SCOUR AND FILL IN ALLUVIAL CHANNELS

WITH PARTICULAR REFERENCE TO BRIDGE SITES

By D. M. Culbertson, L. E. Young, and J. C. Brice

UNITED STATES DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

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FOREWORD

Bridge-site reports prepared for state highway departments contain information on the hydrologic and hydraulic characteristics of a stream and its channel. Some of these reports deal with problems of scour and fill in alluvial channels or with the behavior and stability of channels whose alinement and location have been established by construction activities. The problem is one of predicting how the stream channel may be altered over a period of time because of the changes caused by construction of a new bridge, or by a channel change, or as a result of both activities.

The authors present information on the state-of-knowledge on understanding the behavior of channels in alluvial materials, information which will be useful to all who prepare bridge-site reports. Next the authors consider the problem of predicting scour and fill at highway crossings and present a basis for making estimates of scour under certain conditions. They reach the general conclusion that methods of predicting scour yield uncertain results and that development of more reliable methods should follow the collection and appraisal of additional field data. Thus they propose a program for compiling case histories on scour and fill as described in Part III. It is our hope that all who receive copies of this report will aid us in improving the ability to predict by providing case histories.

Melvin R. Williams, Chief
Surface Water Branch

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SCOUR AND FILL IN ALLUVIAL CHANNELS

With Particular Reference to Bridge Sites

by

D. M. Culbertson, L. E. Young, and J. C. Brice

INTRODUCTION

Scour and fill in alluvial channels present problems of vital impor tance in the construction of river works or structures. Overdesign of structures or costly maintenance and destruction of roads and bridges have been attributed to erroneous predictions of scour and fill. Reliable predictions depend, first, on an evaluation of the many interrelated hydrologic, hydraulic, and morphologic factors that influence channel behavior under natural conditions and, second, on the degree to which construction of river works or structures may alter the interrelationships between the factors. Much study has been devoted to the cause and effect of these interrelated factors, largely in the laboratory, but additional work is needed before scour and fill can be predicted accurately. Improved bridge-site investigations depend on better knowledge of physicaı laws controlling scour and fill and on full appreciation of the complex factors that influence channel behavior.

Scour as used here applied to the net removal of sediment from the bed and banks by action of fluid flow. Conversely, fill refers to the deposition of material on the bed or at the banks. Potentially destructive scour at bridge sites thus involves not only vertical scour at piers, but also lateral shift of the channel against highway embankments, breaching of embankments during overbank flow, and effects of meander cutoffs and other realinements on channel regimen. An evaluation of all these effects is within the experience and purview of the Geological Survey hydrologist and is essential information for the proper design of bridges and highway embankments by the highway engineer.

Bridge-site reports, which have been prepared by district offices since about 1950 as part of their cooperative highway program, have supplied information on the hydrologic and hydraulic characteristics of a channel at the proposed site of a bridge. Among the kinds of information that have been included are the magnitude and frequency of floods, relation of stage to discharge, flow through proposed openings, and backwater from the proposed constriction. Some bridge-site reports have included predictions of scour and fill at bridge piers, but neither procedures for predicting scour nor a discussion of the scour problem has been made available by the Survey.

The purpose of this report is to suggest methods of data collection and analysis that will increase the usefulness of bridge-site reports. To this end a brief discussion is presented of the problems involved in the evaluation of scour and fill in alluvial channels and of some methods that have been proposed for prediction of scour and fill. This report is an abbreviated statement of what seems now to be a reasonably valid description of channel behavior. In view of the uncertainty of predictions of scour as made from hydraulic theory and empirical equations, the need for case histories--which form a basis for prediction from experience--is clearly apparent. Therefore, a program for the compilation of case histories on scour and fill is recommended, and the scope of such a program is outlined briefly in Part III of this report.

P. C. Benedict and R. W. Carter served as consultants during the preparation of this report. Arrangements for the work were made by M. R. Williams and W. W. Hastings. Of the reference sources that were used in preparation, particular acknowledgment is made to the work of C. R. Neill (1964).

PART I. GENERAL CONSIDERATIONS ON SCOUR AND FILL

Morphologic Properties of Alluvial Channels

For purposes of this report, an alluvial channel is arbitrarily defined as a channel whose bed and banks are formed of unconsolidated earth materials that are subject to measurable scour. Unconsolidated earth materials are composed of particles (or clasts) that range in size from clay to boulders. Most studies of scour apply to particles in the size range of sand and fine gravel (about 1/16 mm to 10 mm in diameter); little is known about scour of cobbles or boulders or of clay.

The properties of an alluvial channel that can be observed in the field or on aerial photographs are here called its morphologic or form properties. Among these are channel pattern, width, sinuosity, bank height, and natural levees, all of which are illustrated and described in the appendix. In addition, the shape of the channel in cross section and the configuration of the bed are regarded as morphologic properties. Inasmuch as the flood plain is closely related to the channel, consideration must also be given to its morphologic properties, such as oxbow lakes, meander scrolls, and width of flood plain in relation to channel width.

For purposes of classification, the most important morphologic properties of an alluvial channel are its pattern and its variability of width. On the basis of these properties, four major types of alluvial channels are distinguished: the sinuous (or straight) uniform channel, the sinuous point-bar channel, the point-bar braided channel, and the bar-braided or island-braided drainage course (fig. 13). The properties of an alluvial channel commonly change from place to place along its course, and a morphologic description therefore applies only to a particular reach, or length of channel that is reasonably homogeneous in its properties. Also, the description properly applies only to a particular flow (or stage), which must be arbitrarily designated.

Even in a given reach, the morphologic properties of a channel change with time, and the nature of this change is referred to as channel behavior. Along a sinuous channel, the position of the thalweg is likely to change with discharge, and the channel as a whole is continuously shifting laterally. The rate of shift is an aspect of channel behavior. Braided channels also shift, as do the positions of their anabranches.

Besides its lateral shift, a channel may also change position vertically as material is scoured from, or added to, its bed.

Factors that Influence Channel Properties and Behavior

According to Lane (1957), the most important variables that influence channel form are (1) stream discharge, (2) longitudinal slope, (3) sediment load, (4) resistance of banks and bed to movement by flowing water, (5) vegetation, (6) temperature, (7) geology, and (8) works of man. These variables are also the most important in channel behavior.

Stream discharge depends on precipitation and on the characteristics of the drainage basin, and it is among the few variables that cannot be modified by the activities of the stream. An alluvial channel becomes adjusted in size to transmit the discharge that it receives, although investigation has not yet established just which measure of discharge is most effective in the establishment of channel size. The most useful single representation of the discharge characteristics of a channel at a particular point is a flow-duration curve, and all the characteristics represented by the curve probably influence channel size and general morphology to some extent. In selecting a particular statistical measure of the flow-duration curve for plotting channel size against discharge, Leopold and Maddock (1953) and Lane (1957) chose average discharge because, for most streams, this is the only readily available measure. However, Leopold, Wolman, and Miller (1964, p. 83) reason that the work of perennial streams in scour and fill and in transport of debris is accomplished principally by flows near or above bankfull stage--flows that occur less than 0.4 percent of the time or roughly once a year.

Leopold and Maddock (1953; see also Leopold, Wolman, and Miller, 1964, p. 215) showed that, at a given cross section, width, depth, and velocity increase systematically with discharge. Also, as the discharge of a stream increases in a downstream direction, width, depth and velocity of the flow (at a given flow frequency) increase systematically with discharge. For the rivers studied average width increases downstream at approximately the 0.5 power of average discharge, average depth as the 0.4 power, and average velocity as the 0.1 power. This does not mean, of course, that all rivers have the same width, depth, and velocity at a given discharge; the absolute values of these depend mainly on the cohesiveness of the banks, and the systematic downstream increase applies only if bank cohesiveness remains constant in a downstream direction. Also, each value of width, depth, and velocity used by Leopold and Maddock applies only to the measured section at a gaging station, which may not be representative of the reach in which the gaging station is located. For some channels, especially pointbar channels and braided drainage courses, the standard deviation of width, depth, and velocity in a given reach is likely to be large.

The longitudinal slope of a channel is initially established by the geologic character of the region through which the channel runs: channel slopes in mountain belts are likely to be steep, whereas channel slopes in plains regions are likely to be gentle. The initial slope is modified to a greater or lesser extent by a stream, or by its ancestral streams. With the passage of time, falls and rapids in the channel tend to be obliterated and the longitudinal profile commonly assumes a shape that is concave upward. For practical purposes, however, the longitudinal slope of a channel is largely predetermined by regional geologic slope, and this predetermined slope has an effect on channel morphology and behavior. See Rubey's remarks (1952, p. 135) on the Missouri River and the Platte River regarding this subject.

The cause and effect relations between predetermined slope on the one hand, and channel morphology and behavior on the other, are complex. It is erroneous to assume that a stream assumes a sinuous (meandering) pattern in order to reduce channel slope relative to regional slope. It is also erroneous to assume that a stream meanders because it is flowing on a low regional slope. The relation between slope and channel pattern is affected by discharge, bank cohesiveness, and size of bed material, as well as other variables. On a given regional slope, a small stream may assume a sinuous pattern because its banks have the requisite cohesiveness relative to discharge; on the same slope, a larger stream may assume a braided pattern because its banks have a lesser cohesiveness relative to discharge. In general, the braided pattern is established when the banks have a low resistance relative to slope and discharge; the sinuous pattern, when the banks have a moderate resistance; and the straight pattern, when the banks have a high resistance. But braiding can arise from causes other than low bank resistance; among these are a large supply of coarse bed material from a melting glacier.

The effects of sediment load depend both on the quantity and the particle size of the load. The quantity of load depends mainly on erosion rate in the drainage basin, and particle size depends on the geology and soils in the basin.

The effects of sediment load on channel morphology and behavior are mainly related to (1) the cohesiveness of the load when deposited as bank material and (2) attainment of the slope required for transport of the bedload. If a stream lacks sufficient slope to transport the material being supplied it from the drainage basin, the channel will fill until sufficient slope is attained. Attainment of the requisite slope may be accompanied by a change from a sinuous to a braided pattern. Leopold, Wolman, and Miller (1964, p. 293) have shown that braided channels (mainly in Wyoming and Montana) typically have steeper slopes than meandering channels, but the cause and effect relations are not resolved.

The effects of bank cohesiveness on channel morphology have already been discussed. Unfortunately, no generally accepted method of sampling banks and expressing cohesiveness as a number has been devised; the major difficulty lies in the lack of homogeneity of most banks. Insofar as particle size alone is concerned, the more clay a bank contains, the more resistant it is to scour. Lenses or layers of sand may cause otherwise resistant banks to erode rapidly. Vegetation is a most important factor in bank resistance. Banks that are resistant because of dense vegetal cover or high clay content are usually associated with a sinuous pattern and a deep narrow cross section; less resistant banks, composed mainly of sand and lacking a vegetal cover, are usually associated with a braided pattern and a wide shallow cross section.

Leopold and Wolman (1957) concluded tentatively that resistance to flow is related to the granular roughness of the bed material and to large-scale irregularities on the bed surface. They believe also that a reach of stream will adjust in velocity, depth, and slope simultaneously to accommodate a change in roughness due to bed form for a given flow and sediment discharge. If the flow and sediment discharge remain steady for a period of time, it is reasonable to assume that the roughness will attain a steady value. However, during periods of rising and falling stages in natural streams the changes in flow conditions may occur too rapidly for the bed to adjust its configuration to the new flow and sediment discharge. In such cases the relationship between bed configuration and flow can be somewhat indeterminate. Therefore fluctuations in flow and sediment discharge may be significant factors in the development of channel pattern.

Because temperature has an effect on other variables that are known to influence channel form, it is listed here as an effective variable; but the precise effects of temperature have not been isolated. In northern regions, the formation of ice jams in the spring causes the water level to rise, promotes meander cutoffs, and increases scour. Freezing of banks in the winter may increase their cohesiveness, but thaw in the spring leads to rapid bank sloughing (Leopold and others, 1964, p. 87). Lane and others (1949) attribute a major increase in sediment transport of the Colorado River in the winter to low-water temperatures. According to Colby and Scott (1965) and Brice (1964) changes in viscosity influence not only the fall velocity and vertical distribution of sediment but also the thickness of the laminar sublayer and the bed configuration and resistance to flow; large sediment discharges and small flow resistances are associated with low temperatures. Obviously, the temperature of a region has an important influence on the kind and density of vegetal cover along the streambanks, and hence on the resistance of the banks.

As a variable in connection with stream morphology and behavior, geology refers to the relief of the drainage basin, the character of the bedrock and soil, and the erosion rate; the effects of these have been discussed. In addition, geology refers to the geologic history of the channel. Most stream valleys have had a long geologic history and may have been occupied in the past by streams that differed substantially in discharge and morphology from the modern stream. The deposits of these ancestral streams, as well as their valley slopes, can have an important influence on the modern stream.

Channel behavior and the works of man have a mutual interaction: the works of man affect the channel, and the channel affects the works of man. This report is mainly concerned with this mutual interaction at bridge sites, as discussed in the section entitled "Causes of Scour and Fill."

In discussing the effects of different variables on channel morphology and behavior, it is implied that morphology and slope are adjusted to the integrated effects of all these variables.

This idea of adjustment is called "quasi-equilibrium" by Leopold, Wolman, and Miller (1964, p. 266) and "regime theory" by Blench (1957). In the literature of geology and geomorphology, streams that exhibit evidence of such adjustability and stability have been called "graded." Mackin (1948, p. 471) defined a graded stream as "one in which, over a period of years, slope is delicately adjusted to provide, with available discharge and with prevailing channel characteristics, just the velocity required for the transportation of the load supplied from the drainage basin." However, Mackin has placed too much emphasis on slope; adjustment of width and channel pattern is equally or more important. If the water velocity in an alluvial channel becomes, for any reason, too great for containment by the bank materials, it can be reduced more effectively by an increase in width (and the accompanying decrease in depth) than by a decrease in slope. See also the arguments of Rubey (1952, p. 135) in this connection. An increase in width may be accompanied by a change in channel pattern from sinuous to braided.

No practical criteria are available for the immediate identification of a graded stream in nature. For practical purposes, it must be assumed that all alluvial channels have attained some degree of equilibrium, and that a pronounced change in any of the controlling variables will lead to scour or fill. The scour or fill may represent only temporary fluctuations about some mean value, or it may represent a long-term trend. If the trend is over a period of years or decades, the tendency to scour is usually referred to as degration, and the tendency to fill as aggradation. Obviously, deep temporary scour can be just as disastrous to a bridge as long-term degradation.

Observations on the Nature of Scour and Fill

Local scour and fill result in the enlargement or reduction of a stream cross section by the removal or deposition of material by the flow. The rate of scour or fill is equal to the difference between the rate of supply and the rate of removal of sediment. If the rate of removal is larger than the supply, scour will occur and the result will be a larger flow section, a decrease in velocity, and a reduction in the rate of scour. According to Laursen (1953, p. 181) the principles of local scour are (1) the rate of scour will equal the difference between the capacity for transport out of the scoured area and the rate of supply of material to that area, (2) the rate of scour will decrease as the flow section is enlarged, (3) there will be a limiting depth beyond which scour will not occur, and (4) this limit will be approached asymptotically.

The above principles apply generally to scour around river structures such as a bridge pier. The maximum depth of scour is believed to be influenced mainly by the width of the pier, alinement of the pier with the flow, the velocity and depth of the approach flow, and the particle size of the bed material. However, because the particle size affects both the transport capability and the rate of removal from the scour area, the important effect of particle size is on the side slope of the scour hole; the slope is about equal to the angle of repose of the bed material in water. Theoretically scour must cease when the velocity component at the bed is not large enough to cause sufficient shear at the bed to move the particles. Laursen (1956, p. 35) concluded on the basis of laboratory experiments that "as a first approximation the equilibrium scour depth, with certain qualifications as to flow conditions, appears to be a function only of the geometry, i. e., the relative depth of flow, the shape of the pier, and the angle of attack." According to these experiments neither the velocity of flow nor the size of bed material (within the size range of sand) affects the scour around bridge piers. In natural streams it seems reasonable to assume that the size of bed material as well as other variables do, in fact, influence the depth of scour.

Scour in a reach of alluvial channel may be defined as a net lowering of the average bed altitude in the reach. Local scour refers to the net removal of material from a place in the channel. In many alluvial channels, the bed profile of a reach over a period of time may fluctuate widely about an average position; over a period of years the reach may be either degrading or aggrading as a result of a change in the supply of sediment or other natural alluvial processes. The magnitude of these fluctuations in a straight uniform channel is sometimes erroneously assumed to be high when based on measurements of local scour at a point on the streambed or at one cross section of the stream. Colby (1964b) shows that such measurements usually reflect local alternate scour and fill common in sand-bed streams during runoff events. Even though the composition of the streambed may remain constant throughout a flood, scour (or fill) is limited by the amount of sediment transported and by changes in the rate of sediment transported along the reach. Thus, scour of a channel reach can occur only when the rate at which material supplied to the reach is less than (or more than) the rate at which material is transported from the reach.

This concept of continuity implies a relation between sediment discharge and the characteristics of flow. It should be recognized, however, that the discharge of fine sediment is more closely controlled by factors such as the supply in the drainage basin, intensity of precipitation, and rates of runoff than by the characteristics of flow at a cross section. Moreover, except in reaches where velocity and turbulence of flow are greatly reduced, fine sediment (silt and clay) being transported in the channel generally remains in suspension. Usually, the quantity of fine sediment entering a reach also leaves the reach. Therefore, scour and fill are related almost entirely to the discharge of sand and coarser material and are affected only indirectly by the fine sediment in transport.

The amount of material in transport at a given time limits the rate of scour and fill in channel reaches more than is commonly understood. For example, if all the sand in a flow having a depth of 10 feet and a concentration of 1,000 ppm (parts per million) were deposited instantly, the deposited layer would have a thickness less than 0.008 foot if a weight 85 lbs per cubic foot is assumed for the deposited sand. Conversely, if 0.5 foot of sand of the same underwater weight were instantaneously removed from a long reach of channel and entrained in a clear flow 10 feet deep, the resulting concentration would be about 68,000 ppm--an unreasonable concentration of sand.

Bed changes involving redistribution of large volumes of bed material may result in a change in the shape of the cross section and of the longitudinal bed profile. Although the average altitude of the bed may or may not change, the hydraulic character of the channel may be affected considerably by the redistribution. The most marked bed changes of this type are brought about by the dynamic action of the water in the bends. The high velocities on the outside of the bends scour the bed and create pools in the bends. The material scoured from the bends tends to deposit and form bars where the velocity in the river becomes more or less uniform across its width in the crossings between bends. The result is relatively shallow water depths over the crossing bars and greater depths on the outsides of the bends. This pattern does not remain static, for with increasing discharge the pools tend to be scoured deeper and the crossing bars tend to increase in altitude. When the river stage then falls, the high crossing bar remains, but this condition is relieved in time as the river scours the bar to conform with the lower discharge and relatively higher velocity over the bar. Immediately after a rise the water-surface profile is likely to resemble a series of steps with flat slopes in the bends where the water is deep, and the velocity and friction losses are low and with steep slopes between the bends where the velocities and the frictional and form resistances are high.

Causes of Scour and Fill

Each of the circumstances described below can cause, or can be associated with, scour and fill in alluvial channels. Some of these circumstances are due wholly or in part to a bridge or its appurtenant works, and others are not. Of the circumstances not due to a bridge, some are artificial and some are natural. It is not possible to predict with certainty the effect of any given circumstance, but the probable effect can be predicted from theory and experience.

Increase in Stream Discharge

Other variables remaining constant, an increase in discharge is accompanied by an increase in velocity, which is likely to scour the bed and the banks; the increase in discharge may be temporary, seasonal, or long term. Besides the temporary increase in discharge due to rainfall or snowmelt, destructive temporary surges due to the breaking of ice or debris dams sometime occur. Some natural channels, of which Frenchman Creek in Nebraska is an example, are used to transmit seasonal irrigation flows at or near the bankfull stage. Long-term increases in discharge can be artificially induced by interbasin diversion from one channel to another and by urbanization of a drainage basin.

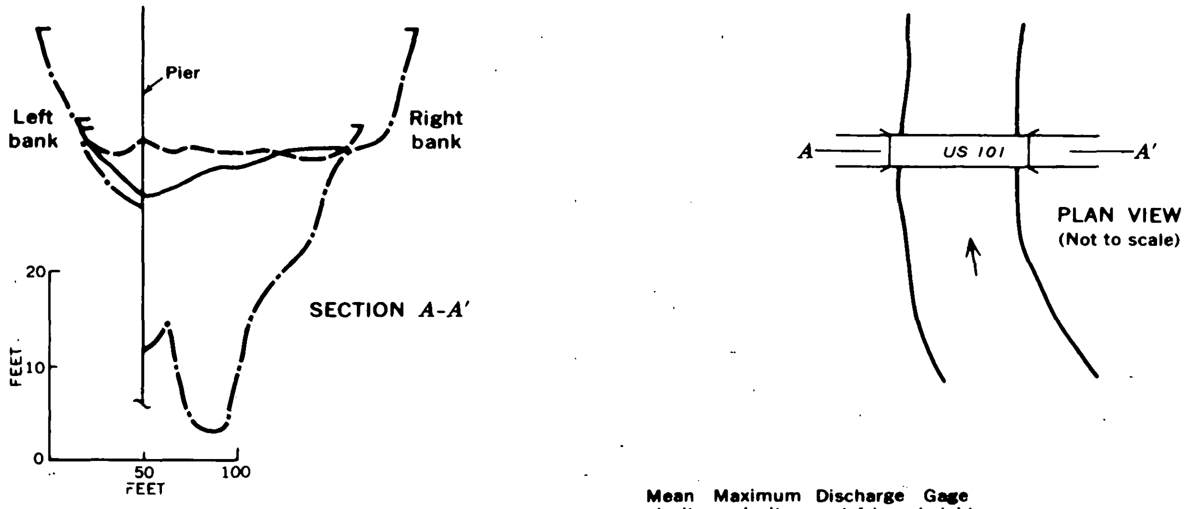
It has been shown (Lane and Borland, 1954; Neill, 1964c) that in some rivers (Rio Grande, Colorado River) there is a redistribution of bed material as discharge increases and then decreases during a runoff event. It is stated that bends and narrow sections tend to scour at high discharges and fill at low discharges whereas cross-overs (points of inflexion) and wide sections have the opposite tendency. According to these investigators the sharper the bend and the greater the constriction of the channel at the bend, the deeper will be the scour. The authors stated that they believe this action to be typical of all Great Plains rivers.

According to Emmett and Leopold (1963) scouring action in some rivers (Arroyo de los Frijoles, Rio Grande del Ranchos in New Mexico and Popo Agie River in Wyoming) affects the entire reach without regard to any of the physical dimensions of the stream; it applies to pool as well as riffle sections and to curved and straight reaches. Colby (1964b) disagrees with this, pointing out that scour or fill at a point is not representative, either quantitatively or timewise, of average scour or fill at a cross section; nor is average scour or fill at a cross section representative of scour or fill in a long reach of channel. However, aside from this disagreement, Emmett and Leopold's point observations show the minimum riverbed elevations (maximum scour) that occurred at these points, which in itself is valuable information.

A bridge site on Redwood Creek at Orick, Calif., provides an example of general scour that is attributed mainly to flood discharge. The bed is of fine gravel (from 2 to 64 millimeters), and drilling has shown that gravel, interbedded with some sand and clay, persists to a depth of at least 50 feet below the normal low-water channel. Figure 1 shows the location of the channel bottom as observed during current-meter measurements made at the downstream side of the bridge on three occasions, before, during, and after a flood event of about a 5-year frequency of occurrence. The discharge, mean velocity in the cross section and maximum observed velocity, are also shown. It appears that this is a case of general scour with the pier causing no appreciable amount of additional scour. Although there is a bend in the channel about 300 feet upstream from the bridge, observations made in connection with current-meter measurements indicate that the flow, as it passes underneath, is perpendicular to the bridge. The scour, at least in part, presumably results from the concentration of flow toward the left bank caused by the bend in the channel.

Increase or Decrease in Load Relative to Discharge

Channel fill is likely to result from a long-term increase in load relative to discharge, whereas scour is likely to result from a decrease in load. The most common cause of increase in load is rapid erosion in a drainage basin that has been deforested, improperly cultivated, or overgrazed. The most common cause of decrease in load is



	Mean velocity (fps)	Maximum velocity (fps)	Discharge (cfs)	Gage height (ft)
———— December 30, 1965	4.44	5.82	3,130	10.00
—·—·— January 4, 1966	7.16	9.94	30,200	19.87
— — — February 3, 1966	3.38	4.42	1,350	8.57

Figure 1.—Scour at bend during floodflow, Redwood Creek at Orick, California.

the construction of an upstream reservoir in which sediment accumulates. Channel scour downstream from a dam has been recorded in many localities.

Changes in Local Base Level

The local base level of a channel is the level of the body of water--, lake, reservoir, or master stream--into which the channel discharges. Changes in local base level can be either temporary or long term. In general, scour will take place in an alluvial channel whose base level has been lowered, whereas fill will take place in a channel whose base level has been raised. Available measurements indicate that the scour or fill effects of a change in base level do not extend very far upstream.

Changes in Channel Slope

Other variables remaining constant, an increase in channel slope is accompanied by an increase in water velocity and consequent scour of the bed and banks. Conversely, a decrease in channel slope may result in filling of the channel. Tectonic uplift or downwarping of the earth's crust can bring about regional changes in channel slope, but most changes are likely to be local. A common cause of local increase in channel slope on a sinuous channel is the cutting off of a meander loop, either naturally or artifically; at the point of cutoff the channel slope is increased by the amount of fall in the former loop. According to Blench (1966, p. 180), "the effect on the river, if it remains of regime type, is bound to be violent bed-erosion in the straightened reach, initial bed-erosion and degradation upstream and initial bed-deposition and rise of specific gages downstream." However, this statement is not well substantiated by experience, and case histories on the effects of cutoff are much needed.

Among the ways in which local channel slope has been artificially increased are removal of a downstream control point, such as a bedrock outcrop or an artificial weir, dredging in a reach, mining of sand and gravel in a reach, and sediment deposition from a tributary.

Lateral Shift or Redirection of Channel

Lateral shift refers to a gradual or minor lateral migration of a channel, whereas redirection refers to a sudden change in course that is usually brought about by diversion, either natural or artificial. Lateral shift or redirection may involve the channel as a whole; or it may involve only the thalweg of a channel or the anabranches of a braided drainage course.

At the bends of a sinuous channel, the flow impinges against the outside of the bank at a point downstream from the apex of the bend, causing the bank there to be scoured and to shift laterally. As illustrated in figure 2A, a bend may shift laterally against a bridge embankment, where expensive erosion control measures will be required. In a braided drainage course, the effect of channel shift can be compounded by the growth of a bar or island, which deflects the flow against the embankment and obliquely against the piers (fig. 2B).

Temporary shift of the thalweg of a sinuous channel is likely to occur during flood, and shift of the anabranches of a braided drainage course is to be expected. For a sinuous channel, the thalweg at flood has a somewhat straighter course than does the low-water channel; at

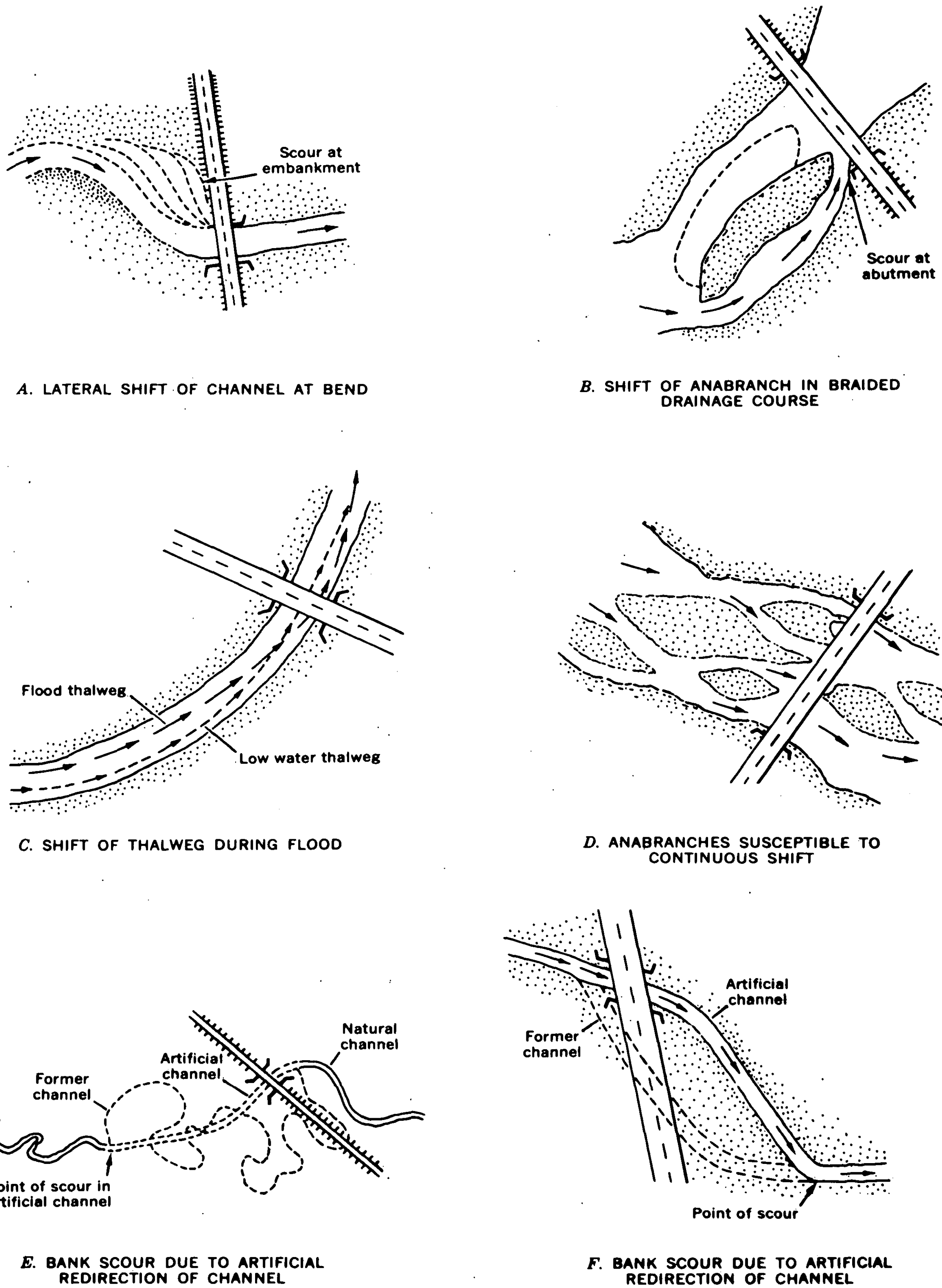


Figure 2.—Scour associated with lateral shift or redirection of flow.

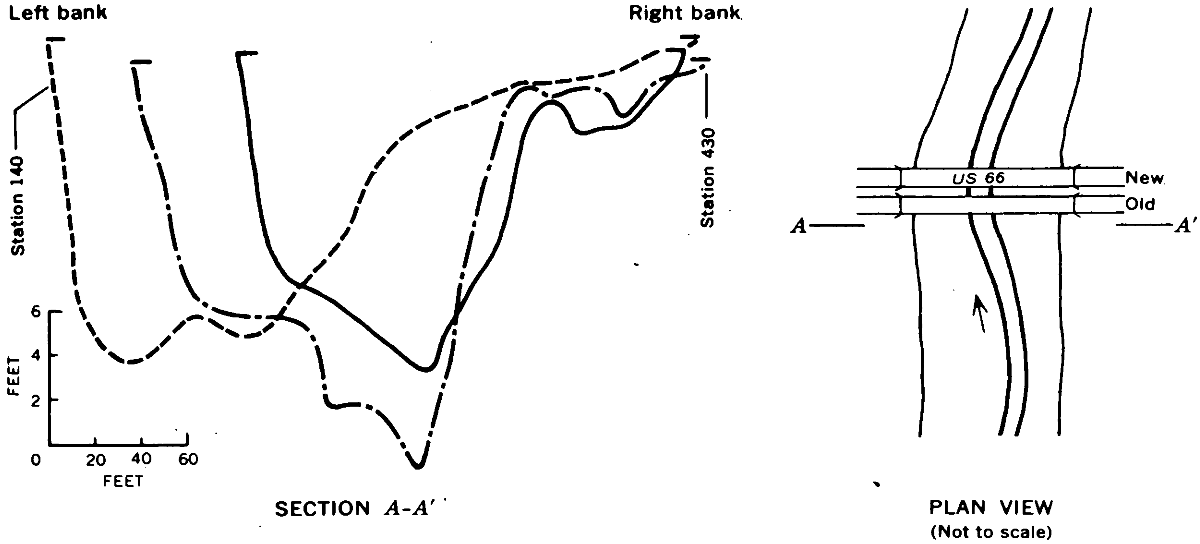
a bend, the floodflow cuts across the point bar deposits and impinges against the bank somewhat farther downstream than does the low-water channel. This point of impingement and scour at flood stage may coincide with the abutment of a bridge, as illustrated in figure 2C. The anabranches of a braided drainage course, illustrated in figure 2D, are likely to shift continuously during moderate and high stages, and the location of some of the anabranches will coincide from time to time with a pier. However, only a moderate depth of scour, on the order of a few feet, is to be expected from this.

Lateral scour that may result from artificial redirection of a channel is illustrated in figure 2E, which represents an actual case of channel straightening at a bridge approach on Frenchman Creek in Nebraska. Because the natural channel entered the artificial channel at an unfavorable angle, lateral scour began almost immediately at the point of impingement. The artificial channel would probably have eventually become sinuous as a result of downstream propagation of the initial flow deflection, but the installation of jacks at the point of impingement has (at least temporarily) halted this process. The hypothetical case of channel redirection illustrated in figure 2F illustrates a similar case of bank scour due to an unfavorable entrance angle.

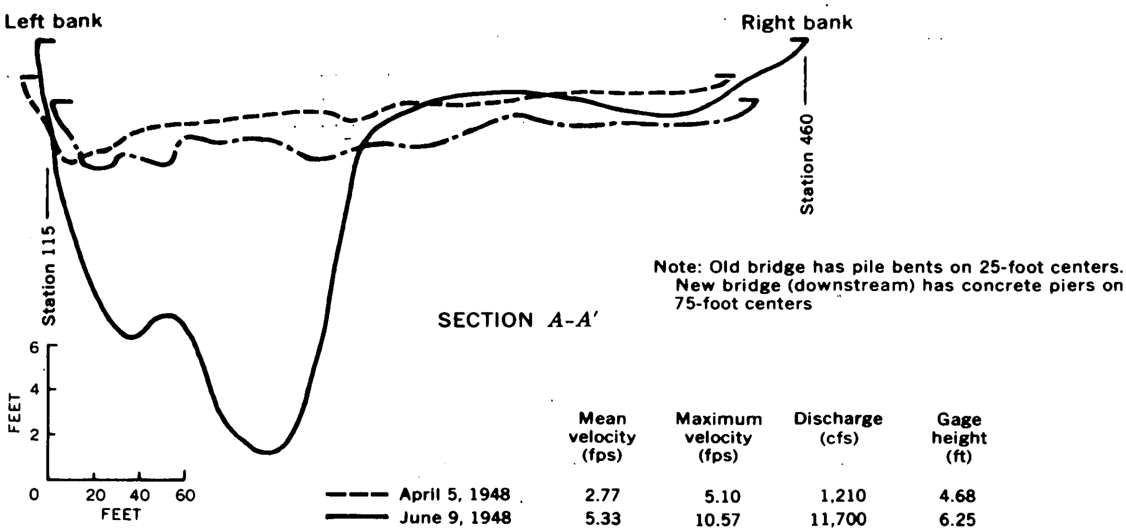
The Rio Grande at Old Town Bridge, Albuquerque, N. Mex., provides an example of the lateral shift of anabranches in a braided sand-bed drainage course. At this locality, the channel is confined by artificial levees to a width of about 1,500 feet.

Most of the floods occurring at this location result from snowmelt runoff although some are a combination of snowmelt and rainfall, and occasionally a flash flood occurs during late summer from precipitation only. The channel locations depicted in figure 3 and discussed below reflect conditions that existed during periods of snowmelt runoff.

A Geological Survey gaging station was established at the Old Town bridge in January 1942. The following chronological tabulation of gage-structure relocations is indicative of the migratory nature of the main channel. "Gage established 300 feet from left end of bridge in January 1942; moved 125 feet to left in September 1947; moved 30 feet left and 60 feet downstream to downstream side of new bridge (channel migration not involved) in April 1954; moved 700 feet to right in April 1959 over a newly-dug pilot channel; moved 145 feet to left in June 1960."



	Mean velocity (fps)	Maximum velocity (fps)	Discharge (cfs)	Gage height (ft)
——— April 6, 1942	3.85	8.82	6,930	4.87
—·— May 2, 1942	3.44	7.94	8,490	4.37
– – – May 15, 1942	4.85	11.33	13,900	5.09



Note: Old bridge has pile bents on 25-foot centers. New bridge (downstream) has concrete piers on 75-foot centers

	Mean velocity (fps)	Maximum velocity (fps)	Discharge (cfs)	Gage height (ft)
– – – April 5, 1948	2.77	5.10	1,210	4.68
——— June 9, 1948	5.33	10.57	11,700	6.25
—·— June 28, 1948	2.80	4.91	1,250	3.48

Figure 3.—Shift of thalweg and local scour during floodflows, Rio Grande at Albuquerque, New Mexico.

This reach of the Rio Grande provides a good example of the migratory nature of the main channel in a wide sand-bed stream. As shown by data from current-meter measurements in figure 3, the main channel moved about 100 feet to the left during a 39-day period of snowmelt runoff between April 6, 1942, and May 15, 1942. Also shown on figure 3 is the location of the streambed before, during, and after a period of snowmelt runoff as observed during current-meter measurements on April 5, June 9, and June 28, 1948. Note the lowering of the channel bottom by as much as 12 feet during the runoff event, followed by filling in to nearly the same elevation as before.

In 1959 a pilot channel was dug in the vicinity of the bridge in an attempt to move the main channel to a location near the center and about 850 feet from the left end of the bridge. The high water of April 1959 did follow this pilot channel. However, shortly thereafter the main channel began migrating toward the left bank and by June 1965 had moved to a location about 550 feet from the left end of the bridge.

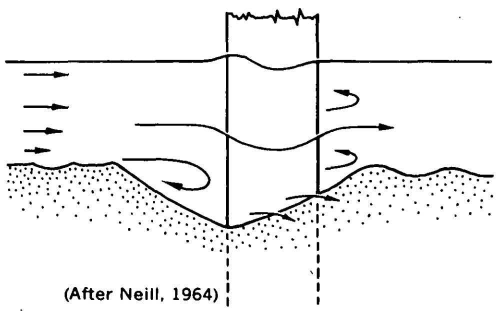
The channel changes in this reach of the Rio Grande presumably would be the same whether or not the bridge were there. The bridge offers no contraction to the flow, and the current-meter measruement soundings are made far enough upstream from the pile bents so that they should not reflect any local scour around the piles. The data are useful in showing the amount of lateral and vertical movement of the main channel that might occur during snowmelt runoff events on a similar reach of river under similar conditions. The futility of any attempt to redirect the main-channel flow by a pilot channel also is indicated.

Downstream Progression of Sand Waves

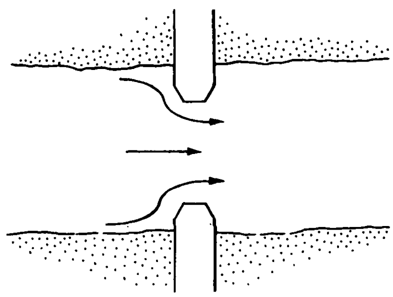
In a sand-bed channel, much of the movement of bedload takes place by the downstream progression of sand waves. The height of these is likely to be no more than a few feet on rivers of small or moderate size, but heights of 20 to 30 feet have been measured in the lower Mississippi River by Carey and Keller (1957, p. 1331-7). These authors also report a marked rise and fall of crossing with change in river stage, and suggest that the movement of bedload may be very different in bends as contrasted with crossings. Although the movement of sand waves is not regarded as scour and fill in the usual sense, the passage of the trough of a sand wave beneath a bridge can easily be confused with local scour at a pier.

Obstacles in Path of Flow

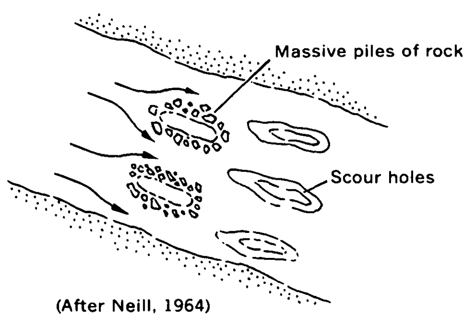
Analysis of the manner in which obstacles cause scour and fill is complex, but in general an obstacle disturbs the flow pattern so as to produce some areas of low velocity and others of strong turbulence. The areas of low velocity are conducive to fill, and the areas of turbulence are conducive to scour. Scour by upward vortex action has been termed "kolk" by Matthes (1947, p. 255), who considered it one of the most important forms of stream dynamics. Among the common obstacles that can cause scour and fill at bridge sites are bridge piers and abutments, fallen trees, and debris. Situations involving one or the other of these are illustrated in figure 4. As is well known, piers that are skewed to the direction of flow are especially susceptible to scour; the skewness not only causes a greater disturbance to the flow pattern but also, in effect, increases the degree of constriction of the channel by the piers.



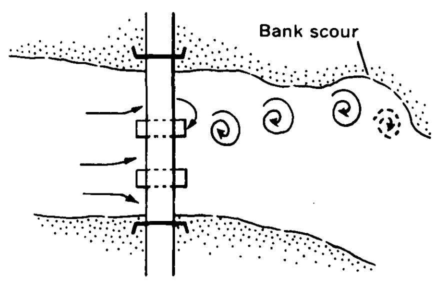
A. LOCAL SCOUR AT A PIER



B. SCOUR AT A PROJECTING ABUTMENT



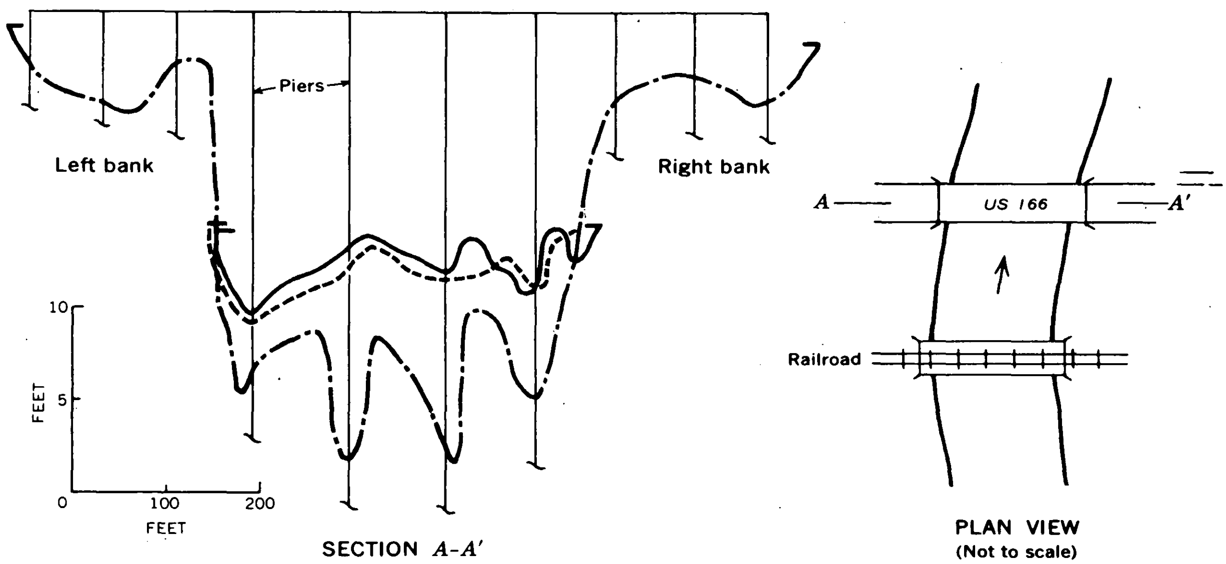
C. SCOUR DOWNSTREAM FROM RIPRAP AROUND PIERS



D. BANK SCOUR FROM VORTEXES ORIGINATING AT A PIER

Figure 4.—Scour associated with obstacles in path of flow.

Measurements of local scour at bridge piers have been made at the U.S. Highway 166 bridge on the Arkansas River at Arkansas City, Kans. The location of the channel bottom on the downstream side of the bridge, as observed during current-meter measurements on three occasions in 1948, is shown in figure 5. The discharge, mean velocity in the cross section, and maximum observed velocity are also shown. These measurements were made before, during, and after a flood event slightly larger than the mean annual flood. There seems to be about 2-4 feet of general scour in the main channel and about 6-8 feet of additional local scour around the piers during the high-flow measurement.



	Mean velocity (fps)	Maximum velocity (fps)	Discharge (cfs)	Gage height (ft)
——— June 2, 1948	1.53	2.32	1,100	8.47
—·— July 24, 1948	4.06	7.44	32,200	19.11
----- August 31, 1948	2.06	3.45	2,060	8.95

Figure 5.—Local scour around bridge piers, Arkansas River at Arkansas City, Kansas.

Available information shows no relation between discharge and depth of scour. For example, the channel bottom was at about the same position at discharges of 66,200 cfs (cubic feet per second) (May 18, 1967) and 32,200 cfs (July 24, 1948).

A bridge referred to by Neill (1964b, p. 26) location of which was not given, provides an example of failure attributed mainly to skewed piers in a sand-bed channel. Figure 6 shows the principal features at the twin-bridge site. Neill reports: "The piers had shallow footings capping 30-ft long piles, were skewed at least 25 degrees to the main flow, and were long relative to width." "During a flood both central piers of the upstream half of the structure collapsed." "The depth of scour below riverbed at time of failure is unknown, but one month later holes nearly 40 feet below normal riverbed levels still existed downstream from the bridge." "A report on the failure indicates that it might be ascribed to a combination of factors, among which were reduction in effective waterway area by the long skewed piers, local scour around the piers, and possibly general riverbed degradation due to special circumstances causing an abnormal stage-discharge relation." This case emphasizes the danger of constructing piers skewed to the flow, especially where twin bridges are constructed.

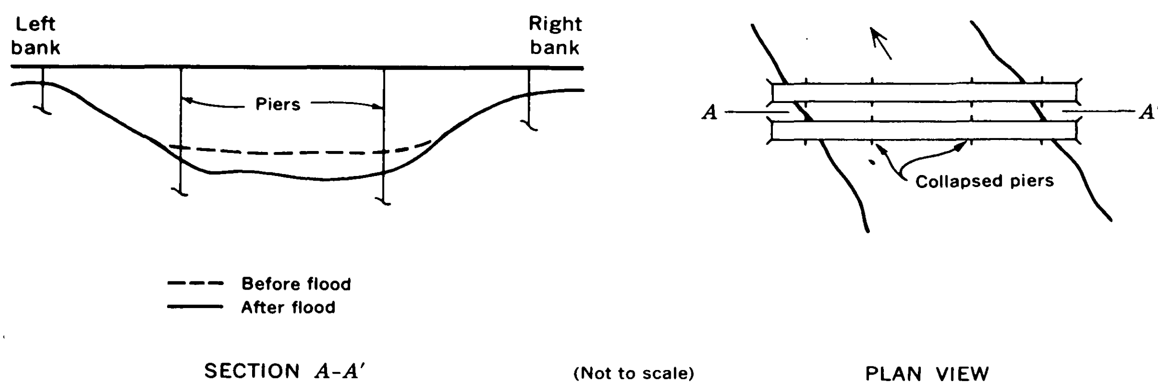


Figure 6.—Local scour associated with skewed piers, Unknown River.

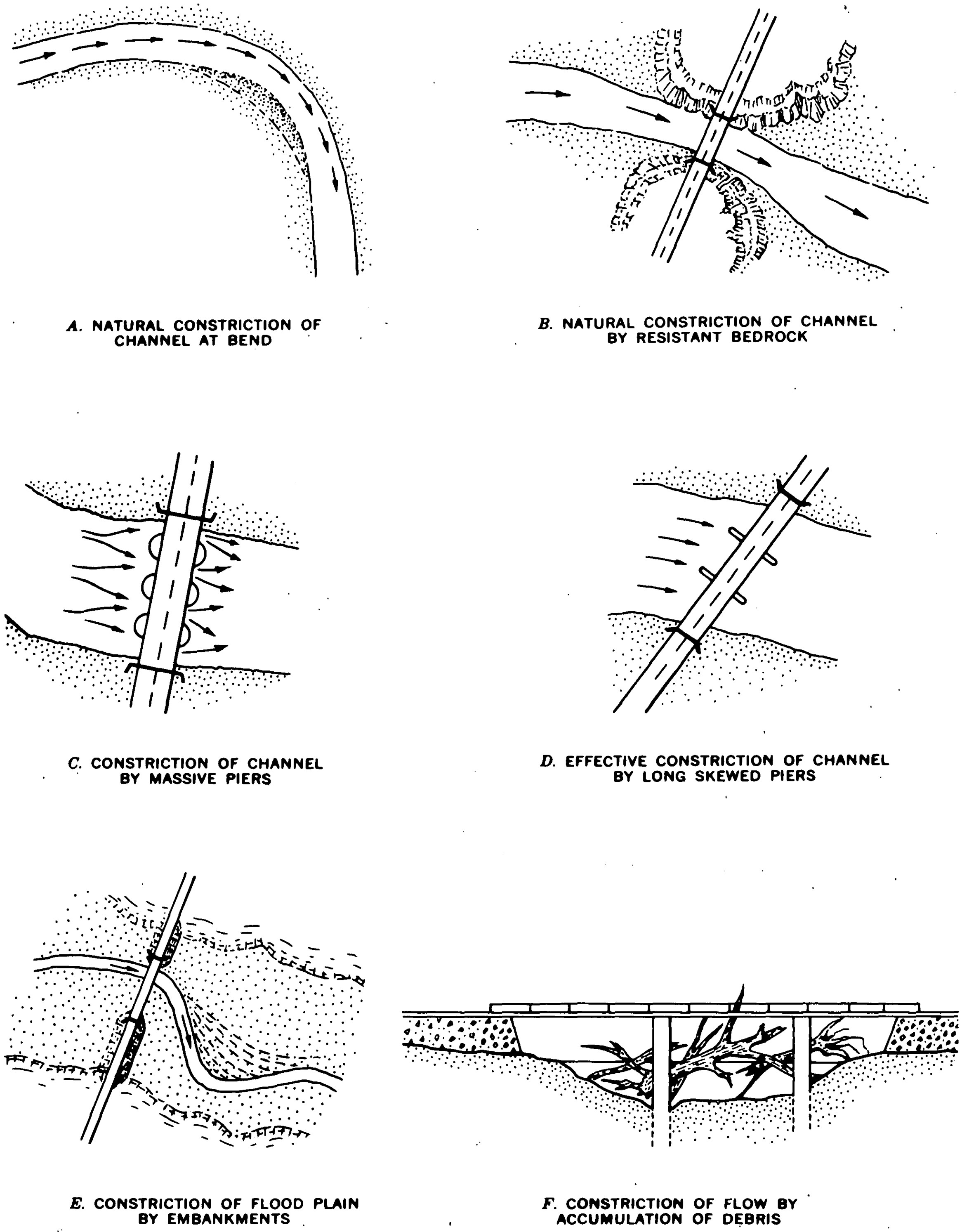
Constriction of Flow

If the width of a channel is constricted either naturally or artificially, both depth and velocity are likely to increase, and the increase in velocity may be accompanied by scour. Sinuous channels tend to be somewhat narrower (and deeper) at bends than at crossings, and bends are therefore most susceptible to scour (fig. 7A). Alluvial channels are commonly constricted where they pass through an area of unusually resistant bedrock (fig. 7B); the banks at the constriction may or may not be composed of bedrock, but the bed is likely to consist of alluvium and hence is susceptible to scour. Some types of braided drainage courses are characterized by extreme variations in width, but the causes of constriction may be difficult to assign. However, variations in density of vegetal growth along the banks are a potential cause of width variation along any alluvial channel. Artificially induced constrictions at bridge sites are illustrated in figure 7C through 7F.

A bridge site on the Little Wabash River at Louisville, Ill., provides an example of scour that is attributed mainly to constriction of the flood plain. At the bridge site, which is on Illinois F.A.S. Route 799, the channel of the Little Wabash is sinuous and about 300 feet wide; the flood plain is about 1 mile wide. The bed of the main channel is fairly stable; however, the flood plain is composed of silt and clay which is subject to scour, especially in areas of sparse vegetation. The bridge at this site spans not only the main channel but about 300-400 feet of the flood plain. Figure 8 shows the scouring of the flood plain at the downstream side of the bridge, which occurred during the floods of January 1950 and June 1957. The peak discharges of these floods were 43,000 cfs (1950) and 22,000 cfs (1957) with estimated frequencies of occurrence of 50 and 8 years, respectively.

Both scour holes apparently are a result of the extreme contraction from the nearly mile-wide flood plain to the 600-foot-wide bridge opening located near the right-bank edge of the flood plain. The fact that the 50-year flood did not scour a hole near the left-bank side of the bridge is not readily explainable, although the season of the year and prevailing vegetation may have been partly responsible.

Spur dikes were constructed on the upstream side (fig. 8) of the bridge opening as recommended in a 1958 Geological Survey bridge-site report. Except for a minor enlargement of the left-bank scour



A. NATURAL CONSTRICTION OF CHANNEL AT BEND

B. NATURAL CONSTRICTION OF CHANNEL BY RESISTANT BEDROCK

C. CONSTRICTION OF CHANNEL BY MASSIVE PIERS

D. EFFECTIVE CONSTRICTION OF CHANNEL BY LONG SKEWED PIERS

E. CONSTRICTION OF FLOOD PLAIN BY EMBANKMENTS

F. CONSTRICTION OF FLOW BY ACCUMULATION OF DEBRIS

Figure 7.—Scour associated with constrictions of flow.

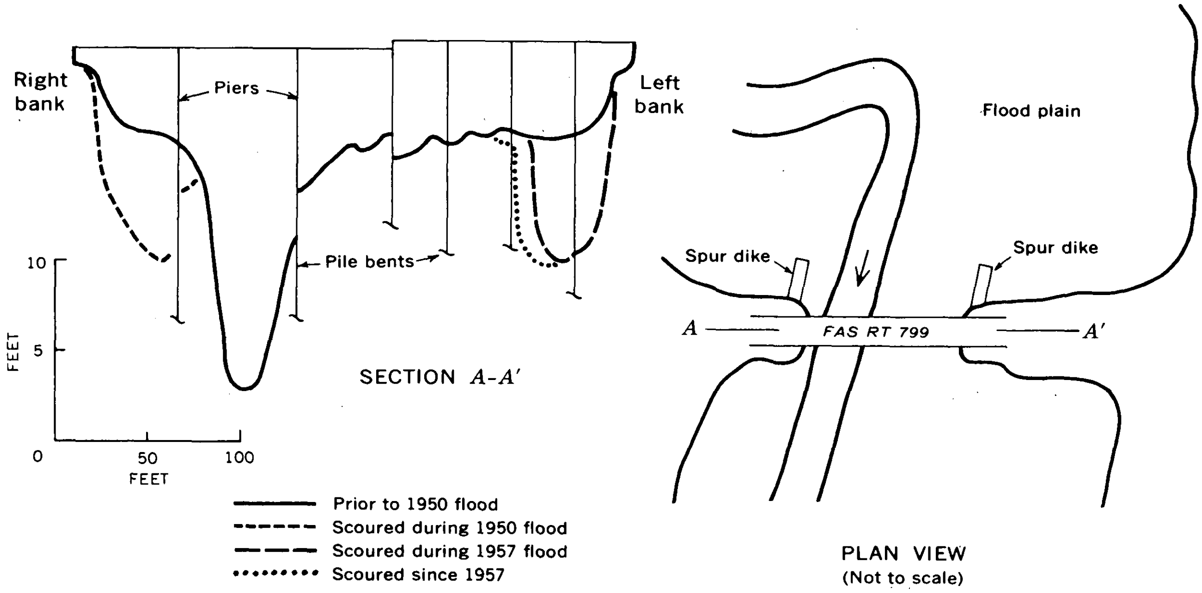


Figure 8.—Scour associated with constriction, Little Wabash River at Louisville, Illinois.

hole, no additional scour has occurred at the site to date (1966) even though a flood nearly equal in magnitude to the 1950 flood occurred in 1961.

Failure of a bridge on Interstate Highway 6, across Bijou Creek at Wiggins, Colo., is tentatively attributed to the accumulation of flood debris at two bridges upstream from the failed bridge. Surprisingly, the two upstream bridges remained virtually intact while sections of the newer downstream bridge were undermined and transported several hundred feet downstream. This occurred during an extreme flood event (probably exceeding a 100-year flood discharge) in June 1965. (See photographs of fig. 9.) Bijou Creek is an ephemeral stream having a wide, sand-bed channel.

A large amount of drift lodged at the upstream bridges resulted in a reduced waterway opening and a consequent increase in velocity. Although the exact cause of bridge failure is unknown, the increase in velocity due to a reduction in area no doubt resulted in more scour than would have occurred otherwise. It is also possible that the accumulated drift on the upstream bridges may have directed the flow at an angle toward the piers of the downstream bridge causing large scale eddies, again increasing the amount of scour.

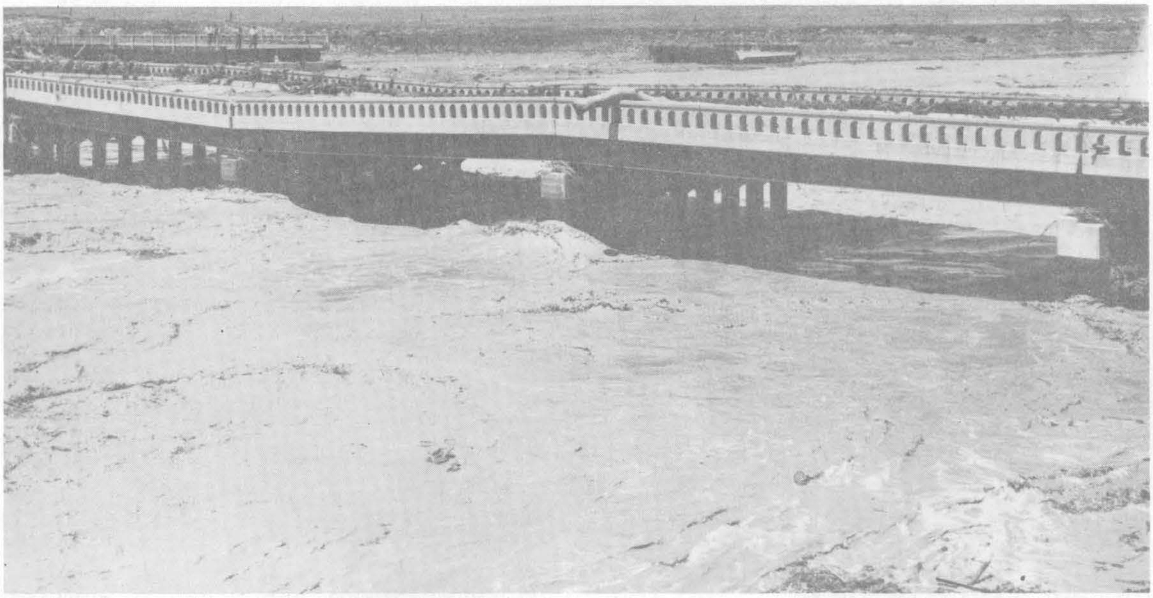


Figure 9.—Bijou Creek at Interstate Highway 6 crossing at Wiggins, Colorado, after flood of June 1965.

PART II. COLLECTION OF FIELD DATA AND PREDICTION OF SCOUR AND FILL

Collection of Data

Two concepts important in the study of channel behavior provide guidelines for the kinds of data needed to aid in predicting the effect of road and bridge construction on alluvial channels. These concepts are (1) alluvial channels attain a state of quasi-equilibrium in which the width, depth, and slope are adjusted mainly to the flow of water and sediment through the channel, and (2) scour and fill represent a response to changes in all controlling variables resulting from either natural causes or manmade causes such as the construction of a bridge crossing and bridge piers.

Consideration of the equilibrium concept suggests the need for data on the hydrologic and related properties of the drainage basin. These properties include the geology, topography, soils, vegetal cover, climate, annual and seasonal precipitation, erosional history of the channel, and upstream impoundments or diversions. Information needed at the reach or section under study includes the stage of bankfull discharge, flood frequency, flow duration, relation of flow in the channel to overbank flow, and the location and characteristics of nearby tributary streams. Because equilibrium values of width, depth, and slope are not static but fluctuate constantly about an average, data are needed to establish the average and magnitude of the fluctuations. In addition to measurements of width, depth, and slope, information should be acquired on water temperature, bed form, and sediment discharge including range in concentration and size distribution of suspended sediment; and on the size, shape, density, and cohesiveness of particles composing the bed and banks.

In many studies it will be impracticable to obtain quantitative data for each of the above factors. However, the important channel, hydraulic, and sediment transport characteristics at many streams generally can be easily obtained. For predicting scour in a gradual width constriction of a uniform reach of channel three or more sets of data describing these characteristics should be collected at one or two representative sections upstream from the constriction. The sets of data should represent a wide range in flow conditions preferably obtained at low, bankfull, and flood stages; they should include information at least on the following items:

A. Channel properties

1. Morphologic properties (fig. 13)
2. Channel shape (cross profile of sections including flood plain)
   a. Effective width
   b. Mean depth
3. Reach slope
   a. Bed slope
   b. Water-surface slope at high stages
4. Bed form

B. Velocity

1. Vertical distribution
2. Lateral distribution
3. Direction of flow

C. Sediment transport

1. Concentration of suspended sediment
2. Particle size distribution of suspended sediment
   a. Vertical distribution
   b. Lateral distribution
3. Particle size distribution of bed material
   a. Lateral distribution
4. Water temperature

D. Botanical and geological evidence, if any, of maximum flood stages

For the prediction of scour around a bridge pier the information in items B and C above should be collected one or more times for the highest flows possible at the section in which the bridge is to be placed. At least one cross section should be surveyed in the approach section about one bridge-opening width upstream from the bridge site. All methods for predicting scour around a pier require information on the dimensions and aspect of the pier; thus the following additional information is needed:

A. Geometry of pier

1. Width
2. Length (if other than circular)
3. Alinement with flow for range in discharge (if other than circular)

B. Bridge construction

1. Planned protective works that may influence velocity distribution at the bridge section
2. Plans for backfill around pier, if applicable, or for scour aprons or riprap around pier
3. Susceptibility of site to ice jams or drift

Prediction of Average Scour and Fill for a Gradual Width Constriction

Several empirical equations or methods have been developed for predicting scour and fill for a gradual width constriction in sand-bed streams under equilibrium conditions; none is applicable to all kinds of channels or to abrupt constrictions such as those generally encountered at bridge sites. The accuracy of prediction of any equation depends largely on the accuracy to which the hydraulic, sediment, and channel characteristics previously described are known or can be estimated. Most equations derived recently are based on the principle of continuity using a flow formula and a sediment transport formula. The Manning formula combined with the equation of continuity of water discharge can be written to relate the depth d_2 in a constricted section to the depth d_1 in an unconstricted section,

$$Q_w = \frac{1.49}{n_1} b_1 d_1^{5/3} S_1^{1/2} = \frac{1.49}{n_2} b_2 d_2^{5/3} S_2^{1/2} \tag{1}$$

or

$$\frac{d_2}{d_1} = \left[\frac{n_2 b_1 S_1^{1/2}}{n_1 b_2 S_2^{1/2}}\right]^{3/5}$$

in which,

Q_w is the rate of water discharge; and for the unconstricted and constricted sections respectively, n_1 and n_2 are the Manning roughness coefficients, b_1 and b_2 are the widths, and S_1 and S_2 are the slopes; the depths are assumed to be equal to the hydraulic radius.

Straub (1940) combined equation (1) with a form of duBoys bed-load formula,

$$Q_s = \psi_1 b_1 \gamma d_1 S_1 (\gamma d_1 S_1 - \tau_c) = \psi_2 b_2 \gamma d_2 S_2 (\gamma d_2 S_2 - \tau_c) \tag{2}$$

in which,

Q_s is the rate of bedload discharge, ψ is the duBoys transport coefficient which depends on sediment size, γ is the specific weight of water, and $\tau_c = \gamma dS$ is the critical tractive force in pounds per square foot at which general sediment movement begins.

For the derivation, a state of equilibrium is assumed to exist and the flow is confined within the main channel. If assumptions also are made that $\psi_1 = \psi_2$, $n_1 = n_2$, and the total tractive force on the bed $\tau_1 = \gamma d_1 S_1$ and $\tau_2 = \gamma d_2 S_2$, the relative depths are

$$\frac{d_2}{d_1} = \left[\frac{b_1}{b_2}\right]^{3/7} \left[\frac{-\frac{\tau_c}{\tau_1} + \left[\left(\frac{\tau_c}{\tau_1}\right)^2 + 4\left(\frac{b_1}{b_2}\right)\left(1 - \frac{\tau_c}{\tau_1}\right)\right]^{1/2}}{2\left(1 - \frac{\tau_c}{\tau_1}\right)}\right]^{3/7} \tag{3}$$

The derivation of equation (3) requires a quadratic solution and if τ_c is small compared with τ_1, equation (3) reduces to

$$\frac{d_2}{d_1} = \left(\frac{b_1}{b_2}\right)^{0.64} \tag{4}$$

Equation (4) agrees with the equation developed empirically by Griffith (1939) from a large amount of data obtained for rivers and canals. Equation (4) is recommended for use in obtaining rough approximations of average scour and fill in sand-bed streams with reasonably uniform, within-bank flow where the width constriction is less than about 25 percent.

Laursen (1962) used the Manning formula and a form of the total sediment-load relationship proposed by him (1958) to derive an equation for predicting scour and fill in a long constriction for floodflow conditions (overbank flow in approach section). The equation, based on assumptions of equilibrium, Manning's n, and tractive force given for equation (3), may be expressed as

$$\frac{d_2}{d_1} = \left(\frac{Q_1}{Q_2}\right)^{6/7}$$

For within-bank flow he derives an equation similar to (4). Laursen's todal-sediment-load relationship involves a ratio of the shear velocity, $u_* = \sqrt{gdS}$ to the fall velocity, ω, of the bed sediment. This ratio reportedly provides a basis to account for changes in the mode of transport, mainly bedload in the unconstricted section, to the constricted section where much of the bedload probably moves in suspension. Adjustment of the exponent of the constriction ratio by the ratio $\frac{u_*}{\omega}$ is reported as

$$\frac{d_2}{d_1} = \left(\frac{b_1}{b_2}\right)^{0.50} \qquad \frac{u_*}{\omega} < 1/2$$

$$\frac{d_2}{d_1} = \left(\frac{b_1}{b_2}\right)^{0.64} \qquad \frac{u_*}{\omega} = 1$$

$$\frac{d_2}{d_1} = \left(\frac{b_1}{b_2}\right)^{0.69} \qquad \frac{u_*}{\omega} > 2$$

The use of Laursen's equation is not recommended at this time partly because the applicability of $\frac{u_*}{\omega}$ in describing changes in the mode of sediment transport is uncertain. The adjustments are presented here with the hope that measurements in the field may demonstrate whether or not the use of these or similar refinements is indeed warranted.

A second practical method of estimating scour and fill in a long constriction in sand-bed streams involves the use of a general relationship between mean velocity and bed-material discharge. For many sand-bed streams Colby (1964a) shows that bed-material discharge is roughly proportional to the width of flow and to about the third power of the mean velocity. Applying this relationship and the principle of continuity in Manning's equation, bed-material discharges at sections 1 and 2 (see equation 1) are

$$Q_{bm} = k_1\, b_1 \left(\frac{1.49}{n_1}\, d_1^{\,2/3} S^{1/2}\right)^3 = k_2\, b_2 \left(\frac{1.49}{n_2}\, d_2^{\,2/3} S_2^{\,1/2}\right)^3 \qquad (5)$$

in which,

> Q_{bm} is the rate of bed-material discharge in tons per day per foot of channel width and k_1 and k_2 are coefficients which depend on the mean velocity, depth of flow, water temperature and concentration of fine sediment (silt and clay); the other symbols and subscripts are as previously described.

If the assumptions with respect to flow conditions specified for equation (3) are applied to equation (5), equations (1) and (5) can be combined to yield

$$\frac{d_2}{d_1} = \left(\frac{n_2}{n_1}\right)^{1/3} \left(\frac{k_2}{k_1}\right)^{1/3} \left(\frac{b_1}{b_2}\right)^{2/3} \qquad (6a)$$

or

$$\frac{d_2}{d_1} = \left(\frac{b_1}{b_2}\right)^{0.67} \qquad \text{when } n_1 = n_2 \text{ and } k_1 = k_2 \tag{6b}$$

In a relatively straight channel, differences in the magnitude of resistance to flow may be due largely to differences in the form of bed roughness in the constricted and unconstricted sections. As the form of bed roughness changes, values of n can change a considerable amount (Simons and Richardson, 1962). For such changes the bed form should be considered in estimating values of n in equation (6a). The following table based on field and laboratory flume measurements may be used to estimate ranges in Manning's n for different forms of bed roughness in sand-bed streams.

Form of bed roughness	Range in Manning's n
Ripples	0.020 - 0.028
Dunes	0.021 - 0.035
Plane	0.010 - 0.020

For constrictions less than about 25 percent where the velocity is not increased appreciably the ratio $\left(\frac{k_2}{k_1}\right)^{1/3}$ does not differ much from unity when the distribution of bed-material size throughout the reach is uniform. The value k_1 can be obtained directly from the relation $Q_{bm} = k_1 b_1 V_1^3$. Theoretically the value k_2 can be estimated by trial and error from figures 10 and 11 and the relation

$$\frac{Q_{bm}}{Q_w} = \frac{k_2 b \left(\frac{1.49}{n} d^{2/3} S^{1/2}\right)^3}{b \frac{1.49}{n} d^{5/3} S^{1/2}} = k_2 \left(\frac{1.49}{n}\right)^2 d^{1/3} S \tag{7}$$

However, until field studies are made to determine the magnitude of the ratio $\left(\frac{k_2}{k_1}\right)^{1/3}$ a value of unity will need to be assumed. Equation

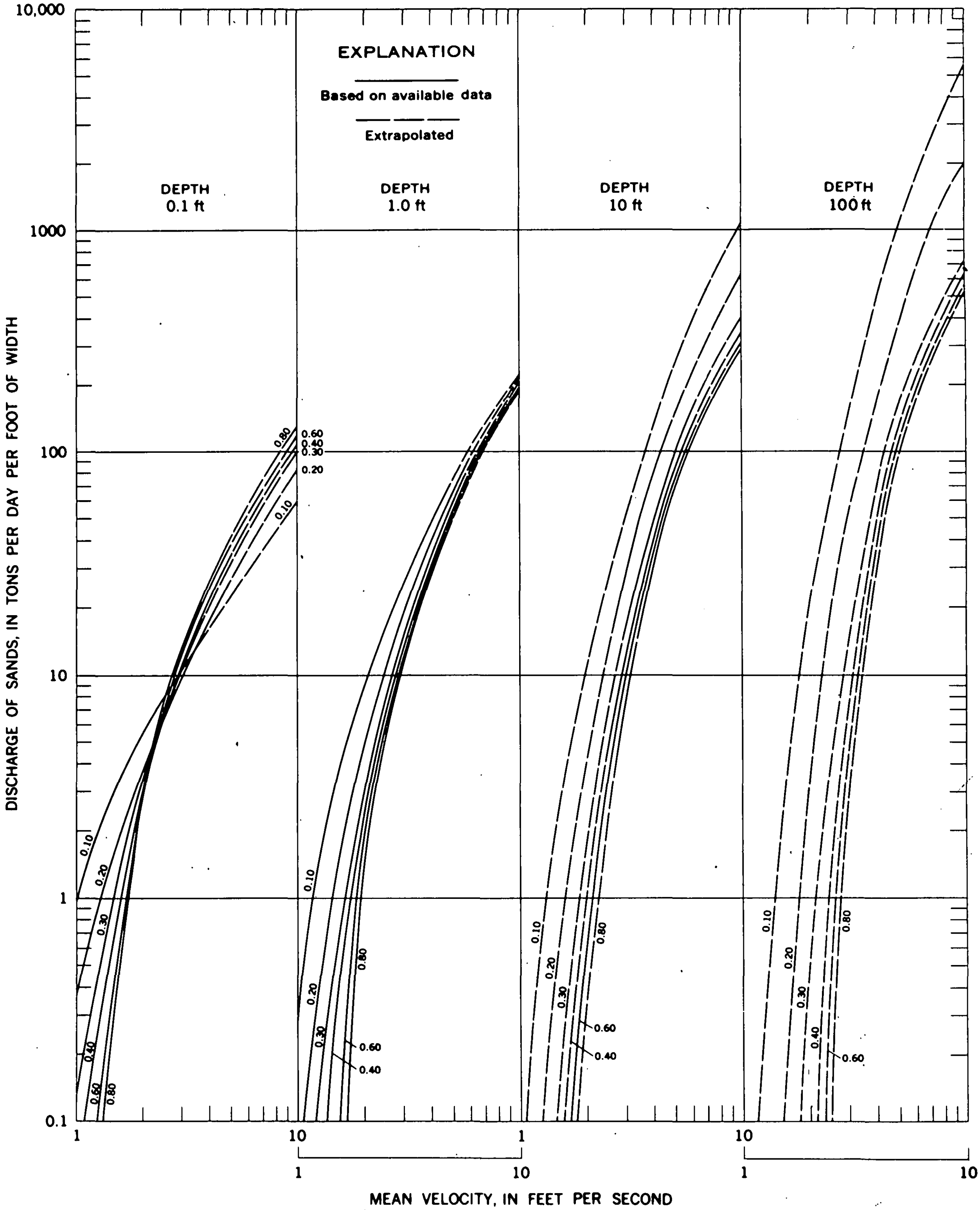


Figure 10.—Relationship of discharge of sands to mean velocity for six median sizes of bed sands, four depths of flow, and a water temperature of 60° F. (From Colby, B. R., Discharge of Sands and Mean-Velocity Relationships in Sand-Bed Streams; U.S. Geol. Survey Prof. Paper 462–A).

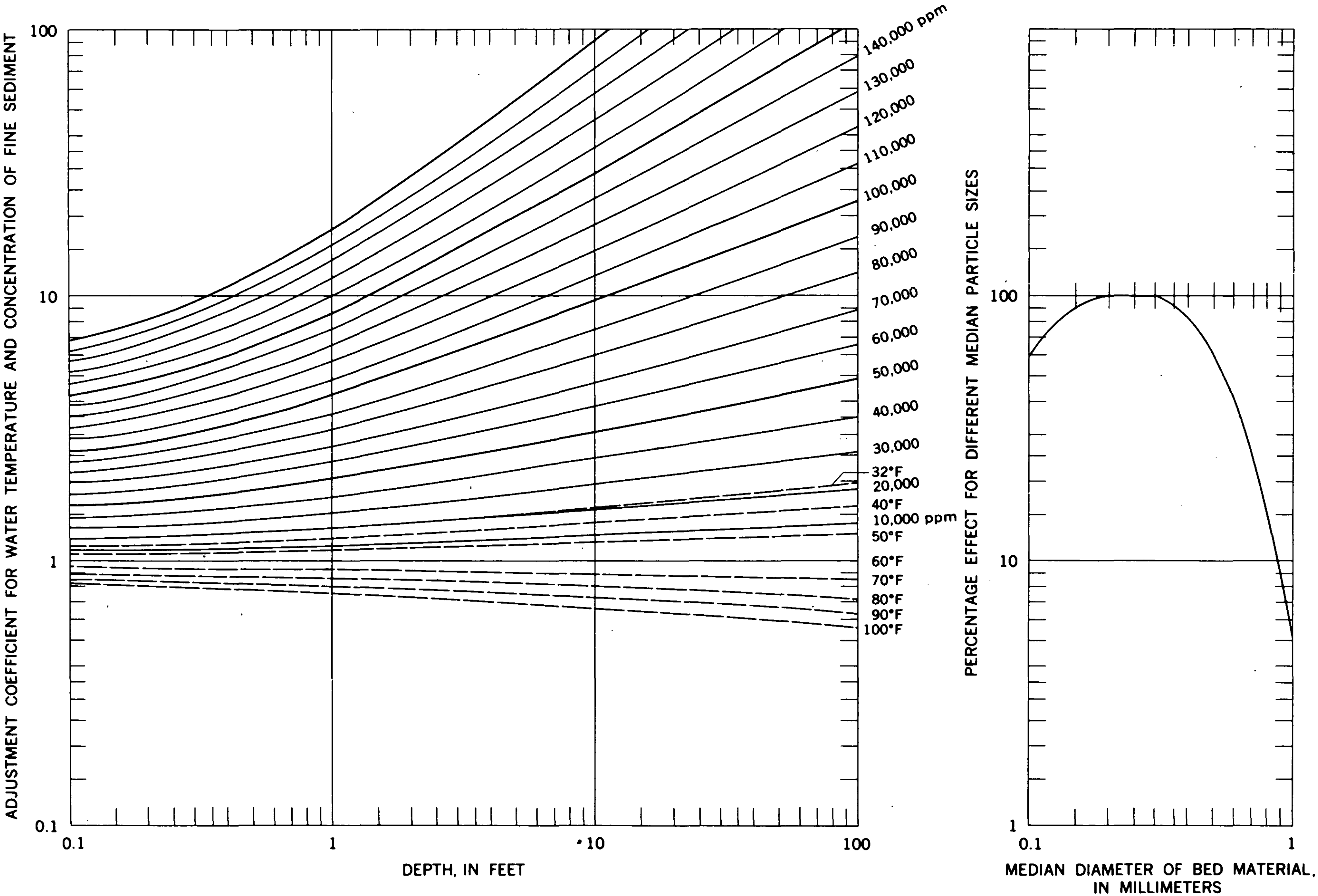


Figure 11.—Approximate effect of water temperature and concentration of fine sediment on the relationship of discharge of sands to mean velocity. (From Colby, B. R., Discharge of Sands and Mean-Velocity Relationships in Sand-Bed Streams: U.S. Geol. Survey Prof Paper 462–A).

(7) indicates, correctly that the effect of depth on the concentration of bed-material load is small compared with that of slope. For equilibrium conditions this equation may be useful to compute the concentration of bed-material load if the depth-slope product $d^{1/3} S$ is known.

Conversely, if the concentration of bed material load in the constriction is measured, the energy gradient can be determined by trial and error from the computed energy gradients and associated depths of flow for different assumed cross sections.

Many bedload or bed-material-discharge equations could be combined with the Manning or other flow equations to compute the ratio of the depths of flow in any two sections for a particular flow under equilibrium conditions. The Modified Einstein total-load procedure of Colby and Hembree (1955), and the bedload equation of Meyer-Peter and Muller (1948) probably are most applicable.

Graphical aids for evaluating scour and fill in a long constriction in sand–bed streams can be developed from the relationships of figure 10. Nordin (1964) recognized that either the bed material transport per foot of width or the concentration plotted as functions of velocity and depth provides information useful in the design of stable channels. Figure 12, redrafted from figure 10, shows these relationships for the 0.3° mm sand for a water temperature of 60° F; superimposed on the graphs are lines of constant Froude number and unit water discharge. If the slope of the energy gradient is constant, lines of constant Froude number on the graphs represent lines of constant Chezy C or roughness. With a given set of assumptions, figure 12 may be used to indicate the stability of a channel and thus the tendency for scour or fill. For example, in figure 12A, assume that slope and roughness do not change. Then the intersection of the line of constant Froude number through the point of known velocity and depth of flow in the normal section with the unit water discharge calculated from the known or assumed width of the constriction gives the velocity and depth that will occur in the constricted section. Similarly, in figure 12B, the intersection of the line of constant concentration through the point of known velocity and depth with the unit water discharge at the constriction will indicate the depth and velocity required for continuity of sediment transport. If the extension of the constant Froude number line lies to the left of the equal concentration line, fill is indicated; an

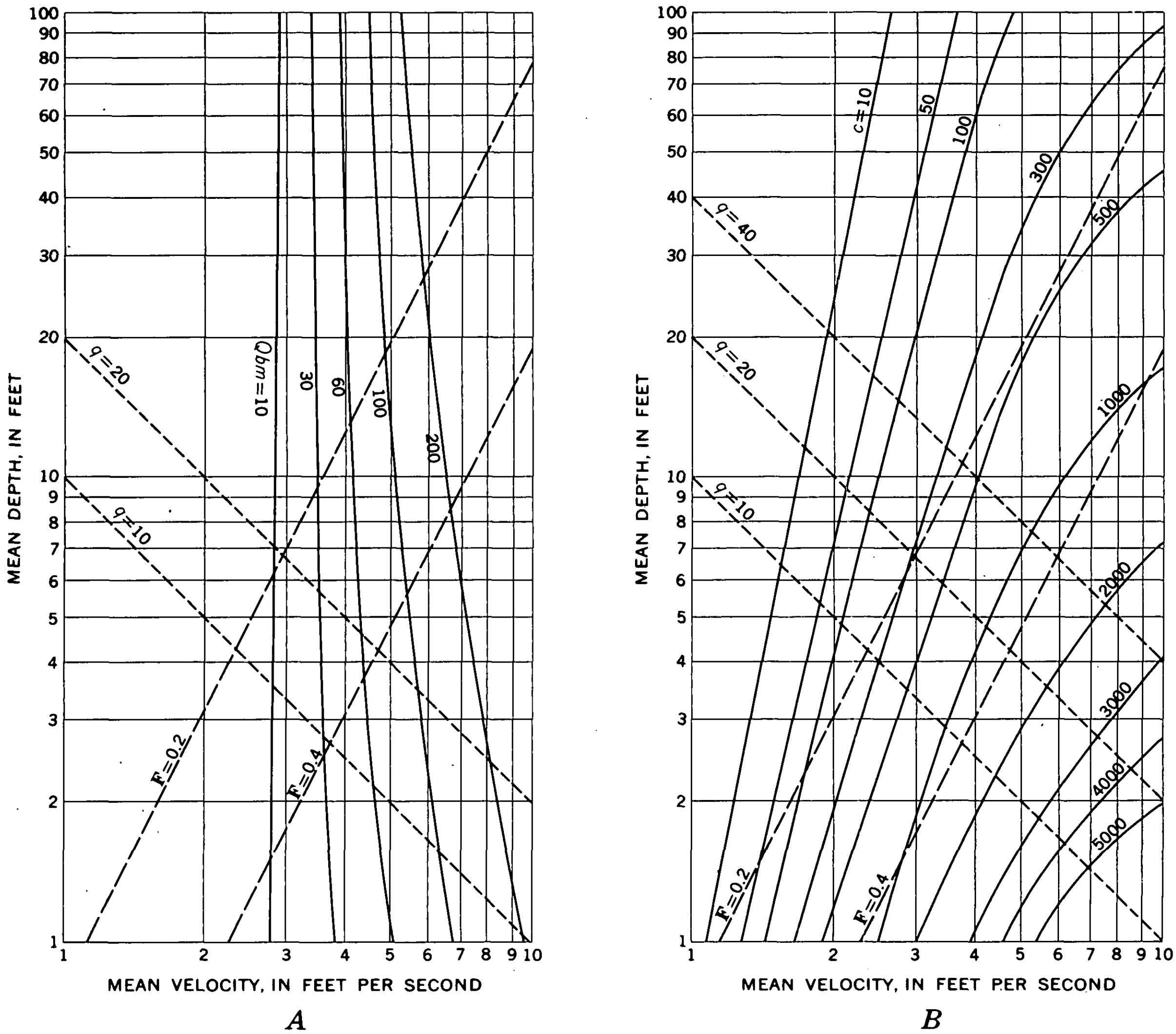


Figure 12.—Bed-material discharge and concentration as a function of velocity and depth (Water temperature 60° F and median diameter of bed material 0.30 mm).

extension of the constant Froude number line that lies to the right of the equal concentration line indicates scour.

For conditions of fluctuating water discharge and sediment transport, estimates of average scour and fill in a gradual constriction must be based on actual or synthetic stage-discharge and discharge-sediment transport relationships. The detailed method described by Colby (1964b, p. 14-20) probably is most applicable especially if streamflow records in or near the reach are available for a considerable length of time. The regime equations of Lacey (1934) and Blench (1957) are not recommended for use at this time largely because a great amount of experience and knowledge of local conditions is required to apply properly the regime slope formula.

Each of the above methods should be applied judiciously with as complete a knowledge as possible of the bed form and the relation between the discharge of bed material and the flow. Relating scour and fill adequately with the complexities of sediment discharge depends largely on the accumulation of reliable field data. Some of the complexities are stated by Brooks (1958, p. 547) who concluded on the basis of laboratory studies that "neither the velocity nor the sediment-discharge concentration could be expressed as a single-valued function of the bed shear stress, or any combination of depth and slope, or bed hydraulic radius and slope... . The dificulty arises because the changeable bed configuration caused extremely large variations in the channel roughness." Thus only approximations of scour and fill can be made at the present time. Nevertheless, the above methods can be used to advantage in some problems of channel behavior.

Prediction of Scour at Bridge Piers and Abutments

There is no established theory from which the probable extent and depth of scour at a bridge can be predicted with a reasonable degree of confidence. Research now in progress in the United States and other countries may provide useful design data in the future.

As discussed in a previous section, scour at a bridge crossing can result from a variety of causes. However, two major distinctions can be made: (1) scour resulting from action of the stream itself that would occur whether or not the bridge structure were in place and (2) scour resulting from the bridge structure. This section of the report is concerned only with scour resulting from the bridge structure for which further distinctions can be made: (1) scour resulting from the constriction of flow by the bridge and its associated highway embankments (area occupied by piers should be considered also) and (2) local scour resulting from turbulence caused by piers and abutments.

Magnitude and location of scour due to an abrupt constriction is not only a function of the reduction in size of flow area but also depends on other factors such as the size of bed material, alinement of channel with respect to the bridge crossing, channel curvature, vegetation, and distribution of overbank flow. Magnitude and location of local scour due to piers and abutments is, again, not only a function of the alinement and geometry of the structures but also is a function of factors such as those given above.

Scour in Channels other than Sand Channels

A search of the literature has shown that there is very little information available for use in predicting scour of channels other than sand channels. Regime formulas such as Blench's (1957) are not considered adequate for predicting scour resulting from bridge constrictions. One major shortcoming in the use of any of the regime formulas is the fact that an independent determination of the water-surface elevation for the design flood must somehow be made because regime depths are measured from the water surface.

Blench (1957, p. 48) gives a factor for adjusting the regime depth to scoured depth around piers. However, even though the water-surface elevation could be determined independently, Blench states that scour depths predicted by use of this factor should be used only for pier scour apron design depths and not for predicting depth of scour that might occur without aprons.

For the reasons given above it is recommended that neither Blench's nor any other regime formulas be used for prediction of depth of scour in a bridge constriction.

Case histories, as proposed in Part III of this report, would be applicable to the problem of predicting scour in gravel-bed channels.

Thus, experience with scour and fill at one locality would form a basis for prediction at another locality of similar characteristics.

Scour in Sand Channels

In the previous section of this report a method for predicting scour in a straight gradually-contracting sand channel is presented. Scour determined in this manner could be used as a very rough estimate of the minimum scour that might be expected at a bridge crossing due to the constriction only, keeping in mind, of course, that a bridge opening commonly represents an abrupt constriction, not a gradual constriction. If the approach channel were fairly straight and consisted mostly of sand (no appreciable vegetation) throughout its width and if the overbank flow were not too great, a rough estimate of the minimum average scour could be made. However, with vegetation in the overbank area, maldistribution of the overbank flow between one bank and the other, channel curvature, or any combination of these conditions the scour may be far from uniform across the bridge opening. Careful consideration of these conditions can lead to rough prediction as to where the maximum scour might occur, but no reasonable estimate of the depth of maximum scour is possible.

Site reports should include estimates of scour only when the method used is fully described and the limitations of the method specified. When the depth of scour around a bridge pier must be predicted, the Laursen (1962) method is recommended. The depth of scour as determined by Laursen's method is defined as the distance between the ambient streambed and the bottom of the scour hole around a pier. The only streambed elevations normally available along the centerline of a proposed bridge crossing are for low-water conditions. Because of the uncertainty as to the streambed elevation at a given location in the cross section during a flood runoff event, the lowest elevation of the low-water cross section at the proposed bridge crossing should be considered as the ambient streambed elevation in the main channel. If high-water information is available, it should, of course, be utilized. Any estimated general scour due to the constriction should be added to the computed local scour around a pier to determine the maximum estimated scour below the ambient streambed.

Laursen's (1962) method is based on model studies, and his curve of relationship between depth of scour, depth of flow in the approach, and width of pier (fig. 13) fits the entire available range of data on model piers in sand reasonably well as an upper enveloping curve. In figure 10, d_s is the depth of scour below the ambient streambed, y is the depth of flow in the approach channel upstream from the pier, and w is the width of the pier. According to Laursen's investigation, bed material size (within the range of sand sizes used, 0.46 to 2.3 mm) had little effect on the amount of scour around a bridge pier and, therefore, was not a factor in the final analysis. As would be expected, shape of piers and angle of approaching velocities did affect the depth of scour observed in the laboratory flume. Table 1 below contains coefficients for adjusting the basic square-nosed pier scour depth as determined from figure 10 to that which would be applicable for the particular pier-nose shape being considered.

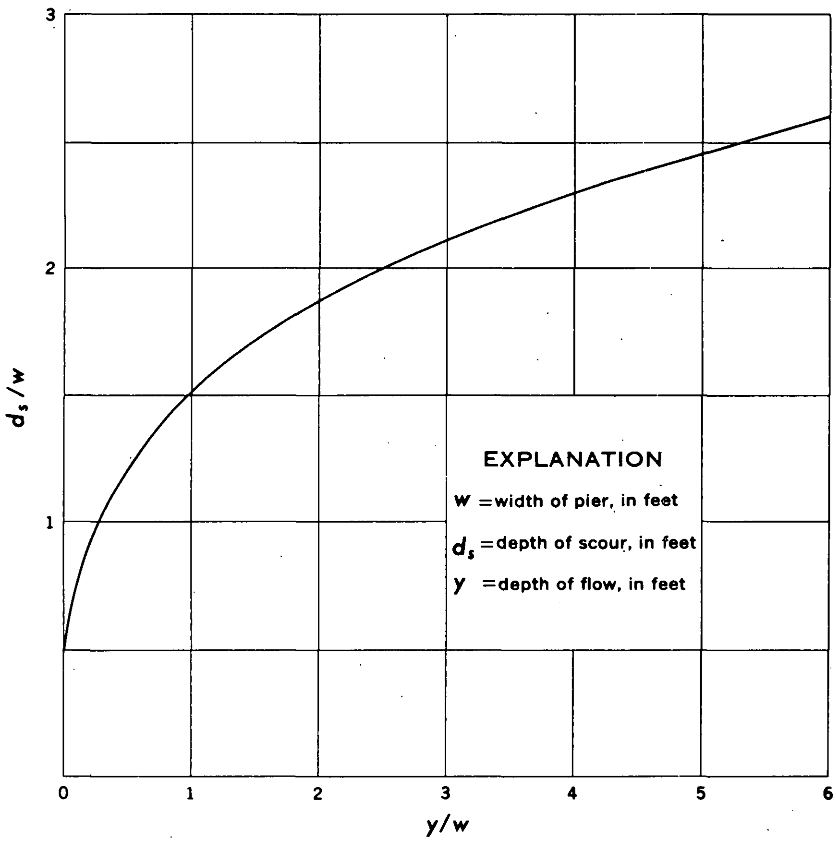


Figure 13.—Laursen's design data for local scour at rectangular bridge piers.

Table 1.—Shape coefficients (K_s) for nose forms.

Nose form	Length-width		K_s
Rectangular			1.00
Semicircular			.90
Elliptic		2:1	.80
		3:1	.75
Lenticular		2:1	.80
		3:1	.70

As an example, let us determine the scour that might be expected around a pier with an elliptical nose, 4 feet in width and with a 3:1 length-width ratio, in a sand-channel stream where the design flood depth at the bridge site has been determined to be 10 feet. For $y/w = 10/4 = 2.5$, figure 13 indicates a value for d_s/w of 2.0; therefore, d_s is 8 feet. From table 1, the shape adjustment for the proposed pier is 0.75. Assuming that there is no general scour in the bridge opening and that the approach velocity is directed toward the pier with no angularity, the estimated depth of scour would be 8×0.75 or 6 feet.

Although Laursen also gives coefficients for adjusting the basic scour depth for angle of attack of approach velocities, it is recommended that they not be used. This recommendation is made because most piers will probably be other than square-nosed and according to Laursen, his angle of attack adjustment is applicable only to square-nosed piers. It should be stated clearly in any bridge-site report that, except for round piers, the predicted scour depth is applicable only if the piers are alined with the flow and that if they are not, some unknown amount of additional scour probably will occur.

A note of caution with respect to use of Laursen's data for scour around bridge piers is in order. Laursen made only one comparison between model and field conditions (Laursen and Toch, 1956) and discussion of his work (Laursen, 1962, p. 180-209) by several well-known hydraulicians indicate that others do not agree entirely with his theory and concepts.

A limited investigation by the authors using data from Geological Survey current-meter measurements made from bridges proved inconclusive. In general, the scour predicted by Laursen's method was greater than that observed during the current-meter measurement, which tends to verify the statement made earlier relative to Laursen's curve fitting the entire range of data on model piers in sand beds reasonably well as an upper enveloping curve. However, depths observed during the current-meter measurements are not necessarily representative of the maximum scour that may have existed adjacent to the piers. Nevertheless, until something better is available, it is recommended that Laursen's method be used in the manner described above, where a prediction of pier scour depth must be made.

Design curves for scour at abutments are also presented by Laursen (1962) but are not recommended for use at the present time. Few others have pursued the investigation of scour at abutments, and there is very little information concerning the subject in the literature. Until such time as more factual information is available we should refrain from making estimates of the amount of scour caused by bridge abutments.

As in the case of channels other than sand channels, case histories of existing bridges on the same or similar rivers should be cited when available as examples of what has happened in similar situations. All known physical differences between the two sites including channel characteristics, flow characteristics, sediment transport and bed material characteristics, and bridge hydraulic geometry differences should be noted.

PART III. COMPILATION OF CASE HISTORIES ON SCOUR AND FILL

Although laboratory research on alluvial channels may lead to more reliable predictions of scour and fill based on hydraulic theory and empirical equations, the scour and fill problem is inherently complicated, and evaluations based on field experience are needed. The importance of case histories on scour and fill has been recognized by several Survey hydrologists and others (Neill, 1964b, p. 34); however, there is no nationwide program for the compilation of case histories at the present time (1967). Two kinds of case histories are proposed here: (1) case histories of river reaches where bridges have failed owing to scour and (2) case histories at reaches where significant scour is known to have occurred at bridge piers and abutments or in meander cutoffs.

In order to indicate the scope and direction of a program for data collection and compilation of case histories, a generalized outline of desired items is given below. For the case histories involving bridge failure the items listed under background information are applicable as well as item II, B-4 under Channel Behavior. Sites for which background information is unavailable should not be selected. For the second category of case histories all the items on the outline are desirable. Such detailed information is needed in order that valid conclusions can be drawn from the case histories. In the selection of sites that show significant scour the State Department of Highways should be consulted. In general, scour around bridge piers that exceeds half the mean depth of the mean annual flood certainly would be considered significant. Sites chosen for study should represent a range in types of channel, in discharge and sediment transport, in particle size of bed material, and in bridge geometry (size and shape of piers and abutments). Because the usefulness of case histories can be substantially increased by relating them to type of channel, a scheme for classification of alluvial channels has been prepared and included in the appendix.

Suggestions for Preparation of Case Histories on Scour and Fill

1. Background information

Ideally, the following kinds of information should be obtained for case history purposes as well as for existing studies that require bridge-site reports. The aerial photographs and topographic maps should include not only the stream channel but also the parts of the valley flat susceptible to flooding and should extend a minimum distance of about 25 channel widths on either side of the bridge site. The morphologic properties should be based on criteria given in the appendix; the site survey and preparation of flood history records should be made in accordance with standard Geological Survey procedures.

A. Photographs and maps
   1. Aerial photographs of reach
   2. Topographic map of reach
   3. Color slides of bed and banks

B. Bridge construction and maintenance
   1. Depth of piling, foundation of piers
   2. Foundation of abutments
   3. Dimensions of piers and abutments
   4. Scour apron or riprap around piers and abutments
   5. Pertinent geological data, logs of bore holes

C. Morphologic properties (see appendix)

D. Flood history
   1. Flood frequency
   2. Flow duration

E. Surveys
   1. Cross sections
   2. Slope
      a. Streambed
      b. Low-water surface profile
      c. High-water marks, if available

II. Channel behavior and associated hydraulic conditions

The number of hydraulic, sediment transport, morphometric, and related measurements will vary from place to place. The measurements listed below for at least 10 flood events is considered the minimum for analysis. Determination of the bed form and measurements of scour holes must be determined by echo-sounding instruments; at least one portable sounder and one or more additional sounders for installation at the pier or abutment under study are needed.

A. Flow characteristics

1. Vertical velocity distribution and direction of flow, approach section
2. Vertical and transverse velocity distribution and direction of flow, upstream side of bridge
3. Description of major eddies and changes in water-surface elevation near the piers and abutments

B. Sediment characteristics

1. Concentration of bed material discharge, approach section
2. Concentration of suspended sediment, bridge section
3. Particle size distribution of suspended sediment and bed material in bridge and approach sections
4. Water temperature

C. Bed form

1. Longitudinal profile
2. Dune length and amplitude

D. Scour and fill

1. Depth of scour around piers and abutments
2. Shape of scour hole around piers and abutments
3. Depth of scour at bridge section
4. Lateral scour in approach section

III. Compilation, analysis, and interpretation

APPENDIX

A Scheme for the Classification and Description of Alluvial Channels

The different kinds of natural alluvial channels differ not only in general appearance but also in their natural behavior and their response to artificial interference, such as constriction at bridge sites. Evaluations of scour and fill at the site of a proposed bridge should therefore be made with knowledge of the type of channel that is being bridged, and case histories should be categorized according to type of channel as well as type of bridge.

The importance of channel type is recognized by engineers, who have employed morphologic terms describing channel pattern (meandering, braided), as well as terms describing the bed material (sand bed, gravel bed) and terms that apparently imply the tendency of the channel to scour (stable, unstable). The classification used by Lane (1957) combines pattern and bed material and further categorizes braided channels as high-slope or low-slope.

General descriptions of alluvial channels such as meandering, braided, and straight are of limited value. Moreover, these type descriptions do not constitute a classification of channels because they are not mutually exclusive: meandering reaches are commonly braided, and braided reaches are commonly straight or of very low sinuosity. The classification illustrated in figure 14 is based on morphologic properties that are significant indicators of channel behavior. It is true that the full significance of many of these properties is not known at present, but enough is known to make the classification useful. Among the aspects of channel behavior relevant to scour and fill at bridge sites, which can be inferred from morphology, are lateral shift rate of the channel as a whole, shift of the thalweg or the individual channels of a braided drainage course, and (possibly) frequency of bankfull flow.

The classification illustrated in figure 14 is based on morphologic properties as observed on aerial photographs, without which it cannot be applied. Neither topographic maps nor field observations are adequate for observation of the properties. In applying the classification, a channel is first placed (on the basis of variability of width and channel pattern at normal discharge) into one or another of four major types: T1, sinuous or straight uniform channel; T2, sinuous point-bar channel; T3, point-bar braided channel; or T4, bar-braided or island-braided drainage course. This description is then supplemented by the other properties shown in figure 14 that apply, and symbols are supplied for brevity in writing the description. A discussion of each of the morphologic properties and its significance is given below.

Variability of Unvegetated Channel Width

According to Sigafoos (1964), the channelward limit of perennial woody plants represents, on the inside of bends, the level of the maximum discharge during extended periods of low flow or, on the outside of bends, the edge of the channel that is encroaching on a flood plain as a result of lateral erosion. This limit, which can be distinguished in the field and on aerial photographs, seems to be the best available reference for the measurement of channel width, and the width so measured is here termed "unvegetated channel width." A preliminary study of aerial photographs indicates that uniformity of unvegetated channel width is characteristic of many sinuous rivers in southeastern United States, in the plains region of Canada, and in Alaska. Variability of channel width is characteristic of many sinuous rivers in the arid or semiarid parts of the United States. Uniformity of unvegetated channel width implies a cohesiveness of bank materials, imparted either by a high clay content or by a dense vegetal cover. It may imply that no important quantity of bedload is being transported in the channel.

Channel Pattern at "Normal" Discharge

Leopold and Wolman (1957, p. 39) distinguish three gradational kinds of channel pattern--meandering, braided, and straight. The term meandering is difficult to define, but it implies both a certain degree of sinuosity and a certain regularity in size and repetition of bends. The term sinuous, which is both descriptive and readily expressed as a number, better serves the purposes of classification. The sinuosity of a reach can be expressed as the ratio of channel length to airline distance. See figure 13, S2. Thus, for a reach having a sinuosity of 1.5, the length of the reach as measured along the channel is 1.5 times the airline length. Channel length is usually obtained from maps.

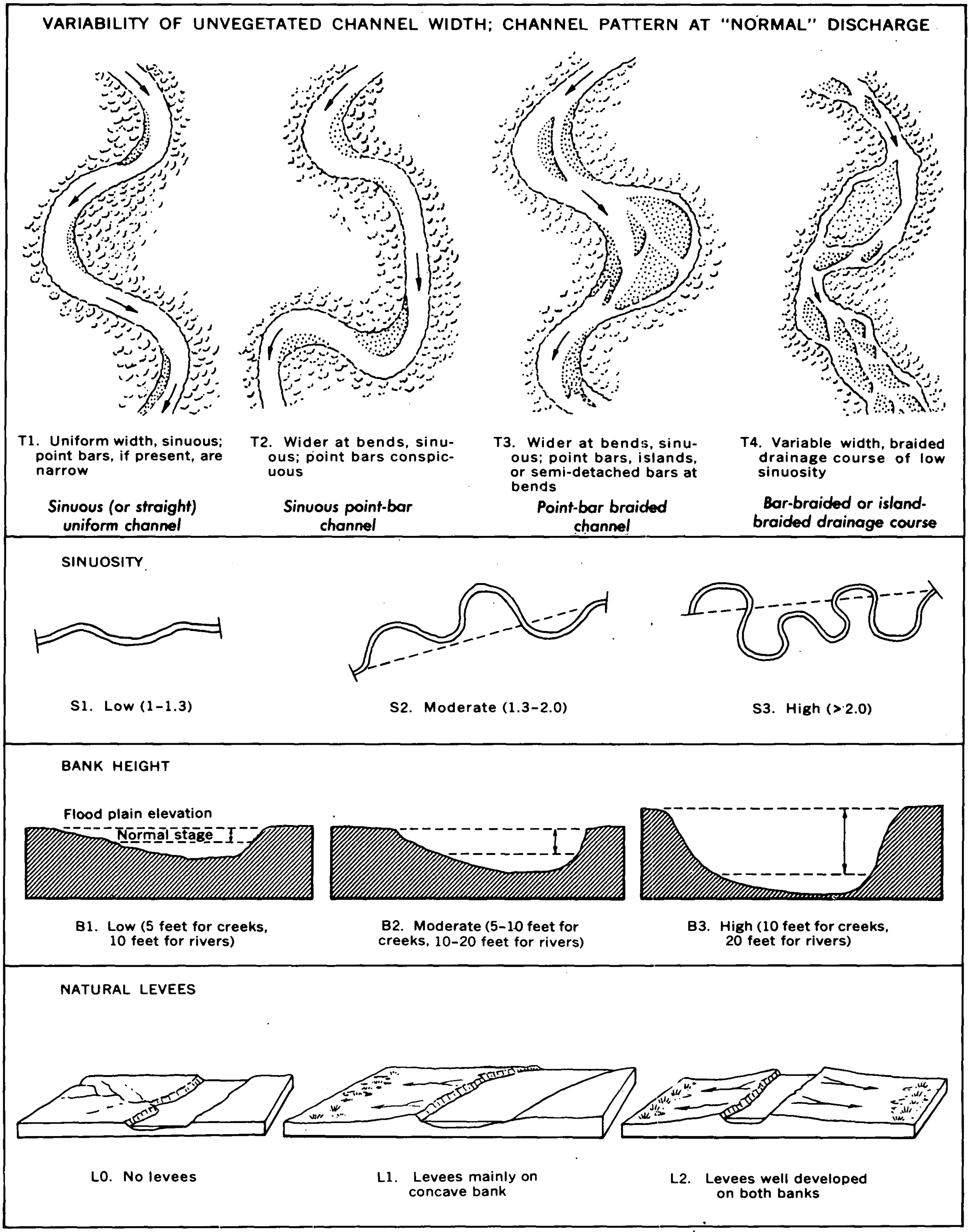
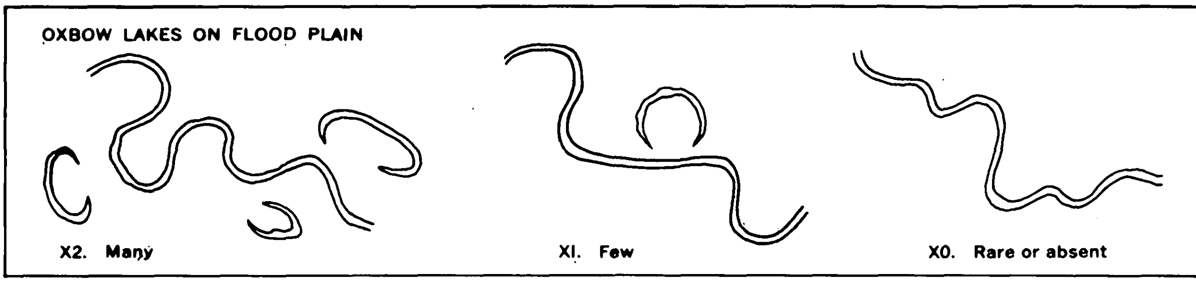
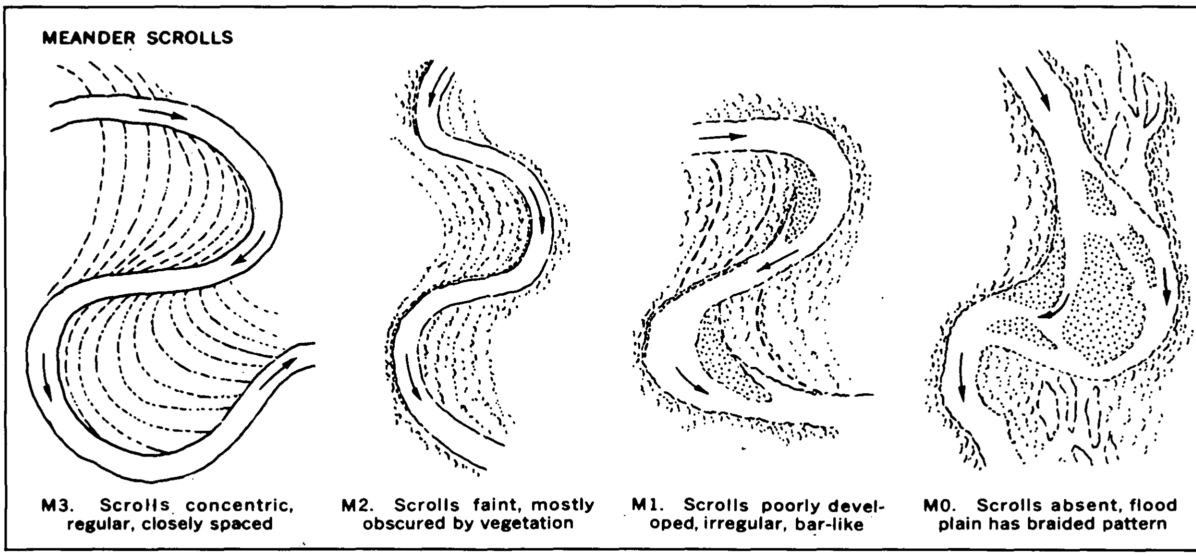
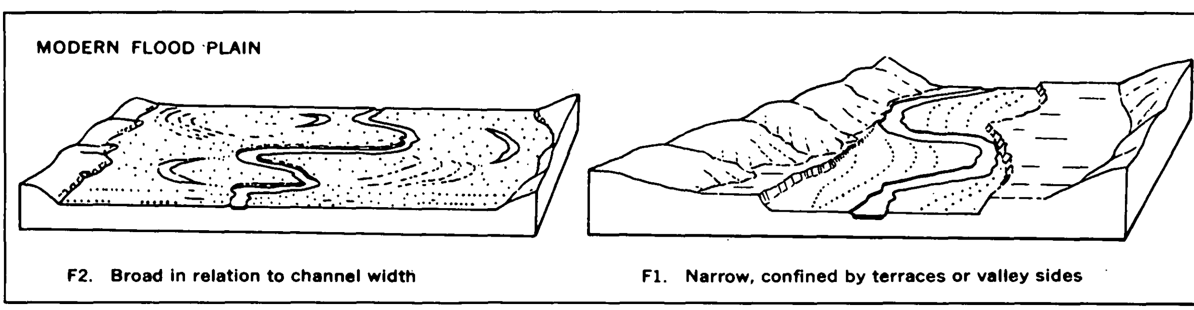
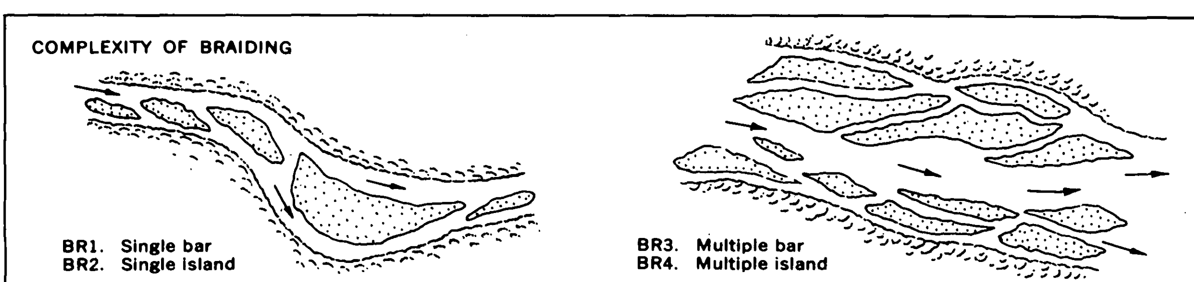


Figure 14.—Morphologic properties of alluvial channels and drainage courses (as observed on aerial photographs).


OXBOW LAKES ON FLOOD PLAIN
X2. Many
XI. Few
X0. Rare or absent


MEANDER SCROLLS
M3. Scrolls concentric, regular, closely spaced
M2. Scrolls faint, mostly obscured by vegetation
M1. Scrolls poorly developed, irregular, bar-like
M0. Scrolls absent, flood plain has braided pattern


MODERN FLOOD PLAIN
F2. Broad in relation to channel width
F1. Narrow, confined by terraces or valley sides


COMPLEXITY OF BRAIDING
BR1. Single bar
BR2. Single island
BR3. Multiple bar
BR4. Multiple island

The sharpness of a bend can be expressed as the ratio of radius of curvature to channed width, and for natural streams the values of this ratio tend to fall in the range of 2 to 3. The resistance to flow in a curving channel of uniform cross section falls to a sharply defined minimum when the radius of curvature is between 2 and 3 times the channel width. If the first bend upstream from a proposed bridge site is sharp, mention should be made of this fact in the bridge-site report. The bend may change in a few years in such a way as to deflect the flow at the site.

The braided pattern is characterized by channels that successively divide and rejoin, and the ground between two channels is called an island if it is permanently vegetated or a bar if weeded or bare. One type of braiding (figure 14, T3) is associated with point bars, whick (like other bars) are unvegetated according to the usage followed here.

A channel that looks unbraided at high stage may look decidedly braided at low stage. If one channel is to be compared with another and inferences as to channel behavior are to be made from pattern, all pattern descriptions must apply as nearly as possible to the same stage. The problem of representing a stream at a particular stage is encountered by the Topographic Division, whose policy thereto is given by the following quotation (U.S. Geological Survey, 1954):

> The most appropriate stage to adopt is that prevailing during the greater part of the year, the so-called "normal" stage...for a perennial river, this usually corresponds to the water level filling the channel to the line of permanent vegetation along its banks. Normal water stage of major streams can best be determined from long-range stream-gage data compiled by the Water Resources Division.

However, sand bars in streams are commonly represented on topographic quadrangle maps, and the line of permanent vegetation is doubtless above the normal stage.

In practice, the channel pattern description must apply to whatever river stage is represented on the available aerial photographs. The description will not be seriously affected by stage unless the river was at a very high or very low stage when the photographs were taken. The approximate river stage should be stated in connection with the description.

Bank Height

As with channel pattern, bank height is best expressed in relation to normal stage, and it is measured upward to the surface of the modern flood plain. Most rivers are bordered by terraces, and care must be taken not to measure the bank height to a terrace surface. The modern flood plain is the lowest flat surface along the river, and the one most often flooded. An abnormally great bank height suggests that the river is actively degrading its channel, and high banks are commonly associated with infrequent bankfull flows. A slow rate of lateral shift may also be indicated unless the channel is incised into easily erodible silt, as are many ephemeral channels in the Great Plains.

Natural Levees

Natural levees are best identified on a carefully surveyed cross profile that extends beyond the river banks for a distance of several hundred feet onto the modern flood plain. Their presence is indicated by a topographic slope away from the riverbank. Well-developed natural levees tend to restrict the gradual lateral shift of the channel, but sudden relocations of levee-bounded channels takes place by flood discharge through breaks (crevasses) in the levees.

Speight (1965, p. 35) suggests that bankfull flow may be much more frequent in the levee-bounded channel than in the braided channel, and of intermediate frequency in the point-bar channel. A different view is expressed by Leopold and others (1964, p. 319) who write that "There is a remarkable similarity in the frequency of bankfull stage on a variety of rivers in diverse physiographic settings and differing greatly in size. The recurrence interval of the bankfull stage appears to be in the range of 1 to 2 years, although some localities studied diverge greatly from this value."

Oxbow Lakes, Meander Scrolls, and Lateral Shift of Sinuous Channels

Both oxbow lakes and meander scrolls are formed by the lateral shift of a bend, usually at high stage. The oxbow lake is formed by erosion at the outside of a bend, which cuts through a narrow neck to an adjoining bend. Scrolls are narrow curving ridges and swales on the point-bar deposits at the inside of a bend. On some rivers, the ridges are formed by accretion, during flood, along a line of willows or other trees that were seeded at the water's edge during a previous flood.

Many recent oxbow lakes are perhaps the most easily observed and convincing evidence of lateral channel shift. The recency of an oxbow lake is not easy to judge accurately, as the time required for filling and overgrowth by vegetation depends both upon the climate and the size of the lake. An oxbow lake representing the former channel of a small stream may be almost obliterated in a decade, whereas a lake representing the former channel of a large river may survive for several hundred years.

Many oxbow lakes are commonly associated with regular, concentric meander scrolls, which are also an indication of rapid lateral shift. Many rivers on the plains of Alberta and Manitoba, of which the Pembina is an often-illustrated example, are characterized by high sinuosity, concentric scrolls, and many oxbow lakes. Where the scrolls are marked by concentric bands of trees, the height and age of which decreases successively toward the channel, shift rate can be estimated from the ages of the trees. Scrolls such as those illustrated in figure 14 are formed during high stages--at or near bankfull--and an abundance and regularity of the scrolls indicates frequent high stages.

Lateral shift at a bend upstream from a bridge can deflect the flow against the bridge abutment, and a rapidly shifting bend can actually encroach against a bridge embankment and break through it during flood. Unfortunately, no generalizations can be made as to rates of lateral shift that might be anticipated; measurements have shown highly variable rates even from one bend to the next in the same reach. Moreover, as noted by Wolman and Leopold (1957, p. 97), a bend may undergo little lateral shift during one period of time, but very rapid shift during a succeeding period. Symmetrical bends whose radius of curvature is in the range of 2 to 3 times channel width are less susceptible to shift than are sharp, asymmetrical bends.

The best estimate as to the probable shift of a bend upstream from a bridge site is obtained by a measurement of its past shift as shown on aerial photographs. For much of the United States, photographs made in the 1930's are available, and these can be compared with current photographs. Aerial photographs made at different dates are usually on file in county Soil Conservation Service offices. If the photographs to be compared are not of the same scale, the one having the smaller scale should be enlarged to correspond with the other. The study reach, together with reference points shown on both photographs (houses, barns, section corners, rock outcrops), is traced onto frosted acetated film from the latest photographs. The film is then placed over the other photograph, the reference points are matched, and the position of the study reach at the earlier date is shown in color. Serious error due to distortions in scale on the photographs is avoided by choosing photographs on which the study reach is approximately in the center.

The Modern Flood Plain

The modern flood plain is the lowest flat surface along a stream. Definition is difficult and controversial; according to Leopold and others (1964), it is currently under construction by the stream and is flooded with a recurrence interval of about 1.5 years. On aerial photographs, the modern flood plain can usually be identified by features such as recent scrolls and oxbow lakes that are made by lateral shift of the channel. These features can sometimes be seen on terrace surfaces, but there they are less distinct. Flood plains are widened by lateral cutting of a stream against its valley sides. If the flood plain is narrow, the stream will encounter its valley sides at many places along its course. If a stream having a wide flood plain becomes incised, the new flood plain is developed at a lower elevation by cutting away the former flood plain, remnants of which may survive as terraces for a long period of time.

The general width and alinement of a floodflow approaching a bridge can be discerned from the boundaries of the modern flood plain upstream from the bridge. A major flood may inundate low terrace surfaces as well as the modern flood plain, but the major part of the flow is likely to be transmitted within the boundaries of the flood plain. Since the constriction on flow that may be imposed by bridge approaches applies not only to flow within the channel but also to overbank flow, the degree to which the bridge approaches constrict the flood plain must be given consideration. In particular, constriction of a narrow flood plain--on which the overbank flow is likely to reach substantial depths and velocities--makes the bridge approaches liable to destruction during flood.

Braiding and the Lateral Shift of Braided Channels

Bars or islands that divide the flow in a channel are the most important elements of the braided pattern. Variations in the size, the number, and the distribution of these gives rise to many diverse kinds of braiding, of which two major kinds are illustrated in figure 14, T3-T4. The point-bar braided channel is braided mostly at bends, and most of the islands or bars have apparently originated from point-bar deposits; it is transitional between a braided and an unbraided channel. Where bars or islands are more numerous or more consistently distributed, the term "braided drainage course" is appropriate. According to its degree of complexity, the braiding of a drainage course can be described as single-bar (or island) or multiple-bar (or island) braiding. The term single implies that the braiding at a typical cross section is due to a single bar (or island) rather than to two or more bars (or islands). Vegetal cover distinguishes an island from a bar, and islands are likely to be more permanent than bars.

As a river course becomes more braided, it is very likely to become wider and less sinuous, especially if the braiding is due to the growth of channel bars or islands. However, a low sinuosity of the drainage course is not necessarily accompanied by a low sinuosity of the individual channels (sometimes called anabranches) between islands and bars. The channels of glacial outwash braiding are characteristically sinuous, and this sinuosity may be a morphologic indication of aggradation. The braided North and South Loup Rivers in Nebraska are very probably degrading (Brice, 1964, p. D9), as is the Platte River in Nebraska. The trend of anabranches in the Platte has an angular rather than a sinuous aspect (as shown in figure 14, BR3-BR4).

Some kinds of braided drainage are subject to wide fluctuations of discharge and have no well-defined banks. This is particularly true of glacial outwash drainage, for which the term bankfull has no significance. During high stages, channels that were abandoned at low stages are reoccupied, and a complete shift in the positions of anabranches may occur. Other multiple bar or multiple island drainage courses have well-defined banks; examples are the Platte River in Nebraska and the upper Mississippi in Iowa. Because of large channel-storage capacity, overbank floods along the Platte in Nebraska are less frequent than might be expected along a sinuous river of the same discharge.

The lateral shift rate of braided drainage courses that have well-defined banks is probably on the same order of magnitude as for sinuous point-bar channels. Along the braided course, however, migration is not confined to the outside of bends but can take place all along the banks by the lateral cutting of anabranches. The banks of rivers such as the Platte in Nebraska and the Tanana in Alaska are characteristically scalloped by the lateral cutting of anabranches. As a braided drainage course shifts laterally, channel bars (rather than point bars, as in a sinuous channel) are added to the side opposite the shift so that width does not continue to increase. A large standard deviation in channel width is characteristic of braided drainage courses that have well-defined banks.

Insofar as scour and fill are related to shifts in the anabranches of a braided drainage course, continuous and rapid changes can be anticipated both at average and at high stages. Three cross profiles of the braided Middle Loup River at Dunning, Nebr., measured at intervals of about 10 days and at nearly the same discharge (about 425 cfs) are given by Brice (1964, p. D18). The maximum depth of any channel remained at about 2.5 feet and the unvegetated channel width at about 340 feet; but the channels and bars changed completely in position from the time of one measurement to the next.

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