined from figure 20 or 23 should be multiplied by the value determined from figure 21. For culverts with beveled entrances, the value determined from figure 20 or 23 should be multiplied by the value determined from figure 22.

LINE 23

Variable: CHAR5, KWING

Format: A5, 1X, F10.0

Example: KWING= 1.10

Explanation:

CHAR5 must be KWING.

KWING gives the adjustment factor for the effect of wingwalls on the discharge coefficient for flow types 1, 2, and 3 when wingwalls are present for box culverts. Values are given in figure 24 of Bodhaine (1968). The value should be between 1 and 1.25. Wingwalls do not change the discharge coefficient for a pipe culvert set flush with a vertical headwall.

LINE 24

Variable: CHAR5, KPROJ

Format: A5, 1X, F10.0

Example: KPROJ= 0.96

Explanation:

CHAR5 must be KPROJ.

KPROJ is the adjustment factor for the effect for projecting entrances for flow types 1, 2, and 3 (Bodhaine, 1968, p. 41–42). KPROJ is a function of the length of projection as detailed by Bodhaine (1968, p. 42). The value should be between 0.9 and 1.

LINE 25

Variable: CHAR3, C46

Format: A3, 1X, F10.0

Example: C46= 0.85

Explanation:

CHAR3 must be C46.

C46 is the discharge coefficient for culvert-flow types 4 and 6. This coefficient is purely a function of geometry and must therefore contain all the adjustments for wingwalls, projecting entrance, rounding, beveling, and other conditions discussed in Bodhaine (1968, p. 42–43). This value should be between 0.6 and 1.

LINE 25–1

Variable: HEAD

Format: A80

Example 1: TYPE 5 flow parameters

Example 2: Type 5 flow parameters

Explanation:

HEAD gives heading information for the input of optional type 5 flow parameters and parameters to define the look up of discharge coefficients for other flow types. The first six characters of the heading line must be TYPE 5 or Type 5. The remainder of the line can be any suitable title. Input of parameters for type 5 flow is optional. However, the file TYPE5.TAB (retrieved electronically as described in section 5.1) must be included in an FTABIN (section 5.13) command to provide a variety of tables that define the boundary between type 5 and type 6 flow and the discharge coefficients for type 5 flow. If the type 5 parameters are omitted, the default values are: RBVALUE=0.0, WWANGLE=0.0, and TYPE5SBF= 0.75 (see Lines 25–2, 25–3, and 25–4).

LINE 25–2

Variable: RBVALUE

Format: 8X,F10.0

Example: RBVALUE= 0.03

Explanation:

RBVALUE is the relative rounding/beveling for the culvert entrance. This value is used to define the discharge coefficient for type 5 flow. It also is used to define KRB if table look up is requested by the user. RBVALUE should be ≥ 0 and ≤ 0.14. The default value of RBVALUE is 0.0.

LINE 25–2–1

Variable: BVANGLE

Format: 8X,F10.0

Example: BVANGLE= 45.0

Explanation:

BVANGLE is the angle in degrees of the bevel if the entrance to the culvert is beveled. If the entrance is rounded or sharp-edged, this value is 0.0. A nonzero value for BVANGLE indicates that the RBVALUE is utilized for beveling and not rounding. BVANGLE must be ≥ 0 and ≤ 90 degrees. RBVALUE and BVANGLE are used to define KRB if table look up is requested by the user.

LINE 25–3

Variable: WWANGLE

Format: 8X,F10.0

Example: WWANGLE= 45.0

Explanation:

WWANGLE is the wingwall angle in degrees. A value of 0 means that the plane of the wingwall is perpendicular to the culvert barrel. A value of 90 means that the plane of the wingwall is parallel with the barrel. The default value of WWANGLE is 0.0.

LINE 25–3–1

Variable: LPOVERD

Format: 8X,F10.0

Example: LPOVERD= 0.1

Explanation:

LPOVERD is the average projection length of the culvert barrel relative to the culvert maximum inside vertical dimension. LPOVERD must be ≥ 0. This value defines KPROJ when table look up is requested by the user.

LINE 25–4

Variable: TYPE5SBF

Format: 9X,F10.0

Example: TYPE5SBF=0.75

Explanation:

TYPE5SBF is the value of relative water-surface height in the barrel or the barrel exit that will result in full flow in the culvert barrel. The relative water-surface height is expressed in relation to the maximum vertical dimension of the culvert barrel. Thus, a value of 0.75 specifies that water in the culvert barrel must be flowing at a water-surface height equal to or greater than 0.75 (the default value determined from engineering judgment) of the maximum vertical dimension at the exit before full flow in the culvert will result. TYPE5SBF must be ≥ 0 and ≤ 1. For type 5 flow, submergence and full flow are considered to have identical flow and hydraulic characteristics. No effort is made to distinguish between full flow and submergence because no data on which to base such a distinction are available.

LINE 25–5

Variable: HEAD

Format: A80

Example: TABLE numbers for type 5 flow

Explanation:

HEAD gives a heading for optional input specifying the table numbers for type 5 flow. These tables provide information of the boundary between type 5 and type 6 flows, and discharge coefficients for type 5 flow. The first five characters of the heading must be TABLE or Table. The remainder of the line can be any suitable heading. The type 5 parameters and table numbers are specified, and then the type 5 parameter input must be specified before the table numbers.

LINE 25–6

Variables: TB6ADR, TB7ADR, TB8ADR, TB15ADR, TB16ADR(1:4)

Format: free, one or more spaces must separate numbers

Example: 9980 9981 9982 9983 9984 9985 9986 9987

Explanation: Table numbers for tables of information used in computing type 5 flows are specified in this line. All the tables refer to Bodhaine (1968). If this information is omitted, the default table numbers are given in the current example. The default function tables are stored in a file, TYPE5.TAB, which is available by electronic retrieval as described in section 5.1. These numbers should be supplied only if there is some conflict between the default table numbers and a planned or previously used table-numbering scheme.

TB6ADR is the 2-D table of type 10 representing table 6 in Bodhaine (1968)–"Discharge coefficients for box or pipe culverts set flush in a vertical headwall with variation of head and entrance rounding or beveling, type 5 flow."

TB7ADR gives the 2-D table of type 10 representing table 7 in Bodhaine (1968)–"Discharge coefficients for box culverts with wingwalls with variation of head and wingwall angle, θ, type 5 flow."

TB8ADR gives a 1-D table of type 2 representing the discharge coefficients for flared pipe-end sections.

TB15ADR gives a 2-D table of type 10 representing the data presented in figure 13.

TB16ADR(1) through TB16ADR(4) give the table numbers for 2-D tables of type 10 for the four parts of figure 14.

LINE 25–7

Variable: HEAD

Format: A80

Example: TYPE 1 parameters

Explanation:

HEAD gives a heading for the optional parameters for type 1 flow. These optional parameters relate to the limits for type 1 flow. The first six characters of the line must be either TYPE 1 or Type 1. Type 1 parameters must be specified after the Type 5 parameters if both are specified. The following defaults are used if this input is omitted: TY1YTD= 0.95 and TY1HTD= 1.4.

LINE 25–8

Variable: TY1YTD

Format: 7X,F10.0

Example: TY1YTD= 0.95

Explanation:

TY1YTD is the relative water-surface height in the culvert-barrel entrance for the upper limit of type 1 flow. TY1YTD specifies the upper limit for the type 1 flow rate because the flow rate is determined from critical depth at the entrance of the culvert barrel. The relative water-surface height is relative to the maximum vertical dimension of the culvert barrel. For example, a value of 0.95 indicates the water-surface height in the barrel entrance will be at 0.95 of the maximum vertical dimension at the maximum type 1 flow. This limit is needed because critical flow increases without bound as the water-surface height of the flow approaches the soffit of a closed conduit with converging walls. TY1YTD must be $\geq 0.5$ and $< 1$.

LINE 25–9

Variable: TY1HTD

Format: 7X,F10.0

Example: TY1HTD= 1.4

Explanation:

TY1HTD is the maximum relative head permitted for type 1 or type 2 flow at their upper limits. Experiments and field observations indicate that full flow in culverts will result if the approach head measured relative to the invert of the culvert inlet is 1.5 or greater. Full flow may result at a lower approach head, and for type 2 flow, full flow may begin for a relative head as small as 1.2. The specification of the relative water-surface height using TY1YTD may, for culverts other than box culverts, result in a relative-head ratio that is greater than 1.5. If the ratio is greater than 1.5, this result is ignored and the relative-head ratio is set to the value given by TY1HTD in CULVERT-command computations. The type 1 flow conditions at that limit are then computed for the maximum type 1 flow. The limit is not set at 1.5 to permit computation of a transition zone between the low-head free flows, types 1 and 2, and the high-head free flows, types 5 and 6. TY1HTD must be ≥ 1.

LINE 26

Variable: HEAD

Format: A80

Example: Roadway description

Explanation:

HEAD gives a subheading for the roadway description. A format similar to that used in the EMBANKQ command is applied here.

LINE 27

Variable: TAB(1)

Format: 7X, I5

Example: PLCWTB= 9994

Explanation:

TAB(1) is the table number for the function table listing the low-head weir coefficient for a paved surface. The table number in this example is the default value, and this table may be retrieved electronically as described in section 5.1.

LINE 28

Variable: TAB(2)

Format: 7X, I5

Example: GLCWTB= 9995

Explanation:

TAB(2) is the table number for the function table listing the low-head weir coefficient for a graveled surface. The table number listed in this example is the default value, and this table may be retrieved electronically as described in section 5.1.

LINE 29

Variable: TAB(3)

Format: 7X, I5

Example: PHCWTB= 9996

Explanation:

TAB(3) is the table number for the function table listing the high-head weir coefficient for a paved surface. The table number listed in this example is the default value, and this table may be retrieved electronically as described in section 5.1.

LINE 30

Variable: TAB(4)

Format: 7X, I5

Example: GHCWTB= 9997

Explanation:

TAB(4) is the table number for the function table listing the high-head weir coefficient for a graveled surface. The table number listed in this example is the default value, and this table may be retrieved electronically as described in section 5.1.

LINE 31

Variable: TAB(5)

Format: 7X, I5

Example: PSUBTB= 9998

Explanation:

TAB(5) is the table number for the function table listing the submergence correction factor for a paved surface. The table number listed in this example is the default value, and this table may be retrieved electronically as described in section 5.1.

LINE 32

Variable: TAB(6)

Format: 7X, I5

Example: GSUBTB= 9999

Explanation:

TAB(6) is the table number for the function table listing the submergence correction factor for a graveled surface. The table number listed in this example is the default value, and this table may be retrieved electronically as described in section 5.1.

LINE 33

Variable: HEAD

Format: A80

Example: OFFSET CREST WIDTH APPROACH SURFACE

Explanation:

HEAD gives a heading for subsequent columns of input.

LINE 34 (Repeated as necessary to include all offsets describing the roadway embankment.)

Variables: OFF(I), CREST(I), WIDTH(I), APPROC(I), SURF(I)

Format: 4F10.0, 1X, A8

Explanation: The values given on this line define, subsection-by-subsection, the geometry of the crest of the roadway applied in computation of flow over the roadway.

OFF is the horizontal offset for which geometric characteristics are entered on this line.

CREST is the crest elevation.

WIDTH is the width of the crest in the direction of flow.

APPROC is the elevation of the approach channel. If the approach velocity should be ignored, then an approach elevation that is much lower than the crest elevation should be specified so that the computed velocity head will be small.

SURF is the the type of surface, and the designation applies to the line segment beginning at the offset for which the surface type is given. For example, if the first line of the roadway-crest specification gives the type of surface as GRAVEL and the second line of the roadway-crest specification gives the type of surface as PAVED, then the roadway crest between the first and second offset is taken to be of a roughness similar to a graveled roadway. Two closely spaced points should be placed on the crest at the change in roughness to represent the transition between the two surface conditions. The end of the weir specification is indicated by entering END for the type of surface. Thus, if the third line of the input in this example contained END for the type of surface, then the weir crest between the second and third offset would have a roughness similar to a paved roadway.

These geometric characteristics are input for the boundaries of the subsections. The crest elevation, crest width, and approach-channel elevation are assumed to change linearly between the given points on the crest as illustrated in figure 18 (in section 5.6). To make input easier, the values for width, approach-channel elevation, and surface type propagate downward into fields left blank. Thus, if the elevation of the approach channel is constant and the width is constant, only the first line of the specification must contain the elevation of the approach channel and the width of the weir crest.

LINE 35

Variable: HEAD

Format: A80

Example: Head sequence definition

Explanation:

HEAD gives the heading for the parameters listing the sequence of upstream heads and the distribution of the partial free drops used to define the downstream heads for the 2-D table.

LINE 36

Variable: CHAR5, NFRAC

Format: A5, 1X, I5

Example: NFRAC= 11

Explanation:

CHAR5 must be NFRAC.

NFRAC is the number of partial free drops used in computing the table. Complete details on partial free drops are given in the discussion of 2-D function tables in section 11.2 of the documentation report for FEQ (Franz and Melching, 1997).

LINE 37

Variable: CHAR6, POWER

Format: A6, 1X, F10.0

Example: POWER= 2.

Explanation:

CHAR6 must be POWER=.
POWER is the power applied to distribute the proportion of free drop from a value of 0 to 1. The proportion of free drop is given by

$$P_i = \left(\frac{i-1}{NFRAC-1}\right)^{POWER}$$

for $i = 1, \ldots, NFRAC$.

LINE 38 (Repeated as necessary to input all the upstream heads used in computing the 2-D table.)

Variable: HUVEC(I)

Format: F10.0

Example: 2.0

Explanation:

HUVEC is the upstream head to use in computing the 2-D table. The sequence of heads should be positive and strictly increasing. The end of head input is signaled by a negative value for head. The heads specified here will be the values of head that appear in the table. It is the user's responsibility to choose a spacing that is appropriate for head distribution for the culvert and roadway embankment simulated. Generally, the spacing should be small for the low heads and larger for the high heads. The head interval should become small when flow over the roadway, if any, begins. A spacing of 0.1 ft or even 0.01 ft may be needed to define the low-head range of the table if the range of heads is small. Generally, no more than about 20 subdivisions should be used to represent the range of heads expected. More subdivisions can be used, but this results in larger tables.

## 5.6 EMBANKQ Command

Purpose: The Hulsing (1967) procedure for flow over embankment-shaped weirs is implemented as outlined in section 4.3. Flow over a variety of weirs can be computed if the appropriate tables are provided.

Notes: A warning message has been added to EMBANKQ to alert the user to potentially unrealistic results for flow over the embankment when the height of the embankment above the approach section becomes small relative to the head on the embankment. If the ratio of piezometric head to the weir height becomes much greater than 4 or 5, the coefficients used for flow over the weir are inaccurate. The depth at which the weir-flow coefficients become inaccurate is not known. However, if the head to height ratio goes above 7, the weir-flow coefficients are certainly inaccurate. The message is only a warning, and the flow will be computed in FEQUTL for whatever ratio is present. The user must decide if the result is reasonable. The flow at each point along the crest of the embankment is limited to be no more than the critical flow rate in the approach section. Therefore, when weir subsections with small heights are present in the stream system, the critical flow in the approach section is applied. However, no warning is issued when this is done. The best method to apply for weir subsections with small heights is to divide the embankment into subsections and apply CHANRAT (section 5.3) for those sections with crest elevations very close to the approach section elevation.

LINE 1

Variable: TABLE, TYPE, HLCRIT, HLMAX

Format: 7X, I5, A5, A5

Example: TABLE#= 9900

Explanation:

TABLE is table number for the table to be computed in FEQUTL.

TYPE is the table type and can be either 6 or 13 with 13 applied by default if TYPE is omitted.

HLCRIT is the critical ratio between approach head and embankment width that distinguishes between high-head and low-head flow. Ratios at or greater than HLCRIT correspond to high-head flow and ratios less than HLCRIT correspond to low-head flow. The default value is 0.15 based on Hulsing (1967) and Kindsvater (1964).

HLMAX is the maximum ratio of approach head to embankment width that can be applied without generating a warning message in EMBANKQ. This warning message alerts the user to the possibility that the weir coefficients may no longer be valid at head ratios greater than HLMAX. The approximate upper limit of the head-to-width ratio in the experiments defining the weir coefficients is represented in HLMAX. HLMAX defaults to 0.32 based on Hulsing (1967) and Kindsvater (1964).

LINE 2

Variable: TAB(1)

Format: 7X, I5

Example: PLCWTB= 9994

Explanation:

TAB(1) is the table number for the function table listing the low-head weir coefficient for a paved surface. The table number listed in this example is the default value, and this table may be retrieved electronically as described in section 5.1.

LINE 3

Variable: TAB(2)

Format: 7X, I5

Example: GLCWTB= 9995

Explanation:

TAB(2) is the table number for the function table listing the low-head weir coefficient for a graveled surface. The table number listed in this example is the default value, and this table may be retrieved electronically as described in section 5.1.

LINE 4

Variable: TAB(3)

Format: 7X, I5

Example: PHCWTB= 9996

Explanation:

TAB(3) is the table number for the function table listing the high-head weir coefficient for a paved surface. The table number listed in this example is the default value, and this table may be retrieved electronically as described in section 5.1.

LINE 5

Variable: TAB(4)

Format: 7X, I5

Example: GHCWTB= 9997

Explanation:

TAB(4) is the table number for the function table listing the high-head weir coefficient for a graveled surface. The table number listed in this example is the default value, and this table may be retrieved electronically as described in section 5.1.

LINE 6

Variable: TAB(5)

Format: 7X, I5

Example: PSUBTB= 9998

Explanation:

TAB(5) is the table number for the function table listing the submergence correction factor for a paved surface. The table number listed in this example is the default value, and this table may be retrieved electronically as described in section 5.1.

LINE 7

Variable: TAB(6)

Format: 7X, I5

Example: GSUBTB= 9999

Explanation:

TAB(6) is the table number for the function table listing the submergence correction factor for the graveled surface. The table number listed in this example is the default value, and this table may be retrieved electronically as described in section 5.1.

If PSUBTB and GSUBTB are given as zero, then no submergence computations are done and the resulting function table will be type 2. If they are nonzero, then submergence computations are done and the resulting function table will be type 13.

LINE 8

Variable: LABEL

Format: 6X, A80

Example: LABEL=FLOW OVER BUTTERFIELD ROAD AT DRY CREEK

Explanation:

LABEL is a user-supplied label that will be output as part of the heading for the table produced in FEQUTL computations.

LINE 9

Variable: HEAD

Format: A80

Example: OFFSET CREST WIDTH APPROACH SURFACE

Explanation:

HEAD gives a heading for subsequent columns of input.

LINE 10

Variables: OFF(I), CREST(I), WIDTH(I), APPROC(I), SURF(I)

Format: 4F10.0, 1X, A8

Explanation: The values given on this line define, in a subsection-by-subsection approach, the geometry of the crest of the embankment-shaped weir applied in computation of the flow over the embankment.

OFF is the horizontal offset.

CREST is the crest elevation.

WIDTH is the width of the crest in the direction of flow.

APPROC is the elevation of the approach channel. If the approach velocity should be ignored in the computations, then an approach elevation that is much lower than the crest elevation should be specified so that the velocity head computed will be small.

SURF is the type of surface, and the designation applies to the line segment beginning at the offset for which the surface type is given. For example, if the first line of the weir-crest specification gives the type of surface as GRAVEL and the second line of the weir-crest specification gives the type of surface as PAVED, then the weir crest between the first and second offset is taken to be of a roughness similar to a graveled roadway. Two closely spaced points should be placed on the crest at the change in roughness to represent the transition between the two surface conditions. The end of the weir specification is indicated by giving END for the type of surface. Thus, if the third line of the input in this example had END for the type of surface, then the weir crest between the second and third offset would have a roughness similar to a paved roadway.

These geometric characteristics are input for the boundaries of the subsections. The crest elevation, crest width, and approach-channel elevation are assumed to change linearly between the given points on the crest, as illustrated in figure 18. To make input easier, the values for width, approach-channel elevation, and surface type propagate downward into fields left blank. Thus, if the elevation of the approach channel is constant and the width is constant, only the first line of the specification must contain the elevation of the approach channel and the width of the weir crest. The surface value also propagates so that for constant surface type, only the first line must have PAVED or GRAVEL. END is specified for the final line to indicate the end of geometric input.

LINE 11

Variable: HEAD

Format: A80

Example: UPSTREAM HEADS TO USE IN COMPUTING THE TABLE

Explanation:

HEAD gives the heading for subsequent column of input.

The following two lines (11a and 11b) are optional. However, if one is applied, the other also must be applied. If they are omitted, NFRAC defaults to 21 and POWER defaults to 2.

LINE 11a

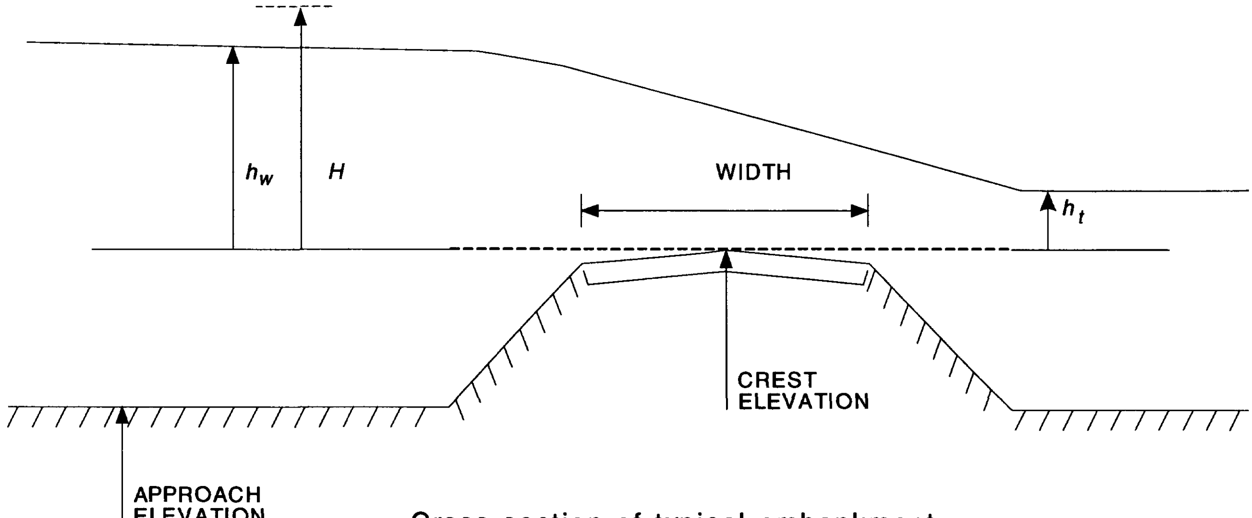
Variable: CHAR5, NFRAC

Format: A5, 1X, I5

Example: NFRAC= 11

Explanation:

CHAR5 must be NFRAC.



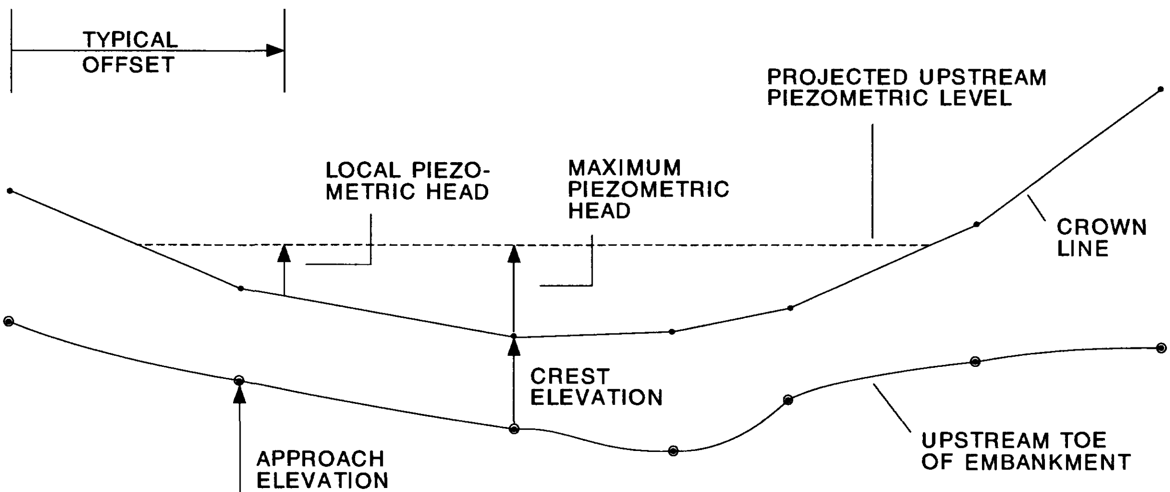

Cross section of typical embankment

**EXPLANATION**

$H$ TOTAL-ENERGY HEAD ON EMBANKMENT OR ROADWAY CREST

$h_w$ WATER-SURFACE HEAD ON EMBANKMENT OR ROADWAY CREST

$h_t$ DOWNSTREAM WATER-SURFACE HEAD AT EMBANKMENT OR ROADWAY CREST




Upstream view of typical embankment

**Figure 18.** Geometry of an embankment or roadway crest applied in computation of flow hydraulics in the EMBANKQ and CULVERT commands in the Full EQuations UTiLities model.

NFRAC is the number of partial free drops used in computing the table. Complete details on partial free drops are given in the discussion of 2-D function tables in section 11.2 of the documentation report for FEQ (Franz and Melching, 1997).

LINE 11b

Variable: CHAR6, POWER

Format: A6, 1X, F10.0

Example: POWER= 2.

Explanation:

CHAR6 must be POWER=.

POWER is the power applied to distribute the proportion of free drop from a value of 0 to 1. The proportion of free drop is given by

$$P = \left(\frac{i-1}{NFRAC-1}\right)^{POWER}$$

for $i = 1, \ldots, NFRAC$.

LINE 12 (Repeated as necessary to input all the upstream heads used in computing the 2-D table.)

Variable: HUVEC(*)

Format: F10.0

Explanation:

HUVEC is the upstream head to use in computing the 2-D table. The sequence of heads should be positive and strictly increasing. The end of head input is signaled by a negative value for head. The heads specified here will be the values of head that appear in the table. It is the user's responsibility to choose a spacing that is appropriate for head distribution for the embankment simulated. Generally, the spacing should be small for the low heads and larger for the high heads. A spacing of 0.1 ft or even 0.01 ft may be needed to define the low-head range of the table if the range of heads is small. Generally, no more than about 20 subdivisions should be used to represent the range of heads expected. More subdivisions can be used, but this results in larger tables.

## 5.7 EXPCON Command

Purpose: A 2-D table to approximate the flow through a channel transition is computed in the EXPCON command. The transition is defined by an upstream cross section, a downstream cross section, the bottom elevations, the distance between the sections, and parameters relating to the computation of friction and shock losses. The methods utilized in FEQUTL are discussed in section 3.2.

LINE 1

Variable: HEAD

Format: A80

Example: CROSS SECTION TABLES

Explanation:

HEAD gives a heading for the information to follow. Heading can be any string, but it must appear as the first item of input after the EXPCON command.

LINE 2

Variables: HEAD

Format: A80

Example: LOC TAB# DIST DATUM

Explanation:

HEAD gives the headings for the columns of information to follow.

LINE 3

Variables: CHAR4, XTABL, XL, ZBL

Format: A4,I5,F5.0,F10.0

Example: UP 938 0.0 653.9

Explanation:

CHAR4 must be UP or an error statement is issued.

XTABL is the function-table number of the upstream cross section.

XL the distance value associated with that cross section.

ZBL is the bottom elevation of the cross section.

The elevation and distance are in feet or meters, as required by the UNITS selection in the standard header (section 5.1).

LINE 4

Variables: CHAR4, XTABR, XR, ZBR

Format: A4,I5,F5.0,F10.0

Example: DN 940 121. 652.7

Explanation:

CHAR4 must be DN or an error statement is issued.

XTABR is the function-table number of the downstream cross section.

XR is the distance value associated with that cross section.

ZBR is the bottom elevation of the cross section.

The elevation and distance are in feet or meters, as required by the UNITS selection in the standard header (section 5.1). The length of the transition is given by the absolute value of the difference in the upstream and downstream distance values. If friction losses are to be ignored, the length of the transition should be zero.

LINE 5

Variable: HEAD

Format: A80

Example: COEFFICIENTS AND OUTPUT TABLES

Explanation:

HEAD describes the information that follows in the input.

LINE 6

Variable: HEAD

Format: A80

Example: DIR TAB# KA KD LABEL

Explanation:

HEAD provides headings for the columns of information to follow.

LINE 7

Variables: CHAR4, UDTAB, KACCUD, KDECUD, LABUD

Format: A4,I5,F5.0,F5.0,1X,A50

Example: UD 300 0.2 0.4 TEST OF THE EXPCON FEQUTL CODE: UD

Explanation: Information for the table describing flow from upstream to downstream is specified on this line.

CHAR4 must be UD.

UDTAB is the table number for the table to be computed.

KACCUD is the loss coefficient to apply to the velocity-head difference for accelerating flow.

KDECUD is the loss coefficient to apply to the velocity-head difference for decelerating flow.

LABUD is a label to print with the output table for identification.

Both loss coefficients must be between 0 and 1.

LINE 8

Variables: CHAR4, DUTAB, KACCDU, KDECDU, LABDU

Format: A4,I5,F5.0,F5.0,1X,A50

Example: DU 301 0.2 0.4 TEST OF THE EXPCON FEQUTL CODE: DU

Explanation: Information for the table describing flow from downstream to upstream is specified on this line.

CHAR4 must be DU.

DUTAB is the table number for the table to be computed. If DUTAB=0, then no table for flow from downstream to upstream is produced. The remaining information for Line 8 must be supplied and valid.

KACCDU is the loss coefficient to apply to the velocity-head difference for accelerating flow.

KDECDU is the loss coefficient to apply to the velocity-head difference for decelerating flow.

LABDU is a label to print with the output table for identification.

Both loss coefficients must be between 0 and 1.

LINE 9

Variable: SMOOTH

Format: 7X,F10.0

Example: SMOOTH= 0.2

Explanation:

SMOOTH is the value of the velocity difference, $\Delta V$, for smoothing the losses near the point of zero difference in velocity head. If SMOOTH = 0.0, then no smoothing is done.

LINE 10

Variable: TGMEAN

Format: 6X,F10.0

Example: GMEAN= 0.5

Explanation:

TGMEAN is the value of the parameter, $\alpha$, for computing the generalized mean. Values that are too large in absolute value may result in a failure due to floating-point overflow. The limit depends on the computer utilized and cannot be easily defined. A maximum absolute value of about 100 should be applicable on IBM mainframes, and numbers near 1,000 might be applicable on most microcomputers. Numbers as large as 1,000 are only needed if it is desired to force a mean value close to the value of either of the end-point conveyances. If the absolute value of GMEAN is less than 0.01, it is taken to be zero to prevent floating-point overflow during the computations.

LINE 11

Variable: HEAD

Format: A80

Example: HEAD SEQUENCE FOR TABLE

Explanation:

HEAD is a descriptive label for subsequent input.

LINE 12

Variable: NFRAC

Format: 6X,I5

Example: NFRAC= 11

Explanation:

NFRAC is the number of partial free flows to use in computing the 2-D table of type 14. Complete details on partial free flow are given in the discussion of 2-D function tables in section 11.2 of the documentation report for FEQ (Franz and Melching, 1997).

LINE 13

Variable: POWER

Format: 6X, F10.0

Example: POWER= 2.

Explanation:

POWER is the power used to distribute the partial free-flow factors between 0 and 1. The partial free flow is given by

$$P_i = \left(\frac{i-1}{NFRAC-1}\right)^{POWER}$$

for $i = 1, \ldots, NFRAC$.

LINE 14 (Repeated as necessary to input all the downstream heads used in computing the 2-D table.)

Variable: HDVEC(I)

Format: F10.0

Explanation:

HDVEC is the downstream piezometric head applied in computing the table. The downstream piezometric heads are entered in an ascending sequence. The input of the list is terminated when a negative head is encountered. The datum for heads is the maximum of the two elevations for the cross sections defining the transition.

Note: Results for each downstream head are printed with EXPCON. The upstream piezometric head at free flow and information on the partial free flows are listed. An example of this output is given below. The location of the control can be UP, DN, or BOTH. The string BOTH denotes that the control is submerged and that both the upstream and downstream conditions define the flow. The sense of the flow is EXP for expanding flow and CON for contracting flow. The upstream piezometric head need not be greater than the downstream piezometric head. In this example, the upstream piezometric head is greater than the downstream piezometric head because the flow is contracting throughout the transition. A check on the convergence tolerances is given at the end of the table. The check gives the maximum error in the energy balance (in terms of head) relative to the change in energy and location. In this message, PFQ is an abbreviation for Partial Free Flow.

```
Dwns piezometric head=     9.000   Ups head at free flow=   10.831
```

| Fraction of Free Flow | Upstream Piezometric Head | Downstream Piezometric Head | Flow through Transition | Location of Control | Sense of Flow |
|---|---|---|---|---|---|
| 1.0000 | 10.8312 | 9.0000 | 417.67 | DN | CON |
| 0.9549 | 10.7316 | 9.0000 | 398.82 | BOTH | CON |
| 0.9095 | 10.6320 | 9.0000 | 379.88 | BOTH | CON |
| 0.8639 | 10.5325 | 9.0000 | 360.83 | BOTH | CON |
| 0.8181 | 10.4331 | 9.0000 | 341.67 | BOTH | CON |
| 0.7719 | 10.3335 | 9.0000 | 322.39 | BOTH | CON |
| 0.7254 | 10.2338 | 9.0000 | 302.98 | BOTH | CON |
| 0.6786 | 10.1340 | 9.0000 | 283.43 | BOTH | CON |
| 0.6314 | 10.0337 | 9.0000 | 263.73 | BOTH | CON |
| 0.5839 | 9.9332 | 9.0000 | 243.87 | BOTH | CON |
| 0.5359 | 9.8325 | 9.0000 | 223.82 | BOTH | CON |
| 0.4874 | 9.7314 | 9.0000 | 203.57 | BOTH | CON |
| 0.4384 | 9.6304 | 9.0000 | 183.10 | BOTH | CON |
| 0.3887 | 9.5297 | 9.0000 | 162.36 | BOTH | CON |
| 0.3384 | 9.4299 | 9.0000 | 141.33 | BOTH | CON |
| 0.2872 | 9.3323 | 9.0000 | 119.94 | BOTH | CON |
| 0.2349 | 9.2388 | 9.0000 | 98.12 | BOTH | CON |
| 0.1813 | 9.1523 | 9.0000 | 75.74 | BOTH | CON |
| 0.1259 | 9.0779 | 9.0000 | 52.58 | BOTH | CON |
| 0.0675 | 9.0234 | 9.0000 | 28.18 | BOTH | CON |

```
Max.  error in energy relative to energy loss= 9.1E-03 at PFQ=    0.0000
```

## 5.8 FEQX Command

Purpose: Cross-section function tables containing the cross-section hydraulic characteristics needed in the FEQ model for simulating flow in a branch are computed in the FEQX command. Coordinate points on the boundary of the cross section are given in a fixed format.

LINE 1

Variable: TAB, CIN

Format: 7X, I5, A50

Example: TABLE#=00025 MONOTONE SAVE22

Explanation:

TAB is the table number that identifies the cross-section function table computed from the cross-section boundary description specified in the subsequent lines.

CIN is an alphanumeric field in which the user may specify several options after the table number. The options are as follows.

EXTEND: A vertical, frictionless extension is added to the first or last point of the cross section, as needed, to match the point of maximum elevation in the cross section.

MONOTONE: The offsets for the cross section are examined to ensure that they are increasing. This is useful in preliminary checking of cross sections for natural streams.

NEWBETA: The momentum-flux correction coefficient, $\beta$, and the kinetic-energy-flux correction coefficient, $\alpha$, are computed by application of a method suggested by Schönfeld (1951) and discussed in section 3.1.2. The geometric mean of the critical flows estimated using the momentum and energy principles is tabulated in this option.

NEWBETAE: Same as NEWBETA except that the critical flow tabulated is based on the energy principle.

NEWBETAM: Same as NEWBETA except that the critical flow tabulated is based on the momentum principle.

NEWBETA, NEWBETAM, and NEWBETAE can only be used for cross sections that do not have converging boundaries. Thus, these options imply checking for monotonicity.

OLDBETA: The coefficients $\alpha$ and $\beta$ for the cross section are computed from equations 7 and 8 in section 3.1.1. The velocity-distribution coefficients, $\alpha_i$ and $\beta_i$, in each subsection of the cross section in these equations are taken to be 1.0 if USGSBETA=NO in the Standard Header Block (section 5.1). If USGSBETA=YES, then these coefficients are estimated as described following equation 8 in section 3.1.1. In either case, the critical flow in the cross section is estimated as if the velocity distribution coefficients are both 1. Thus, critical flow is computed ignoring the effect of velocity distribution.

SAVEnn: A copy of the resulting table is saved internally in the FEQUTL computations in type nn format, where nn gives the two-digit table type with the valid range from 20 to 25.

SAVE: Same as SAVE21.

NOSAVE: A copy of the table is not saved internally in the FEQUTL computations. This is the default action if none of the save options are given.

OUTnn: A copy of the table is output to the standard function-table file in the Type nn format. If no output option is given, a cross-section function table of type 21 is output to the standard-function table file.

NOOUT: Output of the table to the standard function-table file is suppressed.

LINE 2

Variables: STAT, LEFT, RIGHT

Format: 8X, F10.0, 6X, F10.0, 7X, F10.0

Example: STATION= 8.256 LEFT= 100.0 RIGHT= 967.

Explanation:

STAT is the station of the cross section.

LEFT is the offset on the left side of the cross section where a vertical frictionless wall is added in the computation of the cross section.

RIGHT is the offset on the right side of the cross section where a vertical frictionless wall is added in computation of the cross section.

Thus, encroachments on the cross section can be indicated without changing the cross section. If LEFT ≥ RIGHT, then the encroachments are not calculated. LEFT is set equal to RIGHT by default if the input is omitted.

LINE 3

Variables: NAVM, SCALE, SHIFT

Format: 5X, I5, 7X, F10.0, 7X, F10.0

Example: NAVM=00001 SCALE= 1.0 SHIFT= 0.2

Explanation:

NAVM specifies the methodology for computing the effective roughness of a compound cross section and also provides optional values for scaling of the offsets and shifting of the elevations. If NAVM= 0, the total conveyance is computed from the sum of the subsection conveyances (given by equations 5 and 6). This is the method applied for most open channels and results in the total discharge equal to the sum of the subsection discharges. If NAVM=1, a weighted-average Manning's *n* value is computed with the wetted perimeter in each subsection as the weight. The conveyance for the cross section is then computed with the weighted-average *n* value. This is the method usually applied for closed conduits with abrupt changes of roughness around the perimeter and results in the total discharge equal to an assumed uniform flow velocity times the flow area.

SCALE is multiplied with the offsets and can be applied to adjust for scaled measurements from a map. The default value is 1.

SHIFT is added to the elevation of each point on the boundary of the cross section. The default value is 0.

LINE 4

Variables: NSUB, N(1), ..., N(NSUB)

Format: 4X, I5, 6F10.0,/,(9X, 6F10.0)

Example: NSUB 3 0.03 0.02 0.04

Explanation:

NSUB is the number of subsections. The valid range for NSUB is from 1 to 96.

N(*i*) is Manning's *n* for each subsection for the cross section.

The divisions between subsections are defined by frictionless, vertical lines. If variations in Manning's *n* with depth are required, the FEQXEXT command (section 5.9) must be applied.

LINE 5

Variable: HEAD

Format: A80

Example: OFFSET ELEVATION SUB

Explanation:

HEAD is a user-defined heading to describe the information on subsequent lines.

LINE 6 (Repeated for each point on the boundary.)

Variables: X(*i*), Z(*i*), SB(*i*)

Explanation:

X(*i*) is the offset of the coordinate point *i* on the boundary of the cross section.

Z(*i*) is the elevation of the coordinate point *i* on the boundary of the cross section.

SB(*i*) is the subsection number for the coordinate point *i* on the boundary of the cross section. If SB(*i*) is left blank or zero, the subsection number from the previous point will be assigned to the current point. The last point on the cross-section boundary is indicated by a subsection number of −1.

The boundary is assumed to be adequately defined by connecting these coordinate points with straight lines. The input for a point applies to the line segment connecting that point to the next point. Thus, a subsection assignment is not needed for the last point because no line segment connects it and a subsequent point. Therefore, the subsection for the last point is used as a flag to signal the end of the cross-section specification.

A closed-conduit section can be specified by defining the offsets and elevations of points around the perimeter of the section. The description should begin at the high point of the section and should not close completely so that a free surface remains. The closed-conduit section should be traversed in a counterclockwise direction when specifying points on the boundary.

## 5.9 FEQXEXT Command

Purpose: Hydraulic characteristics of a cross section are computed and a cross-section function table is output with the FEQXEXT command. Frictionless line segments and roughness values that vary with water level are included in FEQXEXT, and these features represent an extension of the FEQX command.

Notes: A more flexible input for the cross-section boundary points is available in FEQXEXT than in FEQX. In the FEQX command, it is required that the line of information for each boundary point (that is the line giving the offset, the elevation, and the subsection number) be in a fixed order (offset first, elevation second, and subsection number last) and in fixed columns (1–10 for offset, 11–20 for the elevation, and 21–25 for the subsection number).

A free format of boundary-point input is allowed in FEQXEXT, but the fixed order is retained. A more complex description of the variation of roughness on the channel boundary also is permitted in FEQXEXT. Application of this more complex description will add one or more values to each line of information for a point on the cross-section boundary. To distinguish the end of one value and the beginning of another value, a delimiter is required in FEQXEXT. The delimiters permitted are one or more spaces or a comma. All of the values for a point must appear on a single line of the input.

Default values are available for much of the information in FEQXEXT. For example, the default value for the subsection number for all but the first point on the boundary is the number for the preceding point on the boundary. The subsection number needs to be given only for the first point in each subsection.

The roughness for each line segment on the boundary may be specified in FEQXEXT, not just each subsection as in FEQX. This value appears after the subsection number in the input. If the default value for the subsection number is to be used by omitting the number for a boundary point, then an asterisk must be used to request the default value, or two consecutive commas must be used to indicate the place that the subsection number would have occupied had it been given. If this is not done, the line-segment roughness value will be taken as being a subsection number because it is the third value seen on the line of input. The third value is always the subsection number. The asterisk or the dual commas indicate that the third value and the line-segment roughness value are given the proper input order.

In general, any value that has a default that is skipped over in a line must have its place shown by either an asterisk or by a pair of commas. If this is not done, the results of the command will be in error and an error message may be issued.

LINE 1

Variable: TAB, CIN

Format: 7X, I5, A50

Example: TABLE#=00025 MONOTONE SAVE22

Explanation:

TAB is the table number that identifies the cross-section function table computed from the cross-section boundary description specified in the subsequent lines.

CIN is an alphanumeric field in which the user may specify several options after the table number. The options are as follows.

EXTEND: A vertical, frictionless extension is added to the first or last point of the cross section, as needed, to match the point of maximum elevation in the cross section.

MONOTONE: The offsets for the cross section are examined to ensure that they are increasing. This is useful in preliminary checking of cross sections for natural streams.

NEWBETA: The momentum-flux correction coefficient, $\beta$, and the kinetic-energy-flux correction coefficient, $\alpha$, are computed by application of a method suggested by Schönfeld (1951) and discussed in section 3.1.2. The geometric mean of the critical flows estimated with the momentum and energy principles are tabulated in this option.

NEWBETAE: Same as NEWBETA except that the critical flow tabulated is based on the energy principle.

NEWBETAM: Same as NEWBETA except that the critical flow tabulated is based on the momentum principle.

NEWBETA, NEWBETAM, and NEWBETAE can only be used for cross sections that do not have converging boundaries. Thus, these options imply checking for monotonicity.

OLDBETA: The coefficients $\alpha$ and $\beta$ for the cross section are computed from equations 7 and 8 in section 3.1.1. The velocity-distribution coefficients, $\alpha_i$ and $\beta_i$ in each subsection of the cross section in these equations are taken to be 1.0 if USGSBETA=NO in the Standard Header Block (section 5.1). If USGSBETA=YES, then these coefficients are estimated as described following equation 8 in section 3.1.1. In either case, the critical flow in the cross section is estimated as if the velocity distribution coefficients are both 1. Thus, critical flow is computed ignoring the effect of velocity distribution.

SAVEnn: A copy of the resulting table is saved internally in the FEQUTL computations in type nn format, where nn gives the two-digit table type with the valid range from 20 through 25.

SAVE: Same as SAVE21.

NOSAVE: A copy of the table is not saved internally in the FEQUTL computations. This is the default action if none of the save options are given.

OUTnn: A copy of the table is output to the standard function-table file in the Type nn format. If no output option is given, a cross-section function table of type 21 is output to the standard-function table file.

NOOUT: Output of the table to the standard function-table file is suppressed.

LINE 2

Variables: STAT, LEFT, RIGHT

Format: 8X, F10.0, 6X, F10.0, 7X, F10.0

Example: STATION= 8.256 LEFT= 100.0 RIGHT= 967.

Explanation:

STAT is the station of the cross section.

LEFT is the offset on the left side of the cross section where a vertical frictionless wall is added in computation of the cross section.

RIGHT is the offset on the right side of the cross section where a vertical frictionless wall is added in computation of the cross section.

Thus, encroachments on the cross section can be indicated without changing the cross section. If LEFT ≥ RIGHT, then the encroachments are not calculated. LEFT is set equal to RIGHT by default if the input is omitted.

LINE 3

Variables: VARN, SCALE, SHIFT

Format: 5X, A4, 7X, F10.0, 7X, F10.0

Example: VARN=NCON SCALE= 1.0 SHIFT= 0.2

Explanation:

VARN specifies the variation of Manning's *n*. Three options are available for VARN: NCON–constant *n*; HYDY–*n* varies with hydraulic depth in each subsection; MAXY–*n* varies with maximum water-surface height in each subsection. HYDY is the default option for VARN.

SCALE is multiplied with the offsets and can be used to adjust for scaled measurements from a map. The default value is 1.

SHIFT is added to elevation of each point on the boundary of the cross section. The default value is 0.

LINE 4

Variables: NSUB, N(1),...,N(NSUB)

Format: 4X, I5, 6F10.0,/,(9X, 6F10.0)

Example: NSUB 3 0.03 0.02 0.04

Explanation:

NSUB is the number of subsections. The valid range for NSUB is from 1 to 96.

N(*i*) is Manning's *n* for each subsection for the cross section.

The divisions between subsections are defined by frictionless, vertical lines.

LINE 5

Variable: HEAD

Format: A80

Example: OFFSET ELEVATION SUB N0 Y1 N1 Y2 N2 Y3 N3 Y4 N4

Explanation:

HEAD is a user-defined heading to describe the information on subsequent lines. No fixed columns are given for subsequent input, only a fixed order. Therefore, the headings can be spaced for user convenience.

LINE 6 (Repeated for each point on the boundary.)

Variables: X(*i*), Z(*i*), SB(*i*), N0(*i*), (YATN, NATY)(*,*i*)

Example 1: –20.0 675.0 1 0.032

Example 2: –20.0 600.0 * 0.050 20.0 0.035

Explanation:

X(*i*) is the offset of the coordinate point *i* on the boundary of the cross section.

Z(*i*) is the elevation of the coordinate point *i* on the boundary of the cross section.

SB(*i*) is the subsection number for the coordinate point *i* on the boundary of the cross section.

N0(*i*), YATN, NATY are parameters used to describe the variability of Manning's *n* with respect to water-surface height and position in the cross section. The definition of these variables changes depending on the specification of VARN on Line 3 as described in the following discussion.

If VARN=HYDY or VARN=MAXY,

N0 is the value of Manning's *n* at a zero value of water-surface height in a subsection. YATN is the value of hydraulic depth (HYDY) or maximum water-surface height (MAXY) at which a value of the variable Manning's *n* is specified.

In this case, N0 as well as YATN and NATY can only be given at the first point of each subsection. The variation of Manning's *n* is specified by five points: one at zero water-surface height and four others at user-defined levels in each cross section. Linear variation of the *n* value with water-surface height (hydraulic or maximum) is assumed in each subsection. The values of water-surface height given for the variation of Manning's *n* in each subsection must be increasing. If VARN=HYDY or VARN=MAXY, but N0 is not given, then the value of N0 from the subsection *n* value is utilized in FEQXEXT. Moreover, if N0, YATN, and NATY are omitted, the roughness is assumed to be constant for all subsections at the value given for the subsection in the FEQXEXT computations.

If VARN=NCON or if no data are given for vertical variation of roughness,

a wetted-perimeter weighted composite roughness value in each subsection is computed in FEQXEXT. If N0=0 for a line segment, that line segment is treated as frictionless in the computation of the composite roughness value.

It is possible to have four different modes of variation of roughness in a cross section. The first is no variation. The second is variation with the hydraulic depth in the subsection. The third is variation with the maximum water-surface height in the cross section. The fourth and last variation is in the composite value of *n* as the water level in the subsection changes. Not all combinations can result in a cross section simultaneously. However, three of the four combinations can be used simultaneously in a single cross section, if necessary.

The last point on the cross-section boundary is indicated by a subsection number of –1. This convention means that the subsection number for a point applies to the line segment connecting the point to the subsequent point. Thus, a subsection assignment is not required for the last point because no line segment is present between it and a subsequent point. Therefore, the subsection for the last point is used in FEQUTL as a flag to signal the end of the cross-section specification.

The minimum data for the first point of a cross-section boundary are the offset, elevation, and subsection number. The minimum information for all subsequent points is offset and elevation. If more than one subsection is required to describe the cross-section boundary, then a subsection number must be added at the first point in each of the subsections after the first.

A conduit-closed section can be specified by defining the offsets and elevations of points around the perimeter of the section. The description should begin at the high point of the section and should not close completely so that a free surface remains. The closed-conduit section should be traversed in a counterclockwise direction when defining points on the boundary.

Some users have used the columns after the subsection number for a boundary point in the command FEQX for comments about the source of the data for that point. These could include the state plane coordinates of that point, the nature of the point, and related information. The line is not read beyond the subsection number columns in FEQX. However, the entire line is read in FEQXEXT. In order to support these comments, the remainder of a line after the single quote character (') is not read in FEQXEXT. Thus, it becomes possible, where needed, to utilize FEQXEXT and still maintain the unsupported comments on the line.

### 5.10 FEQXLST Command

Purpose: The input for the FEQXLST command is the same as for FEQX except that the offset, elevation, and subsection are input in list format. Each line must have exactly three entries separated by one or more spaces, and the subsection must be given in each case.

### 5.11 FINISH Command

Purpose: The FINISH command should be the last in the input. The files are closed and execution of FEQUTL is terminated after this input.

### 5.12 FLOODWAY Command

Purpose: The FLOODWAY command can be used with FEQX, FEQXEXT, or FEQXLST to define a regulatory floodway for flood-insurance purposes. Further details are given in section 4.7.

Notes: A floodway-definition table, stored in a file, is applied with the FLOODWAY command to define the manner in which subsequent cross sections in the input file are modified. In this way, only one copy of the floodway table is needed for a stream system. This reduces errors and helps maintain consistency. Only two lines must be added to the input files to invoke the FLOODWAY command in FEQUTL. These two lines are the command FLOODWAY given above and the file name defined on Line 1.

LINE 1

Variable: FILNAM

Format: 5X, A48

Example: FILE=FLOODWAY.UMS

Explanation:

FILNAM is the file name containing the floodway table specifying which cross sections are used and the method applied to define the encroachment limits.

The floodway table consists of the following lines.

LINE 1

Variable: HEAD

Format: A80

Example: Floodway specification for West Branch Salt Creek

Explanation:

HEAD is a descriptive heading given by the user.

LINE 2

Variable: GLBCON

Format: 16X, F10.0

Example: Conveyance loss= 0.05

Explanation:

GLBCON is the global value for the fraction of total conveyance lost on one side of the stream. The total loss is twice the given value. This global value is used if the LOSS field in Line 5 for a cross section is left blank and the OPTION field in Line 5 contains CONV.

LINE 3

Variable: GLBELV

Format: 15X, F10.0

Example: Elevation loss= 0.7

Explanation:

GLBELV is the global value for the decrease in elevation from the standard flood level for defining the floodway using the elevation option. This global value is used if the LOSS field in Line 5 for a cross section is left blank and the OPTION field in Line 5 contains ELEV.

LINE 4

Variable: HEAD

Format: A80

Example: XSEC OPTN ELEV FEQBOT LEFT RIGHT LOSS

Explanation:

HEAD gives the headings for subsequent columns in the floodway table.

LINE 5 (Repeated as required to compute the floodway specification.)

Variables: TAB, OPT, ELEV, BOT, LEFT, RIGHT, LOSS

Format: I5, 1X, A4, 1X, F8.0, 4A8

Explanation:

TAB is the table number of the cross section to be modified. If a cross section with the given table number appears in subsequent input in FEQX, FEQXLST, or FEQXEXT, then that cross section is analyzed applying the information in the remainder of the line to define a floodway cross-section table. If a table number is given in TAB and no subsequent cross section with a matching number is present in the input, then the information is read but not used. If a cross section is input without an entry in the floodway table, then the cross section is processed as usual. The input is terminated by assigning a negative value for the table number.

OPT specifies the options for modifying the cross section. Valid options are ELEV, CONV, and USET.

The data required in the following fields depend on which option is selected.

If OPT = ELEV

ELEV is the water-surface elevation applied to compute the conveyance in the cross section. Normally, the water-surface elevation corresponding to the 100-year flood is utilized. The elevation in ELEV must be specified, and it is an error if the value given in ELEV is lower than the minimum point of the cross section or higher than the last point on either the left or the right end of the cross-section boundary description.

BOT is the elevation of the bottom of the cross section as specified in the profile in the FEQ schematization of the stream. This must be given only if it differs from the elevation of the minimum point in the cross-section boundary description. If left blank, the bottom profile given in the FEQ schematization for this cross section matches the minimum elevation in the cross-section boundary description. The symbol 'same' is printed if the field is left blank.

LEFT is the limit of the encroachment from the left of the main channel. If an offset is to the left of LEFT (that is, farther from the main channel) is computed in the floodway-boundary determination, then that offset is retained. However, if the offset computed for the definition of the floodway is closer to the main channel than LEFT, the floodway boundary is limited to LEFT. In a case where the value in LEFT overrides the computed left boundary of the floodway, the decrease in the standard-flood elevation requested in LOSS is not attained, and the user must examine the FEQUTL output to determine what portion of the requested decrease was attained. If this information is left blank, the encroachment is unlimited and the symbol '+inf', denoting positive infinity, is printed as the limit.

RIGHT is the limit of the encroachment from the right of the main channel. RIGHT serves the same function as LEFT, but for the right side of the main channel. If this information is left blank, the encroachment is unlimited and the symbol '–inf', denoting negative infinity, is printed as the limit.

LOSS is a decrease from the standard-flood elevation given in ELEV. For example, if the floodway is to start at an elevation of 672 ft above sea level and the standard-flood elevation is 672.7 ft above sea level, then the value in the LOSS column should be 0.7 ft. If the LOSS column is blank, the global value of the decrease (Line 3) is applied.

If OPT=CONV

ELEV is the water-surface elevation applied to compute the conveyance in the cross section. Normally, the water-surface elevation corresponding to the 100-year flood is utilized. The elevation in ELEV must be specified, and it is an error if the value given in ELEV is lower than the minimum point of the cross section or higher than the last point on either the left or the right end of the cross-section boundary description.

BOT is the elevation of the bottom of the cross section as specified in the profile in the FEQ schematization of the stream. This must be given only if it differs from the elevation of the minimum point in the cross-section boundary description. If left blank, the bottom profile given in the FEQ schematization for this cross section matches the minimum elevation in the cross-section boundary description. The symbol 'same' is printed if the field is left blank.

LEFT is the limit of the encroachment from the left of the main channel. If an offset that is to the left of LEFT (that is, farther from the main channel) is computed in the floodway-boundary determination, then that offset is retained. However, if the offset computed for the definition of the floodway is closer to the main channel than LEFT, the floodway boundary is limited to LEFT. If the computed value for left or right floodway boundary corresponding to the requested reduction in conveyance is overridden by the input boundaries of the floodway (LEFT or RIGHT), the user must examine the FEQUTL output to determine what part of the requested reduction in conveyance was attained. Thus, if the specified value of LEFT results in a 3-percent reduction in conveyance on the left side of the channel, the requested reduction in conveyance is 10 percent, and the specified value of RIGHT is not limiting, then only 8 percent of the requested 10-percent reduction in conveyance is attained. If this information is left blank, the encroachment is unlimited and the symbol '+inf', denoting positive infinity, is printed as the limit.

RIGHT is the limit of the encroachment from the right of the main channel. RIGHT serves the same function as LEFT, but for the right side of the main channel. If this information is left blank, the encroachment is unlimited and the symbol '–inf', denoting negative infinity, is printed as the limit.

LOSS is the loss of conveyance utilized to determine the encroachment limits for the floodway. This loss value is evenly divided between the left and the right sides of the channel. If the LOSS column is blank, the global value of the reduction in cross-section conveyance (Line 2) is applied.

In both the ELEV and CONV options, the values of BOT, LEFT, and RIGHT are optional and may be left blank if the default values are suitable. LEFT and RIGHT can be applied to preserve a specified floodway width because these values always override any computed encroachment inside the specified limits.

In OPT = USET

ELEV is the water-surface elevation applied to compute the conveyance in the cross section. Normally, the water-surface elevation corresponding to the 100-year flood is utilized. The elevation in ELEV must be specified, and it is an error if the value given in ELEV is lower than the minimum point of the cross section or higher than the last point on either the left or the right end of the cross-section boundary description.

BOT is the elevation of the bottom of the cross section as specified in the profile in the FEQ schematization of the stream. This must be given only if it differs from the elevation of the minimum point in the cross-section boundary description. If left blank, the bottom profile given in the FEQ schematization for this cross section matches the minimum elevation in the cross-section boundary description. The symbol 'same' is printed if the field is left blank. In this case, specification of BOT is optional.

LEFT is a fixed left boundary for the floodway encroachment, which must be specified in this option.

RIGHT is a fixed right boundary for the floodway encroachment, which must be specified in this option.

LOSS is not required in this option.

A summary of the floodway table is printed at the completion of the output with the values of LEFT and RIGHT replaced by the limits computed by the selected option when appropriate.

## 5.13 FTABIN Command

Purpose: FTABIN is a command used to read and store function tables in FEQUTL for later access in the processing of commands. The function tables can appear in sequence following the FTABIN command. These are called local tables. This is a convenient way to enter the function tables that specify the weir coefficients and submergence factors for the EMBANKQ command (section 5.6).

Notes: The FTABIN command is terminated with a table number of −1, that is, TABLE#= −1. The other source for the function tables is in a function-table file. The file name for this file is given after a negative table number, differing from −1. The file is then opened, read, and closed in FTABIN. Once a file has been read, the next occurrence of TABLE#= in the input file for FEQUTL is read in FTABIN.

The file name for the function-table file is given after the negative table number. An example is TABLE#= −15CULVERT.TAB. In this case, a file named CULVERT.TAB is identified in the current directory with FTABIN. If this file is found, the file is opened and read to the end and then closed before the next table number in the input file is read. This mode of accessing function tables permits the convenient storage and retrieval of function tables. All references to files should be present after the local tables have been input.

The table numbers used for the tables input under FTABIN should be unique. They can be referenced by subsequent commands in the input to FEQUTL as required.

## 5.14 GRITTER Command

Purpose: A generalization of the Ritter (1892) solution for the peak outflow following the instantaneous failure of a dam is computed in the GRITTER command. Discussion of this command is given in section 4.5.

LINE 1

Variables: NAME, APPTAB

Format: A8, I5

Example: APPTAB#= 731

Explanation:

NAME must be APPTAB#=.

APPTAB is the table number for the approach cross section to the dam site. This is the cross section of the prismatic, horizontal, frictionless reservoir presumed to be upstream from the dam before the instantaneous removal of the dam. In the course of the computations, this table is replaced by a table containing the Escoffier stage variable (Henderson, 1966, p. 314). Thus, the table is lost to subsequent commands. This table should not contain critical flow. Types 20, 21, 23, and 24 are acceptable.

LINE 2

Variables: NAME, CONTAB

Format: A8, I5

Example: CONTAB#= 25

Explanation:

NAME must be CONTAB#=.

CONTAB is the table number for the constricted-flow relation produced in CRITQ (section 5.4) or some similar computation. The table must give the flow for each water-surface height in the reservoir where the water-surface height is measured from the water-surface elevation in the reservoir upstream from the breach to the bottom of the reservoir.

LINE 3

Variables: LABEL

Format: A79

Example: DEPTH DISCHARGE Test of the Ritter solution.

Explanation:

LABEL is a heading for the subsequent values of water-surface height and discharge in the reservoir before the failure and a descriptive label for the dam analyzed.

LINE 4 (Repeated as many times as needed to represent the range of water-surface heights and flows required for the analysis of various failures.)

Variables: Y1, Q1

Format: 2F10.0

Explanation:

Y1 is the before-failure, water-surface height in the reservoir. The sequence is terminated by giving a negative value for the water-surface height.

Q1 is the before-failure flow rate in the reservoir.

## 5.15 HEC2X Command

Purpose: An input file for HEC-2 (U.S. Army Corps of Engineers, 1990a) is scanned in the HEC2X command, the cross sections in the file are read, and either the cross-section table or the input for the CHANNEL command (section 5.2) or the FEQX command (section 5.8) is computed.

Notes: The input files for HEC-2 need not be changed. Lines that are not needed are skipped in HEC2X computations. The only lines detected and used are X1, X4, GR, NC, NH, and ER Lines in the HEC-2 input. Limited checking of the data is done in HEC2X, but it is assumed that detailed checking has already been done on the input data.

LINE 1

Variables: CHAR4, MODE

Format: A4,1X, A8

Example: MODE=DIRECT

Explanation:

CHAR4 must be MODE.

MODE specifies the mode of analysis applied in HEC2X. A cross-section table is computed directly from the HEC-2 input in the DIRECT mode. Input for the FEQX command (section 5.8) is computed from the HEC-2 input in the INDIRECT mode. In the INDIRECT mode, it is possible to modify the FEQX input to correct for any problems in the subdivision of the cross section in the HEC-2 input. In the last mode, a variant of INDIRECT called CHANNEL, the input for a CHANNEL command (section 5.2), is computed and placed in a file. The flow lengths between sections are used with the CHANNEL command to compute estimates of the sinuosity for the cross sections. The keywords CHANNEL, DIRECT, and INDIRECT also can be in lowercase.

LINE 2

Variables: CHAR6, INFILE

Format: A6, 1X, A64

Example: INFILE=MODEL01.INP

Explanation:

CHAR6 must be INFILE.

INFILE is the file name of the file containing the HEC-2 input.

LINE 3

Variables: CHAR7, OUTFIL

Format: A7, 1X, A64

Example: OUTFILE=HECFEQX

Explanation:

CHAR7 must be OUTFILE.

OUTFILE is the file name to use in storing the FEQUTL input when MODE=INDIRECT or MODE=CHANNEL. OUTFILE must still appear when MODE=DIRECT, but the file name may be left blank.

LINE 4

Variables: CHAR8, CIN

Format: A8,A72

Example: OPTIONS: OUT22 MONOTONE NEWBETA

Explanation:

CHAR8 must be OPTIONS:.

CIN are the options to use in computing the table for the FEQX input. These options are the same as for the FEQX command (section 5.8).

LINE 5

Variables: CHAR8, BEGTAB, TABINC

Format: A8, 2I5

Example: BEGTAB#= 700–2

Explanation: Each cross-section table in FEQ must have a table number.

CHAR8 must be BEGTAB#=.

BEGTAB is the table number for the first cross section found in the HEC-2 input.

TABINC is the table number increment (TABINC) added to BEGTAB (and all subsequent table numbers) resulting in the table numbers for all cross sections found in the HEC-2 input. The table increment may be negative as shown.

LINE 6

Variables: CHAR8, BEGSTA, STADIR

Format: A8, F10.0, I5

Example: BEGSTAT=0.00000000 1

Explanation:

CHAR8 must be "BEGSTAT=".

BEGSTA is the beginning station for the first cross section.

STADIR indicated that the distance between cross sections in the HEC-2 input should be added (+1) or subtracted (–1) from BEGSTAT and all subsequent stations along the channel. Thus, the stations may increase or decrease as the file named in INFILE (Line 2) is processed. If STADIR is omitted, it is assumed that the increments are positive. The main-channel length increments are used in HEC2X to compute the stations.

LINE 7

Variables: CHAR4, SFAC

Format: A4, 1X, F10.0

Example: SFAC= 5280.

Explanation:

CHAR4 must be SFAC.

SFAC is the conversion factor from the units used in HEC2 for the distance between cross sections to the units in the stationing in the unsteady-flow model. SFAC is a divisor on the distances used in HEC2. If the distances in HEC2 are in feet, as in most cases, then SFAC=5,280 will produce stations along the channel in miles.

## 5.16 MULCON Command

Purpose: A single cross-section function table is computed in the MULCON command to represent the hydraulic characteristics of one or more conduits. The conduits may be circular, rectangular, true elliptical, nominal elliptical, reinforced-concrete arch pipe, or corrugated-metal arch. For two or more conduits, the hydraulic characteristics at a given water-surface elevation are aggregated in MULCON. Only a cross-section table for the barrels of a culvert or for a storm sewer are computed. No culvert losses are computed. Computation of culvert losses is done in the CULVERT command with the cross-section function table developed in MULCON and entered on Line 14 of the input to the CULVERT command as part of the description of the culvert.

Notes: In closed conduits, the conveyance will decrease with depth as the conduit approaches the full-flow condition. Two options are allowed in FEQUTL. The first option, selected by giving the table number as positive, is to propagate the conveyance of the full conduit to smaller depths where the conveyance may actually be higher than the full-flow conveyance so that the maximum conveyance in the conduit is the full-flow conveyance. This means that the maximum conveyance in the conduit that usually results at depths close to the crown of the pipe is overridden. This is done because the point of maximum conveyance is often close enough to the crown of the conduit such that attainment of the maximum conveyance is unlikely. As the water surface approaches the crown of the conduit, the flow can easily oscillate between full flow and part-full flow as the air cavity is removed. This results because the normal undulations in the water surface now have great effects in that the pipe is filled momentarily. Also, the normal variation in water-surface height in the pipe will often contribute to the instability close to the crown. In the second option, selected by giving a negative table number, warning messages for decreasing conveyance are issued, but the decreasing conveyance is retained for further computations. The conveyance in the hypothetical slot is forced to be a constant with the value given by the full-flow conveyance in both options.

LINE 1

Variable: TAB, CIN

Format: 7X, I5, A50

Example: TABLE#= 9 OUT22

Explanation:

TAB is the table number of the cross-section table computed in FEQUTL.

CIN are user-specified options for cross-section table computations. The user may specify the same options after the table number as in FEQX (section 5.8). If the table number is positive, the conveyance is not permitted to be larger than the full-flow conveyance at any water level. If the table number is negative, the conveyance is computed with no modifications.

LINE 2

Variable: WSLOT

Format: 6X, F10.0

Example: WSLOT= 0.01

Explanation:

WSLOT is the width of the hypothetical slot used to maintain a free surface in the conduit. This width is used for each conduit and the final slot for the table is the sum of the slot widths. The final width should be made small so that the area of flow is not greatly increased for the expected surcharge levels. The final slot width is NPIPES×WSLOT, where NPIPES is the number of conduits involved.

LINE 3

Variable: HSLOT

Format: 6X, F10.0

Example: HSLOT= 50.0

Explanation:

HSLOT is the height of the hypothetical slot above the invert of the conduit, which has the minimum elevation. HSLOT is overridden on output so that any value greater than the vertical distance from invert to top of the conduit is acceptable.

LINE 4

Variable: NPIPES, ZEPS

Format: 7X, I5, F10.0

Example: NPIPES= 3 0.05

Explanation:

NPIPES is the number of conduits present. Valid range is $1 \leq \text{NPIPES} \leq 96$.

ZEPS is the difference in elevation across a mud line, if one is present, in the conduit. The default value of ZEPS is 0.02 ft.

LINE 5

Variables: TYPE(i)

Format: 5X, 6A10,/,(5X, 6A10)

Example: TYPE= CIRC NHE

Explanation:

TYPE specifies the type of conduit. Valid types are given in table 6. The nominal-elliptical conduit is called nominal because it is elliptical in name only as it is composed of four circular arcs that approximate an elliptical shape. The difference between a nominal-elliptical conduit and a true-elliptical conduit is only at most a few percent.

**Table 6.** Types for conduits simulated in the Full EQuations UTiLities model

| Type | Description |
|---|---|
| CIRC | Any circular conduit. |
| NHE | Nominal-elliptical conduit with major axis horizontal. |
| NVE | Nominal-elliptical conduit with major axis vertical. |
| TE | True-elliptical pipe. |
| RCPA | Reinforced-concrete pipe-arch conduit. |
| BOX | Rectangular opening. |
| CMPA | Corrugated-metal pipe arch, $2\frac{2}{3}$- by $\frac{1}{2}$-inch corrugations. Post-1980. |
| CMPAB | Corrugated-metal pipe arch, $2\frac{2}{3}$- by $\frac{1}{2}$-inch corrugations. Pre-1980. |
| CMPA1 | Corrugated-metal pipe arch, 3- by 1-inch corrugations. Post-1980. |
| CMPA1B | Corrugated-metal pipe arch, 3- by 1-inch corrugations. Pre-1980. |
| SPPA18 | Structural-plate pipe arch, 6- by 2-inch corrugations. 18-inch corners |
| SPPA31 | Structural-plate pipe arch, 6- by 2-inch corrugations. 31-inch corners |

LINE 6

Variables: SPAN(*i*)

Format: 5X, 6F10.0,/,(5X, 6F10.0)

Example: SPAN= 4.0 4.5 4.0

Explanation:

SPAN is the maximum horizontal dimension of the opening for each of the conduits.

LINE 7

Variables: RISE(*i*)

Format: 5X, 6F10.0,/,(5X, 6F10.0)

Example: RISE= 3.0 2.5 5.0

Explanation:

RISE is the maximum vertical dimension of the opening for each conduit.

The combination of SPAN and RISE defines the size of the conduit. The required information depends on the TYPE of the conduit. If TYPE is CIRC, then SPAN defines the diameter and RISE is ignored. If TYPE is NHE, either RISE or SPAN, or both, may be given. The equivalent-diameter circular pipe from the RISE or SPAN, or from both if both are given, is computed in FEQUTL. If only one of the two values is given, then that value defines the equivalent diameter. If both values are given, then the RISE is taken as the defining value, and a warning message is issued if the equivalent diameter computed from the SPAN differs from the equivalent diameter computed from the RISE by more than 3 percent. If TYPE is NVE, the same rules as for NHE apply. If TYPE is

TE, then both the SPAN and the RISE must be given because there is no standard shape for a true elliptical pipe. Finally, if TYPE is any of the arch shapes, then either RISE or SPAN, or both, may be given. If RISE or both are given, the SPAN is computed from the RISE and, if the SPAN is given, a warning message is issued if the SPAN computed from the RISE differs by more than 2 percent from the SPAN as given. If only the SPAN is given, then the RISE is computed from the SPAN. The priority given to the value of RISE is based on the belief that this dimension usually is easier to measure in the field than is the SPAN.

For arch shapes, only certain standard sizes are available, and these sizes do not have a constant-scale relation. Thus, any given size cannot be scaled to represent a larger or smaller size. However, linear interpolation between the standard sizes is applied for the dimensions so that nonstandard sizes can be approximated. The true-elliptical shape is provided so that nonstandard elliptical pipe can be represented in a cross-section table.

In MULCON as in MULPIPES, each pipe is considered a different subsection of a cross section. Thus, the values of ALPHA and BETA computed in FEQUTL may differ from 1.0 even if USGSBETA=NO is the selected option (section 5.1).

The number of sides of the polygon used to approximate the multiple conduits is fixed at 40 by MULCON. Furthermore, the datum point for the cross-section description is the invert of the conduit with the minimum invert elevation. The polygon is adjusted so that the full-flow area is matched. As a result, the invert of the polygon will be slightly below the invert of the conduit and, thus, the elevation reported for the cross-section table may be a small negative value and the maximum water-surface height before entering the slot will be slightly larger than the RISE of the conduit. These differences are always much smaller than the manufacturing tolerances allowed for the conduit.

LINE 8

Variables: BOTTOM(*i*)

Format: 5X, 6F10.0,/,(5X, 6F10.0)

Example: BOTT= 0.5 0.0 0.5

Explanation:

BOTTOM is the height of the invert of each conduit above the invert of the conduit with the smallest invert elevation. In the example, the invert of two conduits is 0.5 ft above the invert of the remaining conduit.

LINE 9

Variables: ROUGH(*i*)

Format: 5X, 6F10.0,/,(5X, 6F10.0)

Example: ROUG= 0.02 0.03 0.02

Explanation:

ROUGH is the Manning's *n* for each of the conduits.

The following two lines are optional. They are used to specify a mud line in the conduit to represent the accumulation of sediment in the conduit. The mud line is assumed to be essentially horizontal with the difference in elevation across it given by ZEPS in Line 4. If all the mud lines are at the minimum elevation in the cross section, then ZEPS may be 0. If ZEPS is 0 and a mud line is not at the minimum elevation in the cross section, a warning message will be issued and one end of the mud line will be incremented by 0.053 ft to force the relation between top width and depth to be one to one.

LINE 10

Variables: ZMUD(*i*)

Format: 5X, 6F10.0,/,(5X, 6F10.0)

Example: MUDL= 0.55 0.6 1.0

Explanation:

ZMUD is the thickness of the sediment measured from the invert of each conduit. The part of the conduit boundary that is below the sediment line is truncated in FEQUTL computations. If a conduit has no sediment, the thickness value is zero.

LINE 11

Variables: ROUGH(*i*)

Format: 5X, 6F10.0,/,(5X, 6F10.0)

Example: ROUG= 0.035 0.055 0.02

Explanation:

ROUGH is the Manning's *n* for the sediment in the conduit. A perimeter-weighted composite Manning's *n* is computed in MULCON for the conduit if a mud line is present.

## 5.17 MULPIPES Command

Purpose: A single cross-section function table is computed in the MULPIPES command to represent the hydraulic characteristics of one or more circular conduits. For two or more conduits, the hydraulic characteristics at a given water-surface elevation are aggregated. The same values are computed in the MULCON and MULPIPES commands. However, the MULCON command was added at a later time so that MULPIPES is retained for support of older FEQUTL input files. A cross-section table is computed in MULPIPES only for the barrels of a culvert or for a storm sewer. No culvert losses are computed. Computation of culvert losses is done in the CULVERT command (section 5.5) using the cross-section function table developed in MULPIPES and entered on Line 14 of the input to the CULVERT command as part of the description of the culvert.

Notes: In closed conduits, the conveyance will decrease with depth as the conduit approaches the full-flow condition. Two options are allowed in FEQUTL. The first option, selected by giving a positive table number, is to propagate the conveyance of the full conduit to smaller depths where the conveyance may actually be higher than the full-flow conveyance, so that the maximum conveyance in the conduit is the full-flow conveyance. This means that the maximum conveyance in the conduit that usually results at depths close to the crown of the pipe is overridden. This is done because the point of maximum conveyance is often close enough to the crown of the conduit such that attainment of the maximum conveyance is unlikely. As the water surface approaches the crown of the conduit, the flow can easily oscillate between full flow and part-full flow as the air cavity is removed. This results because the normal undulations in the water surface have great effects in that the pipe is filled momentarily. Also, the normal variation in water-surface height in the pipe will often contribute to the instability close to the crown. In the second option, selected by giving a negative table number, warning messages for decreasing conveyance are issued, but the decreasing conveyance is retained for further computations. The conveyance in the hypothetical slot is forced to be a constant with the value given by the full-flow conveyance in both options.

LINE 1

Variable: TAB, CIN

Format: 7X, I5, A50

Example: TABLE#= 9 OUT

Explanation:

TAB is the table number of the cross-section table computed in FEQUTL.

CIN are user-specified options for cross-section table computations. The user may specify the same options after the table number as in FEQX (section 5.8). If the table number is positive, the conveyance is not permitted to be larger than the full-flow conveyance at any water level. If the table number is negative, the conveyance is computed with no modifications.

LINE 2

Variable: NSIDES

Format: 7X, I5

Example: NSIDES= 30

Explanation:

NSIDES is the number of sides in the polygon used to approximate the multiple pipes. The polygon is sized so that the area of the polygon and the pipes are the same when the pipes are flowing full. A hypothetical slot is added to the top of each pipe and the aggregated slot is included in the cross-section table to maintain a free surface at all stage levels. The minimum permitted value for NSIDES is 10. Values of 20 to 30 represent the pipes to a precision higher than applied in the manufacturing processes used to make the pipes.

LINE 3

Variable: WSLOT

Format: 6X, F10.0

Example: WSLOT= 0.01

Explanation:

WSLOT is the width of the hypothetical slot used to maintain a free surface in the pipe. This width is used for each pipe, and the final slot for the table is the sum of the slot widths. The width should be small so that the area of flow is not greatly increased for the expected surcharge levels. The final slot width is NPIPES×WSLOT where NPIPES is the number of pipes.

LINE 4

Variable: HSLOT

Format: 6X, F10.0

Example: HSLOT= 50.0

Explanation:

HSLOT is the height of the slot above the invert of the conduit with the lowest invert elevation. HSLOT is overridden on output so that any value greater than the top of the largest conduit is acceptable.

LINE 5

Variable: NPIPES, ZEPS

Format: 7X, I5, F10.0

Example: NPIPES= 3 0.05

Explanation:

NPIPES is the number of conduits. The valid range is 1 ≤ NPIPES ≤ 96.

ZEPS is the difference in elevation across a mud line, if one is present, in the pipe. The default value of ZEPS is 0.02 ft.

LINE 6

Variables: DIAM(*i*)

Format: 5X, 6F10.0,/,(5X, 6F10.0)

Example: DIAM= 4.0 4.5 4.0

Explanation:

DIAM is the diameter of each of the pipes in feet or meters.

LINE 7

Variables: BOTTOM(*i*)

Format: 5X, 6F10.0,/,(5X, 6F10.0)

Example: BOTT= 0.5 0.0 0.5

Explanation:

BOTTOM is the height of the invert of each pipe above the invert of the pipe with the smallest invert elevation. In the example, the invert of two pipes is 0.5 ft above the invert of the remaining pipe.

LINE 8

Variables: ROUGH(*i*)

Format: 5X, 6F10.0,/,(5X, 6F10.0)

Example: ROUG= 0.02 0.03 0.02

Explanation:

ROUGH is the Manning's *n* for each of the pipes.

The following two lines are optional. The lines are utilized to specify a mud line in the conduit to represent the accumulation of sediment in the conduit. The mud line is assumed to be essentially horizontal with the difference in elevation across it given in ZEPS in Line 5. If all the mud lines are at the minimum elevation in the cross section, then ZEPS may be 0. If ZEPS is 0 and a mud line is not at the minimum elevation in the cross section, a warning message is issued in FEQUTL computations, and one end of the mud line is incremented by 0.053 ft to force the relation between top width and depth to be one to one.

LINE 9

Variables: ZMUD(*i*)

Format: 5X, 6F10.0,/,(5X, 6F10.0)

Example: MUDL= 0.55 0.6 1.0

Explanation:

ZMUD is the thickness of the sediment measured from the invert of each conduit. The part of the conduit boundary that is below the sediment line is truncated in FEQUTL computations. If a conduit has no sediment, the thickness value is 0.

LINE 10

Variables: ROUGH(*i*)

Format: 5X, 6F10.0,/,(5X, 6F10.0)

Example: ROUG= 0.035 0.055 0.02

Explanation:

ROUGH is the Manning's *n* for the sediment in the conduit. A perimeter-weighted composite Manning's *n* for the conduit is computed in MULPIPES if a mud line is present.

## 5.18 QCLIMIT Command

Purpose: A reasonable estimate of the maximum flow in a closed conduit when the conduit is flowing full is computed in the QCLIMIT command for defining the free-flow limit for the EXPCON command (section 5.7). Critical flow is used in EXPCON to determine the location of a control, but when a closed conduit is flowing full, critical flow is undefined. Therefore, some reasonable flow must be set as the maximum possible so that EXPCON can be used with closed conduits. QCLIMIT should be utilized for each closed-conduit cross section appearing in the EXPCON command.

LINE 1

Variable: TABLE

Format: 7X, I5

Example: TABLE#= 291

Explanation:

TABLE is the table number of the cross-section table to be limited by critical flow. This table must already have been input to FEQUTL with the FTABIN command (section 5.13) or have been saved with SAVE22 or SAVE25 on a previous computation for a closed conduit (sections 5.16, 5.17, and 5.19). The table must be of type 22 or 25.

LINE 2

Variable: FACTOR

Format: A7, F10.0

Example: FACTOR= 1.25

Explanation:

FACTOR is a multiplying factor to change the limiting value from that given by the built-in extrapolation. The limiting value is computed in QCLIMIT assuming that the logarithm of critical flow and the logarithm of water-surface height are linearly related. The two topwidths in the closed conduit that are closest to the hypothetical slot at the top of the conduit are detected and utilized for extrapolation. Critical flow is undefined in a closed conduit. The critical flow produced with the top width of the hypothetical slot is so large that the computations in EXPCON will be nonsensical to applications. EXPCON **must** include a maximum flow that is reasonable. When the cross section is such that a physically meaningful free surface is present, then critical flow represents this value. In other cases, a value that is reasonable must be provided. The friction slope calculated in the computation of the maximum flow is printed so that the reasonableness of the maximum flow can be assessed. If the friction slope in the closed conduit at maximum flow is too small, then FACTOR should be used to increase the maximum flow so that the friction slope will be so large that no flow greater than the maximum is possible. The goal is to obtain a maximum flow that is larger than any that will be calculated but not a maximum flow that is several times larger than any calculated flow.

## 5.19 SEWER Command

Purpose: A cross-section function table for a single circular conduit is computed in the SEWER command. A cross-section table is computed in the SEWER command only for the barrel of a culvert or for a storm sewer. No culvert losses are computed. Computation of culvert losses is done in the CULVERT command (section 5.5) with the cross-section function table developed in SEWER and entered on Line 14 of the input to the CULVERT command as part of the description of the culvert.

Notes: In closed conduits, the conveyance will decrease with depth as the conduit approaches the full-flow condition. Two options are allowed in FEQUTL. The first option, selected by giving a positive table number, is to propagate the conveyance of the full conduit to smaller depths where the conveyance may actually be higher than the full-flow conveyance so that the maximum conveyance in the conduit is the full-flow conveyance. This means that the maximum conveyance in the conduit that usually results at depths close to the crown of the pipe is overridden. This is done because the point of maximum conveyance is often close enough to the crown of the conduit such that attainment of the maximum conveyance is unlikely. As the water surface approaches the crown of the conduit, the flow can easily oscillate between full flow and part-full flow as the air cavity is removed. This results because the normal undulations in the water surface have great effects in that the pipe is filled momentarily. Also, the normal variation in depth in the pipe will often contribute to the instability close to the crown. In the second option, selected by giving a negative table number, warning messages for decreasing conveyance are issued, but the decreasing conveyance is retained for further computations. The conveyance in the hypothetical slot is forced to be a constant with the value given by the full-flow conveyance in both options.

LINE 1

Variable: TAB, CIN

Format: 7X, I5, A50

Example: TABLE#= 9 NOOUT

Explanation:

TAB is the table number of the cross-section table computed in FEQUTL.

CIN are user-specified options for cross-section table computations. The user may specify the same options after the table number as in FEQX (section 5.8). If the table number is positive, the conveyance is not permitted to be larger than the full-flow conveyance at any water level. If the table number is negative, the conveyance is computed with no modifications.

LINE 2

Variable: D

Format: 9X, F10.0

Example: DIAMETER= 3.5

Explanation:

D is the diameter of the pipe in feet or meters.

LINE 3

Variable: NSIDES

Format: 7X, I5

Example: NSIDES= 30

Explanation:

NSIDES is the number of sides in the polygon used to approximate the circular conduit. NSIDES should be ≥ 10. The polygon is sized so that the area of the polygon and the area of the circular conduit are the same when the conduit is flowing full. A hypothetical slot is added to the top of the pipe and included in the cross-section table to maintain a free surface at all stage levels.

LINE 4

Variable: WSLOT

Format: 6X, F10.0

Example: WSLOT= 0.01

Explanation:

WSLOT is the width of the hypothetical slot to maintain a free surface in the pipe. The width should be small so that the area of flow is not greatly increased for the expected surcharge levels.

LINE 5

Variable: HSLOT

Format: 6X, F10.0

Example: HSLOT= 50.0

Explanation:

HSLOT is the height of the hypothetical slot above the conduit invert. HSLOT is overridden on output, so that any value greater than the top of the pipe is acceptable.

LINE 6

Variable: N

Format: 2X, F10.0

Example: N= 0.025

Explanation:

N is Manning's *n* for the conduit.

The following two lines are optional. The lines are used to specify a mud line in the conduit to represent the accumulation of sediment in the conduit. The mud line is horizontal in all cases with a single pipe.

LINE 7

Variables: ZMUD

Format: 5X, F10.0

Example: MUDL= 0.55

Explanation:

ZMUD is the thickness of the sediment measured from the invert of the pipe. The part of the conduit boundary that is below the sediment line is truncated in the capacity computations.

LINE 8

Variables: NMUD

Format: 5X, F10.0

Example: NMUD= 0.035

Explanation:

NMUD is the Manning's *n* for the sediment in the pipe. A perimeter-weighted composite Manning's *n* for the pipe is computed if a mud line is present.

## 5.20 UFGATE Command

Purpose: The hydraulic characteristics of an underflow gate (sluice gate or tainter gate) are computed in the UFGATE command and are placed in a series of 2-D tables each for a given gate setting referenced in a table of type 15. A detailed discussion of the computational procedures is given in section 4.8.

LINE 1

Variable: TAB

Format: 7X, I5

Example: TABLE#= 527

Explanation:

TAB is the table number of the table of type 15 to be computed. The gate opening in distance units is the argument, and the table number of the 2-D table of type 13 for that gate opening is the function value in this table. Key values for defining the boundaries between weir flow and orifice flow also are included in this table.

LINE 2

Variable: LABEL

Format: 6X, A50

Example: LABEL= Lock and Dam 21.

Explanation:

LABEL is a descriptive label for the table of type 15. Each of the 2-D tables computed for the table of type 15 contains this label, or as much of the label as will fit, given with the prefix of the gate opening.

LINE 3

Variable: APPTAB

Format: 7X, I5

Example: APPTAB= 1012

Explanation:

APPTAB is the table number of the cross-section function table for the approach section of the gate. Table types 22 and 25 are suitable. The invert elevation for this cross section is determined from the elevation given in the table.

LINE 4

Variable: DEPTAB

Format: 7X, I5

Example: DEPTAB= 1010

Explanation:

DEPTAB is the table number of the cross-section function table for the departure section of the gate. Table types 22 and 25 are suitable. The invert elevation for this cross section is determined from the elevation given in the table.

LINE 5

Variable: SILLZ

Format: 9X, F10.0

Example: SILLELEV= 652.3

Explanation:

SILLZ is the elevation of the gate sill. This elevation must not be less than the elevation of the departure section nor of the approach section. This elevation defines the datum for measuring heads.

LINE 6

Variable: GATEW

Format: 8X, F10.0

Example: GATEWID= 58.25

Explanation:

GATEW is the width of the gate. This value must be > 0. This is the sum of all gate widths if more than one gate is present and if all gates will have the same vertical opening during gate operation. If different types of gate or identical gates with different vertical openings during operation are present, they should be represented in separate tables.

LINE 7

Variable: CD

Format: 3X, F10.0

Example: CD= 0.98

Explanation:

CD is the discharge coefficient to approximate losses in the approach reach. A value of 1.0 implies no losses. Losses are generally small, and values much smaller than 1.0 should be carefully reviewed.

LINE 8

Variable: CCTAB

Format: 6X, I5

Example: CCTAB= 251

Explanation:

CCTAB is the table number of the function table providing the coefficient of contraction for the gate. For sluice gates, the argument is the ratio of the gate opening to approach head. For tainter gates, the argument is the acute angle, measured in degrees, that the gate lip makes with the horizontal. This table is optional. If this table omitted, the user provides a contraction coefficient in the table below. If contraction coefficients are not given below, then CCTAB must be given.

LINE 9

Variable: FWFOTR

Format: 9X, F10.0

Example: FWFOTRAN= 0.2

Explanation:

FWFOTR is the proportion of the current gate opening over which a linear variation is applied to the contraction coefficient from 1.0 at the upper limit of free-weir flow to the value at the lower limit of standard free-orifice flow. Free-orifice and submerged-orifice flows in this interval are called nonstandard because they have a nonstandard value of contraction coefficient.

LINE 10

Variable: MAXHU

Format: 8X, F10.0

Example: MAXHEAD= 60.0

Explanation:

MAXHU is the maximum upstream head (at section 1) for flow through the gate. This is utilized in FEQUTL to determine the range of heads appearing in the 2-D tables. This head is measured from the sill of the gate.

LINE 11

Variable: MINHU

Format: 8X, F10.0

Example: MINHEAD= 30.0

Explanation:

MINHU is the minimum nonzero upstream head (at section 1) for flow through the gate. This is utilized in FEQUTL to determine the range of heads in the 2-D tables.

LINE 12

Variable: LIPREC

Format: 10X, F10.0

Example: PRECISION= 0.02

Explanation:

LIPREC is the linear interpolation precision required in FEQUTL computations defining the series of upstream heads. The precision is expressed in terms of the absolute value of the relative error. Thus, a value of 0.02 indicates that the absolute value of the interpolation error for the free flow in the 2-D tables computed in the UFGATE command will be less than or equal to 0.02 times the free-flow value for heads between the minimum and maximum head given in Lines 10 and 11. This is an approximate criterion; the errors may occasionally be larger than the precision requested. Precision values less than 0.001 and greater than 0.1 are not supported.

This value also is used to define the sequence of partial free drops for the 2-D tables. The selected precision will only be met approximately because the variation of submerged flows is more complex than the variation of free flows.

The spacing of the upstream heads and the spacing of the partial free drops is based on the accuracy of linear interpolation applied to a simple power function. A simple power function is $ax^b$ where $a$ and $b$ are parameters. The relative error in linear interpolation over an interval $(x_1, R_1 x_1)$ where $x_1 > 0$ and $R_1 > 1.0$ is

$$\varepsilon_{li} = r^b \left[ 1 + \frac{1 - r}{r(R - 1)} \left( R_1^{\ b} - 1 \right) \right] - 1 , \tag{122}$$

where $r = x_1/x$ and $1/R_1 \le r \le 1$. If $R_1$ and $b$ are fixed, the relative error is defined and the maximum relative error in the interval is a function of $R_1$ and $b$. The special file required in FEQUTL computations, TYPE5.TAB, contains two 2-D tables of type 10 (table numbers 10001 and 10002) that define the value of $R_1$ as a function of $b$ and the maximum absolute value of the relative error. TYPE5.TAB may be retrieved electronically as described in section 5.1. Thus, for simple power-function interpolation, the relative accuracy of linear interpolation is defined by the ratio of the function argument at the end points of the interval of integration.

This method is applied in the UFGATE command for assignment of the upstream heads and the partial free drops to the 2-D tables of type 13 computed. For example, free-weir flow varies approximately at the 1.5 power of the head on the sill of the gate opening. Free-orifice flow varies approximately at the 0.5 power of the difference between the head at section 1 and the head at the vena contracta of the jet emerging from the gate opening. However, the drop to free flow for free-orifice flow appears to vary more like the head difference to the 1.5 power. The spacing ratio for the 1.5 power is smaller than for the 0.5 power. Consequently, the 1.5 power is applied to define the spacing. Submerged flows, at higher levels of submergence, vary at the 0.5 power of the partial free drop. However, as the degree of submergence becomes smaller, the power changes and can become very large at small levels of submergence for submerged-orifice flow. Key values of upstream head are always present and override the simple power-function spacing.

The effect that changing the value of PRECISION has on an example underflow gate is listed in table 7. The gates described in table 7 are the tainter gates at Lock and Dam 21 on the upper Mississippi River near Quincy, Ill. Each of these 10 gates are 20 by 64 ft. The table gives the size of the 2-D table computed for a gate opening of 4 ft. The root-mean-square (RMS) error is computed for submerged flows from the values midway between the partial free drops used in the computation of the table. Thus, the information listed in table 7 is not a measure of the average error of interpolation; rather, it is a measure of the average error of interpolation at the points of interpolation where the error tends to be the largest.

**Table 7.** Effect of the value of the parameter PRECISION on the size of a two-dimensional function table representing the hydraulic characteristics of Lock and Dam 21 on the upper Mississippi River near Quincy, Illinois, computed in the Full EQuations UTILities model

[RMS, root mean square]

| Precision | Number of upstream heads | Number of partial free drops | Reported RMS error |
|---|---|---|---|
| 0.005 | 21 | 19 | 0.005 |
| .020 | 13 | 11 | .016 |
| .050 | 10 | 9 | .032 |

LINE 13

Variable: HEAD

Format: A80

Example: Opening 2-D Table Cc Value Lip Angle

Explanation:

HEAD is a descriptive heading for the gate-opening table.

LINE 14 (Repeated as needed for the range of computed gate openings.)

Variables: HG, TAB2D, CCVAL, ANGLE

Format: F10.0, I10, 2F10.0

Example: 0.5 560

Explanation:

HG is the gate opening in feet or meters.

TAB2D is the table number for the 2-D function table that is computed for that gate opening.

CCVAL is an optional value. If CCVAL is given, the value in CCTAB (Line 8) is overridden.

ANGLE indicates that a tainter gate is represented if a nonzero value is entered. For tainter gates, the contraction coefficient is primarily a function of the lip angle and only slightly dependent on the gate-opening ratio.

The computed gate openings must be presented in increasing order. The input is terminated by input of a gate opening that is less than the preceding opening.

Interpolation between 2-D tables for tables of type 15 is based on heads relative to the gate opening. Each table must be computed to head values that permit interpolation in the interval between the two tables. This can result in large head values if care is not taken in the selection of the sequence of gate openings. For example, if the initial gate opening is 0.1 and the next gate opening in the sequence is 0.5, then the 2-D table for the gate opening of 0.5 must be computed to a maximum head five times larger than the maximum head for the 2-D table for a gate opening of 0.1. If the value of MAXHEAD (Line 10) is 30 for a gate opening of 0.1, the table for the 0.5 gate opening must be computed to a head of 150. This will be higher than the cross sections for the approach and departure section. These cross sections must be extended, most simply with vertical walls, so that the maximum head required can be computed. Thus, the ratio between adjacent gate openings in the gate-opening sequence should be two or less. This must be balanced by the number of tables that will be computed. One 2-D table of type 13 is computed for each gate opening in the sequence.

LINE 15

Variable: HEAD

Format: A80

Example: Partial free drop parameters

Explanation:

HEAD is the description for the next set of input.

LINE 16

Variable: MINPFD

Format: 7X, F10.0

Example: MINPFD= 0.005

Explanation:

MINPFD is the minimum value of partial free drop to apply in computation of the submerged flows for the gate.

If the minimum value is too small, excessive numbers of the partial free drop will be generated. Convergence problems may result in FEQ simulations of the flow through the gate if the flow through the gate is nearly completely submerged. When the flow is deeply submerged, the flow through the gate varies with the square root of the head difference across the gate. As this difference becomes small, the rate of change of flow with the change in head difference increases without bound. Thus, the first derivative of the flow with respect to each of the heads becomes very large. Also, the derivative changes rapidly because, in the limit as the head difference approaches zero, the rate of change of flow with change in head difference approaches infinity. Large derivatives such as these can sometimes prevent the iterative computations in FEQ from converging. This usually can be remedied by making the minimum partial free drop larger. The linear-interpolation approximation then reduces the computed first derivative at high levels of gate submergence relative to the computations with a smaller partial free drop. If the MINPFD is too large, the approximation to the flow at high submergence levels may be inaccurate. However, accurate measurement and computation of highly submerged flows is difficult. Therefore, high accuracy at high levels of submergence cannot be expected.

LINE 17

Variable: BRKPFD

Format: 7X, F10.0

Example: BRKPFD= 0.5

Explanation:

BRKPFD is the value of partial free drop at which variation of the submerged flows changes. The initial spacing of the partial free drops from MINPFD (Line 16) to BRKPFD is computed by application of a power of 0.5. Reasonable results up to a partial free drop of about 0.5 are usually obtained with this spacing. The power values for orifice flow will then begin to get larger and can become quite high as the partial free drop approaches 1.0. A value of 0.5 is a good starting value for BRKPFD and can be refined if needed on the basis of the results from the UFGATE command.

LINE 18

Variable: LIMPFD

Format: 7X, F10.0

Example: LIMPFD= 0.99

Explanation:

LIMPFD is the limiting value of partial free drop less than 1.0. Orifice flow can decrease rapidly as the submergence of the emerging jet of water begins. It is helpful to have a value of partial free drop close to 1.0, so that this initial drop is isolated. The initial drop in flow tends to be large when the sluice gate width is close to the approach- and departure-channel widths. A starting value of 0.99 is suggested. If convergence problems at the gate result in FEQ simulations and these problems can be traced to the rapid change of the flow near the initiation of submergence, then it may be necessary to make LIMPFD smaller so that the drop in flow is spread over a larger interval. This makes the values in the table less precise in the reproduction of the computed flows for the underflow gate. However, the theory on which the submergence computations are based is less defined when the submergence levels are small. Therefore, additional computational smoothing at small submergence levels is acceptable if it facilitates convergence in FEQ simulation.

LINE 19

Variable: FINPOW

Format: 7X, F10.0

Example: FINPOW= 2.0

Explanation:

FINPOW is the power to apply in computation of the spacing for the partial free drops from BRKPFD to LIMPFD. The value must be between 1.0 and 3.0. The display of the power in the UFGATE output provides a guide of the value to apply. The power will be changing continuously over this region of partial free drops. A power value commensurate with the local power near LIMPFD is a guide for the selection of FINPOW. The larger the power, the closer the spacing of the partial free drop values.

User Output from UFGATE

A summary for each upstream head and for each gate opening is output from the UFGATE command, in addition to the look up tables placed in the function-table file. Each summary table lists the partial free drop, the drop in water-surface level from sections 1 to 4, the head at section 3 and section 4, the flow type, the value of the contraction coefficient used (for free-orifice and submerged-orifice flow), the discharge, and the power of a simple power function fit to the variation of discharge with partial free drop. The power can be used to adjust BRKPFD and FINPOW to better approximate the flow under the gate for different vertical gate-opening heights. An estimate of the maximum relative error and the square root of the average squared relative error (root-mean-squared, or RMS, error) also are computed in UFGATE. The error is computed at each point midway between the partial free drops defined by PRECISION, MINPFD, BRKPFD, LIMPFD, and FINPOW with the exception of the intervals between a partial free drop of 0.0 and MINPFD and between LIMPFD and 1.0. The error tends to be near the largest value over an interval at the midpoint of the interval. The maximum error can be larger, and sometimes considerably larger, than indicated in the parameter PRECISION. The maximum error seems to result for interpolation across the boundary between submerged-weir and submerged-orifice flow between the upstream head of the gate opening, $h_g$, and the upstream head at the upper limit of free-weir flow, $h_{1fwul}$. Such interpolation would result infrequently in most applications of the UFGATE command. The RMS error as given is a measure of the larger interpolation errors that can result. The average error of interpolation would be less than the reported value because the error of interpolation is zero at the end points of each partial-free-drop interval. The average error of interpolation for submerged flows is approximately 0.7 times the reported error.

## 5.21 WSPROQZ Command

Purpose: The input fragments to be placed in a WSPRO (Shearman, 1990) input file to control the number and nature of the water-surface profiles computed for a bridge are prepared in WSPROQZ to compute the data for a 2-D table of type 14. This table is computed with the WSPROT14 command (section 5.22) once the needed runs of the WSPRO software have been made to define the water-surface profiles through the bridge. Thus, two separate runs of FEQUTL are needed to compute a 2-D table of type 14 to represent a bridge. A discussion of WSPROQZ and WSPROT14 is given in section 4.1.

LINE 1

Variable: QNTAB

Format: 6X, I5

Example: QNTAB= 1100

Explanation:

QNTAB is the cross-section function table number for the cross section used in computing a flow given a friction slope. This flow is used to define the maximum flow for each downstream water-surface elevation to be placed in the 2-D table. The friction slope used for each downstream water-surface elevation is given in the following lines of input. This maximum flow at each downstream water-surface elevation becomes the free flow in the 2-D table of type 14 in FEQ simulation. This free flow must be larger, for the given downtream water-surface elevation, than any flow that will be calculated in the simulation of the unsteady flow through the bridge in FEQ. If the flow is not larger, the maximum flow will be considered as a true free flow in FEQ simulation. This will produce invalid results.

LINE 2

Variables: QCTAB

Format: 6X, I5

Example: QCTAB= 1000

Explanation:

QCTAB is the cross-section function table number for the cross section used in computing a critical-flow value for a given downstream water-surface elevation. An elevation offset may be given later in the input to define the water-surface elevation in the critical-flow section. If the table for QCTAB is zero or blank, a critical flow is not computed in WSPROQZ. If the flow from QNTAB (Line 1) is too large, a water-surface profile through the bridge may not be computed in WSPROQZ because the flow in the bridge opening will be supercritical. If QCTAB is given, the maximum flow is limited to the critical flow estimated from QCTAB.

LINE 3

Variables: HDATUM

Format: 7X,F10.0

Example: HDATUM=1093.8

Explanation:

HDATUM is the elevation of the datum used for computing heads in the 2-D function table. This information is placed in a WSPRO comment and is read in the WSPROT14 command. It is assumed that the flow is zero when the head is zero in FEQ simulation. Therefore, the head datum is the maximum bottom elevation of any cross section in the profile between the exit section and the approach section in the WSPRO description of the bridge.

LINE 4

Variables: PFQMIN

Format: 7X,F10.0

Example: PFQMIN= 0.2

Explanation:

PFQMIN is the minimum value of partial free-flow fraction to use in defining the partial free flows for the water-surface profiles computed in WSPRO. The value of zero partial free flow is automatically included in WSPROT14. PFQMIN should be smaller than any fraction expected in the unsteady-flow computations in FEQ.

LINE 5

Variables: NFRAC

Format: 6X,I5

Example: NFRAC= 8

Explanation:

NFRAC is the number of partial free flows to use for a given downstream water-surface elevation in computing the profiles in WSPRO. The partial free flow is given by

$$P_i = PFQMIN + (1 - PFQMIN)\left(\frac{i-1}{NFRAC-1}\right)^{POWER}, \qquad (123)$$

for $i = 1,\ldots,NFRAC$.

LINE 6

Variables: POWER

Format: 6X,F10.0

Example: POWER= 0.5

Explanation:

POWER is the power for computing the partial free-flow values in the relation defined previously. If POWER=1, the partial free flows are uniformly distributed between PFQMIN and 1.0. If POWER is greater than 1, the partial free flows are nonuniformly spaced with the closer spacing being toward PFQMIN. Otherwise, if POWER is less than 1, the partial free flows have closer spacing toward 1.0. A spacing option should be selected that enhances the accuracy of linear interpolation in the table.

LINE 7

Variables: MAXPRO

Format: 7X,I5

Example: MAXPRO=200

Explanation:

MAXPRO is the maximum number of profiles that can be computed in a single run of WSPRO. Most WSPRO packages are limited to 20 profiles, but versions with extended memory on 486 and Pentium personal computers are available. Input fragments are broken in WSPROQZ computations into blocks that do not exceed this number of profiles for input to WSPRO. However, the breaks must come between downstream water-surface elevations. Each set must complete an integral number of downstream water-surface elevations. For example, if the profile storage limit is 20 and NFRAC is 10, then only two tail-water elevations will be included in each input fragment. For the same limit, a value of 15 for NFRAC would include only one tail-water elevation in the input fragment. In these cases utilizing WSPRO packages with limited profile output, WSPROQZ and WSPRO must be run several times to cover the entire range of upstream and downstream water-surface elevations of interest. The WSPRO output files obtained are then input in sequence on Line 4 of the WSPROT14 command (section 5.22), and the 2-D tables of type 14 are prepared in FEQUTL.

LINE 8

Variables: LINE

Format: A80

Example: DNSWSE MaxFlow Slope Offset

Explanation:

LINE is the heading for the data to follow.

LINE 9 (Repeated as needed to represent the range of tail-water elevations to be included in the 2-D table describing bridge hydraulics determined from WSPRO simulation.)

Variables: DNSWSE, MAXQ, MAXQS, QCOFF

Format: 4F10.0

Example: 1094.6 0.0005

Explanation:

DNSWSE is the downstream water-surface elevation. The downstream water-surface elevation must be given on each line of input. Input is terminated by including a line with a value of DNSWSE that is less than the preceding value.

MAXQ is the maximum flow rate. MAXQ is a maximum flow rate estimated by the user. If this flow rate is given, it is the maximum flow rate used in the table and the other columns of data are ignored.

MAXQS is the friction slope for computation of the maximum flow rate. MAXQS is the friction slope to use with the conveyance found in the cross-section function table referenced by QNTAB (Line 1) to estimate the maximum flow.

QCOFF is the elevation offset for calculation of critical flow. If QCTAB (Line 2) is nonzero, the elevation offset is used with DNSWSE to compute a critical flow. If both the critical flow and the friction-slope-based flow are greater than zero, the minimum value of the two flows is retained in WSPROQZ. If only one of these flows is greater than zero, it is retained as the maximum flow in WSPROQZ.

## 5.22 WSPROT14 Command

Purpose: One or more printer output files from WSPRO (Shearman, 1990) are read, and a 2-D table of type 14 is computed in the WSPROT14 command. The files were computed in WSPRO by application of the flows, elevation, and control information prepared with the WSPROQZ command (section 5.21). The approach section must be named APPRO and the departure section must be named EXIT.

LINE 1

Variable: TAB

Format: 7X, I5

Example: TABLE#= 527

Explanation:

TAB is the table number of the 2-D table to be computed.

LINE 2

Variable: HEAD

Format: 6X, A80

Example: LABEL= Simple Bridge: Barren Creek

Explanation:

LABEL is the label for the 2-D table to be computed.

LINE 3

Variable: LINE

Format: A80

Example: File names

Explanation:

LINE is the heading for the file names to follow.

LINE 4 (Repeated to supply all the file names needed for the 2-D table.)

Variables: NAME

Format: A64

Example: drycr1.prt

Explanation:

NAME is the output file name generated in WSPRO, which is the source of water-surface profiles used to prepare the 2-D table. A blank line terminates the input of file names.

## 5.23 WSPROX Command

Purpose: An input file for the WSPRO (Shearman, 1990) software is scanned, the cross sections in the file are read, and either the cross-section table or the CHANNEL command (section 5.2) or the input for the FEQXEXT command (section 5.9) is computed in the WSPROX command.

Notes: The input files for WSPRO need not be changed, and lines that are not used will be skipped. Some checking of the data is done, but detailed checking should be done on the input in the WSPRO software.

LINE 1

Variables: CHAR4, MODE

Format: A4,1X, A8

Example: MODE=DIRECT

Explanation:

CHAR4 must be MODE.

MODE specifies the mode of analysis applied in WSPROX. In the DIRECT mode, a cross-section table is computed directly from the WSPRO input. In the INDIRECT mode, input for the FEQXEXT command (section 5.9) is computed from the WSPRO input. In the INDIRECT mode, it is possible to modify the FEQXEXT input to correct for any problems in the subdivision of the cross section in the WSPRO input. In the last mode, a variant of INDIRECT, called CHANNEL, the input for a CHANNEL command (section 5.2) is computed and placed in a file. The flow lengths between sections are utilized in the CHANNEL command to compute estimates of the sinuosity for the cross sections. The keywords CHANNEL, DIRECT, and INDIRECT also can be in lowercase.

LINE 2

Variables: CHAR6, INFILE

Format: A6, 1X, A64

Example: INFILE=drycrk.dat

Explanation:

CHAR6 must be INFILE.

INFILE is the file name of the file containing the WSPRO input.

LINE 3

Variables: CHAR7, OUTFIL

Format: A7, 1X, A64

Example: OUTFILE=WSPROSTU.FF

Explanation:

CHAR7 must be OUTFILE.

OUTFIL is the file name for storing the FEQXEXT input when MODE=INDIRECT. OUTFIL also is used to store the input to the CHANNEL command when MODE=CHANNEL. This line must appear when MODE=DIRECT, but the file name may be left blank.

LINE 4

Variables: CHAR8, CIN

Format: A8,A72

Example: OPTIONS: OUT22 MONOTONE NEWBETA

Explanation:

CHAR8 must be OPTIONS:.

CIN are the options to use in computing the table for the FEQXEXT input (section 5.9). These options are the same as for the FEQXEXT command.

LINE 5

Variables: CHAR8, BEGTAB, TABINC

Format: A8, 2I5

Example: BEGTAB#= 700 –2

Explanation:

CHAR8 must be BEGTAB#=. Each cross-section table in the FEQ model must have a table number.

BEGTAB is the table number for the first cross section found in the WSPRO input.

TABINC is the table increment added to BEGTAB (and all subsequent table numbers) resulting in the table numbers for all cross sections found in the WSPRO input. The table increment may be negative as shown.

LINE 6

Variables: CHAR8, BEGSTA, STADIR

Format: A8, F10.0, F5.0

Example: BEGSTAT=0.00000000 1

Explanation:

CHAR8 must be BEGSTAT=.

BEGSTAT is the beginning station for the first cross section.

STADIR indicates that the distance between cross sections in the WSPRO input should be added (+1) or subtracted (–1) from BEGSTAT and all subsequent stations along the channel. Thus, the stations may increase or decrease as the file named in INFILE (Line 2) is processed. If STADIR is omitted, the increments are assumed to be positive in WSPROX. The main-channel length increments or stations are used in WSPROX to compute the stations for the cross-section function tables.

LINE 7

Variables: CHAR4, SFAC

Format: A4, 1X, F10.0

Example: SFAC= 5280.

Explanation:

CHAR4 must be SFAC.

SFAC is the conversion factor from the units used in WSPRO for the distance between cross sections to the units in the stationing in the unsteady-flow model. SFAC is a divisor on the distances used in WSPRO. If the distances in WSPRO are in feet, then SFAC=5280 will produce stations along the channel in miles.

## 5.24 XSINTERP Command

Purpose: One or more cross-section tables between available tables are computed by interpolation in the XSINTERP command. A branch break may be required at a junction and no measured cross section is close to the junction. However, cross sections may be available upstream and downstream from the junction. Cross-section tables between available tables can be estimated because extrapolation beyond measured cross sections cannot be done.

Notes: The rule for interpolation is identical to that used in branches in FEQ (linear interpolation at constant depth). The resulting cross-section tables contain all the distinct breakpoints in the pair of available tables used to define them. The maximum arguments for the intermediate tables are set to the smaller of the maxima for the defining pair of tables. Interpolation over large distances may not be valid, so this command must be used with caution.

LINE 1

Variable: SFAC

Format: 5X, F10.0

Example: SFAC=5280.0

Explanation:

SFAC is the multiplying factor for converting the stations for the nodes given in the single Branch Description Block (section 13.2) in the FEQ input (Franz and Melching, 1997) used to specify the interpolation. In this example, the stations given in the Branch Description Block are in miles.

LINE 2

Variable: NODEID

Format: 7X, A4

Example: NODEID=YES

Explanation:

NODEID indicates whether an identification string is used for the nodes on a branch. NODEID=YES indicates that an identification string of up to eight characters may be given in the branch tables for each node on a branch. The string may be left blank if no printed node identification is desired. However, space for the string is still required when it is blank.

LINE 3

Variable: HEAD

Format: A80

Example: NODE XNUM STATION ELEVATION

Explanation:

HEAD is a user-defined heading to describe the information on subsequent lines. This information is the same as for a Branch Description Table (section 13.2) in the FEQ input (Franz and Melching, 1997), but with options suppressed.

LINE 4 (Repeated as needed for each node on the pseudo branch.)

If NODEID=NO, then

Variables: NODE, XTAB, X, Z

Format: 2I5, 2F10.0

If NODEID=YES, then

Variables: NODE, NAME, XTAB, X, Z

Format: I5, 1X, A8, 1X, I5, 2F10.0

Explanation: The values describing each node on the single pseudo branch used in XSINTERP to define the interpolation are specified on this line.

NODE is the node number. The end of the branch table is indicated by assigning a negative value for the NODE entry. The remainder of the line containing the terminating node number may be blank. The number for the first node on each branch must be given. The NODE column may be left blank for the other nodes, and the node number will be computed in FEQ simulation.

NAME is the optional identification string for the node.

XTAB is the number of the table giving the hydraulic characteristics of the cross section at the node.

X is the station of the node.

Z is the elevation of the minimum point in the stream at the node.

Interpolation is requested with the XTAB input described as follows. The station and elevation given on this line are used in FEQUTL unless the table option for these fields is invoked. If the elevation and station for the node are to be determined from the given cross-section table, the string 'TAB' or 'tab' must be inserted in either the elevation or the station column. The cross-section table must have already been input with FTABIN (section 5.13) or must have been stored with the SAVE option (sections 5.8-5.10). Not all the values need to be given for each node.

To request interpolation of a cross-section table, a negative cross-section table number at the node at the location requiring a table must be assigned. A positive table number must be present at some point above and at some point below the point of interpolation. More than one table can be interpolated between available tables. A minus sign in the rightmost column of the field for the table number indicates that an available table number will be used for interpolation in FEQ simulation. The user must ensure that any table number used in FEQUTL does not conflict with any other used in either FEQUTL computations or in FEQ simulation. The next unused table numbers are always taken in FEQUTL computations and FEQ simulation. A table number may be selected in FEQUTL computations or FEQ simulation that will appear in a subsequent command. If the station and elevation values are given, they will be used. The interpolation of hydraulic characteristics is done for given water-surface heights as a weighted average of the values at the measured cross sections surrounding the given location (station) with the weights linearly proportional to the distance from the given location to the measured cross section. Because the interpolation is done for hydraulic characteristics at given water-surface heights, the specified value of the thalweg elevation is only used to determine the bed slope of the stream in the vicinity of the interpolated cross section. If the station and elevation values are omitted, the station values are distributed uniformly and interpolated linearly for the elevation in FEQ simulation.

## REFERENCES CITED


Ahlberg, J.H., Nilson, E.N., and Walsh, J.L., 1967, The theory of splines and their applications: New York, Academic Press, 284 p.

Bodhaine, G.L., 1968, Measurement of peak discharges at culverts by indirect methods: U.S. Geological Survey Techniques of Water-Resources Investigations, book 3, chap. A3, 60 p.

Bradley, J.N., 1970, Hydraulics of bridge waterways: Hydraulic Design Series No. 1, U.S. Department of Transportation, Federal Highway Administration, Bureau of Public Roads, 111 p.

Brater, E.F. and King, H.W., 1976, Handbook of hydraulics, 6th ed.: New York, McGraw-Hill, variable pagination.

Carter, R.W., 1957, Computation of peak discharge at culverts: U.S. Geological Survey Circular 376, 25 p.

Chow, V.-T., 1959, Open-channel hydraulics: New York, McGraw-Hill, 680 p.

DeLong, L.L., 1989, Mass conservation—1-D open-channel flow equations: Journal of Hydraulic Engineering, American Society of Civil Engineers, v. 115, no. 2, p. 263-269.

Elevatorski, E.A., 1958, Discharge characteristics of irrigation delivery gates: Tucson, University of Arizona Bulletin, v. XXIX, no. 1, Civil Engineering Series no. 12, Engineering Experiment Station, 20 p.

Federal Emergency Management Agency, 1995, Flood insurance study guidelines and specifications for study contractors: Washington, D.C., variable pagination.

Fisk, G.G., 1988, Discharge ratings for control structures at McHenry Dam on the Fox River, Illinois: U.S. Geological Survey Water-Resources Investigations Report 87-4226, 24 p.

Franz, D.D., 1977, Dam-break flood wave analysis—Problems, pitfalls, and partial solutions: Proceedings, Dam-Break Flood Model Workshop, U.S. Water Resources Council, Washington, D.C., p. 354-383.

Franz, D.D., 1982, Tabular representation of cross-sectional elements: Journal of the Hydraulics Division, American Society of Civil Engineers, v. 108, no. HY 10, p. 1070-1081.

Franz, D.D. and Melching, C.S., 1997, Full equations (FEQ) model for the solution of the full, dynamic equations of motion for one-dimensional unsteady flow in open channels and through control structures: U.S. Geological Survey Water-Resources Investigations Report 96-4240, 258 p.

Henderson, F.M., 1966, Open channel flow: New York, MacMillan Publishing Co., Inc., 522 p.

Henry, H.R., 1950, Discussion on 'Diffusion of submerged jets', by M.L. Albertson, Y.B. Dai, R.A. Jensen, and H. Rouse: Transactions American Society of Civil Engineers, v. 115, p. 687-694.

Horton, R.W., 1907, Weir experiments, coefficients, and formulas: U.S. Geological Survey Water Supply and Irrigation Paper 200, Series M, General Hydrographic Investigations, 24, 195 p.

Hulsing, H., 1967, Measurement of peak discharge at dams by indirect methods: U.S. Geological Survey Techniques of Water-Resources Investigations, book 3, chap. A5, 29 p.

Hulsing, H., Smith, W., and Cobb, E.D., 1966, Velocity-head coefficients in open channels: U.S. Geological Survey Water-Supply Paper 1869-C, 45 p.

Kindsvater, C.E., 1964, Discharge characteristics of embankment-shaped weirs: U.S. Geological Survey Water-Supply Paper 1617-A, 114 p.

Miller, S., and Chaudhry, M.H., 1989, Dam-break flows in curved channels: Journal of Hydraulic Engineering, American Society of Civil Engineers, v. 115, no. 11, p. 1465-1478.

Portland Cement Association, 1964, Handbook of concrete culvert pipe hydraulics: Skokie, Ill., Portland Cement Association, 267 p.

Preissmann, A., 1961, Propagation des intumescences dans les canaux et rivieres: Grenoble, France, First Congress of the French Association for Computation, p. 433-442.

Rao, G. and Rajaratnam, N., 1963, The submerged hydraulic jump: Proceedings of the American Society of Civil Engineers, v. 89, no. HY1, p. 139-162.

Ritter, A., 1892, Die Fortpflanzung der Wasserwellen: Zeitschrift des Vereines Deutscher Ingenieure, v. 36, no. 33, p. 947-954.

Schneider, V.R., Board, J.W., Colson, B.E., Lee, F.N., and Druffel, L., 1977, Computation of backwater and discharge at width constrictions of heavily vegetated flood plains: U.S. Geological Survey Water-Resources Investigations Report 76-129, 64 p.

Schönfeld, J.C., 1951, Propagation of tides and similar waves: Delft, The Netherlands, Technical University Master's Thesis, 232 p.

Shearman, J.O., 1990, Users manual for WSPRO—A model for Water-Surface PROfile computations: Washington D.C., Federal Highway Administration, Report FWHA-IP-89-027, 187 p.

Shearman, J.O., Kirby, W.H., Schneider, V.R., and Flippo, H.N., 1986, Bridge waterways analysis model: Federal Highway Administration Research Report, FHWA/RD-86-106, U.S. Department of Transportation, 112 p.

Toch, A., 1955, Discharge characteristics of tainter gates: Transactions, American Society of Civil Engineers, v. 120, p. 290-300.

U.S. Army Corps of Engineers, 1990a, HEC-2 water surface profiles, User's manual: Hydrologic Engineering Center, Davis, California, variable pagination.

U.S. Army Corps of Engineers, 1990b, HEC-1 flood hydrograph package, User's manual: Hydrologic Engineering Center, Davis, California, variable pagination.



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# APPENDIXES



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# APPENDIX 1: LIST OF NOTATION

The following symbols are used in this report.

| | |
|---|---|
| $a$ | An averaging parameter used to compute the mean conveyance in a flow expansion or contraction |
| $a_i$, $b_i$ | Limits of a tabulation interval in a cross-section table |
| $A$ | Total cross-sectional area |
| $A_c$ | Flow area at critical depth |
| $A_{if}$ | Area for full flow in the culvert barrel at section $i$ |
| $B_g$ | Width of a gate opening |
| $B_i$ | Channel width at section $i$ at an underflow gate |
| $\tilde{B}_i$ | The ratio between the channel width at section $i$ at an underflow gate and the gate-opening width |
| $c(y_1)$ | Flood-wave celerity at water-surface height $y_1$ |
| $C_c$ | Contraction coefficient of the full barrel area of a culvert giving the flow area at the vena contracta |
| $C_{co}$ | Contraction coefficient for orifice flow at an underflow gate |
| $C_d$ | Culvert discharge coefficient |
| $C_{dc}$ | Discharge coefficient for a critical contraction |
| $C_{dfo}$ | Discharge coefficient for free-orifice flow at an underflow gate |
| $C_{dfw}$ | Discharge coefficient for free-weir flow at an underflow gate |
| $C_{dso}$ | Discharge coefficient for submerged-orifice flow at an underflow gate |
| $C_{dsw}$ | Discharge coefficient for submerged-weir flow at an underflow gate |
| $C_i$ | A constant coefficient used when computing a nonuniform velocity distribution equal to a function of Manning's $n$ and the cross-section boundary slope at line segment $i$ |
| $C_u$ | Unit conversion for Manning's equation equal to 1.49 in English units and 1 in metric units |
| $C_{wr}$ | Weir coefficient for a roadway embankment |
| $D$ | Maximum inside vertical dimension of a culvert barrel |
| $D_{vc}$ | Maximum inside vertical dimension of a culvert barrel at the vena contracta |
| $\Delta E_{1f}$ | Energy loss from the approach section (section 1) to the roadway crest when flow over the roadway is free of downstream effects |
| $\Delta E_{1s}$ | Energy loss from the approach section (section 1) to the roadway crest when flow over the roadway is submerged from downstream |
| $\Delta E_{143i}$ | Energy loss from the approach section (section 1) to section 43 for flow over a roadway crest at incipient flow submergence from downstream |
| $\Delta E_{143s}$ | Energy loss from the approach section (section 1) to section 43 for flow over a roadway crest when the flow is submerged from downstream |
| $f_c(C_c)$ | Piezometric depth ratio to the maximum vertical dimension of a culvert as a function of the contraction coefficient |
| $f_{CH}(\ )$ | Function that gives the weir discharge coefficient for high-head flow |
| $f_{CL}(\ )$ | Function that gives the weir discharge coefficient for low-head flow |
| $f_{DB}(y)$ | Function that yields the flow through a dam breach for each water-surface height in the reservoir |
| $f_{ec}(X)$ | Function yielding the product of the energy-loss coefficient and the difference in the product of the velocity and the energy-flux correction coefficient from the downstream section to the upstream section of a flow expansion or contraction |

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|---|---|
| $f_s(\,)$ | Weir-submergence function |
| $f_t(y_t)$ | Piecewise linear approximation in a function table of function $f_t$ at argument value $y_t$ |
| $f_{t_i}$ | The *i*th tabulated value in a function table |
| $\mathbf{F}$ | Froude number |
| $F_E$ | Total flux of kinetic energy through the cross section |
| $F_{E_i}$ | The flux of kinetic energy for line segment *i* of the cross section |
| $\mathbf{F_g}$ | Gate-opening Froude number for orifice flow at an underflow gate |
| $F_M$ | Total flux of momentum through the cross section |
| $F_{M_i}$ | The flux of momentum for line segment *i* of the cross section |
| $g$ | Acceleration of gravity |
| $h(s)$ | Local height of the water surface in a cross section at offset *s* |
| $\bar{h}(s)$ | Average local water-surface height between adjacent cross sections at offset *s* in a curvilinear channel |
| $h_g$ | Gate-opening height |
| $\tilde{h}_i$ | The ratio between the piezometric head at section *i* at an underflow gate and the gate-opening height |
| $h_I$ | Piezometric downstream head at incipient flow submergence measured from the roadway crest |
| $h_{p_i}$ | Piezometric head at section *i* of an underflow gate |
| $h_t$ | Downstream (tail water) head causing flow submergence at a weir |
| $h_w$ | Water-surface head on a roadway embankment, roadway crest, or weir |
| $h_{1foll}$ | Upstream piezometric head at section 1 (approach section) for an underflow gate at the lower limit of free-orifice flow |
| $h_{1fwul}$ | Upstream piezometric head at section 1 (approach section) for an underflow gate at the upper limit of free-weir flow |
| $h_{4fwul}$ | Downstream piezometric head at section 4 (departure section) for an underflow gate at the upper limit of free-weir flow |
| $h_{4swso}$ | The piezometric head at section 4 (departure section) for an underflow gate at the boundary between submerged-weir and submerged-orifice flow for a piezometric head at section 1 (approach section) midway between the piezometric head equal to the gate opening and the piezometric head equal to the upper limit of free-weir flow |
| $H$ | Piezometric head on a weir or roadway embankment measured from the minimum point on the weir or roadway embankment |
| $J$ | First moment of area with respect to the water surface |
| $k_A$ | Energy-loss coefficient for accelerating (contracting) flow |
| $k_D$ | Energy-loss coefficient for decelerating (expanding) flow |
| $k_{ec}$ | Energy-loss factor for flow expansion or contraction |
| $k(s)$ | Local conveyance at offset *s* in a cross section of a curvilinear channel |
| $K$ | Total channel conveyance |
| $\bar{K}$ | Mean conveyance |
| $K_f$ | The mean full-flow conveyance in a culvert barrel |
| $K_{2f}$ | Conveyance at full flow at the culvert entrance (section 2) |
| $K_{23}$ | The value of conveyance for a culvert that gives the correct barrel-friction loss computed in the steady-flow profile computations for flow types 2 and 3 |
| $L_{aj}$ | The cumulative distance along the main-channel axis to the *j*th cross section |
| $L_{ij}$ | The cumulative distance along the ith flow line at the *j*th cross section |
| $\Delta L(s)$ | Distance between two adjacent cross sections at offset *s* in a curvilinear channel |

| | |
|---|---|
| $m$ | Number of subsections in a cross section |
| $m_s$ | Slope of a boundary line on the channel cross section |
| $M_A(x,y_0)$ | The weight coefficient that will result in a valid volume per unit length when multiplied with the cross-sectional area at location $x$ for water-surface height $y_0$ |
| $M_Q(x,y_0)$ | The weight coefficient that will result in a valid momentum content per unit length when multiplied with the total flow rate through the cross section at location $x$ for water-surface height $y_0$ |
| $M_r$ | Momentum flux for flow over the roadway at a culvert |
| $n_c$ | Number of cross sections considered in the computation of sinuosity |
| $n_i$ | Manning's roughness coefficient for subsection $i$ of a cross section |
| $n_p$ | Number of surveyed points used to describe a cross section |
| $n_s$ | Number of line segments below the water surface in the cross section; used when computing a nonuniform velocity distribution |
| *NDDABS* | The allowable absolute deviation from normal depth in the computation of the water-surface profile in the CHANRAT command |
| *NDDREL* | The allowable relative deviation from normal depth in the computation of the water-surface profile in the CHANRAT command |
| $q(s)$ | Flow per unit width in a cross section at offset $s$ |
| $q_r$ | Flow over a roadway-embankment weir per unit width of roadway |
| $q_w(s)$ | Flow over a weir per unit width at offset $s$ |
| $Q$ | Total flow rate in the cross section |
| $Q_B$ | Flow rate in a culvert barrel |
| $Q_C$ | Critical flow rate determined for steady flow in a compact channel ($\alpha = \beta = 1$) |
| $Q_E$ | Critical flow rate determined from minimization of specific energy in a channel where $\alpha \neq 1$ |
| $Q_f$ | Free-weir or free-orifice flow at an underflow gate |
| $Q_i$ | Flow rate represented by conditions at line segment $i$ in the cross section |
| $Q_M$ | Critical flow rate determined from minimization of specific force in a channel where $\beta \neq 1$ |
| $Q_r$ | Flow rate over the roadway at a culvert |
| $Q_w(z_w)$ | Total flow over a weir for a given upstream water-surface elevation |
| $P_e$ | Roadway embankment height |
| $P_i$ | The wetted perimeter for subsection $i$ of the cross section |
| $R(s)$ | Hydraulic radius at offset $s$ in the cross section |
| $R_{hg}$ | Fraction of the gate-opening width over which the transition in contraction coefficient between weir flow and orifice flow is applied |
| $s$ | Offset distance across a cross section |
| $s_B$ | Beginning offset for the top width in a cross section at a given water-surface height |
| $s_E$ | Ending offset for the top width in a cross section at a given water-surface height |
| $S_A$ | Appropriate slope to use when approximating a nonuniform velocity distribution for estimation of $\alpha$ or $\beta$; should be the energy slope, $S_e$, when estimating $\alpha$, and the friction (momentum) slope, $S_f$, when estimating $\beta$ |
| $S_c$ | Critical slope in a culvert barrel |
| $S_e$ | The energy slope for flow in a channel |
| $S_f$ | The friction (momentum) slope for flow in a channel |
| $S_h(x_1, x_2)$ | The correct volume of water between cross sections at locations $x_1$ and $x_2$ for a given water-surface height |

| | |
|---|---|
| $S_q(x_1, x_2)$ | The correct momentum content of the flow between cross sections at locations $x_1$ and $x_2$ for a given water-surface height |
| $S_0$ | Bottom slope of the channel, positive when the bottom elevation decreases in the downstream direction |
| $T$ | Top width of the flow |
| $T_c$ | Top width of the water surface at critical depth |
| $T_i$ | Top width of the water surface for subsection $i$ of the cross section |
| $V(s)$ | Flow velocity at offset $s$ in the cross section |
| $V$ | Cross-sectional average velocity |
| $V_D$ | Velocity at a dam site after failure |
| $V_{D_1}$ | Velocity at a dam site before failure |
| $\Delta V$ | Velocity difference specified to define a continuous energy-loss function as flow reverses in the vicinity of a flow expansion or contraction |
| $W(s)$ | Crest width of a weir represented at the local offset $s$ |
| $x$ | Distance along the distance axis for the channel (main-channel axis) |
| $dx$ | Distance increment along the main-channel axis |
| $dx^{(i)}$ | Distance increment on flow line $i$ in a curvilinear channel |
| $\Delta x$ | Distance between cross sections |
| $\Delta x_{12}$ | Distance between the approach section (section 1) and entrance section (section 2) of a culvert |
| $\Delta x_{23}$ | Length of a culvert |
| $X$ | The difference in the product of the velocity and the energy-flux correction coefficient from the downstream section to the upstream section of a flow expansion or contraction |
| $X_f$ | A general designation of parameters on which the first moment of area with respect to the water surface is functionally dependent |
| $y(x)$ | The height of the water surface above the minimum point in the cross section at the location given by $x$ |
| $y_c$ | Critical depth (water-surface height) |
| $y_n$ | Normal depth (water-surface height) for a given flow |
| $y_s$ | The stopping water-surface height for computation of the water-surface profile in the CHANRAT command |
| $y_t$ | A nontabulated argument value for which a function value is sought by interpolation from a function table |
| $y_{t_i}$ | The $i$th argument value tabulated in a function table |
| $y_{1fw}$ | The limiting water-surface height at section 1 (approach section) of an underflow gate for free-weir flow for a given gate opening |
| $y_{2max}$ | Maximum water-surface height at the culvert entrance (section 2) for culvert-flow type 1 |
| $y_{4f}$ | The water-surface height at section 4 (departure section) of an underflow gate at the free-flow limit for a given gate opening |
| $y_{4sw}$ | The limiting water-surface height at section 4 (departure section) of an underflow gate for submerged-weir flow for a given gate opening |
| $z(s)$ | Elevation of the cross section boundary at offset $s$ |
| $z_{b_i}$ | Minimum bottom elevation at section $i$ of a culvert |
| $z_{ci}$ | Elevation of the culvert invert at the downstream end |
| $z_e$ | Total-energy line elevation |
| $z_i$ | Boundary elevations of the surveyed points used to describe a cross section |
| $z_j$ | Bottom elevation at section $j$ of an underflow gate relative to the datum for the stream system |
| $z_m$ | Elevation of the minimum point on the cross-section boundary |

| | |
|---|---|
| $z_w$ | Water-surface elevation |
| $z_{w_{1max}}$ | Maximum water-surface elevation at section 1 for culvert-flow type 1 |
| $z_{3p}$ | Elevation of the piezometric surface at the exit section (section 3) of a culvert |
| $dz_e$ | Differential increment in the total-energy line elevation |
| $\Delta z$ | Difference in bottom elevation between sections 2 and 3 of an underflow gate |
| $\alpha$ | Kinetic-energy-flux correction coefficient |
| $\beta$ | Momentum-flux correction coefficient |
| $\mu$ | The slope of the sinuosity for a submerged line segment on the cross-section boundary |
| $\sigma_i$ | The sinuosity in the cross section applicable to the *i*th subsection |
| $\sigma_{ij}$ | The sinuosity at the *j*th cross section of the *i*th flow line |
| $\sigma(s)$ | The rate of change of distance along the flow line at offset *s* to the rate of change of distance along the main-channel axis (sinuosity at offset *s*) |
| $\omega(y)$ | Escoffier stage variable used in the generalized Ritter dam-break solution |



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# APPENDIX 2: DIMENSIONS OF ARRAYS AND SPECIFICATION OF FORTRAN UNIT NUMBERS IN THE FULL EQUATIONS UTILITIES MODEL

Proper application of FEQUTL for compilation of hydraulic characteristics of cross sections and control structures requires the use of many arrays and the specification of Fortran unit numbers for input files, output files, and other operations. Many of the arrays have identical dimensions that have increased throughout the years as Fortran compilers and operating systems have become more efficient. To facilitate changes in the size of the arrays, the dimensions of the arrays are specified in an INCLUDE file named ARSIZE.PRM, which is used when the program is compiled. The contents of ARSIZE.PRM are described in this appendix. Typically, the sizes of these arrays will not need to be changed from the values in ARSIZE.PRM that may be obtained by electronic retrieval from the World Wide Web (WWW) at http://water.usgs.gov/software/feq.html and by anonymous File Transfer Protocol (FTP) from water.usgs.gov in the pub/software/surface_water/feq directory. However, for very large stream systems, some of the dimensions may need to be changed as described herein. Because FEQUTL has been developed over a period of more than 20 years, many aspects of the code use Fortran unit numbers to identify input files, output files, and other program features. Selection and application of these unit numbers also are discussed in the following section.

## Dimensions of Arrays in the Full Equations Utilities Model

Function tables listing hydraulic characteristics of cross sections and control structures larger than permitted by the size declared for a variety of vectors and arrays cannot be computed in FEQUTL. (A vector is an array with only a single dimension.) The sizes of these arrays and vectors have been declared by use of Fortran parameters. A file, ARSIZE.PRM, contains these dimension parameters in a PARAMETER statement. An INCLUDE compiler directive appears with ARSIZE.PRM for the arguments in any program unit in which one or more of the parameters in ARSIZE.PRM are required to establish the dimension of some array or vector.

Many of the parameters giving the dimensions begin with the letter "M" and may be followed with the letter "R" to denote the number of rows for a vector or an array. All vectors are viewed as being column vectors. Therefore, each row for a vector contains only one element. The second letter may be "C" to denote the number of columns for arrays—that is, the number of elements in each row of the array. The remaining four characters available in a Fortran name are the same as, or are related to, the variable name being dimensioned. Some parameters that are used for many different vectors or arrays do not follow these guidelines.

MAXCMD Maximum number of commands for FEQUTL.

MCDT10 Maximum number of columns in a 2-D table of type 10.

MFTNUM Same as PMXTAB—maximum table number.

MNBN Maximum number of nodes on a culvert barrel in the CULVERT command (section 5.5).

MNDEP Maximum number of water-surface height (depth) values in an interpolated cross section.

MNMID Maximum number of cross sections interpolated between known cross sections.

MORG Offset value for the first command-line argument. On personal computer systems this should be 1 if the supplied routines for retrieval of command-line arguments are used. If the compiler differs from Lahey, then the value should be set to get the first file argument. On Unix systems, MORG=0 is normally required.

MRFTAB Maximum row in a function table. This value gives the size of the vector used to store function tables.

MUNIT Maximum unit number for input/output unit numbers.

PMXELM Maximum number of cross-section hydraulic characteristics in an internal table.

PMXFRC Maximum number of fractions of free drop or free flow for computing 2-D tables.

PMXNFL Maximum number of flow lines when defining correction coefficients for channel curvilinearity.

PMXNHG Maximum number of gate openings for an underflow gate. This value defines the maximum number of 2-D tables of type 13 that appear in a table of type 15.

PMXNHU Maximum number of upstream or downstream heads for computing 2-D tables.

PMXNIG Size of vectors used in computing the indefinite integral of the breakpoint density when finding optimum tables.

| | |
|---|---|
| PMXOFF | Maximum number of offsets for profile of an embankment in the EMBANKQ command (section 5.6). |
| PMXPNT | Maximum number of points in a cross section. |
| PMXSEC | Maximum number of cross sections in the function table. |
| PMXSUB | Maximum number of subsections in a cross section. |
| PMXTAB | Maximum table number. |
| XSCOML | Length in 4-byte words of the common blocks for cross sections. |
| XTIFOFF | Cross-section table initial offset. The offset of the first value in the body of the table. |

## Input-Output Unit Number Selection

FEQUTL has been operational long enough that some components predate recent developments in operating systems. In the past, some versions of Fortran and some operating systems required that an input or output operation in a computer program must be associated with a file on a hard disk using a unit number. Thus, the user had to specify an explicit unit number in order to associate the file on the hard disk with the proper point of input or output in the Fortran program. In addition, it was not possible to reference a file name as such in Fortran programming in the past. Therefore, the intermediary of a unit number had to be applied.

As a consequence, a considerable history of input streams was developed for FEQUTL that required explicit unit numbers. These numbers continue to be supported in FEQUTL to maintain consistency with past use even though the use of unit numbers is no longer required in the current Fortran compilers and operating systems. As time permits and demand dictates, the old usage of unit numbers will be replaced with new usage that applies the more flexible facilities available on current operating systems. In the interim, the following guidelines for choosing unit numbers are offered.

1. Each operating system/language combination has a unique upper limit for unit numbers. In some cases, this is 99, but it may be larger or smaller than this value. The purpose of MUNIT in the INCLUDE file ARSIZE.PRM is to set this level so that the input can be checked in FEQUTL computations to make sure that the specified unit numbers are not too large for the operating system.
2. Fortran programming has defined standard unit numbers since the early beginning of the language, in the 1960's. Unit 5 was defined as a standard input, unit 6 as standard output to a line printer, and unit 7 was defined as output to a standard card punch. Card punches are not used anymore, and line printers are rarely used at this time.
3. Command-line arguments are used in FEQUTL. A command line is the line following the DOS prompt on a computer that uses the DOS operating system and the UNIX prompt on a computer that uses the UNIX operating system. This is the line where words and strings of symbols are typed to tell the computer what actions should be done (the line where commands are issued to the computer). The first item entered on a command line is the command. Items that follow the command, usually separated from the command and from each other by one or more spaces, are called command-line arguments. Three arguments are required in FEQUTL simulation. The first argument is the name of the file that contains the input to FEQUTL as defined in the Input Description for the Full Equations Utilities Model (section 5). This is the standard input file. The second argument is the name of the file that contains the items that are computed in the course of a simulation. This is the standard output file. The third argument is the name of the file that contains the tables computed with FEQUTL. This is the standard table file. An example command line for FEQUTL is

FEQUTL FEQUTL.IN FEQUTL.OUT FEQUTL.TAB

where

| | |
|---|---|
| FEQUTL.IN | is the name of the standard input file, |
| FEQUTL.OUT | is the name of the standard output file, and |
| FEQUTL.TAB | is the standard table file. |

The names for these three files are selected by the user and can be any valid name available in the operating system. As many as 64 characters may be used for the specification of the file name in FEQUTL. Therefore, a path can be included with the name.

4. Two standard unit numbers that relate to the standard input and standard output files for FEQUTL are defined in a file STDUN.PRM, which may be retrieved electronically as described in section 1.1. These are the unit numbers that are equivalent in concept to unit numbers 5 and 6 in traditional Fortran. The Fortran parameter STD5 defines the unit

number to use for processing the standard input file. The Fortran parameter STD6 defines the number to use for processing the standard output file. These parameters are 5 and 6, respectively, by default for DOS systems, but they need not have those values. The values included in STDUN.PRM are STD5=35 and STD6=36, but any valid values that the user selects may be used. Once selected, however, the unit numbers cannot be used for another purpose in the input to FEQUTL.

5. The Fortran-defined unit designation for writing to the display screen is used in FEQUTL. The unit field in an output statement in Fortran is given as an asterisk to denote output to the display screen. This means that an output to the standard output unit, STD6, will appear in the standard output file, whereas an output to a unit designated by an asterisk is to the display screen. This is the result on DOS systems. Some UNIX systems, however, define the asterisk unit differently. On these UNIX systems, the asterisk unit is associated with the standard output unit, 6. If this also is the unit used for the standard output file, then no text is written to the display screen and all text appears in the standard output file. Therefore, to write to the display screen when running the program under UNIX, do not assign number 6 to STD6. Also, the standard unit number 5 is commonly associated with the keyboard in some UNIX systems. Therefore, STD5 and STD6 should not have the values of 5 and 6 under UNIX, but should be given some other numbers before the program is compiled. Values of 3 and 4 have been used in the past and have worked. On UNIX systems, unit numbers 5, 6, and 7 should be avoided because they may have a special meaning.
6. Aside from the standard unit numbers specified for STD5 and STD6 and the traditional standard unit numbers of 5, 6, and 7, the user may select the unit numbers. This choice is limited only by the following constraints.
   a. The same unit number should not be used more than once in any context other than the input of files containing function tables.
   b. A unit number larger than the maximum value set by parameter MUNIT in the INCLUDE file ARSIZE.PRM at the time the program was compiled should not be used.

   The units that have been referenced in FEQUTL simulation are monitored, and any duplicate reference results in an error.
7. Standard numbers are recommended for files that appear in a common context. Five additional unit numbers are defined in the file STDUN.PRM to describe these common contexts. In FEQUTL, STD7 is used to process the function-table file computed with FEQUTL; STD10 is used in floodway computations; and STD48, STD49, and STD50 are used in the HEC2X (section 5.15) and WSPROX (section 5.23) commands. The values included in STDUN.PRM are STD7=7, STD10=10, STD48=48, STD49=49, and STD50=50, but any values that the user selects may be valid.



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# APPENDIX 3: Full Equations Utilities Model Error Messages and Warnings: Version 4.0

Messages are issued to the user in three categories in FEQUTL computations. The first category consists of error messages describing some condition in the input that makes it impossible for the instructions entered by the user to be done in FEQUTL. In many cases of FEQUTL computations, the execution of the current command will stop, the input for the current command will be skipped, and execution of the following command will be attempted. Thus, each command in the input will be processed, but only those without detected errors will be completed. Therefore, the user must always check for detected errors before assuming that all the commands have been processed correctly.

The second category of messages consists of warning messages reporting conditions that might indicate a user error or which highlight the possibility of some later computational problem. Usually, when warnings are issued, some assumption is made in the FEQUTL computations to circumvent the problem and allow the computations to continue. The user should always check the warning messages to make sure that the default action taken in FEQUTL computations has not affected the results.

The third category of messages consists of bug messages reporting conditions that should not occur. Bug messages are usually indicative of some problem in the computer code and should not be seen often. However, conditions not yet tested may be present in an application and a bug may be revealed. The messages concerning bugs are not reported here. Users should contact Linsley, Kraeger, Associates in Mountain View, Calif., to resolve any problems with bug messages.

Some parts of the software in FEQUTL are taken from FEQ. The parts of FEQUTL that are taken from FEQ also contain the same error, warning, and bug messages as in FEQ. A message with a number less than 500 is from the FEQ software copied in FEQUTL and is described in the FEQ message summary given in appendix 4 of the FEQ documentation report (Franz and Melching, 1997). The description of the message may not refer directly to FEQUTL, but the nature of the error is the same. The principal operations copied from FEQ involve the storage of, and the look up from, function tables. Thus, errors of argument out of range or missing tables will be issued utilizing messages from FEQ. All messages with numbers greater than 500 are described here.

A message that is common in both FEQ and FEQUTL is error 500. It appears in both descriptions because it commonly occurs and is the boundary for the messages for the two codes. All messages given in FEQUTL are of the form *ERR:nn*, *WRN:mm*, or *BUG:kk* where nn, mm, and kk are the respective message numbers. Error messages in any other form originate from the computer operating system and not in FEQUTL.

## *ERR:nn* MESSAGES

FEQUTL contains a fairly extensive set of error messages to detect errors in the input as early as possible. However, errors could be encountered that are not yet detected in the FEQUTL software. When previously undetected errors are identified, the program code will be changed so that these errors may be detected before computational problems or incorrect results are caused. However, it is possible to specify the input so that no errors are detected in FEQUTL computations and still the input is improperly defined through some error on the part of the user. As a simple example, the offsets utilized for the boundary points on a cross section may be given in a valid form and also may specify a valid cross section. However, the cross section may not be the correct size because an incorrect map scale was applied to the measurements. This error cannot be detected in FEQUTL computations because the input is valid, but incorrect for the application. Thus, there are three types of errors possible: an error that can be detected in FEQUTL computations and is detected; an error that could have been detected in FEQUTL computations, but no code for the detection is available; and an error that, by its nature, cannot be detected at any time in FEQUTL computations. Over time as the model is applied, the number of errors of the first type will increase and the number of errors of the second type will decrease. However, the number of errors of the third type will stay the same.

The error messages are given in numerical order in the following list. Gaps may be present in the order as changes are made so that the absence of a numbered message does not necessarily imply that some message has been omitted. Furthermore, the order of numbering is arbitrary.

In many cases the message includes numbers and, in a few cases, character strings. Values of numbers and character strings will depend on the specific occurrence of the error. The positions of these occurrence-dependent values are denoted by 'nn' for an integer number, 'ff' for a floating point number (one containing a decimal point or in the floating point format), and 'aa' for a character string.

**∗ERR:500∗ CONVERSION ERROR IN LINE:**

A line of input that cannot be converted from character form to internal form has been detected. This can result from many user errors. An input field that should contain a number probably included one or more characters. Therefore, the conversion cannot be made. This can result from typing the letter 'O' instead of the digit '0'. An input line may have been omitted so that the wrong line of input was read. The values on the line may be in the wrong columns so that an input field that should contain a number contains an alphabetic or special character that should not appear. Also, all the input items may be numbers, but an error in spacing the input places two decimal points in one field.

**∗ERR:501∗ UNKNOWN COMMAND.**

A command has been read that cannot be found in the current list of commands. The current list of commands is defined by the standard header information (section 5.1) that appears at the head of each input to FEQUTL. It might be that the current version of FEQUTL supports the command invoked, but the header information is from a previous version of FEQUTL that does not support the command. The header information must be corrected and the model run attempted again. The command could have been mistyped and, therefore, could not be found.

**∗ERR:502∗ INVALID VALUES FOR NRZERO OR DZLIM BOTH MUST BE > 0.0**

The input values for NRZERO, the depth for the near-zero values, and DZLIM, the maximum change in argument, both applying to cross-section tables only, must be > 0 (see section 5.1). At least one of the values has been given as zero.

**∗ERR:503∗ TOO MANY COMMANDS IN SYSTEM FILE. LIMIT= nn**

More commands have appeared in the header to the input than are allowed in FEQUTL. The parameter MAXCMD must be increased in the INCLUDE file ARSIZE.PRM (appendix 2) and FEQUTL must be recompiled and linked to allow for more commands.

**∗ERR:504∗ NUMBER OF SUBSECTIONS= nn > nn**

The number of subsections for a cross-section specification has exceeded the number allowed in FEQUTL. The parameter PMXSUB must be changed in the INCLUDE file ARSIZE.PRM (appendix 2), and FEQUTL must be recompiled and linked to permit more subsections.

**∗ERR:505∗ SUBSECTION NUMBER TOO LARGE AT OFFSET= ff**

A line segment of the cross-section boundary has been assigned to a subsection number, which is larger than the number of subsections given earlier in the input when the Manning's *n* values were given (sections 5.8–5.10). Thus, the cross section cannot be processed because the line segment has no assigned value of *n*.

**∗ERR:506∗ ONLY ONE POINT GIVEN ON BOUNDARY OF THE CROSS SECTION.**

At a minimum, two points must be given on the boundary of the cross section before the cross section is defined. A mistake has likely been made in a subsection number such that the input of the cross section is determined to be complete in FEQUTL computations when it is not complete (see sections 5.8–5.10).

**∗ERR:507∗ NUMBER OF POINTS IN CROSS SECTION > nn**

The number of points given on a cross section is larger than the current internal maximum allowed in FEQUTL. The size of the parameter PMXPNT must be increased in the INCLUDE file ARSIZE.PRM (appendix 2), and FEQUTL must be recompiled and linked.

**∗ERR:508∗ SECTION VIOLATES MONOTONICITY AT OFFSET= ff**

The cross-section offsets should be nondecreasing and an offset has been detected that violates this condition. Either the user specification for checking monotonicity of offsets is incorrect or an error in the cross section is present.

### *ERR:509* TABLE# < 0 OR TABLE# > nn

A function-table number is out of range. If the upper range is too small, the parameter PMXTAB in the INCLUDE file ARSIZE.PRM (appendix 2) should be changed to a new value, and FEQUTL must be recompiled and linked.

### *ERR:510* DUPLICATE TABLE NUMBER.

A table number already in use has been detected. The table numbers should be changed so that each table in a run of FEQUTL is unique.

### *ERR:511* UPSTREAM CROSS SECTION MISSING FOR BRIDGE

An upstream cross section must be present for execution of the bridge routine, and no upstream cross section has been read. The last cross section processed, before the bridge routine is called, should be specified as the upstream cross section for the bridge. This bridge-loss method is no longer supported in FEQUTL. It remains in the code for the benefit of users with stream-system models developed for versions of the FEQUTL code prior to version 4.0. These users are encouraged to revise the models to apply the WSPRO (Shearman, 1990) bridge routines (section 4.1).

### *ERR:512* DOWNSTREAM CROSS SECTION MISSING FOR BRIDGE

A downstream cross section must be present for execution of the bridge routine, and no downstream cross section has been read. The downstream cross section for the bridge should appear in the input to FEQUTL before the input of the upstream cross section for the bridge. The upstream cross section for the bridge should appear in the input to FEQUTL immediately before the input for the bridge. This bridge-loss method is no longer supported in FEQUTL. It remains in the code for the benefit of users with stream-system models developed for versions of the FEQUTL code prior to version 4.0. These users are encouraged to revise the models to apply the WSPRO (Shearman, 1990) bridge routines (section 4.1).

### *ERR:513* BASE CURVE# > 3 OR < 1.

In the Bureau of Public Roads (Bradley, 1970) bridge-loss method, three base curves are available for the loss coefficient. A base curve number outside this range has been detected. This bridge-loss method is no longer supported in FEQUTL. It remains in the code for the benefit of users with stream-system models developed for versions of the FEQUTL code prior to version 4.0. These users are encouraged to revise the models to apply the WSPRO (Shearman, 1990) bridge routines (section 4.1).

### *ERR:514* PIER TYPE < 0 OR > 8.

The pier type for the Bureau of Public Roads (Bradley, 1970) bridge-loss method must be in the given range. A pier type has been found that is outside this range. This bridge-loss method is no longer supported in FEQUTL. It remains in the code for the benefit of users with stream-system models developed for versions of the FEQUTL code prior to version 4.0. These users are encouraged to revise the models to apply the WSPRO (Shearman, 1990) bridge routines (section 4.1).

### *ERR:515* NUMBER OF ENTRIES IN PIER NUMBER-WIDTH TABLE > nn

The number of entries in the pier description in the Bureau of Public Roads (Bradley, 1970) bridge-loss method is too large. The current limit is 25 and cannot easily be changed. This bridge-loss method is no longer supported in FEQUTL. It remains in the code for the benefit of users with stream-system models developed for versions of the FEQUTL code prior to version 4.0. These users are encouraged to revise the models to apply the WSPRO (Shearman, 1990) bridge routines (section 4.1).

***ERR:516*   ELEVATION FOR PIER NUMBER-WIDTH TABLE IS DECREASING AT:   ff**

The elevation in the pier description in the Bureau of Public Roads (Bradley, 1970) bridge-loss method is decreasing and is, therefore, invalid. This bridge-loss method is no longer supported in FEQUTL. It remains in the code for the benefit of users with stream-system models developed for versions of the FEQUTL code prior to version 4.0. These users are encouraged to revise the models to apply the WSPRO (Shearman, 1990) bridge routines (section 4.1).

***ERR:517*   ONLY TYPE RDFLOW IS VALID FOR A BRIDGE**

Only the bridge option RDFLOW is supported for the Bureau of Public Roads (Bradley, 1970) method. If no flow over the roadway is possible, the top of road elevation should be made so large that water will never overtop the road, and flow tables that yield zero flow should be input. This bridge-loss method is no longer supported in FEQUTL. It remains in the code for the benefit of users with stream-system models developed for versions of the FEQUTL code prior to version 4.0. These users are encouraged to revise the models to apply the WSPRO (Shearman, 1990) bridge routines (section 4.1).

***ERR:518*   SUBSET AND SECTION ARE DISJOINT**

A subset from a cross section has been specified, either in the bridge computations or in a floodway specification. The subset is such that it is not contained within the cross section. Therefore, the subset cannot be computed. The specification of the subset should be checked for the location of the center of the bridge opening relative to the upstream cross section. The Bureau of Public Roads (Bradley, 1970) bridge-loss method is no longer supported in FEQUTL. It remains in the code for the benefit of users with stream-system models developed for versions of the FEQUTL code prior to version 4.0. These users are encouraged to revise the models to apply the WSPRO (Shearman, 1990) bridge routines (section 4.1).

***ERR:519*   EXPECTED Q CARD BUT FOUND:   aa**

A printer output file from WSPRO should contain a Q card—that is, a line specifying the flow. The Q card was not found in the FEQUTL computations; instead, the given string was found. A problem may be in WSPROT14 (section 5.22): the version of WSPRO utilized could have changed the output from the pattern utilized in the version of WSPRO on which command WSPROT14 is based, or the printer file may be incomplete.

***ERR:520*   NEGATIVE DEPTH= ff AT NORMAL-FLOW SECTION.**

A water-surface elevation given in the WSPROQZ command (section 5.21) is below the bottom of the normal-flow section. Either the normal-flow section contains an invalid bottom elevation or the water-surface elevation is in error.

***ERR:521*   NUMBER OF SUBAREAS= nn INCONSISTENT WITH NUMBER OF n VALUES=nn**

The number of subareas and the number of *n* values must agree in a WSPRO input. A disagreement between these two values has been found in WSPROX (section 5.23).

***ERR:522*   NUMBER OF n VALUES=nn INCONSISTENT WITH NUMBER OF BREAKPOINTS ON ND.**

The number of *n* values must be compatible with the number of breakpoints on the ND record giving the variation of roughness with water level in the WSPROX command (section 5.23). In this case, the numbers disagree.

***ERR:523*   NO GR CARDS FOUND FOLLOWING XT CARD.**

No ground points have been given after a template section header in the WSPROX command (section 5.23). The template section is then undefined.

***ERR:524* THERE ARE nn ITEMS FOR FLOW-LINE DATA. ONLY 1, 3, OR 5 ITEMS ARE VALID.**

An invalid number of flow-line data items have been detected in WSPROX (section 5.23). An odd number of items should always be input.

***ERR:525* SPACE FOR ELEVATION ARGUMENTS EXHAUSTED**

Arguments are added in FEQUTL to those defined by the unique breakpoint elevations, which are found in the cross-section specification in order to improve the accuracy of the conveyance estimation. In this process, the space allocated for these arguments has been filled to capacity. The space allocated for arguments is the same as the number of points in the cross section. Therefore, the PARAMETER PMXPNT must be increased in the INCLUDE file ARSIZE.PRM (appendix 2) and FEQUTL must be recompiled and linked.

***ERR:526* NEGATIVE DEPTH= ff AT CRITICAL-FLOW SECTION.**

In the command WSPROQZ (section 5.21), the elevation derived for the water surface in the critical-flow section has been computed below the bottom of the critical-flow section. The elevation of the bottom of the critical-flow section could be in error. The offset from the water-surface elevation or the water-surface elevation also could be in error.

***ERR:527* FLOW UNDEFINED AT DNS ELEVATION= ff**

In the command WSPROQZ (section 5.21), the flow is undefined. Probably a result of previous errors already reported. A defined flow must be present, and no flows have been read.

***ERR:528* NUMBER OF CONDUITS= nn > nn**

The number of pipes or conduits in a multiple-pipe or multiple-conduit installation (sections 5.16 and 5.17) has exceeded the number allowed in FEQUTL. The maximum number of pipes allowed is the same as the number of subsections. Thus, the parameter PMXSUB must be increased in the INCLUDE file ARSIZE.PRM (appendix 2), and FEQUTL must be recompiled and linked.

***ERR:529* TOO FEW INTERSECTIONS. FLOODWAY ELEVATION LIKELY BELOW SECTION. IL = nn IR = nn**

The defining elevation for the floodway (section 5.12) specified by a given decrement in elevation does not intersect the cross-section boundary. Message may not appear because the condition should be detected in ERR:530.

***ERR:530* DEFINING ELEVATION BELOW CHANNEL BOTTOM.**

The defining elevation for the floodway (section 5.12) specified by a given decrement in elevation is below the current channel bottom. Either the cross section is too high or the defining elevation is too low.

***ERR:531* FLDWAY ELEV= ff HIGHER THAN LEFT END ELEV= ff**

The defining elevation for the floodway (section 5.12) specified by a given elevation is higher than the left end of the cross section. The cross section must always be defined to an elevation at least as high as the defining elevation.

***ERR:532* FLDWAY ELEV= ff HIGHER THAN RIGHT END ELEV= ff**

The defining elevation for the floodway (section 5.12) specified by a given elevation is higher than the right end of the cross section. The cross section must always be defined to an elevation at least as high as the defining elevation.

***ERR:533* INVALID FLOODWAY OPTION IN ABOVE LINE**

A floodway option (section 5.12) has been given that is not supported in FEQUTL. Probably an error in entering the option.

### *ERR:534* IN LINE ABOVE, USET SELECTED BUT ONE OR BOTH LIMITS MISSING.

In the USET option for the floodway (section 5.12), the user must give both limits and one or both limits are missing from the input.

### *ERR:535* NFRAC= nn > MAXPRO=nn. UNABLE TO CONTINUE.

MAXPRO, the maximum number of profiles computed in WSPRO, must be larger than the number of partial free flows to be computed for each downstream elevation. All the profiles for at least one downstream elevation must be completed in WSPROQZ computations (section 5.21). The value of NFRAC is too large for that to be possible. Either NFRAC must be reduced, or a version of WSPRO must be applied with which a larger number of profiles may be computed.

### *ERR:536* RECORD ID= aa UNKNOWN.

A record identification (record id) has been found that is not known. This could be an error in the WSPRO input, or a new record id could have been added to WSPRO after WSPROX (section 5.23) was developed.

### *ERR:537* STANDARD FLOOD ELEVATION BELOW CHANNEL BOTTOM.

The standard flood elevation given for the conveyance-defined floodway (section 5.12) is computed to be below the current channel bottom. Either the cross section is too high or the standard flood elevation is too low.

### *ERR:538* NO INTERVAL FOUND FOR KTAR ON RIGHT

In a conveyance-defined floodway (section 5.12), the target conveyance is computed and a search from left to right is used to find an interval of the cross-section boundary that will contain the value of the reduced conveyance. No such interval could be detected. This indicates that some problem is present in the search method or that something is incorrect for either the shape of or the roughness distribution for the cross section.

### *ERR:539* NO INTERVAL FOUND FOR KTAR ON LEFT

In a conveyance-defined floodway (section 5.12), the target conveyance is computed and a search from right to left is used to find an interval of the cross-section boundary that will contain the value of the reduced conveyance. No such interval could be detected. This indicates that some problem is present in the search method or that something is incorrect for either the shape of or the roughness distribution for the cross section.

### *ERR:540* TABLE NUMBER= nn NOT FOUND

A referenced table number intended to supply information for the command could not be found. The referenced function table must be input using the command FTABIN (section 5.13) before the current command is encountered in the input.

### *ERR:541* X AND Y VALUE COUNT= nn IS ODD. BOTH VALUES MUST BE ON THE SAME INPUT RECORD.

An even number of boundary points on each record of WSPRO input should be detected in WSPROX (section 5.23). The offset and elevation of a point on the boundary of the cross section must both appear on the same input record. A case has been found in which this is not true. This could result from an error in delimiting values on the record.

### *ERR:542* SECTION ID= aa HAS NO STATION VALUE.

The given section has no station value in the WSPRO input. A station value must be entered.

## *ERR:543* CREST BELOW APPROACH INVALID.

In computation of the flow over embankment-shaped weirs, using the EMBANKQ command (section 5.6), the given crest elevation is determined to be below the bottom of the approach channel.

## *ERR:544* WEIR WIDTH MUST BE POSITIVE

In computation of the flow over embankment-shaped weirs, using the EMBANKQ command (section 5.6), the width of the crest is less than or equal to 0. This is invalid. The crest must always have a positive width so that the head relative to the crest can be computed.

## *ERR:545* MORE THAN nn OFFSETS FOR EMBANKMENT

The number of offsets for specifying the embankment crest and approach channel exceeds the space allowed. The parameter PMXOFF must be increased in the INCLUDE file ARSIZE.PRM (appendix 2), and FEQUTL must be recompiled and linked.

## *ERR:546* INVALID SURFACE OPTION: NEED PAVED OR GRAVEL

The only two surface options valid for EMBANKQ (section 5.6) are PAVED or GRAVEL, and some other option (other than END) has been detected.

## *ERR:547* COLUMN ARGUMENTS MUST BE STRICTLY INCREASING

A 2-D table has been detected with column arguments that are not strictly increasing. This indicates an error in the preparation of the table or corruption of the table file.

## *ERR:548* MORE THAN nn UPSTREAM HEADS

More than the allowed number of upstream heads has been requested for EMBANKQ (section 5.6). The parameter PMXNHU must be increased in the INCLUDE file ARSIZE.PRM (appendix 2), and FEQUTL must be recompiled and linked.

## *ERR:549* MORE THAN nn FRACTIONS OF FREE DROP

More than the allowed number of fractions of free drop has been requested. The parameter PMXFRC must be increased in the INCLUDE file ARSIZE.PRM (appendix 2), and FEQUTL must be recompiled and linked.

## *ERR:550* TABLE TYPE= nn UNIMPLEMENTED IN FTABIN. VALID TYPES ARE: nn nn

An unsupported table type has been detected in the FTABIN command (section 5.13). A list of currently supported types is given. The version of FEQUTL must be compatible with the input file processed.

## *ERR:551* NO CONTROL FOUND FOR TRANSITION IN FRFTRN.

A control point for the given downstream head could not be found in either of the two cross sections in EXPCON (section 5.7) computations. This error can usually be eliminated by increasing the extension on the upstream cross-section function table to a large value, usually 100 ft or more above its current extent. The EXT option should be utilized if the table is read from a file. If the table is computed in the same input and is stored using the SAVE option (sections 5.8–5.10), one side of the table may be extended by 100 ft or more, making the extension vertical. If this extension is placed in its own subsection, the extension will be simulated as a frictionless wall. If this does not correct the error, friction losses should be added (if none are present), or friction losses should be reduced, if present. It also may be that the expansion losses are too small. Large amounts of velocity-head recovery may result in problems in finding a critical control.

***ERR:552*   FOUND AT LEAST nn ITEMS. EXPECTED NO MORE THAN nn**

In processing a line of user input, more items have been found than expected. The input for extra input items on a line should be checked. The line where the error was detected is shown as part of the output.

***ERR:553*   EXPECTED AN INTEGER NUMBER BUT FOUND aa INSTEAD.**

In processing a line of user input, a sequence of characters has been detected instead of an integer number. Some error in the order of input values was detected. For free-format input, skipped values must be indicated by a double comma or by an asterisk (*) place holder.

***ERR:554*   EXPECTED A NUMBER BUT FOUND aa INSTEAD.**

In processing a line of user input, a sequence of characters has been detected instead of a number (integer or otherwise). Some error in the order of input values was detected. For free-format input, skipped values must be indicated by a double comma or by an asterisk (*) place holder.

***ERR:555*   EXPECTED AN IDENTIFIER BUT FOUND aa INSTEAD.**

In processing a line of user input, a sequence of characters that is not an identifier has been detected instead of an identifier. The proper spelling of identifier names must be checked. An identifier must begin with an alphabetic character. An error in the order of input values may have been detected. For free-format input, skipped values must be indicated by a double comma or by an asterisk (*) place holder.

***ERR:556*   FOUND ONLY nn VALUES ON LINE BUT EXPECTED nn**

In processing a line of user input, an insufficient number of values was read. The input line must be checked for omitted values.

***ERR:557*   VERTICAL VARIATION OF ROUGHNESS COEF. ALREADY DEFINED IN SUBSECTION NUMBER nn**

A duplicate definition of vertical variation of roughness has been given in the subsection in the FEQXEXT command (section 5.9). Vertical variation of roughness must be specified at only the first point of the subsection.

***ERR:558*   DIGITIZED INPUT NOT SUPPORTED**

A special form of input created by a digitizer is not currently supported in FEQUTL.

***ERR:559*   COEFFICIENT OF DISCHARGE <= 0.0 OR > 1.0**

A coefficient of discharge input by the user has been detected to be invalid.

***ERR:560*   APPROACH SECTION TABLE NUMBER DOES NOT REPRESENT A CROSS SECTION.**

The approach-section table given in CRITQ (section 5.4) or GRITTER (section 5.14) is not a cross-section table. Some error is present either in the number given or in the number assigned to the computed cross-section table.

***ERR:561*   CONSTRICTED SECTION TABLE NUMBER DOES NOT REPRESENT A CROSS SECTION.**

The constricted-section table given in CRITQ (section 5.4) is not a cross-section table. Some error is present in either the number given in CRITQ or in the number assigned to the computed cross-section table.

***ERR:562* SOLUTION DOES NOT EXIST AT DEPTH= ff CONSTRICTED SECTION IS NOT A CONSTRICTION!**

In computation of a critical-flow table utilizing CRITQ (section 5.4), supercritical flow has been computed in the approach section. The computations have not been completed at the given depth. It is likely that the cross section given as the constricted cross section is not a constriction relative to the approach cross section at all depths.

***ERR:563* CONSTRICTED FLOW TABLE NUMBER IS INVALID. TYPE MUST BE 2.**

The constricted-flow table in GRITTER (section 5.14) is of the wrong type. The wrong table number has been specified, or an error in entering the table type has been made.

***ERR:564* MISSING n-VALUE AT DEPTH NUMBER nn**

A value of Manning's *n* is missing at the nn-th depth number for a subsection. The missing *n* value must be supplied.

***ERR:565* BOTTOM ELEV. OF APPROACH SECTION ABOVE BOTTOM ELEV. OF CONSTRICTED SECTION.**

The bottom of the approach section must not be at a higher elevation than the bottom of the constricted section. Gravity and friction forces are ignored, and as a result any drop in elevation in the downstream direction results in errors.

***ERR:566* INSUFFICIENT SPACE IN ITAB/FTAB TO SAVE TABLE IN CRITQ. NEED nn MORE ELEMENTS.**

The critical-flow table is to be saved internally in FEQUTL so that it can be referenced after it is computed just like a table entered utilizing the FTABIN command. Insufficient space has been allocated in the function table-storage system for the critical-flow table. The parameter MRFTAB must be increased in the INCLUDE file ARSIZE.PRM (appendix 2), and FEQUTL must be recompiled and linked.

***ERR:567* aa IS INVALID OPTION FOR VERTICAL VARIATION OF ROUGHNESS.**

The following options are supported in FEQXEXT (section 5.9) for vertical variation of roughness: NCON, HYDY, or MAXY.

***ERR:568* ONLY ONE STATION EXISTS FOR FLOW LINE: aa AT STATION ff**

In computation of sinuosity of a flow line, only one station has been detected on the flow line named. This is insufficient to define sinuosity. At least two stations must be present on the flow line.

***ERR:569* INSUFFICIENT SPACE IN ITAB/FTAB TO SAVE CROSS SECTION TABLE. NEED nn MORE ELEMENTS**

Saving a cross-section table within FEQUTL has been requested but the space in the FTAB/ITAB system is filled to capacity. The parameter MRFTAB must be increased in the INCLUDE file ARSIZE.PRM (appendix 2), and FEQUTL must be recompiled and linked.

***ERR:570* ZERO DEPTH BEFORE NEGATIVE RESIDUAL WHILE SEEKING TYPE 1 LIMIT.**

Zero depth in the approach cross section has been computed in the CULVERT command (section 5.5) when trying to find a negative residual in a search for the limiting elevation at section 1 for culvert-flow type 1. This may indicate a problem with the solution process or a large drop in elevation between the approach section and the entrance to the culvert. A large enough drop may invalidate the solution procedure.

### *ERR:571* RISE= ff < MIN RISE= ff OR > MAX RISE= ff

The value of rise given for an arch-shaped conduit either is less than the minimum value of rise for a standard pipe or it is greater than the maximum value for a standard pipe. If the measurement is not in error, then the internal tables in MULCON (section 5.16) must be extended or detailed measurements must be taken of the dimensions of the conduit so the shape can be defined and a cross-section table computed.

### *ERR:572* SPAN= < MIN SPAN= ff OR > MAX SPAN= ff

Same meaning as ERR:571 except that the span was given as the defining dimension.

### *ERR:573* OFFSET SPACE FILLED IN MULCON.

The space for storing offsets has been filled in MULCON (section 5.16) when processing a request for analysis of multiple conduits.

### *ERR:574* SPAN <= 0.0 INVALID FOR TYPE=CIRC.

The value of span is utilized as the diameter of the pipe; therefore, the value may not be omitted if the type is CIRC in the MULCON command (section 5.16).

### *ERR:575* RISE AND SPAN ARE 0.0. ONE MUST BE > 0.0

Either rise or span must be given in MULCON (section 5.16). A case where neither value was given has been detected.

### *ERR:576* TYPE= aa UNKNOWN

The given pipe type is not known in the MULCON command (section 5.16).

### *ERR:577* RISE AND SPAN MUST BE > 0.0 FOR TYPE TE

Both the rise and span must be given for true-elliptical pipe in the MULCON command (section 5.16) because no standard dimensions are available to infer one dimension from the other when only rise or span is given.

### *ERR:578* APPROACH REACH LENGTH= ff < 0.

The approach-reach length must be positive in the CULVERT command (section 5.5).

### *ERR:579* APPROACH LOSS COEF. < 0 OR > 1.

Loss coefficient is only meaningful between 0 and 1 in the CULVERT command (section 5.5).

### *ERR:580* Not in use.

### *ERR:581* APPROACH EXPANSION COEF. < 0 OR > 1.

Loss coefficient is only meaningful between 0 and 1 in the CULVERT command (section 5.5).

### *ERR:582* ROUNDING/BEVELING FACTOR < 1 OR > 1.5.

The factor to account for rounding/beveling of a culvert entrance is outside the range established by Bodhaine (1968) in the CULVERT command (section 5.5).

### *ERR:583* DEPARTURE CONTRACTION COEF. < 0 OR > 1.

Loss coefficient is only meaningful between 0 and 1 in the CULVERT command (section 5.5).

### *ERR:584* WINGWALL FACTOR < 1 OR > 1.25.

The factor to account for wingwalls is outside the range established by Bodhaine (1968) in the CULVERT command (section 5.5).

### *ERR:585* PROJECTION ADJUSTMENT < 0.90 OR > 1.

The factor to account for a projecting entrance is outside the range established by Bodhaine (1968) in the CULVERT command (section 5.5).

### *ERR:586* LOSS OPTION: aa INVALID.

The only loss option supported is MOMENTUM in the CULVERT command (section 5.5).

### *ERR:587* CULVERT CLASS: aa INVALID.

In the CULVERT command (section 5.5), culvert class must be: BOX, PIPE, MITER, or RCPTG.

### *ERR:588* TYPE 4-6 COEF.: ff < 0.60 OR > 1.

The discharge coefficient is outside the range established in the CULVERT command (section 5.5).

### *ERR:589* TABLE TYPE NOT 6 OR 13.

Only table types 6 or 13 can be computed in the CULVERT command (section 5.5).

### *ERR:590* TABLE NUMBER: nn IS NOT OF A CLOSED CONDUIT.

The given table number does not represent a closed conduit when a table number for a closed conduit is required in the FEQUTL computations.

### *ERR:591* aa IS A BAD CROSS SECTION OPTION.

An unknown option for a cross section has been detected. Valid options are: EXTEND, MONOTONE, NEWBETA, NEWBETAE, NEWBETAM, NOEXTEND, NOOUT, NOSAVE, OLDBETA, OUT1, OUT12, OUT20, OUT21, OUT22, OUT23, OUT24, OUT25, SAVE, SAVE1, SAVE12, SAVE20, SAVE21, SAVE22, SAVE23, SAVE24, and SAVE25.

### *ERR:592* TYPE= nn INVALID FOR 2-D FLOW TABLES.

Only types 6, 13, and 14 are valid for 2-D tables.

### *ERR:593* WEIR COEF. TABLE NUMBER MUST BE GIVEN.

A weir-coefficient table number for flow over embankment-shaped weirs is not available in FEQUTL storage. It must be input using FTABIN (section 5.13).

### *ERR:594* MAXIMUM DEPTH BEFORE POSITIVE RESIDUAL WHILE SEEKING TYPE 1 LIMIT.

The top of the cross-section table has been encountered before finding a positive residual in the search for the limiting elevation at the approach section for culvert-flow type 1. The table must be extended to higher elevations and FEQUTL must be run again.

### *ERR:595* TAB#= nn OVERFLOW SEEKING CRIT. DEPTH FOR FLOW= ff TABLE MAXARG= ff

Critical depth could not be computed even though elevations at the top of the table have been reached. Either the flow is in error or the table must be extended.

***ERR:596* TAB#= nn UNDERFLOW SEEKING CRIT. DEPTH FOR FLOW=ff**

Critical depth could not be computed in the given table even though elevations at the bottom of the table have been reached. The flow is likely invalid or there is a problem in the solution method.

***ERR:597* INITIAL DEPTH= ff ≤ 0 IN SFPSBE.**

The initial depth for the computation of a steady-flow profile for subcritical flow is negative, which indicates an undetected input error or a problem with the solution method.

***ERR:598* TAB#= nn OVERFLOW SEEKING SUBCRITICAL SOLUTION. MAXARG= ff**

A subcritical solution could not be calculated before elevations at the top of the table were reached. The flow is probably too large for the conduit, or there is a problem with the solution method. The table must be extended and FEQUTL run again.

***ERR:599* INITIAL DEPTH= ff ≤ 0 IN SFPSPE.**

The initial depth for the computation of a steady-flow profile for supercritical flow is negative, which indicates an undetected input error or a problem with the solution method.

***ERR:600* TYPE= nn INVALID TYPE FOR SUBMERGENCE TABLE.**

The table type for a submergence table must be 2, 3, or 4 in the CULVERT (section 5.5) or EMBANKQ (section 5.6) commands.

***ERR:601* TABLE#= nn INVALID SUBMERGENCE VALUES AT TABLE START.**

A submergence table in the CULVERT (section 5.5) or EMBANKQ (section 5.6) commands must start with an argument of 0.0 and a function value of 1.0, indicating no reduction in free flow when no submergence is present.

***ERR:602* TABLE#= nn NO SUBMERGENCE IN SUBMERGENCE TABLE.**

Submergence effects on the flow were not detected in a table given as a submergence table in the CULVERT (section 5.5) or EMBANKQ (section 5.6) commands. A submergence table must indicate a reduction in flow at some point resulting from the downstream head on the overflow-crest elevation.

***ERR:603* ROADWAY MOMENTUM FLUX FACTOR= ff < 0 OR > 1.**

The roadway momentum-flux factor must always be positive but must not exceed 1.0 in the CULVERT command (section 5.5).

***ERR:604* WIDTH FACTOR FOR DEPARTURE REACH ≤ 1.0**

The width factor for testing the cross section for the beginning of the departure reach must always exceed 1.0 in the CULVERT command (section 5.5).

***ERR:605* BEGINNING ELEV. FOR DEP. RCH.= ff > CLVRT EXIT ELEV. ff**

The elevation of the beginning of the departure reach must not be higher than the culvert invert (section 5.5). No abrupt positive step can be present at the exit of the culvert.

***ERR:606* UPSTREAM LINEAR SINUOSITY IMPOSSIBLE FOR FLOW LINE: aa AT STATION: ff NO UPSTREAM STATION EXISTS.**

A request for the upstream linear sinuosity in the CHANNEL command (section 5.2) cannot be done at the station because no station is present upstream on the flow line.

***ERR:607* TABLE# ≤ 0**

A table number must always be positive in the context of the type of table under consideration.

***ERR:608* SUBMERGED ROAD FLOW WITH FREE CULVERT FLOW NOT YET SUPPORTED.**

Submerged road flow resulting before the flow through the culvert also is submerged and is not yet supported in FEQUTL.

***ERR:609* ROAD CREST ELEV. ≤ HEAD DATUM INVALID.**

Probable user error. A road crest below the head datum indicates that water is flowing over the road before water will flow through the culvert. This is not a normal road crossing. If the CULVERT code (section 5.5) is used for a nonroad crossing for which this relation between elevations is true, then the culvert-flow and the flow over the weir crest must be computed in separate tables and then combined with Code 5 Type 6 in FEQ simulation.

***ERR:610* FREE DROP= ff ≤ 0 NOT YET SUPPORTED.**

A negative free drop indicates velocity head recovery through the culvert system. The approach losses should be increased in the CULVERT command (section 5.5) to force a drop in water-surface elevation. Increasing APPEXP to 1.0 is one option to circumvent this error.

***ERR:611* H/L CRIT RATIO < 0 IN EMBANK.**

The critical ratio of head to embankment width applied to distinguish high-head flow from low-head flow is negative in the CULVERT (section 5.5) or EMBANKQ (section 5.6) commands. This is not possible, and the ratio is set to the default of 0.15 for flow over embankment-shaped weirs.

***ERR:612* H/L MAX RATIO < 0 IN EMBANK.**

The maximum ratio for head to embankment width applied to issue a warning message is negative in the CULVERT (section 5.5) or EMBANKQ (section 5.6) commands. This is not possible, and the ratio is set to the default of 0.32 for flow over embankment-shaped weirs.

***ERR:613* aa IS AN UNKNOWN UNITS OPTION.**

The units option must be either METRIC or ENGLISH and the input must begin in column 9.

***ERR:614* MAXIMUM NUMBER OF SUBSECTIONS= nn EXCEEDED IN REASUB.**

In the process of reassigning subsection numbers to avoid noncontiguous applications of the same subsection, more subsection numbers have been added than can be currently stored in FEQUTL. The parameter PMXSUB must be increased in ARSIZE.PRM (appendix 2), and FEQUTL must be recompiled and linked.

***ERR:615* NEWBETA FAILURE. VALUE < 1**

Estimates of the kinetic-energy-flux and the momentum-flux correction coefficients are computed in the NEWBETA option. These coefficients should never be less than 1.0, but a value less than 1.0 has been computed.

***ERR:616* RISE AND SPAN MUST BE > 0 FOR TYPE: BOX**

Both the rise and span for a box culvert must be given in the MULCON command (section 5.16).

### *ERR:617* NO CONTROL FOUND FOR TRANSITION IN FRFTRN WITH RESERVOIR.

A control for a transition could not be found in EXPCON (section 5.7) computations when one end of the transition was a reservoir. Reducing or eliminating the frictional term by giving the length of the transition as zero may solve the problem. However, the error may indicate that the cross-section information is erroneous or that the critical-flow value in the cross section is invalid.

### *ERR:618* UPSTREAM SECTION OUT OF ORDER IN EXPCON.

The input line with UP as the location designator does not appear in the expected place in the input for the EXPCON command (section 5.7).

### *ERR:619* DOWNSTREAM SECTION OUT OF ORDER IN EXPCON.

The input line with DU as the location designator does not appear in the expected place in the input for the EXPCON command (section 5.7).

### *ERR:620* LOSS COEFFICIENT < 0 OR > 1: ff

The loss coefficient for the proportion of the difference in velocity heads is out of the valid range for the EXPCON command (section 5.7).

### *ERR:621* U TO D COEFFICIENTS AND TABLE NOT FIRST.

The loss coefficient for flow from the upstream section to the downstream section and the table number used to store the results do not appear in the proper place in the input for the EXPCON command (section 5.7).

### *ERR:622* D TO U COEFFICIENTS AND TABLE NOT SECOND.

The loss coefficient for flow from the downstream section to the upstream section and the table number used to store the results do not appear in the proper place in the input for the EXPCON command (section 5.7).

### *ERR:623* EXPCON REQUIRES AT LEAST ONE CROSS SECTION. NONE WERE FOUND.

No cross sections were detected in the input for the EXPCON command (section 5.7).

### *ERR:624* DOWNSTREAM HEADS NON-INCREASING AT: ff

The downstream heads in EXPCON (section 5.7) must be increasing. A decrease has been found.

### *ERR:625* TAB#= nn OVERFLOW SEEKING NORM. DEPTH FOR FLOW= ff TABLE MAXARG= ff

Normal depth cannot be calculated for the given flow. The cross-section table maximum argument has been exceeded. If the flow is unreasonable, some other error may be present in the input. If the flow is reasonable, a problem may be present with the cross-section table, or a problem may be present in the solution method.

### *ERR:626* TAB#= nn UNDERFLOW SEEKING NORM. DEPTH FOR FLOW= ff

Normal depth cannot be calculated for the given flow. The depth has become zero in the process. If the flow is zero, some other input error may be the cause, or an error is present in the solution method.

### *ERR:627* SLOPE OF CHANNEL IS STEEP.

The slope of the channel is steep for this flow level. Either the channel should be made rougher or the slope should be reduced so that the flow will remain subcritical. CHANRAT (section 5.3) is valid only when the flow is subcritical at all flow levels in the channel.

***ERR:628*  CHANNEL LENGTH ≤ 0.0. MUST BE > 0.0.**

The channel length must be positive in CHANRAT (section 5.3) to be valid.

***ERR:629*  ERRKND= nn INVALID. RANGE 0 THROUGH 3.**

An invalid range for the error kind for integration in CHANRAT (section 5.3) has been detected. This error should not appear unless the user is trying to override the default value.

***ERR:630*  UPSTREAM HEADS NON-INCREASING AT: ff**

A nonincreasing sequence of upstream heads has been detected. They must be strictly increasing.

***ERR:631*  NO SOLUTION IN SFPSBE. YC= ff Q= ff**

A solution for the steady-flow profile in a culvert cannot be calculated. The critical depth and the flow are given in the error message. This error can result for many reasons. It may indicate a problem in the solution pattern for culverts.

***ERR:632*  AT ELEVATION= ff SUBSECTION AREA ≤ 0 IN SUBSECTION NUMBER= nn CHECK FOR INPUT ERROR OR SWITCH TO NAVM= 1.**

A subsection of a cross section with a negative area has been found in the input. This indicates that there is an input error resulting in a large overhang in the channel wall or that an overhang is present. If a large overhang is present, then the method of applying a wetted-perimeter weighted-average value of roughness will have to be used.

***ERR:633*  ONLY ONE POINT REMAINS ON THE CROSS SECTION. AUTOMATIC EXTENSION REQUIRED TO COMPUTE.**

Only one valid point is present in the cross section. This could result if a table is developed to represent the subsection of the stream for CHANRAT (section 5.3) at a culvert or overflow dam. Extension of the low end of the cross section may be done if the boundary at the low side of the section can be treated as frictionless. Otherwise, one or more points should be added to the section description to extend the low side to match the elevation of the high side.

***ERR:634*  Not in use.**

***ERR:635*  Not in use.**

***ERR:636*  Not in use.**

***ERR:637*  LINES OUT OF ORDER. LAST LINE READ:**

A particular line type was expected in the HEC2X command (section 5.15), but it was not read. For example, if the number of points for the GR lines is incorrect on the X1 line of the HEC-2 (U.S. Army Corps of Engineers, 1990a) input, this error will be issued if there are not enough GR lines present. This also can result with X4 and NH lines.

***ERR:638*  GR LINES FOUND BUT NC OR NH LINE MISSING.**

X1 and GR lines have been read in HEC2X (section 5.15) but values of *n* are unknown. Thus, an NC or NH line is missing in the HEC-2 (U.S. Army Corps of Engineers, 1990a) input.

***ERR:639*  X1 REFERS TO PREVIOUS GR DATA BUT NO GR DATA ARE IN HAND.**

An X1 line has indicated that the previous GR lines should be used for the ground points, but the previous GR lines have not been read in HEC2X (section 5.15). Lines may be out of order in the HEC-2 (U.S. Army Corps of Engineers, 1990a) input.

***ERR:640*   NUMNH= nn > 20 ON NH LINE.**

Limit for the number of *n* values on an NH line in the HEC-2 (U.S. Army Corps of Engineers, 1990a) input used in the HEC2X command (section 5.15) has been exceeded.

***ERR:641*   NELT= nn > 20 ON X4 LINE.**

The limit for the number of added ground points on the X4 line in the HEC-2 (U.S. Army Corps of Engineers, 1990a) input used in the HEC2X command (section 5.15) has been exceeded.

***ERR:642*   NH LINE DOES NOT COVER CROSS SECTION.**

The last station on the NH line in the HEC-2 (U.S. Army Corps of Engineers, 1990a) input is less than the last station for the current definition of the ground points for the cross section. Thus, the specification of the horizontal variation of Manning's *n* stops before the end of the cross section is reached.

***ERR:643*   MANNING n= ff <= 0 IN SUBSECTION nn**

A value less than or equal to zero for Manning's *n* has been detected in the given subsection in the HEC-2 (U.S. Army Corps of Engineers, 1990a) input. Probable error in the format of the input so that the value is set to zero in the HEC2X command (section 5.15).

***ERR:644*   TABLE IS NOT FOR CLOSED CONDUIT. NO CHANGES MADE.**

A cross-section table that does not appear to be a closed conduit has been detected in QCLIMIT (section 5.18) computations. Therefore, no changes to the critical flow have been made.

***ERR:645*   CROSS-SECTION TABLE FOR QCLIMIT MUST BE TYPE=22 OR 25 BUT TYPE= nn FOUND.**

The cross-section table must be of type 22 or 25 in QCLIMIT (section 5.18) computations, but another type has been detected. Probable error in the cross-section table number.

***ERR:646*   aa IS INVALID MODE FOR HEC2X COMMAND.**

An invalid string for the mode has been read in the HEC2X command (section 5.15). Valid modes are: INDIRECT, DIRECT, CHANNEL, indirect, direct, or channel.

***ERR:647*   MANNING'S n = 0 IN SUBSECTION nn VALUE SET TO 1.0. PLEASE CORRECT AND RECOMPUTE.**

A zero value for Manning's *n* has been read in the input to FEQX or FEQXLST (sections 5.8 and 5.10, respectively). A value has been given so that computations can continue, but the conveyance results will be incorrect. The missing value should be supplied and the table should be recomputed.

***ERR:648*   NO UPSTREAM HEADS GIVEN**

No upstream heads have been given for the EMBANKQ command (section 5.6). An ascending series of upstream heads must be supplied and the command must be tried again.

***ERR:649*   DOWNSTREAM LINEAR SINUOSITY IMPOSSIBLE FOR FLOW LINE: aa AT STATION:   ff NO DOWNSTREAM STATION EXISTS.**

The sinuosity cannot be computed in the CHANNEL command (section 5.2) using the downstream-linear option because no downstream station is present.

***ERR:650* PARABOLIC SINUOSITY IMPOSSIBLE FOR FLOW LINE: aa AT STATION: ff. THREE CONSECUTIVE STATIONS NEEDED.**

Three consecutive stations are needed on a flow line for the parabolic sinuosity options to be applied in the CHANNEL command (section 5.2).

***ERR:651* TOO MANY ENTRIES IN LSATAB. NUMBER= nn**

The number of flow lines has exceeded the space provided. The parameter PMXNFL in the INCLUDE file ARSIZE.PRM (appendix 2) must be set larger than the maximum number of flow lines expected, and FEQUTL must be recompiled and linked.

***ERR:652* CROSS SECTION SPACE FULL IN INSPNT. NEED nn POINTS BUT ONLY nn AVAILABLE.**

The space for the boundary points on a cross section has been filled to capacity during insertion of offsets for flow lines. The parameter PMXPNT must be increased in the INCLUDE file ARSIZE.PRM (appendix 2) and FEQUTL must be recompiled and linked.

***ERR:653* PWC SINUOSITY OFFSET= ff NOT IN THE OFFSETS FOR THIS CROSS SECTION.**

The offset for the boundary of the part of the cross section to which a value of PWC sinuosity applies must be one of the offsets in the sequence of boundary points. An offset has been read in the CHANNEL command (section 5.2) that does not match any point on the boundary of the cross section.

***ERR:654* NO VALUES FOUND ON INPUT LINE.**

An input line with a label has no other values. At least one value must be given.

***ERR:655* NO HEADING VALUES AVAILABLE. LINES OUT OF ORDER.**

The flow-line names have not been defined, yet information for the lines has been given. A heading line is missing. The order of the input lines must be checked.

***ERR:656* NUMBER OF SECTIONS > nn. INCREASE PMXSEC AND RECOMPILE.**

Too many cross sections given in a sinuosity-definition table. The parameter PMXSEC must be increased in the INCLUDE file ARSIZE.PRM (appendix 2) and FEQUTL must be recompiled and linked.

***ERR:657* LENG SPECIFIED BUT NO INITIAL STATION FOUND. SPECIFY AN INITIAL STATION BEFORE THE FIRST LENG LINE.**

A LENG line has been read in the CHANNEL command (section 5.2), but the initial station is not known. A station line defining the initial value of stationing for each of the flow lines must be supplied.

***ERR:658* INITIAL STATION MISSING FOR LENG FIELD CONTAINING: ff.**

The LENG field in the CHANNEL command (section 5.2) has a missing initial station value. An initial value must be supplied for that flow line.

***ERR:659* STATION MISSING FOR OFFSET: ff**

The station is missing for the given offset in the CHANNEL command (section 5.2). The missing station must be supplied.

***ERR:660*  NUMBER OF SINUOSITIES:  nn DOES NOT MATCH NUMBER OF STATIONS: nn INPUT OUT OF ORDER?**

The number of sinuosities given or implied by sinuosity options on a SINU line in the CHANNEL command (section 5.2) must match the current number of flow lines.

***ERR:661*  BLANK HEADING IN FIELD NO.:  nn INVALID.**

A blank heading value has been found. A heading must always be given explicitly. There are no defaults.

***ERR:662*  STATION MISSING FOR SINUOSITY= ff**

A sinuosity has been given, but no station has been given in the CHANNEL command (section 5.2). Input might be out of order. The station or length line must be ahead of the other lines for a cross section in the sinuosity-definition table.

***ERR:663*  NUMBER OF OFFSETS= nn INCOMPATIBLE WITH NUMBER OF FLOW LINES= nn**

The number of offsets must match the number of flow lines or be one less than the number of flow lines in the CHANNEL command (section 5.2).

***ERR:664*  LABEL FOR 1-D AXIS NOT FOUND. MUST BE AXIS, axis, OR Axis.**

The flow-line label for the longitudinal axis was not detected in the CHANNEL command (section 5.2). One of the three options shown must be used.

***ERR:665*  LENG VALUE NUMBER nn IS UNDEFINED.**

The value nn on the LENG line in the CHANNEL command (section 5.2) is undefined. A default value may have been used in error, or an earlier error has resulted in this error.

***ERR:666*  STAT VALUE NUMBER nn IS UNDEFINED.**

The nn-th value on the STAT line in the CHANNEL command (section 5.2) is undefined. A default value may have been used in error, or an earlier error has resulted in this error.

***ERR:667*  OFFS VALUE NUMBER nn IS UNDEFINED.**

The nn-th value on the OFFS line in the CHANNEL command (section 5.2) is undefined. A default value may have been used in error, or an earlier error has resulted in this error.

***ERR:668*  SINUOSITY DEFINITION:  aa UNKNOWN. ASSUMING CUBIC.**

A sinuosity-definition identifier is unknown. A cubic spline is applied in CHANNEL (section 5.2) computations as a default.

***ERR:669*  SINUOSITY OPTION:  aa UNKNOWN.  ASSUMING LINEAR.**

A sinuosity-definition identifier is unknown. A linear fit is applied in CHANNEL (section 5.2) computations as a default.

***ERR:670*  THERE ARE:  nn VALUES ON THE LINE BUT ONLY nn HEADING VALUES**

A line of input in the sinuosity-definition table in the CHANNEL command (section 5.2) has a number of items differing from the number of headings.

***ERR:671* INVALID NAME FOR AN INPUT LINE: aa. VALID NAMES ARE: STAT, LENG, OFFS, SINU, HEAD, AND END.**

The input line names also may be in all lowercase in the CHANNEL command (section 5.2).

***ERR:672* CHANGE IN SINUOSITY VARIATION INVALID. CHECK NUMBER OF OFFSETS OR STATIONS.**

The sinuosity variation must be either PWL or PWC and cannot change along a flow line in the sinuosity-definition table in the CHANNEL command (section 5.2).

***ERR:673* NUMBER OF FLOW LINES= nn TOO SMALL. MUST BE AT LEAST TWO FLOW LINES.**

Two flow lines is the minimum number required to define the correction coefficients for channel curvilinearity in the CHANNEL command (section 5.2).

***ERR:674* CHANGE IN DIRECTION OF STATIONING AT STATION: ff INVALID.**

The stationing along the flow lines in a sinuosity-definition table in the CHANNEL command (section 5.2) must always increase or always decrease. A direction change has been read.

***ERR:675* STATION MATCH AT STATION: ff INVALID.**

Two consecutive stations match along a flow line in the CHANNEL command (section 5.2). This is invalid. All stations on a flow line must be distinct.

***ERR:676* INCONSISTENT STATIONING. FLOW LINE STATIONS MUST ALL INCREASE OR MUST ALL DECREASE.**

This error may result from a combination of earlier errors in the CHANNEL command (section 5.2).

***ERR:677* OFFSET= ff ≤ PREVIOUS OFFSET= ff**

Offsets on an OFFS line in the CHANNEL command (section 5.2) must always increase.

***ERR:678* CROSS-SECTION STATION= ff NOT FOUND.**

The given station value could not be detected in the sinuosity-definition table. The CHANNEL (section 5.2) input must be checked for a missing cross section in the sinuosity-definition table or for an extra cross section following the sinuosity-definition table.

***ERR:679* INVALID CROSS SECTION COMMAND: aa IN THE CHANNEL COMMAND.**

Valid cross section commands in the CHANNEL command (section 5.2) are: FEQX, FEQXLST, FEQXEXT, and ENDCHAN.

***ERR:680* CHANNEL COMMAND ENDED IMPROPERLY. FINISH ENCOUNTERED BEFORE ENDCHAN.**

ENDCHAN should always be used to end the input for the CHANNEL command (section 5.2).

***ERR:681* SPACE OF nn POINTS IN SETMUD TOO SMALL.**

The space available for adding the points defining a mud line has been filled to capacity. The parameter PMXPNT must be increased in the INCLUDE file in ARSIZE.PRM (appendix 2) and FEQUTL must be recompiled and linked.

***ERR:682* CROSS SECTION TYPE= nn NOT SUPPORTED IN GRITTER. USE TYPES: 20, 21, 23, or 24.**

Not all cross-section types are valid in the GRITTER command (section 5.14).

### *ERR:683* FLOW AT SECTION 1 HAS FROUDE NUMBER= ff SEEKING TYPE 1 FLOW LIMIT.

A flow limit for culvert-flow type 1 has been computed in the CULVERT command (section 5.5), but at this limit the Froude number at the approach section is greater than 1. This means that the type 1 limit is invalid. If this results for the lower limit for culvert-flow type 1, the computations continue because the flow at low heads is likely type 0. However, if this results at the upper limit for culvert-flow type 1, then the approach cross section must be changed. Type 0 flow is designed to represent lower flows, not the high flows at the upper limit for culvert-flow type 1. It may be necessary to place an explicit expansion, computed with the EXPCON command (section 5.7), upstream from the culvert. The approach section used for the culvert computations would then be larger than the culvert barrel so that a reasonable limit for culvert-flow type 1 would result.

### *ERR:684* NEGATIVE DEPTH AT SECTION 1 FOR TYPE 1 FLOW WHEN HEAD RATIO LIMIT THERE= ff AND THE CULVERT VERTICAL DIAMETER= ff

The input value of the maximum ratio of head on the culvert inlet to the maximum vertical culvert dimension at the inlet has been used as a first estimate of the water-surface elevation at the approach cross section in the process of finding the limit of culvert-flow type 1 in the CULVERT (section 5.5) computations. The elevation computed on the basis of this ratio produces a negative depth at the approach section. This negative elevation is most likely caused by an error in the invert elevation at the approach section resulting in a large drop, larger than the maximum vertical dimension of the culvert, between the invert elevation of the culvert at the inlet and the invert elevation of the approach section.

### *ERR:685* CULVERT SOFFIT REACHED IN TY1BDY SEEKING A NEGATIVE RESIDUAL.

Subroutine TY1BDY is applied in the CULVERT command (section 5.5) to compute limits for culvert-flow type 1. In the course of these computations, the depth in the culvert inlet has reached the soffit before a negative residual was found. The computations fail because culvert-flow type 1 should not touch the soffit of the culvert. This message may mean that an error has been made in the specification of the culvert.

### *ERR:686* CULVERT INVERT REACHED IN TY1BDY SEEKING A POSITIVE RESIDUAL.

Same as ERR:685 except that the depth in the culvert has reached the culvert invert.

### *ERR:687* UPPER LIMIT FOR TYPE 1 FLOW DOES NOT EXIST. TYPE 0 FLOW FOUND. CULVERT REPRESENTATION MUST BE CHANGED. SEE ERROR MESSAGE SUMMARY.

Supercritical flow has been computed at the approach section (section 1) in the determination of the upper limit for culvert-flow type 1. This means that the flow is probably type 0 and not type 1. However, type 0 flow for high heads is not supported in the CULVERT command (section 5.5). Type 0 flow should be present only at smaller heads when it is likely that the area of the flow in the approaching stream could be smaller than the flow area at the culvert inlet. This means that the flow is expanding and not contracting into the culvert. All published discharge coefficients and theories of culvert-flow assume that the flow is always contracting. Therefore, several assumptions are made in the CULVERT command to represent type 0 flow. An expansion loss as a multiplication factor on the change in velocity head is used to represent the loss. The culvert representation is changed by explicitly including an expansion flow table, computed applying the EXPCON command (section 5.7). The upstream cross section for EXPCON is the approach section at which ERR:687 resulted. The downstream cross section for EXPCON is constructed to be larger in area at all flow levels than the culvert barrel. Therefore, the discharge coefficient for the culvert entrance is valid in this case. In the field, the approach section may be smaller than the culvert opening, but there is always a cross section at some point between the approach section and the culvert inlet that is larger or at least as large as the inlet area. If no cross section meeting these requirements is available, then some part of the culvert barrel is obstructed and an incorrect barrel description results. In FEQ model simulation, the two structures—the expansion and the culvert—would be connected by a short branch, perhaps 1 or 2 ft long. The cross section in this branch is the downstream cross section for the EXPCON command, which is the same as the new approach section for the culvert. The closeness of the expansion and the culvert entrance renders the discharge coefficients for the culvert less valid than if the standard culvert-approach conditions were present.

### *ERR:688* TABLE#= nn HAS TYPE= nn BUT TYPE= 22 OR 25 IS REQUIRED.

The cross-section table is of the wrong type and does not contain the needed values. A table of type 22 or 25 must be entered.

### *ERR:689* FLOW TYPE 6 LIMIT NOT DEFINED. APPROACH AND/OR DEPARTURE ELEVATION UNREALISTIC.

A limit for culvert-flow type 6 may not be computed in the CULVERT command (section 5.5) if the approach or departure reach has an elevation that is above the inlet or outlet soffit of the culvert.

### *ERR:690* ROW ARG.= ff BELOW RANGE IN TABLE#= nn

The argument on the rows of a 2-D table of type 10 is below the minimum value for row arguments in the table. The table must be extended to lower arguments, or the cause of the smaller than expected argument must be determined.

### *ERR:691* ROW ARG.= ff ABOVE RANGE IN TABLE#= nn

The argument on the rows of a 2-D table of type 10 is above the maximum value for row arguments in the table. The table must be extended to higher arguments, or the cause of the larger than expected argument must be determined.

### *ERR:692* COLUMN ARG.= ff BELOW RANGE IN TABLE#= nn

Same as ERR:690 but for columns instead of rows.

### *ERR:693* COLUMN ARG.= ff ABOVE RANGE IN TABLE#= nn

Same as ERR:691 but for columns instead of rows.

### *ERR:694* PUT1D NEEDS LIMIT OF nn FOR FUNCTION TABLE STORAGE BUT CURRENT LIMIT IS nn

Internally computed values are stored in a 1-D function table with the PUT1D subroutine. The space remaining for function-table storage is too small. The given limit indicates the minimum required space. The parameter PMXTAB must be increased in the INCLUDE file ARSIZE.PRM (appendix 2) by at least the increase shown in the message, and FEQUTL must then be recompiled and linked.

### *ERR:695* DROP FROM SECTION 1 TO SECTION 43= nn INVALID. DROP MUST BE > 0.

The decrease in elevation from the approach section (section 1) to the section just downstream from the exit of the culvert barrel (section 43) is the drop for a culvert. A drop must always be present.

### *ERR:696* INITIAL SUBMERGENCE OF ROADWAY FLOW STARTS AT ELEV.= ff BUT CRITICAL-FLOW ELEV.= ff IN CULVERT EXIT. FLOW OVER THE ROAD CANNOT BE COMBINED WITH CULVERT FLOW WHEN CRITICAL FLOW IN THE CULVERT EXIT CAUSES SUBMERGENCE OF FLOW OVER THE ROAD.

The roadway elevation is too low to combine flow over the road with flow through the culvert. To simulate this condition, flow over the road should be suppressed in the CULVERT command (section 5.5) by assigning a large value for the elevation of the roadway crest. The EMBANKQ command (section 5.6) is applied to compute a separate table to represent the flow over the road. The tables computed in CULVERT and EMBANKQ are applied in parallel in FEQ to represent the two different flow paths.

### *ERR:697* NEGATIVE SINUOSITY FOUND AT STATION: ff

A negative sinuosity has no meaning. It probably resulted from use of a cubic spline when the flow-line distances vary rapidly or erratically. Careful specification of the end conditions for the cubic spline can sometimes eliminate the problem. However, application of the LINEAR option for defining the slopes in the CHANNEL command (section 5.2) will always eliminate the problem.

### *ERR:698* NO SUBCRITICAL SOLUTION IN STEADY-FLOW PROFILE. TRY REDUCING STEP LENGTH

A supercritical flow has been detected in the subroutine SFPSBE, Steady-Flow Profile: SuBcritical using Energy. Computation of the steady-flow profile assuming normal depth was attempted, but normal depth could not be computed. An error may be in some user specification, but this error also could result from an error in the program code.

### *ERR:699* NO RESULT AT SECTION 2 FOR FLOW TYPE 0 AFTER 100 TRIES.

A solution at section 2 for culvert-flow type 0 was not obtained in the CULVERT command (section 5.5). Thus, it is assumed that culvert-flow type 0 cannot result.

### *ERR:700* BARREL FLOWS FULL WITH TYPE 0 FLOW. CULVERT REPRESENTATION MUST BE CHANGED. TYPE 0 FLOW INVALID AT THIS FLOW LEVEL. SEE ERROR MESSAGE SUMMARY.

See ERR:687 for how the representation must be changed.

### *ERR:701* FLOW OVER THE ROAD= ff > CRITICAL FLOW AT SECTION 1= ff FOR TYPE 0 FLOW. CULVERT REPRESENTATION MUST BE CHANGED. SEE ERROR MESSAGE SUMMARY.

Culvert-flow type 0 is not computed in the CULVERT command (section 5.5) if the flow over the road is greater than the critical flow at section 1. Flow over the road and culvert-flow type 0 are inconsistent in any case, and the combination should not be used. The change to the representation is discussed under ERR:687.

### *ERR:702* OFFSET ON CREST NON-INCREASING AT OFFSET= ff

The offsets on an embankment crest for the EMBANKQ command (section 5.6) or in the CULVERT command (section 5.5) must always be increasing. The given offset violated this requirement.

### *ERR:703* NUMBER OF UPSTREAM HEADS= nn TOO SMALL TO ADD HIGH-HEAD FLOW LIMIT.

The head corresponding to the high-head flow limit cannot be added to the flow table because no space remains in the list of heads. The parameter PMXNHU must be increased in the INCLUDE file ARSIZE.PRM (appendix 2) and FEQUTL must be recompiled and linked.

### *ERR:704* NUMBER OF UPSTREAM HEADS=nn TOO SMALL TO ADD HEAD AT ROADWAY CREST.

The head at section 1 corresponding to the minimum elevation of the roadway crest cannot be added to the flow table because no space remains in the list of heads. The parameter PMXNHU must be increased in the INCLUDE file ARSIZE.PRM (appendix 2) and FEQUTL must be recompiled and linked.

### *ERR:705* ROUNDING/BEVELING VALUE < 0.0 or > 0.14

The value given for the relative rounding or beveling for the culvert entrance is outside the range supported in the CULVERT command (section 5.5). The range given is that for the tables for type 5 flow. Ranges may be smaller. The range is truncated at the limit of the particular table involved, and a warning message is issued in FEQUTL computations.

### *ERR:706* WINGWALL ANGLE < 0.0 OR > 90.0 DEGREES.

A wingwall angle outside the valid range has been encountered in the CULVERT command (section 5.5).

### *ERR:707* TYPE 5 SUBMERGENCE RATIO < 0.0 OR > 1.0

The ratio of depth to maximum vertical dimension at the exit that causes culvert-flow type 5 to flow full and become submerged is given the value of 0.75 by default and can be changed by the user. A user-selected value outside this range has been detected in the CULVERT command (section 5.5).

### *ERR:708* RATIO OF DEPTH TO VERTICAL DIAMETER <= 0.5 OR >= 1.0

The ratio for the limit for culvert-flow type 1 has been given outside the valid range in the CULVERT command (section 5.5).

### *ERR:709* RATIO OF HEAD TO VERTICAL DIAMETER < 1.0 OR >= 1.5

The maximum head ratio permitted for culvert-flow type 1 or type 2 is given by default as 1.4. This limit may be changed by the user. The user-selected value is outside the valid limit in the CULVERT command (section 5.5).

### *ERR:710* AT LEAST ONE SUBMERGENCE TABLE IS UNKNOWN. BOTH MUST BE KNOWN.

One or both of the tables specifying submergence on the roadway are missing. Both tables must be present even though no flow over the roadway is simulated. Flow over the roadway is always assumed to be possible in the CULVERT command (section 5.5) if the head is high enough. Therefore, the tables are required in all cases.

### *ERR:711* DROP FROM SECTION 1 TO SECTION 43 < 0.01 NOT YET SUPPORTED.

A drop in water-surface elevation between section 1 and section 43 is required in the CULVERT command (section 5.5). Otherwise, computations cannot continue. The restriction is satisfied in many culverts. Recovery of water-surface elevation from section 1 to section 43 may result for steep culverts under submerged flow conditions with a small approach section. Currently in the CULVERT command, a drop in water-surface elevation must be forced for these culverts by increasing APPEXP, EXPFAC, the barrel roughness, or all three.

### *ERR:712* GATE SILL ELEVATION= ff < ELEVATION OF FLOOR OF DEPARTURE REACH= ff

The sill elevation of the underflow gate must be at or above the elevation of the minimum-elevation point of the cross section in the departure reach in the UFGATE command (section 5.20). The bottom elevation in the cross section given in DEPTAB should be compared with the elevation given for SILLELEV.

### *ERR:713* GATE OPENING WIDTH= ff <= 0.0

An invalid gate-opening width has been detected in the UFGATE command (section 5.20). The GATEWIDTH identifier must be followed by a numeric value that is greater than 0.

### *ERR:714* APPROACH LOSS CD <= 0.0 OR > 1.0

The discharge coefficient for approach losses to the underflow gate must be greater than zero and less than one in the UFGATE command (section 5.20). Approach losses to a gate structure commonly are small so that values of 0.95 to 0.99 are realistic. A value of 1.0 is valid because this indicates that no losses in the approach section result or that the contraction coefficient already reflects those losses.

### *ERR:715* CONTRACTION COEF.= ff <= 0.0 OR > 1.0

The contraction coefficient must be greater than zero or less than or equal to one in the UFGATE command (section 5.20).

## *ERR:716* IN UFGATE: FLAG= nn NO SOLUTION aa

This message can appear in 10 different cases in UFGATE (section 5.20) computations. In all cases an error has been detected in applying the method of false position to determine a solution to a nonlinear equation. The flow area in the approach section and in the departure section must always be larger than the flow area in the gate opening. The flow must always contract upon entering the gate opening and must always expand upon leaving the gate opening. Also, other earlier errors should be checked because computations may continue in UFGATE even if errors have already resulted. The previous errors may be the cause of this error. If none of these conditions apply, then the program code may need to be changed. If FLAG= 1, then an interval that contains a root could not be found. Therefore, false position cannot be applied. Linsley, Kraeger Associates of Mountain View, Calif., should be contacted to make program modification. If FLAG= 2, then a root could not be found in 100 attempts using the method of false position. The tolerances for convergence EPSARG or EPSF may be too small in this case. Making the tolerances slightly larger may allow convergence to a root. If changes in the tolerances do not result in convergence to a root, Linsley, Kraeger Associates of Mountain View, Calif., should be contacted to make modifications in the program.

## *ERR:717* GATE SILL ELEVATION= ff < ELEVATION OF FLOOR OF APPROACH REACH= ff

The sill elevation for the underflow gate must be at or above the elevation of the approach section. The bottom elevation in the cross-section table given in APPTAB in the UFGATE command (section 5.20) should be compared with the elevation given in SILLELEV.

## *ERR:718* LESS THAN TWO GATE OPENINGS GIVEN. UFGATE MUST HAVE AT LEAST TWO OPENINGS.

One or less gate opening has been input to the UFGATE command (section 5.20). At least two gate openings must be present for interpolation to be possible in a table of type 15.

## *ERR:719* CROSS SECTION OFFSET NON-INCREASING AT OFFSET= ff

In standard HEC-2 (U.S. Army Corps of Engineers, 1990a) input, the offsets on the boundary for definition of changes in Manning's *n* in the NH lines must match the offsets on the boundary for definition of the cross-sectional shape in the GR lines. Many HEC-2 data sets have been transformed from other computer models that do not specify agreement in the offsets for defining Manning's *n* and channel elevation. In the analysis of such a nonstandard HEC-2 data set, the offsets on the boundary of the cross section are not increasing when addition of a point to the boundary is attempted in the HEC2X command (section 5.15) so that the added point will match the offset given on the NH line.

## *ERR:720* NO SPACE LEFT IN CROSS-SECTION BOUNDARY WHEN ADDING POINT FOR NH LINE.

A point cannot be added to the cross-section boundary in HEC2X (section 5.15) computations for an offset on the NH line that was not on the boundary specified in the GR line of the HEC-2 (U.S. Army Corps of Engineers, 1990a) input data. This results because space for storing cross-section-boundary points is filled to capacity. The value of the parameter PMXPNT must be increased in the INCLUDE file ARSIZE.PRM (appendix 2) and FEQUTL must be recompiled and linked.

## *ERR:721* RELATIVE PROJECTION < 0.

The relative projection for a culvert cannot be less than zero in the CULVERT command (section 5.5).

## *ERR:722* ANGLE OF INLET BEVEL < 0 OR > 90 DEGREES.

The angle for the beveling of a culvert entrance is outside the valid range in the CULVERT command (section 5.5).

## *WRN:nn* MESSAGES

A variety of conditions, which possibly result in problems in the computations, are detected in FEQUTL. The conditions are such that the user is made aware of their presence so that corrective action, if required, can be taken.

### *WRN:501* SUBSECTION VALUE FOR FIRST POINT IS MISSING. SUBSECTION = 1 ASSUMED.

The subsection for the first point on the cross-section boundary is missing. It is assumed that subsection 1 is meant and the computations continue.

### *WRN:502* UNEXPECTED SLOPE AT LEFT END. SLOPE EXPECTED TO BE < 0 AT LEFT BOUNDARY

The left end of the cross section would normally have a downward slope as the channel is entered with the leftmost point higher than any nearby point. A cross section has been detected for which this is not true. If the cross section is a natural or constructed channel but not a closed conduit, the cross section should be checked to make sure that it is meaningful that the leftmost point of the cross-section boundary is lower than the second from the leftmost point. In most cases, such a condition is not correct.

### *WRN:503* UNEXPECTED SLOPE AT RIGHT END. SLOPE EXPECTED TO BE > 0 AT RIGHT BOUNDARY

The right end of the cross section would normally have an upward slope as the channel is exited with the rightmost point being higher than any nearby point. A cross section has been detected for which this is not true. If the cross section is a natural or constructed channel but not a closed conduit, the cross section should be checked to make sure that it is meaningful that the rightmost point of the cross-section boundary is lower than the second from the rightmost point. In most cases, such a condition is not correct.

### *WRN:504* LINE SEGMENT ENDING AT (ff, ff) IS HORIZONTAL AND NOT AT MINIMUM OR MAXIMUM ELEVATION. RIGHT HAND END INCREMENTED BY ff

Every function given in a function table must be strictly continuous. Therefore, it is not possible to have a horizontal line at any other than the minimum or maximum (the case for some closed conduits) elevation in the cross section. Every invalid horizontal line segment is incremented at its right-hand end by the given amount. If this action is not acceptable, the user must increment one end point so that the line is not horizontal.

### *WRN:505* DECREASE IN CONVEYANCE IN SUBSECTION nn AT ELEVATION = ff

The conveyance as computed in the given subsection at the specified elevation has been calculated to be smaller than the conveyance at the previous elevation in this subsection. This is not hydraulically correct unless the cross section has converging walls. Therefore, in a natural channel, the conveyance should always increase with an increase in the water-surface elevation. Additional subsections may need to be added to the cross-section specification.

### *WRN:506* CONVEYANCE NON-INCREASING AT DEPTH= ff

The conveyance for the entire cross section is nonincreasing at the given depth (water-surface height). This message may not be issued even though WRN:505 is issued because the increase of the conveyance in one subsection is larger than the corresponding decrease in conveyance of some other subsection. A decrease in conveyance with an increase of water-surface height is only possible if the walls of the section are converging. Additional subsections may be needed to properly represent the conveyance for the cross section.

### *WRN:507* BRIDGE SKEW < 0 OR > 45. RESET TO: ff DEGREES.

The bridge skew for the Bureau of Public Roads (Bradley, 1970) bridge method is outside the valid range. The value is reset in FEQUTL computations to be within a valid range. This bridge-loss method is no longer supported in FEQUTL, and it remains in the code for the benefit of users with stream-system models developed for versions of the FEQUTL code prior to version 4.0. These users are encouraged to revise the models to apply the WSPRO (Shearman, 1990) bridge routines (section 4.1).

### *WRN:508* PIER SKEW < 0. RESET TO: ff

The pier skew in the Bureau of Public Roads (Bradley, 1970) bridge method is invalid. It is set to a valid value in FEQUTL computations. This bridge-loss method is no longer supported in FEQUTL, and it remains in the code for the benefit of users with stream-system models developed for versions of the FEQUTL code prior to version 4.0. These users are encouraged to revise the models to apply the WSPRO (Shearman, 1990) bridge routines (section 4.1).

### *WRN:509* M > 1 IN MCOMP. K = ff KSUB= ff

The contraction ratio, M, has been detected to be larger than 1.0, which is not possible. This may result from computing the conveyance for a subset of a cross section. The value will not, in general, differ much from 1.0, and the value is reset to 1.0 in FEQUTL computations.

### *WRN:510* FROUDE NUMBER=ff > 1.0 AT XSID=aa

A Froude number at a point in a profile computed in WSPRO that exceeds 1.0 has been detected in WSPROT14 (section 5.22) computations.

### *WRN:511* NUMBER OF SIDES= nn TOO SMALL. NSIDES RESET TO 10

The number of sides requested for the polygon approximation to a pipe is too small in the MULPIPES (section 5.17) or SEWER (section 5.14) commands. The value is reset to 10 in FEQUTL computations.

### *WRN:512* NUMBER OF SIDES= nn TOO LARGE. NSIDES RESET TO nn

The number of sides requested for the polygon approximation to a pipe is too large in the MULPIPES (section 5.17) or SEWER (section 5.19) commands. The number of sides is reset to the given value. The number of sides is set to the maximum number of points in a cross section less four. This number is more than adequate to approximate a pipe. Application of 20 to 30 sides yields an approximation that is within a fraction of a percent of the true values computed from a perfect circle. Most commercial pipes are not manufactured to this accuracy.

### *WRN:513* NUMBER OF SIDES= nn TOO SMALL. NSIDES RESET TO 10

See WRN:511.

### *WRN:514* NUMBER OF SIDES= nn TOO LARGE NSIDES RESET TO nn

See WRN:512.

### *WRN:515* NO OUTPUT FILE NAME FOR MODE=CHANNEL. USING NAME: CHANNEL

No file name has been given for the output of the CHANNEL command (section 5.2). The name CHANNEL is used and processing continues.

### *WRN:516* MORE THAN ONE LEFT BOUNDARY. ONLY FIRST ONE RETAINED.

In the elevation-defined floodway (section 5.12), more than one left boundary has been found at the given elevation. Only the leftmost boundary has been retained, and the others are taken to be the boundaries of islands.

***WRN:517* MORE THAN ONE RIGHT BOUNDARY. ONLY LAST ONE RETAINED.**

In the elevation-defined floodway, more than one right boundary has been found at the given elevation. Only the rightmost boundary has been retained, and the others are taken to be the boundaries of islands.

***WRN:518* ONE OR MORE ERRORS FOUND. TABLE FILE IS INCOMPLETE OR INVALID.**

If an error is detected in processing the current command, the computations in FEQUTL skip to the next command. When this results, the table computed in the current command was not computed. The table file specified will contain all the tables from the successfully completed commands, and no indication that the table file is incomplete will be given. The output must be searched for the string *ERR: to find all reported errors.

***WRN:519* FREE FLOW= ff DECREASES AT DOWNSTREAM HEAD= ff**

Free flow normally should not decrease with an increase in downstream head. This probably results from a decreasing value of critical flow in one or both cross sections of the transition. Use of the NEWBETAE option can sometimes correct the problem.

***WRN:520* CELERITY DECREASES BY ff PERCENT AT DEPTH= ff**

In compact cross sections (cross sections in which the hydraulic radius and the hydraulic depth increase with the water-surface height), the celerity will never decrease as the water-surface height increases. The meaning of celerity and the related concepts of critical depth and critical flow in noncompact cross sections is unclear. A decrease in celerity with an increase in water-surface height may or may not result in subsequent computational problems. Therefore, it is important in the computation of critical-flow tables (section 5.4) and in the computation of the generalized-Ritter dam-break flood peak (section 5.14) to be aware of cross sections in which the celerity decreases with increasing water-surface height.

***WRN:521* CRITICAL FLOW DECREASES BY ff PERCENT AT DEPTH= ff**

In compact cross sections (cross sections in which the hydraulic radius and the hydraulic depth increase with the water-surface height), the flow rate at critical flow will never decrease as the water-surface height increases. In noncompact cross sections, the critical flow as computed can decrease. It is not yet clear what this decrease means. Therefore, in the computation of a critical-flow table it is unwise to use a cross section for which the critical flow decreases with increasing water-surface height.

***WRN:522* ESCOF. TABLE BELOW RANGE IN XLOOKW TABLE NUMBER = nn STATION NUMBER = ff DEPTH = ff**

The depth (water-surface height) is less than the minimum depth available in the Escoffier table. This message should not appear and may indicate a bug in the GRITTER command (section 5.14).

***WRN:523* ESCOF. TABLE ABOVE RANGE IN XLOOKW TABLE NUMBER = nn STATION NUMBER = ff DEPTH = ff**

The depth (water-surface height) is greater then the maximum depth in the Escoffier table. The cross section for the reservoir in the GRITTER command (section 5.14) must be recomputed so that it is somewhat higher than the maximum dam height to be simulated.

***WRN:524* LEFT HAND SUBSET REQUEST OF ff IS LEFT OF CROSS SECTION BOUNDARY OF ff SUBSET REQUEST SET TO THE CROSS SECTION BOUNDARY**

The offset for the left-hand end of a cross-section subset is off the cross section on the left end in the computation of a floodway, an explicit request for a subset of the cross section, or the contraction ratio in the Bureau of Public Roads (Bradley, 1970) bridge-loss method. The subset boundary is reset to the left end of the cross section and the computations continue.

***WRN:525* RIGHT HAND SUBSET REQUEST OF ff IS RIGHT OF CROSS SECTION BOUNDARY OF ff SUBSET REQUEST SET TO THE CROSS SECTION BOUNDARY**

The offset for the right-hand end of the subset is off the cross section on the right end in the computation of a floodway, an explicit request for a subset of the cross section, or the contraction ratio in the Bureau of Public Roads (Bradley, 1970) bridge-loss method. The subset boundary is reset to the right end of the cross section and the computations continue.

***WRN:526* INVALID RESPONSE FOR USGSBETA. TAKEN AS: NO**

The valid responses to the USGSBETA (section 5.1) are YES or NO. All requests other than YES are taken to be NO. This warning is issued to alert the user to the possibility of an input mistake.

***WRN:527* GIVEN SPAN= ff DIFFERS FROM TABLE SPAN= ff BY > 2%**

The span inferred from the given rise for a reinforced-concrete arch pipe differs by more than 2 percent from the span given in the input. This might indicate an input error, that the pipe is not a pipe arch, or that the pipe does not conform to the standard dimensions programmed in MULCON (section 5.16).

***WRN:528* EQIV. DIA. FROM SPAN= ff DIA. FROM RISE= ff DIFFERENCE INDICATES POSSIBLE ERROR.**

The equivalent diameter of a nominal-elliptical pipe computed from the given span and also computed from the given rise differ by more than 3 percent in MULCON (section 5.16).

***WRN:529* TABLE NUMBER: nn HAS SLOT WIDTH= ff. MAY NOT BE OF A CLOSED CONDUIT.**

The width of the slot in a closed-conduit cross section is checked in FEQUTL. This warning is issued if the slot width is greater than 0.07 and if the cross section is used in a context that requires a closed conduit.

***WRN:530* TEL AT SEC. 2= ff > TEL AT SEC. 1=ff**

The elevation of the total-energy line is checked in the CULVERT command (section 5.5) and any increases in the downstream direction are reported. If the error is small, it may be reasonable to ignore it. The check is sometimes invalid or misleading when flow over the roadway is large relative to the flow through the culvert. Further testing is needed to develop a more refined check.

***WRN:531* TEL AT SEC. 3= ff > TEL AT SEC. 2= ff**

The elevation of the total-energy line is checked in the CULVERT command (section 5.5) and any increases in the downstream direction are reported. If the error is small, it may be reasonable to ignore it. The check is sometimes invalid or misleading when flow over the roadway is large relative to the flow through the culvert. Further testing is needed to develop a more refined check.

***WRN:532* TEL AT SEC. 4= ff > TEL AT SEC. 3= ff**

The elevation of the total-energy line is checked in the CULVERT command (section 5.5) and any increases in the downstream direction are reported. If the error is small, it may be reasonable to ignore it. The check is sometimes invalid or misleading when flow over the roadway is large relative to the flow through the culvert. Further testing is needed to develop a more refined check.

***WRN:533* INVALID HEADWATER RATIO= ff IN FCD123 AT Z1= ff RESET TO MAXIMUM.**

The head-water ratio for a pipe culvert for culvert-flow types 1, 2, and 3 exceeds the maximum of about 1.6 in the figures developed by Bodhaine (1968).

## *WRN:534* UNABLE TO FORCE TYPE 6 Cd TO MATCH TYPE 1 FLOW AT ITS LIMIT. USING TYPE 6 Cd. MANUAL ADJUSTMENT OF 2-D TABLE MAY BE NEEDED.

The transition between culvert-flow type 1 and type 6 is smoothed in the CULVERT command (section 5.5) by selecting the coefficient of discharge for culvert-flow type 6 so that full-barrel flow can match the culvert-flow type 1 at its limit. This match was not possible because the matching coefficient of discharge could not be determined.

## *WRN:535* TEL AT SEC. 4= ff > TEL AT SEC. 1= ff

The elevation of the total-energy line is checked in the CULVERT command (section 5.5) and any increases in the downstream direction are reported. If the error is small, it may be reasonable to ignore it. The check is sometimes invalid or misleading when flow over the roadway is large relative to the flow through the culvert. Further testing is needed to develop a more refined check.

## *WRN:536* NO EXPANSION OF FLOW IN DEPARTURE REACH.

There is a contraction of flow in the departure reach. Current experience indicates that this is a frequent occurrence at low to moderate flow rates. However, this is a departure from the standard culvert tests used to determine exit losses. Therefore, special judgments have been made in computation of the losses in this case. The departure section may not represent the departure reach, an error in the cross sections may be present, or an error in an elevation may be present in the CULVERT command (section 5.5) input.

## *WRN:537* TAB#= nn OVERFLOW SEEKING XS1 DEPTH FOR FLOW= ff IN APPRO.

A solution for the approach reach could not be computed in the CULVERT command (section 5.5) even though the approach cross section has been overtopped. This sometimes results during the process of finding a solution. If the warning persists, the cross section should be extended to some high value or the CULVERT input should be reviewed for errors. Too much flow over the roadway could be a possible cause for the message.

## *WRN:538* FRD. NUM.= ff > 1 FOR BOX CULV TYPE 3 FLOW. AT DEPTH= ff

A Froude number greater than 1 by an internally set tolerance has been detected when computing the loss for culvert-flow type 3 in a box culvert with the CULVERT command (section 5.5). This can result especially at the onset of submergence when the loss coefficients have small inconsistencies. The value is set to 1.0 and the discharge coefficient for free flow is applied.

## *WRN:539* NO ROOT FOR TYPE 1 FLOW. TRYING TYPE 2.

A root for culvert-flow type 1 has not been computed in the CULVERT command (section 5.5), and computations for culvert-flow type 2 are being attempted. This message may indicate some special problems with the computations. However, the flows often appear to be reasonable when this message is issued.

## *WRN:540* NO POSITIVE RESIDUAL FOR TYPE 2 FLOW.

Informative message showing some aspects of the computation process in the CULVERT command (section 5.5). This message may indicate special problems in some cases.

## *WRN:541* NO NEGATIVE RESIDUAL FOR TYPE 2 FLOW.

Informative message showing some aspects of the computation process in the CULVERT command (section 5.5). This message may indicate special problems in some cases.

***WRN:542* AT UPSTREAM HEAD= ff FREE-FLOW TYPE UNCLEAR. UNABLE TO CONTINUE.**

It is possible that an unanticipated flow pattern results, and this pattern cannot be properly interpreted in the flow-classification scheme. In this case, the free-flow type may not be identified in FEQUTL. Sometimes the output to the point of failure can help the user in correcting the problem. In other cases, the program must be changed. If program changes appear to be required, Linsley, Kraeger Associates of Mountain View, Calif., should be contacted.

***WRN:543* NO CONVERGENCE ON DEPTH FOR So=Sc. LAST RELATIVE CORRECTION= ff CONTINUING WITH LATEST ESTIMATE OF DEPTH.**

A search and inverse interpolation are done in the CULVERT command (section 5.5) for the depth (water-surface height) at which the critical slope for a conduit matches the slope of the conduit invert. This interpolation sometimes has insufficient accuracy and subsequent computations fail. Therefore, the interpolation result is refined with an approximation to Newton's method. Sometimes the interpolation result fails to converge to the requested tolerance, and the last result is used and computations continue in the CULVERT command. The poor convergence often results at small depths. The interpolation can be improved, in some cases, if additional points are forced into the conduit cross-section description. This can be done by applying the DZLIM option (section 5.1) in the computation of the table for the conduit. However, care is required because a small DZLIM may increase the number of depth values above the number allowed. Computation for too many depth values should only result for rather large culverts. The conduit tables should be computed with a separate FEQUTL run if DZLIM is applied because the DZLIM option is global, applying to all cross-section tables computed in FEQUTL.

***WRN:544* ROUNDING VALUE= ff > 0.03 TAKEN AS 0.03 FOR FIGURE 16.**

The maximum rounding or beveling value specified for the figures used to determine if flow is type 5 or type 6 for rough pipe culverts is 0.03 (Bodhaine, 1968). Therefore, all values greater than 0.03 are set to 0.03 for table look-up calculations in the CULVERT command (section 5.5).

***WRN:545* HEAD TO WIDTH RATIO= ff > MAX RATIO= ff**

The head to embankment width ratio for an embankment-shaped weir exceeds the maximum ratio. This warning is issued only once even though the condition may occur more than once for a given embankment. This message indicates that the heads may be large enough to invalidate the computed flows because the nature of the flow over the embankment at high heads may not be properly reflected in the weir-coefficient tables. The maximum ratio of 0.32 for embankment-shaped weirs is the approximate limit of experimental verification of the weir-coefficient variation with head.

***WRN:546* LENGTH TO DIAMETER RATIO= ff > 35 WHEN FINDING LIMITING SLOPE FOR TYPE 6/5 BOUNDARY. VALUE IS INACCURATE.**

The figures specifying the criteria for classifying flow as type 5 or type 6 do not go beyond a length to diameter ratio of 35 (Bodhaine, 1968). Values greater than this are set to 35 for table look-up calculations in the CULVERT command (section 5.5). This will lead to some inaccuracy.

***WRN:547* ROAD IS LOWER THAN A CULVERT SOFFIT ELEVATION.**

This warning may indicate an input error in certain cases.

***WRN:548* UNWISE USE OF SUBSECTION NUMBERS SUBSECTIONS HAVE BEEN ADDED TO AVOID REPEATED USAGES. OLD NSUB= nn NEW NSUB= nn PLEASE CHECK FOR VALIDITY**

A unique subsection number must be assigned to each portion of the cross-section periphery with a different roughness, a noncompact shape, or both. Thus, repeated subsection numbers can only appear in an unbroken sequence in the input. New subsection numbers are added in FEQUTL computations to meet this requirement. The roughness values for the new subsection numbers are retained from the old subsection. For example, a concrete-lined channel with a concrete-covered berm must contain at least two subsections to account for the noncompact shape caused by the berm. The roughness is the same for each subsection. A wide, rectangular channel with only part of the channel bottom paved also will require more than one subsection to account for the change of roughness without a change in shape.

***WRN:549* BETA OPTION MUST BE "OLDBETA". THE OPTION HAS BEEN RESET TO "OLDBETA".**

NEWBETA can only be applied to a cross section with no decrease in the offsets.

***WRN:550* EXPCON COMMAND MAY NOT CONVERGE BECAUSE CRITICAL FLOW/CELERITY DECREASES IN TABLE#= ff**

Several assumptions are made about the variation of critical flow in the solution process for the EXPCON command (section 5.7). When overbank flow is simulated, critical flow and velocity may decrease. This may yield incorrect solutions in EXPCON. Unrealistic variation in the results must be checked. The root of the problem is that the concept of critical flow does not extend easily to compound channels. It has been observed in previous computations that one of the free flows may decrease to a completely invalid value. Sometimes a variation in the downstream head sequence can solve the problem. Changes in some of the loss values also may solve the problem.

***WRN:551* CHANRAT COMMAND MAY NOT CONVERGE BECAUSE CRITICAL FLOW/CELERITY DECREASE.**

Several assumptions are made about the variation of critical flow in the solution process for the CHANRAT command (section 5.3). When overbank flow is simulated, critical flow and velocity may decrease with increasing water-surface height. This may yield incorrect solutions in CHANRAT. Unrealistic variation in the results must be checked. The root of the problem is that the concept of critical flow does not extend easily to compound channels. Sometimes a variation in the upstream head sequence can solve the problem.

***WRN:552* RESIDUAL AT CONV.= ff > 0.01 TYPE 2 FLOW NOT POSSIBLE.**

Computations for culvert-flow type 2 did not converge. Thus, another flow type will be computed in the CULVERT command (section 5.5).

***WRN:553* (PIEZOMETRIC HEAD)/(WEIR HEIGHT)= ff > 4. WEIR FLOW MAY BE INVALID.**

In EMBANKQ (section 5.6), the weir coefficients are determined under the assumption that the weir height is large enough to have flow over a weir and not flow over a sill. The boundary between the two flow types is not distinct. A warning is issued at a ratio of 4 to indicate that the ratios are becoming large. The flow over the weir at each point in EMBANKQ computations is limited to critical flow in the approach section. Flow over a sill can be approximated with this assumption. However, if the flow is deep (greater than four times the height of the sill), the sill becomes more like a roughness element of the channel boundary and the assumption of critical depth may no longer be valid.

***WRN:554* EXTENDING LEFT END OF CROSS SECTION BY ff FEET.**

This message is issued whenever a cross-section execution is extended on the left end (the end with the smaller values of offsets) to compute the table of cross-sectional hydraulic characteristics. This extension is only applied if the EXTEND option (section 5.1) of FEQUTL is selected.

***WRN:555*  EXTENDING RIGHT END OF CROSS SECTION BY ff FEET.**

This message is issued whenever a cross-section elevation is extended on the right end (the end with the larger values of offsets) to compute the table of cross-sectional hydraulic characteristics. This extension is only applied if the EXTEND option (section 5.1) of FEQUTL is selected.

***WRN:556*  SOME POINT IN CROSS SECTION HIGHER THAN EITHER END. ALL AREA ABOVE MINIMUM END ELEVATION IS IGNORED.**

A point other than the end points of the cross section has been detected as the highest. The table computations are limited to the minimum-end-point elevation because a high internal elevation is indicative of an error.

***WRN:557*  AT ELEVATION= ff SUBSECTION= nn IS A SINGLE VERTICAL LINE SEGMENT. ACTS AS A FRICTIONLESS WALL.**

A subsection consisting of a single vertical line has no area. Its perimeter does not belong to any other subsection so that it is in effect a frictionless boundary. If this is not what is desired, the input must be changed so that the subsection includes an area.

***WRN:558*  VERTICAL EXTENSION OF A CROSS SECTION END IN ORDER TO MATCH THE OTHER END'S ELEVATION MAY LEAD TO NONSENSICAL RESULTS.**

This message is issued if the EXTEND= YES option is selected in the input-header block (section 5.1). Once the table is computed, there is no consideration of the extension of one side of the cross section in FEQ simulations. Therefore, any section with a large extension should be checked before application in FEQ. In FEQ simulation, it is assumed that the section contains water at all water-surface levels in the table, and warnings about unrealistic results cannot be issued.

***WRN:559*  INVALID RESPONSE FOR EXTEND. TAKEN AS:   NO**

The valid responses for the EXTEND option in the header block (section 5.1) are NO and YES. Responses other than these will result in a default value of NO.

***WRN:560*  TABLE MAY NOT BE FOR A CLOSED CONDUIT. SLOT WIDTH= ff > 0.07**

A slot width wider than expected for most closed conduits has been detected in the QCLIMIT command (section 5.18). If the slot width is larger than expected, the data must be checked to determine the reason for the difference. The computations will continue as if the slot width is correct.

***WRN:561*  NO OUTPUT FILE NAME FOR MODE=INDIRECT. USING NAME:   INDIRECT**

In HEC2X (section 5.15) the indirect mode has been selected, but no file name has been given. The file name INDIRECT is assigned by default. Computations continue and the output will appear in the file INDIRECT.

***WRN:562*  SLOT HEIGHT= ff < MAXIMUM SOFFIT HEIGHT=ff REDOING WITH INCREASED SLOT HEIGHT= ff**

A slot height that is too small had been detected in the MULCON (section 5.16), MULPIPES (section 5.17), or SEWER (section 5.19) commands. It has been increased to allow the computations to continue.

***WRN:563* ROUGHNESS FACTOR FOR LIMITING SLOPE FOR ROUGH PIPES < 0.10 OR > 0.30. VALUE IS INACCURATE.**

A roughness factor is used to classify culvert-flow as type 5 or type 6 for rough pipes in the CULVERT command (section 5.5). The figures in Bodhaine (1968) for flow classification specify the range of this factor between 0.10 and 0.30. However, pipes with roughness values outside this range may be present in a stream network. The figures in Bodhaine (1968) were extrapolated both to larger and to smaller ranges. Outside of the given range, the accuracy of the computations is unknown.

***WRN:564* ROUNDING VALUE= ff > 0.06 TAKEN AS 0.06 FOR FIGURE 13.**

Culvert-flow is classified as type 5 or type 6 for smooth pipes or box culverts with use of figure 13 in the CULVERT command (section 5.5). The maximum value for rounding/beveling in figure 13 is 0.06, and any larger values are set to 0.06 in table look-up calculations.

***WRN:565* RESIDUAL CONVERGENCE RATIO= ff IN SUBROUTINE INVTM WHEN THE RESIDUAL FUNCTION ARGUMENT HAS CONVERGED. THIS MAY INDICATE A CONVERGENCE PROBLEM.**

The specific force function is inverted in the INVTM subroutine to find conjugate depths for a hydraulic jump. Convergence is checked in two ways in the iterative solution process. In the first way, the relative residual value is computed. In the second way, the relative change in the argument to the residual function is computed. If the successive arguments converge before the residual function converges to zero, a convergence problem may be present. This warning is issued if such a situation arises.

***WRN:566* HEAD RATIO= ff > 5.0 FOR TYPE 5 FLOW DISCHARGE COEFFICIENT. VALUE IS INACCURATE.**

The tables for the culvert-flow type 5 discharge coefficient have not been established above a ratio of head to vertical diameter of 5 in the CULVERT command (section 5.5). However, culverts may be present in the stream network for which this ratio is exceeded. The tables have been extended by extrapolation of a constant discharge ratio above the upper limit. This is inaccurate. If culverts that cause this message to be issued are present, the discharge-coefficient tables should be reviewed. These are usually stored in a file named TYPE5.TAB. If necessary, the extrapolation may be changed to better reflect the conditions of a particular culvert.

***WRN:567* QVSTW: TYPE 1 PROFILE PROBLEMS NOT RESOLVED BY FLOW ADJUSTMENT. MAKING TAILWATER ADJUSTMENTS.**

Submerged flows in the culvert are computed in the subroutine QVSTW in the CULVERT command (section 5.5). Submerged-flow computations for culvert-flow type 1 profiles can be difficult in smooth, steep culverts. A flow adjustment procedure for conditions arising when culvert-flow type 1 is the free-flow type is applied to try to compute these profiles in the CULVERT command. These adjustments sometimes fail and then the downstream water-surface elevation (tail water) is adjusted to a higher level.

***WRN:568* QVSTW: MAKING TAILWATER ADJUSTMENT. OLD TAILWATER LEVEL= ff**

Convergence problems noted in WRN:567 could not be solved by flow adjustment. Therefore, downstream water-surface elevation (tail-water) adjustment is applied in the subroutine QVSTM in the CULVERT command (section 5.5). The old downstream water-surface elevation would have been used without adjustment.

***WRN:569* SUB ATMOSPHERIC HEAD= ff AT SECTION 2 MAY CAUSE CAVITATION AND LOSS OF PERFORMANCE.**

The pressure at the vena contracta near the culvert entrance is estimated in the CULVERT command (section 5.5) when the pipe is flowing full. A table of allowable subatmospheric heads as a function of elevation is included in the CULVERT command. When the estimated pressure becomes less than allowable, WRN:569 is written. This should only result at high heads not often encountered for culverts.

***WRN:570* SUBATMOSPHERIC HEAD= ff AT SECTION 2 IMPOSSIBLE. CULVERT WILL NOT PERFORM AS COMPUTED.**

The subatmospheric pressure computed at the vena contracta in the CULVERT command (section 5.5) has become physically impossible. Therefore, the results computed are invalid. The culvert configuration must be changed, usually by rounding the entrance, to prevent this message from appearing. See WRN:569.

***WRN:571* EXTRAPOLATION NOT DONE. SECTION IS SLOTTED.**

A request for extrapolation of a slotted cross section has been detected and is ignored. Slotted sections are always assumed to extend as high as necessary when they are computed. The methods used for extrapolation of the cross-section function table may not work properly with slotted sections.

***WRN:572* UNABLE TO COMPUTE SUBCRITICAL PROFILE FOR TYPE 2. ADJUSTING CRITICAL DEPTH AND TRYING AGAIN. Y3= ff Q3= ff IS= nn SFLAG= nn**

The water-surface profile for culvert-flow type 2 could not be computed to the entrance of the culvert in the CULVERT command (section 5.5). The profile starts at critical depth at section 3, given by Y3. The critical flow is given by Q3, and this is the flow in the barrel. IS and SFLAG are used to diagnose problems should the adjustment fail. Contact Linsley, Kraeger Associates of Mountain View, Calif., if this warning results consistently for a particular stream system.

***WRN:573* UNABLE TO COMPUTE APPROACH REACH FOR TYPE 2. INCREASING CRITICAL DEPTH AND TRYING AGAIN. Y3= ff Q3= ff**

The depth in the approach reach could not be computed in the CULVERT command (section 5.5) for culvert-flow type 2. The critical depth at section 3, Y3, and the critical flow at section 3, Q3, are increased in an attempt to compute the approach-reach results.

***WRN:574* UNABLE TO FORCE TYPE 6 Cd TO MATCH TYPE 61 FLOW AT ITS LIMIT. USING TYPE 6 Cd. MANUAL ADJUSTMENT OF 2-D TABLE MAY BE NEEDED.**

A culvert-flow type 6 coefficient of discharge for which full-pipe flow matches the culvert-flow type 61 at the type 61 upper limit is sought in the CULVERT (section 5.5) computations. The search may not succeed, and this message is issued when it does not. The transition between the flows may be abrupt enough to require some manual adjustment of the table.

***WRN:575* MINIMUM DEPTH AT SECTION 2= ff REACHED AND NO POSITIVE RESIDUAL FOR FLOW TYPE 0 WHEN HOLDING FLOW OVER THE ROAD FIXED.**

A positive residual for culvert-flow type 0 cannot be computed in the CULVERT command (section 5.5). Under these conditions, it is assumed that culvert-flow type 0 cannot be present in subsequent CULVERT command computations.

***WRN:576* TYPE 0 FLOW HAS TAILWATER AT SECTION 43 HIGHER THAN ROAD CREST OR SUBMERGENCE LIMIT BY ff**

The tail water at section 43 is higher than the submergence limit, indicating that the flow over the road must be submerged; but the computations in the CULVERT command (section 5.5) were done with the assumption of no flow over the road. It is assumed that culvert-flow type 0 cannot be present, and computations continue. However, these computations may not be successful. The culvert representation may need to be changed. See ERR:687.

***WRN:577* TYPE 0 FLOW HAS TAILWATER AT SECTION 43 HIGHER THAN ELEVATION AT SECTION 1. THIS IS PECULIAR BUT NOT IMPOSSIBLE. PLEASE REVIEW INPUT CAREFULLY.**

See WRN:576. The culvert representation should probably be changed in the CULVERT command (section 5.5). The flow length assigned to the flow over the roadway may have to be defined more carefully. The flow length can be difficult to assign because flow may move down the road instead of across the road if curbs and gutters are present and the overflow width is poorly defined.

***WRN:578* UNABLE TO COMPLETE PROFILE WHEN ROADFLOW IS CONSTANT.**

It is assumed in CULVERT (section 5.5) computations that culvert-flow type 0 cannot be present. This may be incorrect, and the representation for the culvert may have to be modified as described in ERR:687.

***WRN:579* TYPE 1 FLOW DROWNED ASSUMING FLOW IS TYPE 2. SLOPE REDUCTION IN CULVERT BARREL.**

An attempt is made in CULVERT (section 5.5) computations to reflect culvert barrels with variable slope. However, the analysis rapidly becomes complex. Drowning of culvert-flow type 1 by type 2 flow usually indicates that the invert slope in the barrel decreases in the downstream direction. If the slope change is too large, it may not be possible to analyze the flows in the CULVERT command.

***WRN:580* UNABLE TO FORCE TYPE 6 Cd TO MATCH TYPE 2 FLOW AT ITS LIMIT. USING TYPE 6 Cd. MANUAL ADJUSTMENT OF 2-D TABLE MAY BE NEEDED.**

In CULVERT (section 5.5) computations, a match between full-barrel flow and culvert-flow type 2 at its upper limit is sought to provide a smooth transition between the two flow types. This may not be possible in all cases, and when it is not, manual adjustment of the flows may be required to avoid an abrupt change in flow at the boundary between the two flow types.

***WRN:581* UNABLE TO FORCE TYPE 61 Cd TO MATCH TYPE 2 FLOW AT ITS LIMIT. USING TYPE 6 Cd. MANUAL ADJUSTMENT OF 2-D TABLE MAY BE NEEDED.**

In CULVERT (section 5.5) computations, a match between culvert-flow type 61 and culvert-flow type 2 at its upper limit is sought to provide a smooth transition between the two flow types. This may not be possible, and the transition between the two flow types may be abrupt enough to require manual adjustment.

***WRN:582* THE CULVERT BARREL HAS SLOPE BREAKS. THE CULVERT COMMAND MAY FAIL.**

The ability to represent culverts with barrels with slope breaks is limited in the CULVERT command (section 5.5). If the breaks are small and never represent a control section, the CULVERT command may prove adequate. However, if the breaks are such that a control section forms, it is unlikely that the computations will be successful. It is sometimes possible to divide such a culvert into two sections with the slope break as the point of division. However, it may be difficult to simulate these culverts because the approach and departure reaches that must be formed at the break are fictitious.

***WRN:583* BETAF < 0.0 FOR TYPE 5 FLOW.**

The adjustment factor for momentum flux for the transition from culvert-flow type 5 to type 4 contains an invalid value. It is set to 0 in the CULVERT (section 5.5) computations. The transition may be abrupt or invalid. The flow table computed for the culvert should be checked by the user.

***WRN:584* KWING= ff IGNORED. APPLIES TO BOX CULVERTS ONLY.**

A value of KWING $\neq$ 1.0 has been found for a culvert that is not a box culvert. The wingwall adjustment factor in the CULVERT command (section 5.5) only applies to box culverts.

***WRN:585*  KPROJ= ff IGNORED. DOES NOT APPLY TO BOX CULVERTS.**

A value of KPROJ ≠ 1 has been found for a box culvert. This adjustment only applies to other types of culverts in the CULVERT command (section 5.5).

***WRN:586*  LEFT OVERBANK n=0.0 ON FIRST NC CARD. SETTING n TO 1.0.**

The initial value for Manning's *n* for the left overbank was found to be zero in the HEC2X command (section 5.15). It is set to 1.0 and computations continue.

***WRN:587*  CHANNEL n=0.0 ON FIRST NC CARD. SETTING n TO 1.0.**

The initial value for Manning's *n* for the channel was found to be zero in the HEC2X command (section 5.15). It is set to 1.0 and computations continue.

***WRN:588*  RIGHT OVERBANK n=0.0 ON FIRST NC CARD. SETTING n TO 1.0.**

The initial value for Manning's *n* for the right overbank was found to be zero in the HEC2X command (section 5.15). It is set to 1.0 and computations continue.

***WRN:589*  FLOWS ARE WITHIN 1 PERCENT. UNAVOIDABLE CONVERGENCE DIFFERENCES MAY CAUSE THE WRONG FLOW TYPE TO BE SELECTED AND THE COMPUTATIONS TO FAIL. IF THIS WARNING RESULTS, CHANGE THE UPSTREAM HEAD TO AVOID THE FLOW MATCH.**

The boundary between culvert-flow types 1 and 2 can be subject to small variations. Whenever the flows used to check for the validity of culvert-flow type 1 are in close agreement, subsequent computational problems are more likely. If computational problems result, the upstream head must be changed in the CULVERT command (section 5.5) to avoid computations close to the boundary between culvert-flow types 1 and 2.

***WRN:590*  TYPE 2 FAILURE AT UPS HEAD= ff <= HEAD AT LOWER LIMIT OF TYPE 1= ff IF HEADS ARE CLOSE, INCREASE UPS HEAD TO EXCEED TYPE 1 LOWER LIMIT.**

It is possible for a culvert to be in flow type 2 at small and moderate water-surface heights and to transition to flow type 1 at higher water-surface heights and then return to flow type 2, or more likely to one of the high-head flows as flow water-surface heights approach the crown of the culvert. Thus, there can be a lower limit at section 1 for culvert-flow type 1 and an upper limit at section 1 for culvert-flow type 1. The upper limit for the lower region of culvert-flow type 2 does not always match the lower limit for the culvert-flow type 1 region. This results because of unavoidable approximations in the loss-coefficient curves and tables and in the treatment of losses. It is therefore possible for the head at section 1 to be at a level such that culvert-flow type 1 computations fail and culvert-flow type 2 computations fail. The correction for this problem is to increment the upstream head value in the CULVERT command (section 5.5) at the point where the problem results so that the upstream head is clearly in the culvert-flow type 1 region. If this value of head was added in CULVERT computations to match the minimum point on the roadway, then the minimum point of the roadway also must be adjusted. The increment usually is very small so that computational accuracy will not be greatly affected as a result of these changes.

***WRN:591*  TYPE 2 FAILURE AT UPS HEAD= ff => HEAD AT LOWER LIMIT OF TYPE 1= ff IF HEADS ARE CLOSE, INCREASE UPS HEAD TO EXCEED TYPE 1 LOWER LIMIT BY A LARGER AMOUNT.**

This message is related to that of WRN:590. The computational failure in the CULVERT command (section 5.5) has occurred because the increment to the head at section 1 placed the flow in the culvert-flow type 1 region, but the computational decision process for culvert-flow type 1 resulted in simulation of culvert-flow type 2. This can result because of the inherent convergence differences in computing the limits for culvert-flow types 1 and 2. See message for WRN:589.

***WRN:592* PLEASE REVIEW RESULTS. ONE OR MORE CASES WITH ENERGY GAIN FOUND.**

A case of energy gain from section 1 to section 4 has been detected in the UFGATE command (section 5.20). This could indicate that the convergence tolerances, EPSF and EPSARG, are too small. The values of these tolerances should be reduced by a factor of two or more and the program run again. If the warning persists, a problem may be present in the solution method for the particular case. Contact Linsley, Kraeger Associates of Mountain View, Calif., with the details of the gate being simulated.

***WRN:593* THE SUPERCRITICAL PROFILE FOR TYPE 5 FLOW IS TOO SHORT. THIS SUGGESTS THAT THE EXPANSION LOSS APPLIED AFTER THE VENA CONTRACTA IS TOO LARGE. THE LOSS WILL BE REDUCED ONE OR MORE TIMES TO FIND A LONGER SUPERCRITICAL PROFILE. THE VALUE OF KD THE EXPANSION LOSS IN THE BARREL MAY BE TOO LARGE. VALUES > 0.4 SHOULD BE AVOIDED.**

Computation of a supercritical profile in the CULVERT command (section 5.5) resulted in a gap between the subcritical profile and the supercritical profile because the profile is so short or does not start at all. This implies that no profile is present in this gap. This cannot be correct because a profile of some sort must be present at all locations in the culvert. Therefore, the estimated losses for culvert-flow type 6 applied downstream from the vena contracta location are reduced until a supercritical-profile length is computed that closes the gap.

***WRN:594* NO SUPERCRITICAL PROFILE OF ADEQUATE LENGTH CAN BE COMPUTED. CULVERT BARREL MAY BE NON-PRISMATIC OR HAVE SIGNIFICANT CHANGES IN SLOPE.**

The gap described in WRN:593 cannot be closed in CULVERT (section 5.5) computations. The CULVERT command computations may succeed with small changes in barrel slope or section. However, the culvert-flow type 5 computations are especially dependent on the assumption of a prismatic barrel. All options available in the CULVERT command to close the gap have been attempted and none have succeeded in closing the gap.