SCOUR AROUND BRIDGE PIERS ON STREAMS IN ARKANSAS

By Rodney E. Southard

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CONVERSION FACTORS AND VERTICAL DATUM

Multiply	By	To obtain
inch (in.)	25.4	millimeter
foot (ft)	0.3048	meter
mile (mi)	1.609	kilometer
square mile (mi^2)	2.590	square kilometer
foot per second (ft/s)	0.3048	meter per second
foot per second squared (ft/s^2)	0.3048	meter per second squared
cubic foot per second (ft^3/s)	0.02832	cubic meter per second

Sea level: In this report, "sea level" refers to the National Geodetic Vertical Datum of 1929--a geodetic datum derived from a general adjustment of the first-order level nets of the United States and Canada, formerly called Sea Level Datum of 1929.

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ABSTRACT

Scour around bridge piers is a major concern in the design of a new bridge or the evaluation of the structural stability of an existing bridge. Numerous previous laboratory studies have produced many equations that can be used to estimate local scour at piers. This report describes the results of a study to collect scour data at selected bridges in Arkansas, evaluates the application of several of these local-scour equations to scour at the bridge sites studied, and presents an equation for estimating scour based on the data collected at these sites.

Scour data were collected at 12 sites on streams in Arkansas during 14 flood events. The recurrence intervals of the flood events ranged from 3 years in the Illinois River basin to 100 years in the Red River basin. Scour holes near bridge piers measured as part of this study and included in the analysis described in this report, had depths that ranged from 2.3 to 16.0 feet. Five local-scour equations were evaluated as to their usefulness in estimating the measured scour at the 12 sites studied. Scour depths estimated using one of these equations, the Froehlich equation, had an interquartile range similar in magnitude to the interquartile range of the measured scour depths. The median scour depth estimated using the Froehlich equation was also statistically equal to the median of the measured scour depths at a 0.05 level of significance.

A multiple-linear regression equation was derived from scour data for the 12 sites on Arkansas streams. The independent variables in the regression equation are median bed-material diameter, average velocity, and pier location code and the dependent variable was measured scour depth. The equation had an average standard error of estimate of plus or minus 42 percent.

INTRODUCTION

One of the major concerns in the design of a new bridge or evaluation of an existing bridge is the susceptibility of the bridge piers to scour. Three types of scour can occur at a bridge: general scour, contraction scour, and local scour. General scour is the progressive degradation or lowering of the streambed through natural or man-induced processes. Channel degradation generally results from increased discharge, decreased bedload, or decreased bed-material size (Galay, 1983). Lateral erosion caused by a shift in the flow or meander pattern is included with general scour. Contraction scour is streambed erosion caused by increased flow velocity near a bridge or other channel constriction that results from the decrease in flow area at the contracted opening such as that caused by a bridge, approach embankments, and piers. Local scour is erosion caused by local disturbances in the flow, such as vortices and eddies in the vicinity of piers (Butch, 1991).

Numerous investigators have conducted laboratory studies of local scour and have developed a variety of equations that can be used to estimate scour depths. Some of the independent variables used in many of the equations are median bed-material diameter, pier geometry, flow depth, and velocity. Application of these equations to actual bridge sites commonly results in a wide range of estimated scour depths. One equation may estimate little or no scour at a bridge pier and another equation may over-estimate scour depth.

The need for reliable information and equations to assess the scour potential at bridges has resulted in efforts to collect scour data during floods. Scour depths measured during floods are a result of unique site and flow conditions that are more complex and varied than flows produced in a laboratory. In recent years, studies by several Federal and State agencies have involved the collection of detailed scour data at bridges to develop a National data base that can be used to investigate scour processes and develop scour prediction techniques.

The U.S. Geological Survey (USGS), in cooperation with the Arkansas State Highway and Transportation Department (AHTD), began a study of scour around bridge piers in Arkansas in 1985. The objectives of this study were to (1) collect scour data during flood events, (2) evaluate the usefulness of available scour equations for estimating local scour, and (3) develop an equation that can be used to estimate local scour on Arkansas streams using the data collected. The scour data collected as part of this study also will be included in the National data base for a study currently (1992) being conducted by the USGS and Federal Highway Administration.

Purpose and Scope

This report summarizes scour data collected at 12 study sites during 14 high flow events on streams in Arkansas (fig. 1). The methods used to select the sites are described and the bridge geometry, hydraulic characteristics, and scour measurements at each site are summarized. Data collected and presented in the report include (1) pier type and width, (2) flow velocity, depth, and angle, and (3) median bed-material diameter. Existing local-scour equations were selected and evaluated in this study. The equations were evaluated on the basis of their usefulness in estimating the measured scour at the 12 study sites. A multiple-linear regression equation also was developed by relating factors such as pier location, flow velocity, and median bed-material diameter to measured scour depths at the study sites. Scour estimates calculated using the various equations were then compared to the scour measurements.

Acknowledgments

Thanks are extended to personnel of the Arkansas State Highway and Transportation Department for providing bridge plans, cross-section data, and soil-boring data. Appreciation is specifically extended to the personnel of the Arkansas State Highway and Transportation Department Hydraulics Section for their input and assistance throughout the project.

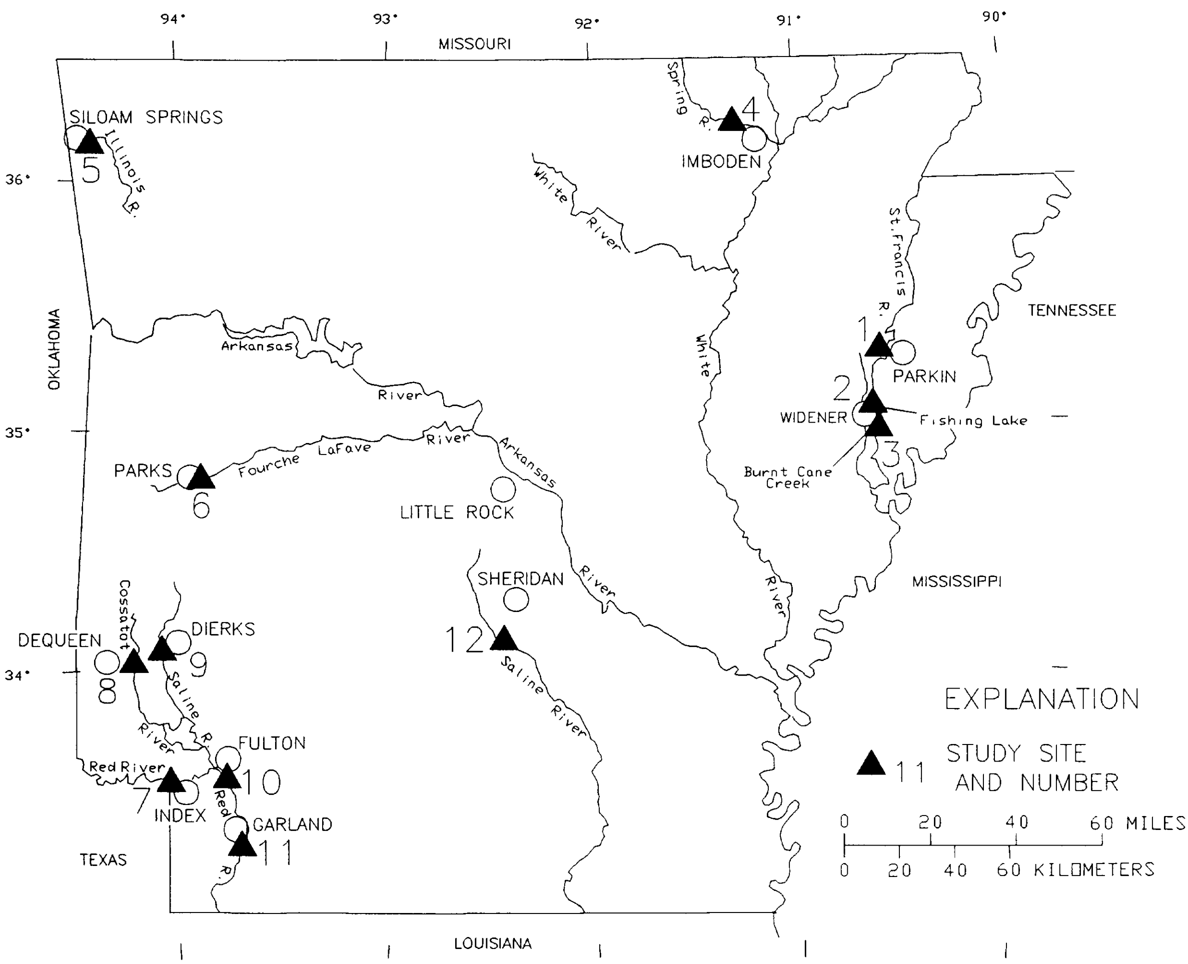

Figure 1.--Location of study sites.

METHODS OF STUDY

From a list of 72 bridges with known scour problems supplied by AHTD, 21 sites were selected for additional data collection. Data collection at these sites included the collection of detailed cross-section, bridge geometry, and bed-material data. Factors considered in selecting the 21 sites included:

- type of scour at the bridge,
- accessibility of the bridge during periods of high flow,
- safety considerations for data-collection crews,
- duration of peak flows,
- availability of cross-section data at the bridge,
- degree to which channel banks and bed were armored with rock,
- amount of debris transported by the stream, and
- bridge design and other factors that might complicate or prevent scour measurements.

At the 21 sites selected, cross sections were obtained along the upstream and downstream sides of the bridge to establish existing conditions. Stationing was established on the bridge handrails for horizontal reference. Bed-material samples were collected to determine the representative size and gradation of channel-bed and flood plain material as outlined by Guy and Norman (1970). The bed-material samples were analyzed using methods described by Guy (1969). Cross sections were measured during high flows and these cross sections were plotted to determine the location and depth of the scour holes. The cross-section measurements included measurements of channel-bed elevations at the end and on each side of the bridge piers. For historical flood measurements, the maximum depth of a scour hole was assumed to be at the lowest channel-bed elevation. For purposes of this report, the depth of a scour hole was calculated as the difference between the elevation of the projected channel cross section across the scour hole and the lowest measured channel-bed elevation of the hole (fig. 2). This projected channel cross section represents the concurrent ambient bed level at the scour hole. Flow depth was calculated as the difference between the elevation of the water surface and the elevation of the projected channel cross section at the scour hole.

Discharge and velocity were determined using standard streamflow-gaging procedures described by Rantz and others (1982). The velocity variable used in existing local-scour equations is the average velocity of the vertical section immediately upstream or downstream of a pier with local scour. For scour measurements on the downstream side of the bridge, average velocity at the pier was calculated as the average of the velocities of the vertical sections on each side of the pier.

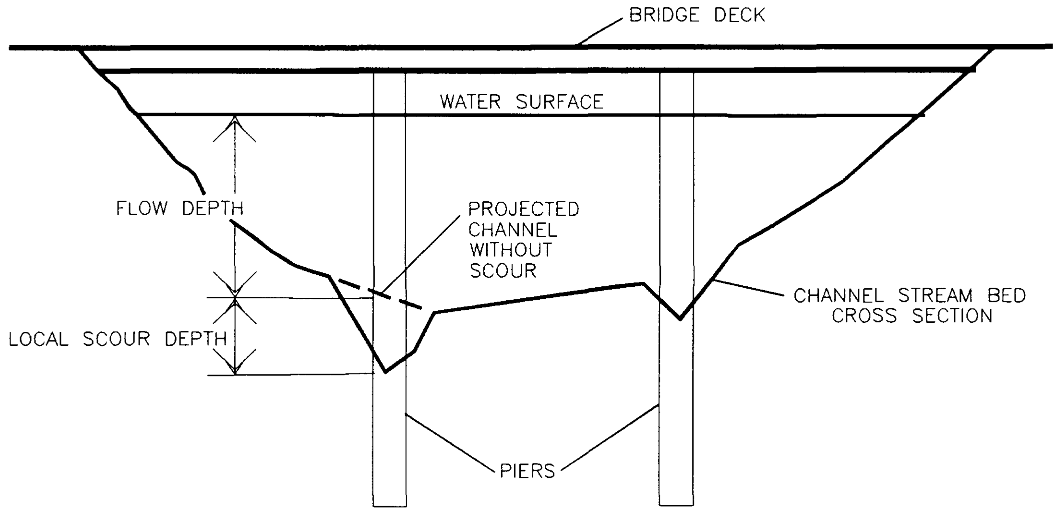

Figure 2.--Flow depth and local scour depth at a bridge pier for a typical channel cross section.

DESCRIPTION OF STUDY SITES

Of the 21 sites where cross-section data were collected, scour around bridge piers was documented at 9 sites. However, scour was also documented at 3 additional sites on the Red River in southeastern Arkansas during the May 1990 flood. The 12 sites at which scour data were collected are listed in table 1. Six of the study sites are at streamflow-gaging stations where previous discharge measurements have been made during extreme flood events. The scour data collected at these 12 sites formed the data base for the analyses described in this report.

The 12 study sites are located in 3 physiographic provinces (fig. 3); the Coastal Plain Province in the southeastern half of Arkansas, the Ouachita Province in the west-central part of Arkansas, and the Ozark Plateaus Province in the northwest and north-central part of Arkansas (Fenneman, 1938). Seven of the study sites are in the Coastal Plain Province, which is underlain by alluvial deposits and other unconsolidated sediments. The composition of the bed material at these sites consists primarily of fine sand, silts, and clays. The remaining five study sites are located in the Ouachita Province and the Ozark Plateaus Province. These provinces are underlain by consolidated rocks consisting mostly of limestones, dolomites, sandstones, and shale. The composition of the bed material at these sites consists primarily of coarse gravel and coarse to fine sands.

Table 1.--*Summary of discharge data at bridge sites in Arkansas*

[mi^2, square mile; ft^3/s, cubic foot per second]

Site number	Station number	Station name and location	Drainage area (mi^2)	Date of measurement	Measured discharge (ft^3/s)	Recurrence interval (years)[1]
1	[2] 07047800	St. Francis River at State Highway 64 at Parkin	--(3)	12-28-87	18,600	25
2	07047908	Fishing Lake at State Highway 70 near Widener	--(3)	12-27-87	17,100	--(3)
3	07047909	Burnt Cane Creek at State Highway 50 near Widener	--(3)	12-26-87	20,200	--(3)
4	[2] 07069500	Spring River at U.S. Highway 62 at Imboden	1,183	5-23-57	44,400	4
5	07195400	Illinois River at State Highway 16 near Siloam Springs	509	11-19-85	24,300	3
6	07261440	Fourche LaFave River at State Highway 28 near Parks	254	5-03-90	33,500	6
7	[2] 07337000	Red River at U.S. Highway 71 at Index	48,030	5-09-90	262,000	[4]100
8	[2] 07340500	Cossatot River at U.S. Highway 71 near DeQueen	360	1-30-69	64,600	12
9	[2] 07341000	Saline River at U.S. Highway 70 near Dierks	121	5-06-61 5-13-68	28,100 56,200	10 80
10	07341500	Red River at Interstate 30 at Fulton	52,336	5-12-90	257,000	--(3)
11	07342000	Red River at U.S. Highway 82 at Garland	52,675	5-14-90	222,000	--(3)
12	[2] 07363200	Saline River at U.S. Highway 167 near Sheridan	1,123	2-01-69 12-29-87	67,000 51,700	20 9

[1]Recurrence interval from Neely (1987).
[2]U.S. Geological Survey streamflow-gaging station.
[3]Indeterminate.
[4]Record furnished by U.S. Army Corps of Engineers, Little Rock District.

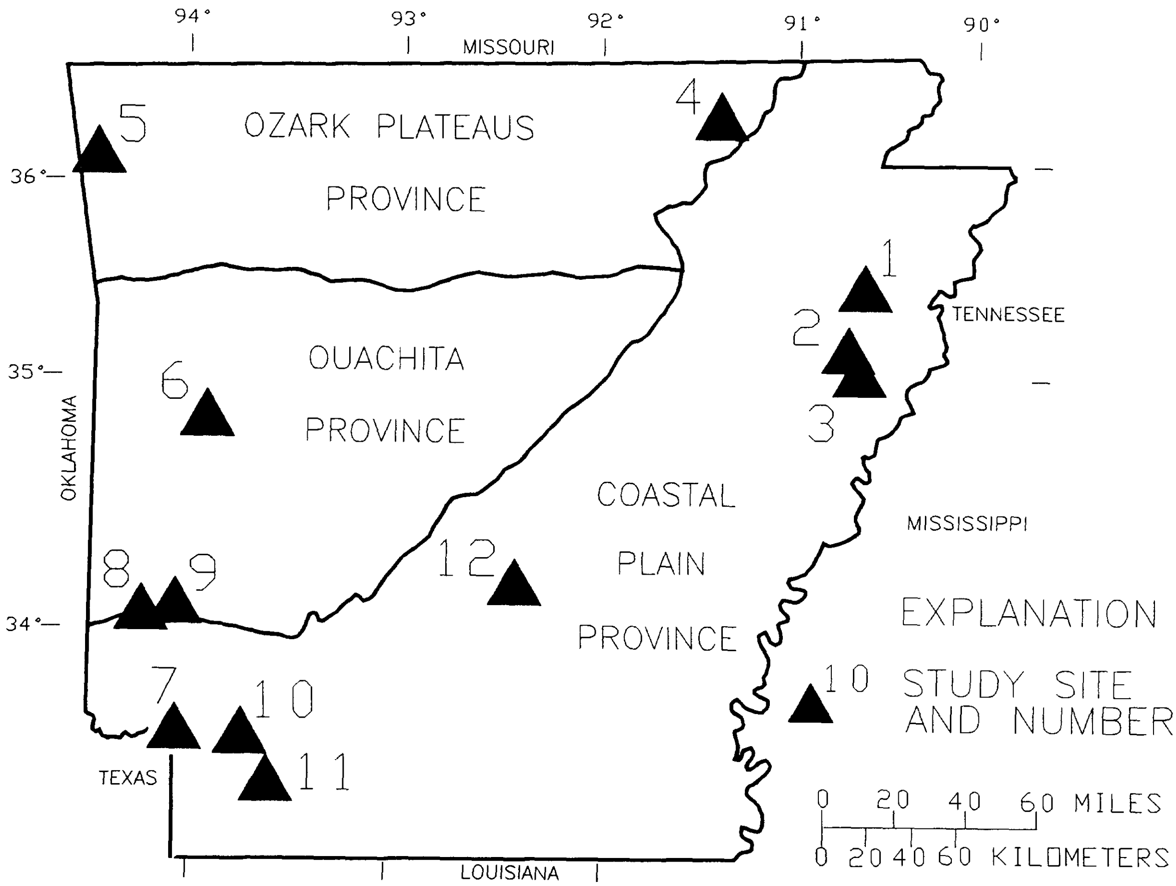

Figure 3.--Location of study sites and physiographic provinces in Arkansas.

Drainage areas, discharges and recurrence intervals for the floods for which scour data were collected are presented for the 12 study sites in table 1. Drainage areas at the 12 sites ranged from 121 mi^2 for Saline River at U.S. Highway 70 near Dierks (site 9) to 52,675 mi^2 for Red River at U.S. Highway 82 at Garland (site 11). At sites where the recurrence intervals[1] of the measured floods were determined, the intervals ranged from 3 years for the Illinois River at State Highway 16 near Siloam Springs (site 5) to 100 years for the Red River at U.S. Highway 71 at Index (site 7).

MEASURED SCOUR DEPTHS

Review of previous discharge measurements made at the six streamflow-gaging stations and discharge measurements made during this study resulted in 22 sets of data describing scour holes ranging from 2.3 ft to 16.0 ft in depth (table 2). The deepest of these scour holes (16.0 ft) was measured during the flood on May 13, 1968, at the U.S. Highway 70 crossing of the Saline River near Dierks (site 9) just minutes before the failure of a bridge pier (fig. 4). The scour undermined the pier and caused the pier and part of the bridge deck to be lowered by about 2 ft. Local scour was measured at four of six streamflow-gaging stations prior to 1985. These scour data were included in the data base because no significant changes have occurred at the bridge sites since the dates of these flood events. The bed-material samples obtained during this study are assumed to be representative of the bed-material size at the time of the historical flood event.

Scour depths of greater than 10 ft were measured at several sites on the Red River in May 1990. Comparisons of cross-section data collected prior to the May 1990 flood and cross-section data collected near the peak of the flood at the U.S. Highway 71, Interstate 30, and U.S. Highway 82 crossings of the Red River (sites 7, 10, and 11) indicates contraction and local scour processes were prevalent. The degree of scouring at the Interstate 30 crossing (site 10) is shown in figure 5. The main channel bed at this site was lowered 15 to 20 ft and local scour holes 8.7 and 14.6 ft deep were measured at stations 580 and 782 ft from the left abutment. At station 460, the channel bed elevation was approximately the same as the elevation of the bottom of the pier located at station 389. Rock riprap was placed in the main channel by AHTD immediately after the flood peak to protect the bridge piers.

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[1]The recurrence interval is the reciprocal of the probability of occurrence multiplied by 100 and is the average number of years between exceedances of a given flood magnitude. The occurrence of floods is random in time; no schedule of regularity is implied. A given flood magnitude can be exceeded at any time during a given period.

Table 2.--*Summary of scour, pier geometry, and hydraulic data collected at study sites with measured scour depths*

[ft, feet; ft/s, feet per second]

					Pier data				Hydraulic data at scour hole section		
Site number	Date of measurement	Measured scour depth (ft)	Distance from left abutment (ft)	Median bed material diameter (ft)	Type of nose	Width (ft)	Width normal to flow (ft)	Location code[1]	Flow depth (ft)	Average velocity (ft/s)	Flow angle (degrees)
1	12-28-87	2.8	300	0.00059	square	3.1	3.1	0	29.9	2.5	0
2	12-27-87	4.0	210	.00108	square	3.0	3.0	0	31.0	4.1	0
3	12-26-87	6.3	332	.00092	round	1.5	1.5	1	12.4	3.3	0
3	12-26-87	4.8	220	.00092	round	6.0	6.0	0	28.7	4.2	0
4	5-23-57	3.3	460	.01280	square	4.6	4.6	0	23.8	4.6	0
5	11-19-85	3.2	766	.05577	square	4.0	4.0	0	19.6	3.0	0
5	11-19-85	2.3	840	.05577	square	4.0	4.0	0	16.7	3.6	0
6	5-03-90	3.3	251	.06890	square	8.5	21.2	1	7.8	3.2	37
6	5-03-90	3.1	331	.06890	sharp	3.0	3.0	0	20.0	7.8	0
7	5-09-90	7.6	720	.00039	round	7.0	7.0	0	40.4	8.7	11
7	5-09-90	11.2	940	.00039	round	7.0	7.0	0	42.8	12.8	8
8	1-30-69	3.4	201	.00036	sharp	4.5	4.5	0	20.6	4.3	0
9	5-06-61	4.0	360	.05906	square	2.6	2.6	0	19.0	5.1	0
9	5-13-68	16.0	120	.05906	square	2.6	2.6	1	8.8	11.4	0
9	5-13-68	5.4	360	.05906	square	2.6	2.6	0	21.2	11.0	0
10	5-12-90	14.6	580	.00059	sharp	7.0	7.0	0	35.3	9.5	0
10	5-12-90	8.7	782	.00059	sharp	6.5	6.5	1	26.7	2.4	0
11	5-14-90	14.4	690	.00105	round	10.0	10.0	0	38.5	6.2	0
11	5-14-90	5.9	890	.00105	round	10.0	10.0	0	44.2	7.7	14
11	5-14-90	10.7	1,296	.00105	round	10.0	10.0	1	29.9	4.8	0
12	2-01-69	4.9	66	.00098	round	1.4	1.4	1	8.4	3.2	23
12	12-29-87	5.0	181	.00098	square	3.8	3.8	1	10.5	1.7	0

[1]0 = pier located on the bed of main channel; 1 = pier located on bank of main channel or on flood plain.

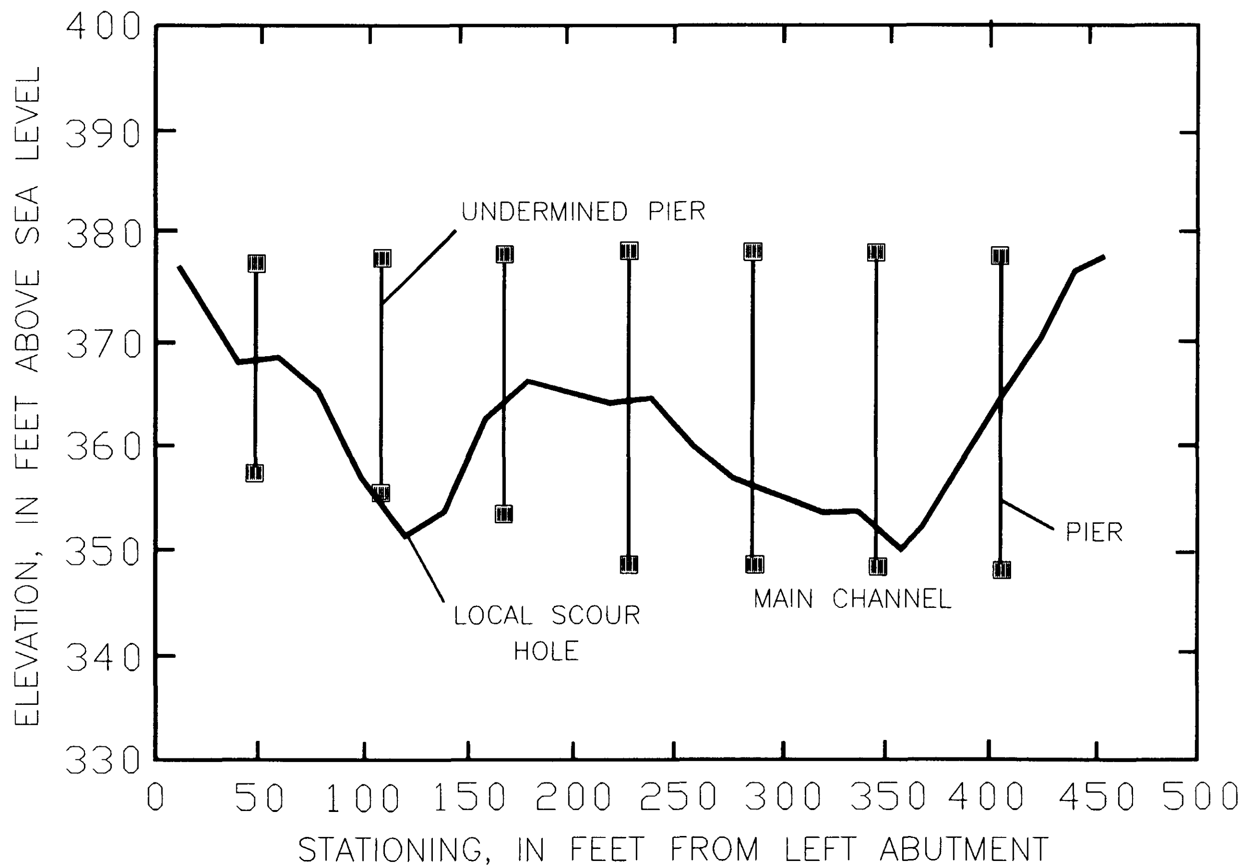

Figure 4.--Cross section of channel of the Saline River at U.S. Highway 70 near Dierks, Arkansas (site 9), along the downstream side of the bridge during the flood of May 13, 1968.

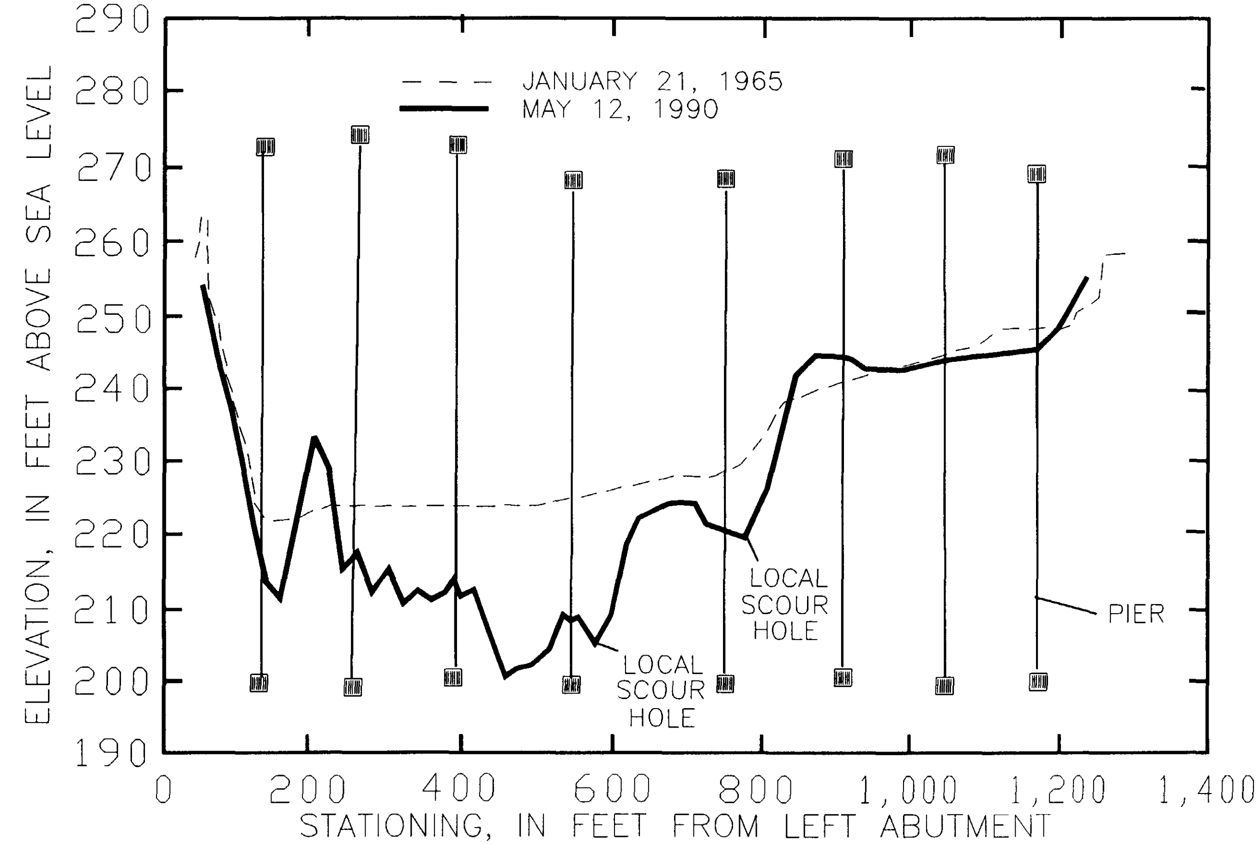

Figure 5.--Channel cross-section data from bridge plans dated January 21, 1965, and cross section of channel of the Red River at Interstate 30 at Fulton, Arkansas, measured along the upstream side of the bridge during the flood of May 12, 1990.

ESTIMATED SCOUR DEPTHS

Several investigators have developed equations to estimate local-scour depths at bridge piers. These equations generally have been based on laboratory studies and commonly yield different estimates of scour depth for the same set of data. To evaluate these equations and their application to streams in Arkansas, five local-scour equations were selected and used to estimate scour depth at the study sites where scour data had been collected. A multiple-linear regression equation for estimating scour depth based on the measured scour data at the 12 study sites was also developed.

Selected Local-Scour Equations

The local-scour equations evaluated in this study were the equations developed by (1) Laursen, (2) Chitale, (3) Carstens, (4) Froehlich, and (5) Colorado State University (CSU). The Laursen, Chitale, and Carstens equations are two-variable equations developed from laboratory studies on scour around bridge piers conducted prior to 1970. The Froehlich and CSU equations are six-variable equations developed since 1987 on larger data bases. Laursen during the 1950's conducted some of the first in-depth studies into quantifying the relation between scour depth and streamflow and pier geometry. The graphical relation developed by Laursen and later transcribed to equation form by Neill was widely used during the 1970's. Chitale's equation is one of the first equations to use Froude number, which is a function of average velocity and flow depth at a pier, as a variable in determining scour depth. The Froude number is also used in the Froehlich and CSU equations. Carsten's equation uses the specific gravity of sand, which is a common bed material in channels of many streams in the Coastal Plain of Arkansas, to calculate estimated scour depth. Currently (1992), the most recently developed equations to compute local scour at piers are the Froehlich and CSU equations. These equations use essentially the same factors to estimate scour depth. Numerous other local scour equations exist (Jarrett and Boyle,1986) but only the five equations listed above were evaluated as part of this study. The equations used in this study are briefly described in the section that follows. The dates shown indicate the times when the equations were developed.

Laursen equation--1956 and 1958:

$$D = 1.5B^{0.7}H^{0.3},$$

where D is scour depth measured from ambient bed elevation, in feet;
B is width of the pier, in feet; and
H is flow depth, in feet.

The Laursen equation was transcribed from its graphical form by Neill (1970) based on Laursen's basic design curve for a square-nosed pier aligned with the flow as reported by Laursen and Toch (1953) and Laursen (1958, 1962).

Chitale equation--1962:

$$D = H\,(6.65(F)-5.49(F)^2-0.51)$$

where F is the Froude number defined as $V/(gH)^{0.5}$: where V is average velocity, in feet per second; g is the acceleration of gravity, in feet per second squared; and other terms are as defined above.

Carstens equation--1966:

$$D = B[0.546[((N_s)^2-1.64)/((N_s)^2-5.02)]^{0.83}],$$

where N_s is $V/[(s-1)gD_m]^{0.5}$: where s is 2.65, the specific gravity of sand; D_m is median bed-material diameter, in feet; and other terms are as defined above.

Froehlich equation--1987:

$$D = B\left[0.32\varnothing\left(\frac{B'}{B}\right)^{0.62}\left(\frac{H}{B}\right)^{0.46}(F)^{0.20}\left(\frac{B}{D_m}\right)^{0.08}\right]$$

where $\varnothing$ is pier shape correction factor,
B' is pier width projected normal to flow: where $B' = (B)\cos(\alpha) + (L)\sin(\alpha)$: α is flow angle in degrees, $\alpha = 0$ for pier aligned with flow, L is length of pier, in feet, and other terms are as defined above.

Colorado State University equation--1990:

$$D = H[2.0K_1K_2\left(\frac{B}{H}\right)^{0.65}(F)^{0.43}]$$

where K_1 is pier shape correction factor, K_2 is flow angle correction factor, and other terms are as defined above.

The measured scour and estimated local-scour depths calculated using each of these equations are listed in table 3. The pier-shape factors used with the Froehlich and CSU equations are listed in table 4. The flow-angle factors used with the CSU equation are listed in table 5.

A method that can be used to summarize the distribution of the estimated scour depths listed in table 3 is the boxplot. In a boxplot diagram, the box represents the interquartile range (25th to 75th percentile); the horizontal line inside the box represents the median; and the relative size of the box above and below the median represents the skew of the data (a larger box above the median line indicates a right-skewed distribution). The vertical line at the top of the box extends to a value less than or equal to the 75th percentile plus 1.5 times the interquartile range, and the vertical line at the bottom of the box extends to a depth value greater than or equal to the 25th percentile minus 1.5 times the interquartile range. Data beyond the vertical lines are individually plotted. Data 1.5 to 3.0 times the interquartile range are "outside values," and occur fewer than once in 100 times for a normal distribution.

Table 3.--*Measured scour depths and scour depths estimated using the Laursen, Chitale, Carstens, Froehlich, Colorado State University, and multiple-linear regression equations*

[--, scour not estimated]

Site number	Measured scour depth (feet)	Estimated scour depth calculated using indicated equation (feet)					
		Laursen equation	Chitale equation	Carstens equation	Froehlich equation	Colorado State University equation	Multiple-linear regression equation (this study)
1	2.8	9.2	--	0.2	4.4	5.1	3.7
2	4.0	9.1	8.0	1.6	4.6	6.2	4.8
3	6.3	4.2	5.3	1.6	2.4	2.9	6.8
3	4.8	14.4	8.9	3.3	5.4	8.9	5.0
4	3.3	11.3	10.6	2.8	4.6	8.3	3.9
5	3.2	9.7	3.9	--	3.2	6.1	2.4
5	2.3	9.2	6.5	--	3.1	9.8	2.8
6	3.3	12.4	4.7	--	6.4	18.2	4.0
6	3.1	8.0	20.3	2.0	1.7	6.3	4.6
7	7.6	17.8	31.3	3.8	8.3	14.0	9.1
7	11.2	18.1	48.3	3.8	9.1	16.7	11.8
8	3.4	10.6	9.2	2.5	3.0	6.4	5.7
9	4.0	7.1	11.9	2.6	2.7	5.8	3.5
10	14.6	17.1	32.6	3.8	10.0	14.3	9.2
10	8.7	14.9	--	3.6	3.6	13.2	5.8
11	14.4	22.5	18.7	5.5	8.7	15.2	6.4
11	5.9	23.4	27.2	5.5	9.6	17.0	7.4
11	10.7	20.8	11.8	5.5	7.6	13.2	8.7
12	4.9	3.6	4.7	.8	1.3	2.6	6.6
12	5.0	7.7	.7	2.2	3.0	4.3	4.4

Table 4.--*Pier-shape factors used with Froehlich and Colorado State University equations for estimating scour depth (from Richardson and Richardson, 1989)*

Type of pier	Pier-shape factor: Froehlich equation ∅	Pier-shape factor: Colorado State University equation (K_1)
Square nose	1.3	1.1
Round nose	1.0	1.0
Sharp nose	.7	.9

Table 5.--*Flow-angle factors used with Colorado State University equation for estimating scour depth* (from Richardson and Richardson, 1989)

[L, length of pier, in feet; B, width of pier, in feet]

Flow angle (degrees)	Flow-angle factor (K_2)		
	L/B =4	L/B = 8	L/B =12
0	1.0	1.0	1.0
15	1.5	2.0	2.5
30	2.0	2.5	3.5
45	2.3	3.3	4.3
90	2.5	3.9	5.0

The boxplots for the measured scour depths and the estimated scour depths based on the five equations described above are shown in figure 6. The boxplot for the measured scour depths indicates that the distribution of the data points is not from a normal distribution and is skewed to the right. If the measured data were from a normal distribution, the scour depth of 16.0 ft would be an "outside value" and would occur fewer than once in 100 times. The right-skewed distribution is also characteristic of the five equations described above and the multiple-linear regression equation developed in this study.

The interquartile range and median were computed for each sample set to compare the distribution of the estimated scour depths to that of the measured scour depths. The interquartile range measures the spread of the data points and the median measures the location of the distribution. The interquartile range is equal to the 75th percentile minus the 25th percentile. From table 6, the interquartile range of the measured scour depths is 4.85 ft. The interquartile ranges for values estimated using the Froehlich and CSU equations were the next lowest and highest ranges at 4.15 ft and 7.65 ft, respectively. The median of the measured scour depths was 4.95 ft. The medians of the scour depths estimated using the Froehlich and Carstens equations were 4.00 ft and 2.60 ft, respectively. The median of the scour depths estimated using the CSU equation was 8.25.The Wilcoxon Signed-Ranks test was used to determine if there were statistical differences between the median of measured scour and the median of each set of estimated scour depths. The null hypothesis for each sample was: the median of the measured scour is equal to the median of the set of estimated scour depths. A two-tail test at a 0.05 level of significance indicated that the median of the scour depths estimated using the Froehlich equations is the only median of estimated scour depths statistically equal to the median of measured scour.

Table 6.--*Statistical characteristics of measured and estimated scour depths*

Statistical characteristic	Measured scour (feet)	Estimated scour depth calculated using indicated equation (feet)					
		Laursen equation	Chitale equation	Carstens equation	Froehlich equation	Colorado State University equation	Multiple-linear regression equation (this study)
Mean	6.6	12.0	15.3	2.8	4.9	9.6	6.0
Minimum	2.3	3.6	.7	.2	1.3	2.6	2.4
Maximum	16.0	23.4	48.3	5.5	10.0	18.2	11.8
Median	4.95	10.2	11.2	2.60	4.00	8.25	5.75
25th percentile	3.30	7.50	5.90	1.60	2.85	5.95	3.95
75th percentile	8.15	16.0	23.8	3.80	7.00	13.6	7.10

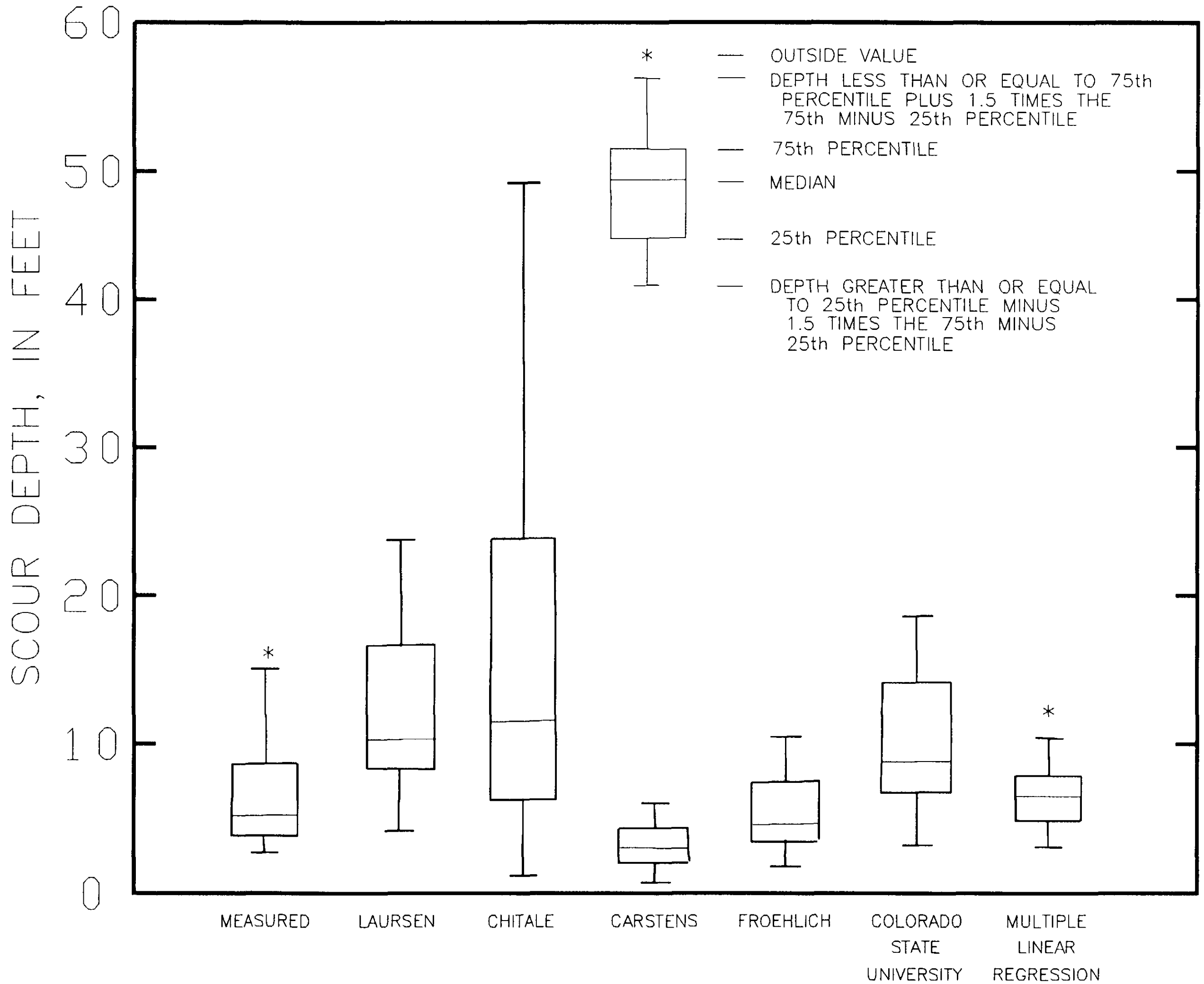

Figure 6.--Boxplots of the distribution of measured scour depths and scour depths estimated using the Laursen, Chitale, Carstens, Froehlich, Colorado State University, and multiple-linear regression equations.

Estimated scour depths were plotted against the residuals (measured scour depth minus estimated scour depth) (figs. 7-11) to identify bias in the estimates. Large negative residuals for values determined using the Laursen and Chitale equations indicated that these equations significantly overestimated the larger measured scour depths as shown in figures 7 and 8. A similar analysis indicated that Carstens' equation underestimated the measured scour depths throughout the range of measured data (fig. 9). Residuals for values determined using Froehlich's equation indicated no significant bias in the estimated depths (fig. 10). Residuals for estimated scour depths determined using the CSU equation indicated a possible bias of overestimation for the larger scour depths (fig. 11).

Results of a correlation analysis between measured scour depths and estimated scour depths are presented in table 7. The strongest relation between measured and estimated scour depths was for depths estimated using the CSU equation (correlation coefficient of 0.49). The next best correlation was for depths estimated using the Froehlich equation (correlation coefficient of 0.46). The analysis also indicated that (1) depths estimated using the Chitale equation were only moderately correlated with depths estimated using the other equations, (2) depths estimated using the Chitale equation were more closely correlated with measured scour depths than were depths estimated using the Laursen and Carstens equations, and (3) there are significant relations among scour depths estimated using the Laursen, Carstens, Froehlich, and CSU equations.

Table 7.--*Correlation analysis for measured and estimated scour depths*

	Correlation coefficient for scour depths estimated using indicated equation (dimensionless)					
	Laursen equation	Chitale equation	Carstens equation	Froehlich equation	Colorado State University equation	Multiple-linear regression equation (this study)
Measured scour depth	0.29	0.44	0.32	0.46	0.49	0.84
Laursen equation		.51	.93	.89	.90	.31
Chitale equation			.46	.58	.75	.52
Carstens equation				.84	.82	.25
Froehlich equation					.90	.41
Colorado State University equation						.52

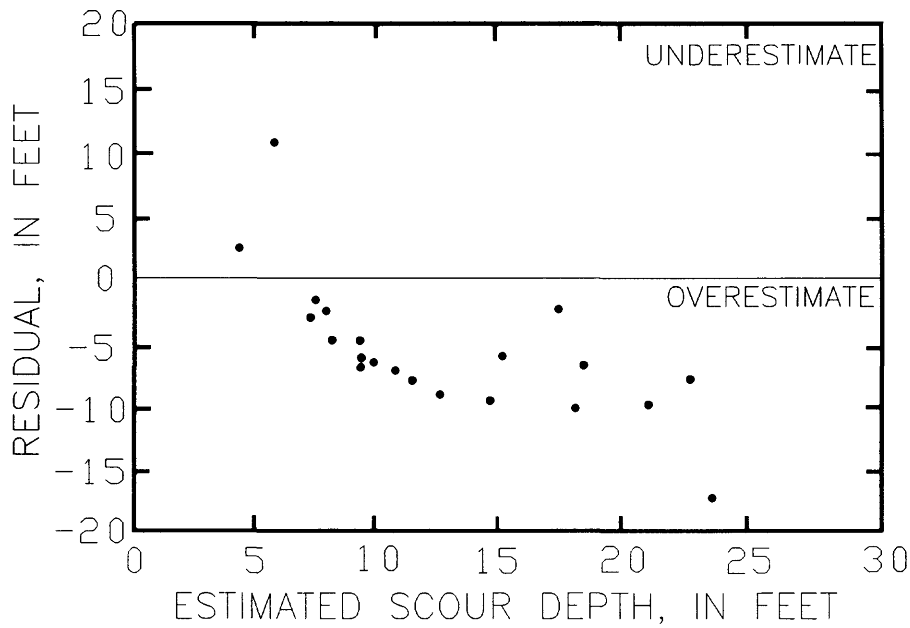

Figure 7.--Relation between scour depth estimated using the Laursen equation and residual from measured scour depth.

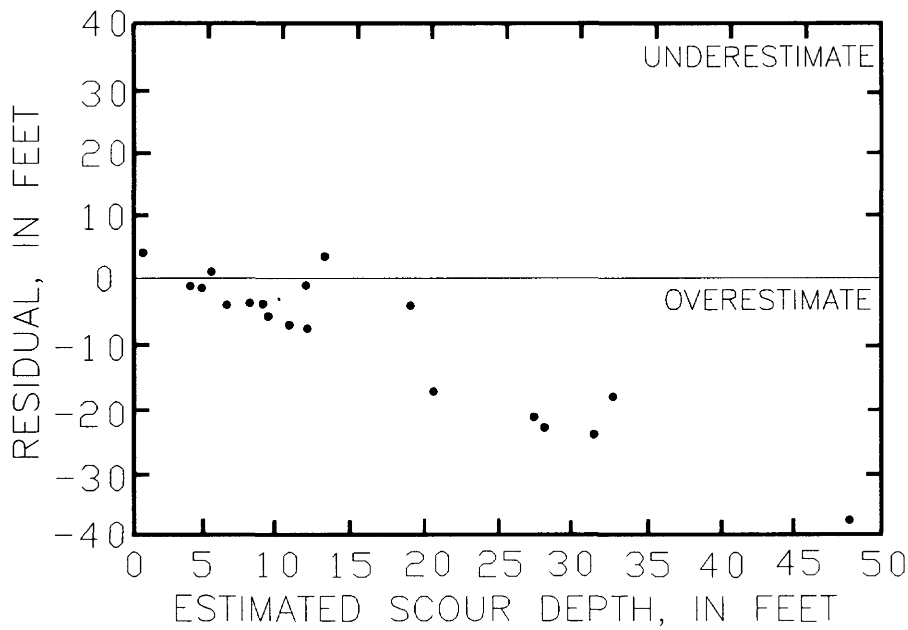

Figure 8.--Relation between scour depth estimated using the Chitale equation and residual from measured scour depth.

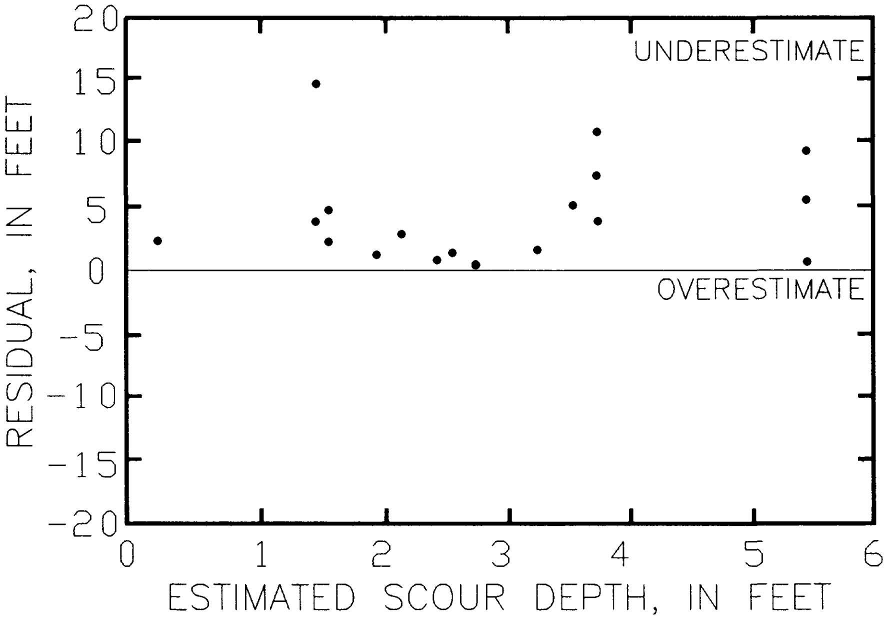

Figure 9.--Relation between scour depth estimated using the Carstens equation and residual from measured scour depth.

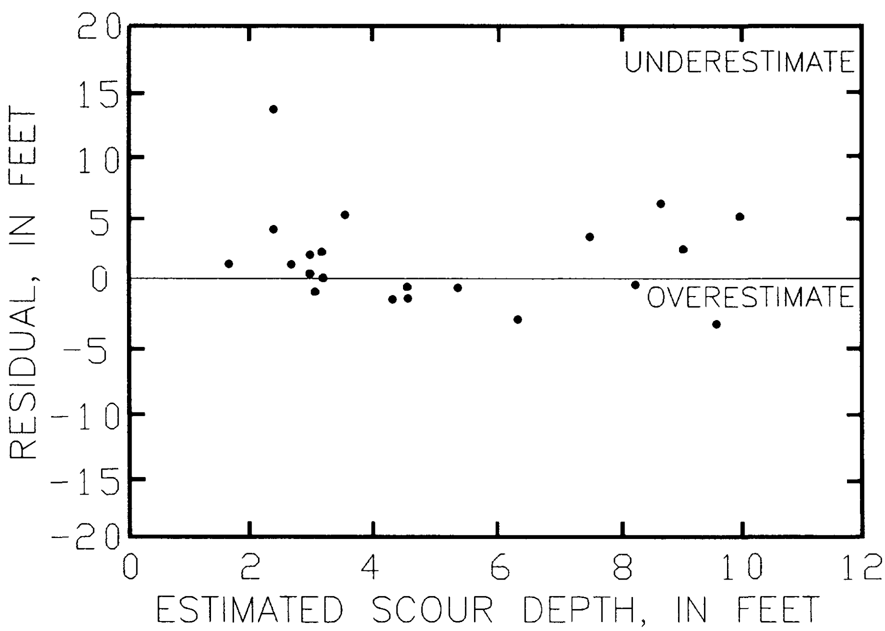

Figure 10.--Relation between scour depth estimated using the Froehlich equation and residual from measured scour depth.

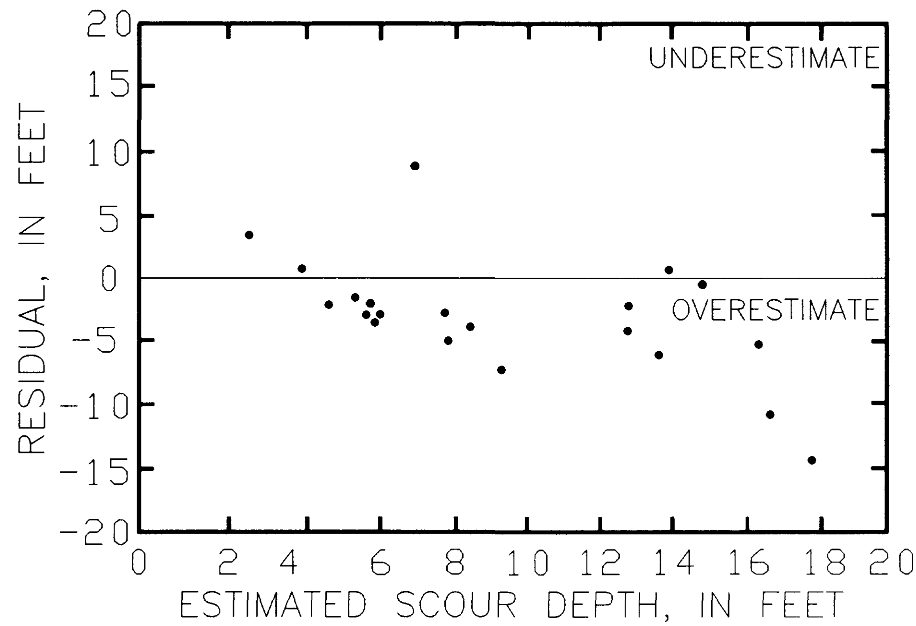

Figure 11.--Relation between scour depth estimated using the Colorado State University equation and residual from measured scour depth.

Multiple-Linear Regression Equation

A multiple linear-regression analysis was made on the 22 sets of data available at the 12 study sites to determine which bridge geometry, hydraulic, and channel bed characteristics were significant on Arkansas streams. Variables used in the equations and included in the regression analysis are listed in table 2. The dependent variable of the analysis was measured scour depths and the independent variables were median bed-material diameter, pier type, pier width, flow depth, Froude number, average velocity, and pier location code. The distribution of the measured scour depths was skewed to the right as indicated by the boxplot of measured scour depths in figure 6. To correct for the right-skewness of the data, a log transformation was applied to all variables used in the analysis except the pier location code. The variables that were statistically significant at the 0.05 level are median bed-material diameter, average velocity, and pier location code. Median bed-material diameter and average velocity are commonly used in existing local scour equations, but the pier location code variable is not used in any of the equations studied.

The pier location code identifies whether the pier is located in the main channel or the flood plain. Piers located on the banks of the main channel are classified as on the flood plain. This characteristic was included in the analysis because: (1) a large scour hole (16.0 ft) on the flood plain of the Saline River at U.S. Highway 70 crossing (site 9) was a very influential data point in the initial analysis and was significantly underestimated using any of the five equations and (2) a scour hole 5.4 ft deep was measured at a pier located in the main channel during this flood, and was overestimated by three of five equations. The only difference in the hydraulic characteristics associated with the scour holes was flow depth (table 2), which was not a statistically significant variable at the 0.05 level in the regression analysis. Further inspection of the data revealed that during the flood of May 3, 1990, at the State Highway 28 crossing of the Fourche LaFave Riversite 6), two scour holes of near equal depth developed (one in the main channel and one on the (flood plain). The existing equations yielded significantly different estimated depths at these two scour holes. For example, the CSU equation indicated an estimated 6.3 ft of scour in the main channel and 18.2 ft of scour on the flood plain.

To determine if a significant relation between scour in the main channel and scour on the flood plain existed, a pier location code of "0" was assigned to piers in the main channel and a value of "1" was assigned to piers on banks of the main channel or on the flood plain. The analysis was computed using a natural log transformation of all variables, except for the pier location code variable. For a pier location code of "0" a factor of one was applied to the estimated scour depth. For sites with a pier location code of "1" the factor applied to the estimated scour depth was $e^{0.476}$ or 1.61. The weighting factors assigned to pier location codes indicated that for similar conditions a scour hole that develops at piers on the flood plain will be 1.61 times deeper than one that develops in the main channel.

The need for a pier location factor is supported by the effect of armoring on the bed of the main channel. Armoring is the deposition of a layer of larger material on the channel bottom due to suspension and transportation of smaller material during normal flow conditions and on the recession of a flood event. This larger material decreases the susceptibility of bed material in the channel to scour. On the flood plain, the effect of armoring is not a significant factor on scour hole development and the flood plain material are more susceptible to scour. Also, the flood plain material usually has a smaller median diameter than the subsurface material in the main channel and is more likely to scour than the main channel bed.

The equation for scour depth (D) resulting from the multiple-linear regression analysis is:

$$D = 0.827\ (D_m)^{-0.117}(V)^{0.684}e^{0.476(c)}$$

where D_m is the median bed-material diameter, in feet, V is the average velocity, in feet per second, and c is the pier location code.

The average standard error of estimate of the multiple-linear regression equation is plus or minus 42 percent. The equation was developed on a limited data base of 22 scour data sets. The log transformation of the variables used in the development of this equation are similar to that used for the other scour equations which require the use of log-transformed data. The variables, median bed-material diameter and average velocity, have been shown to be statistically significant on larger data bases (Froehlich and CSU's equations). The scour depths estimated using this equation are presented in table 3, and the distribution of estimated depths is shown in figure 6. The relation between estimated scour depths and residuals is shown in figure 12 and no bias in results is indicated. Application of the regression equation is limited to sites with a median bed-material diameter between 0.00036 ft and 0.0689 ft and an average velocity of 1.7 to 12.8 ft/s. The independent variables were plotted against the residuals from the regression analysis in figures 13-15 to check the assumptions of constant variance and independence. The graphs indicate no

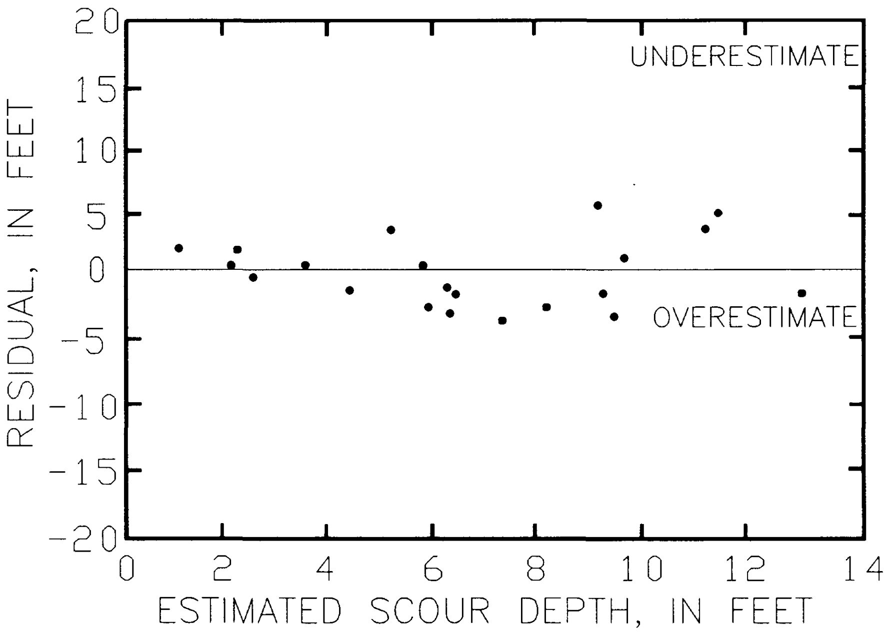

Figure 12.--Relation between scour depth estimated using the multiple-linear regression equation and residual from measured scour depth.

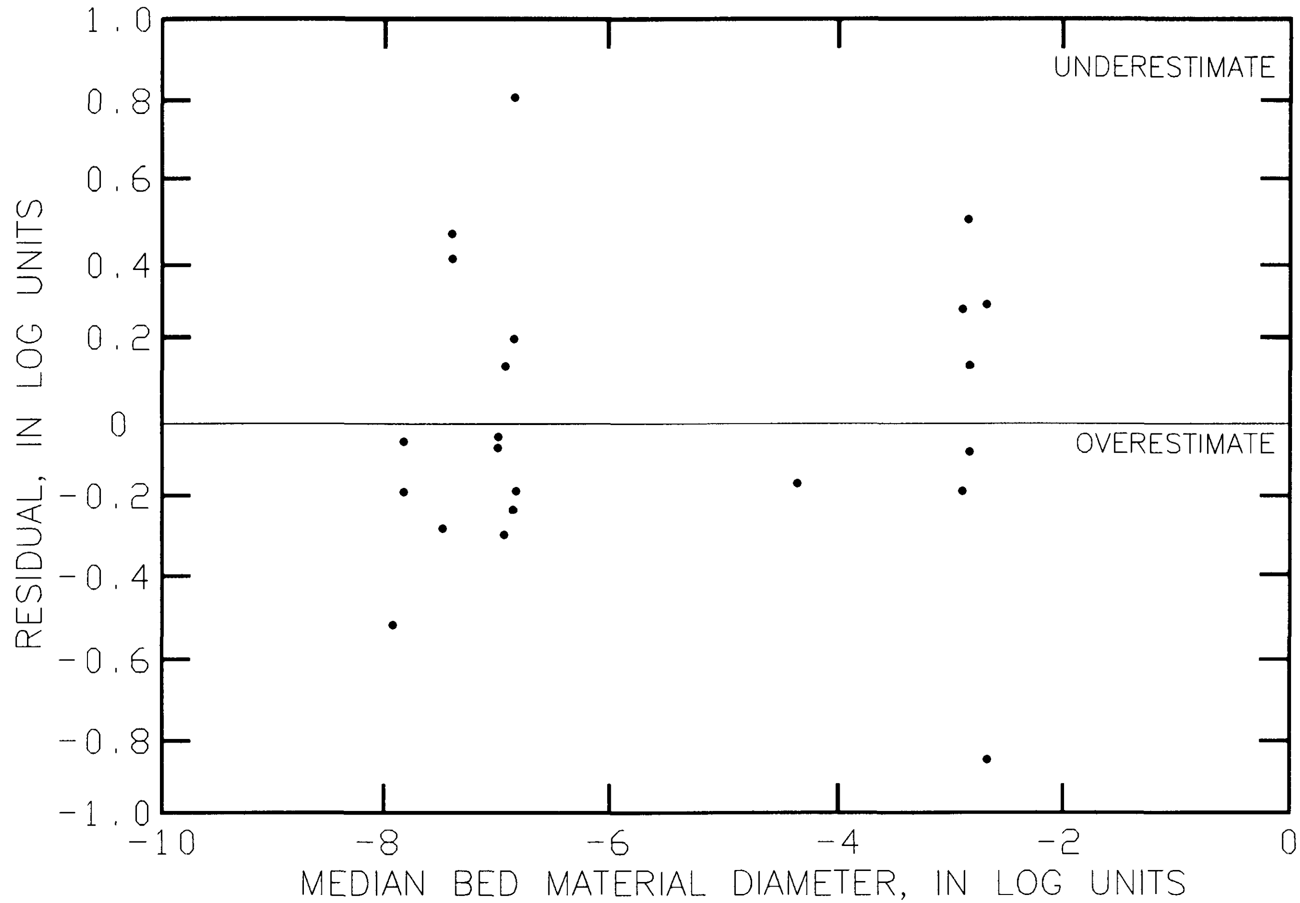

Figure 13.--Relation between median bed-material diameter and residual from multiple-linear regression analysis.

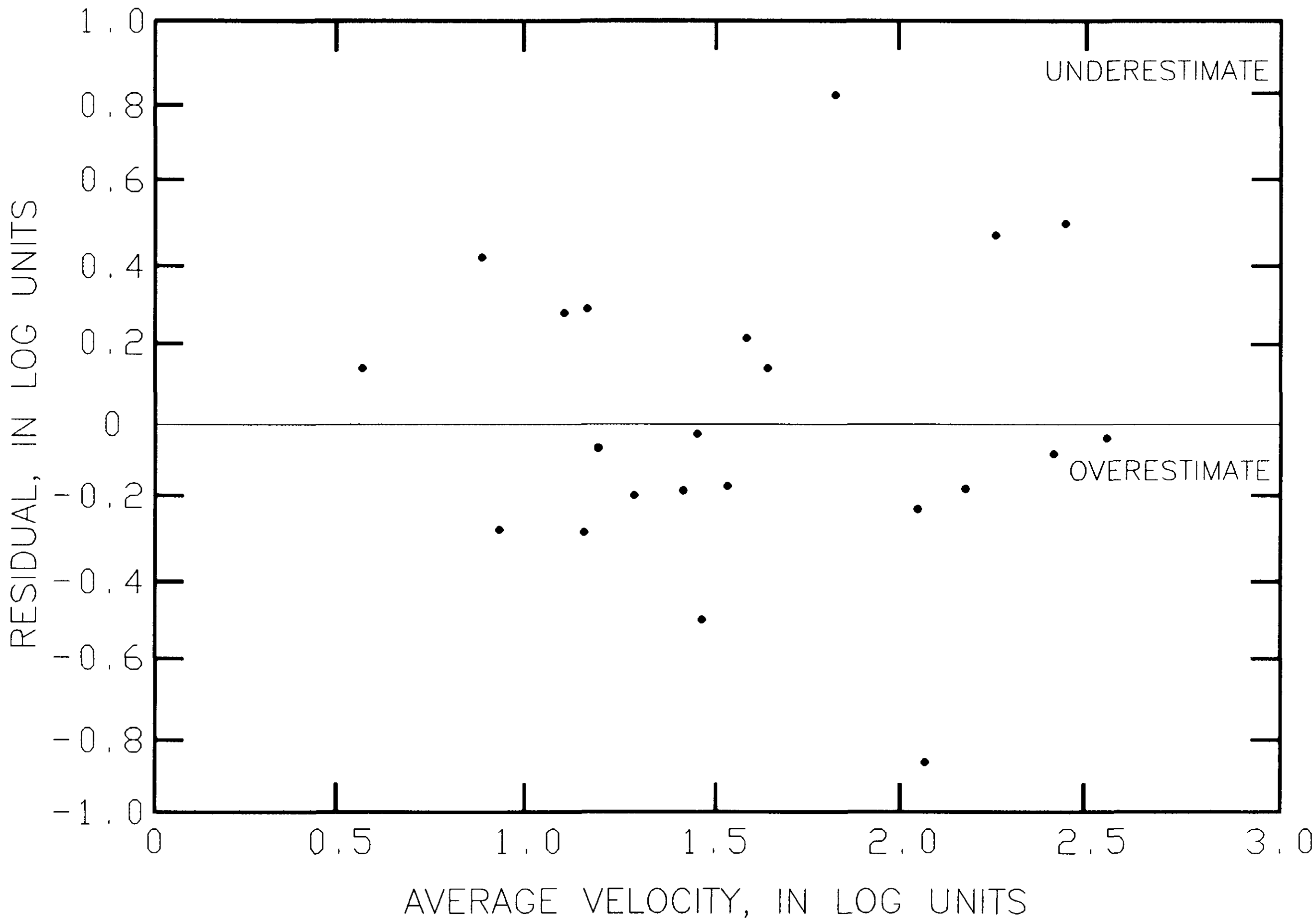

Figure 14.--Relation between average velocity and residual from multiple-linear regression analysis.

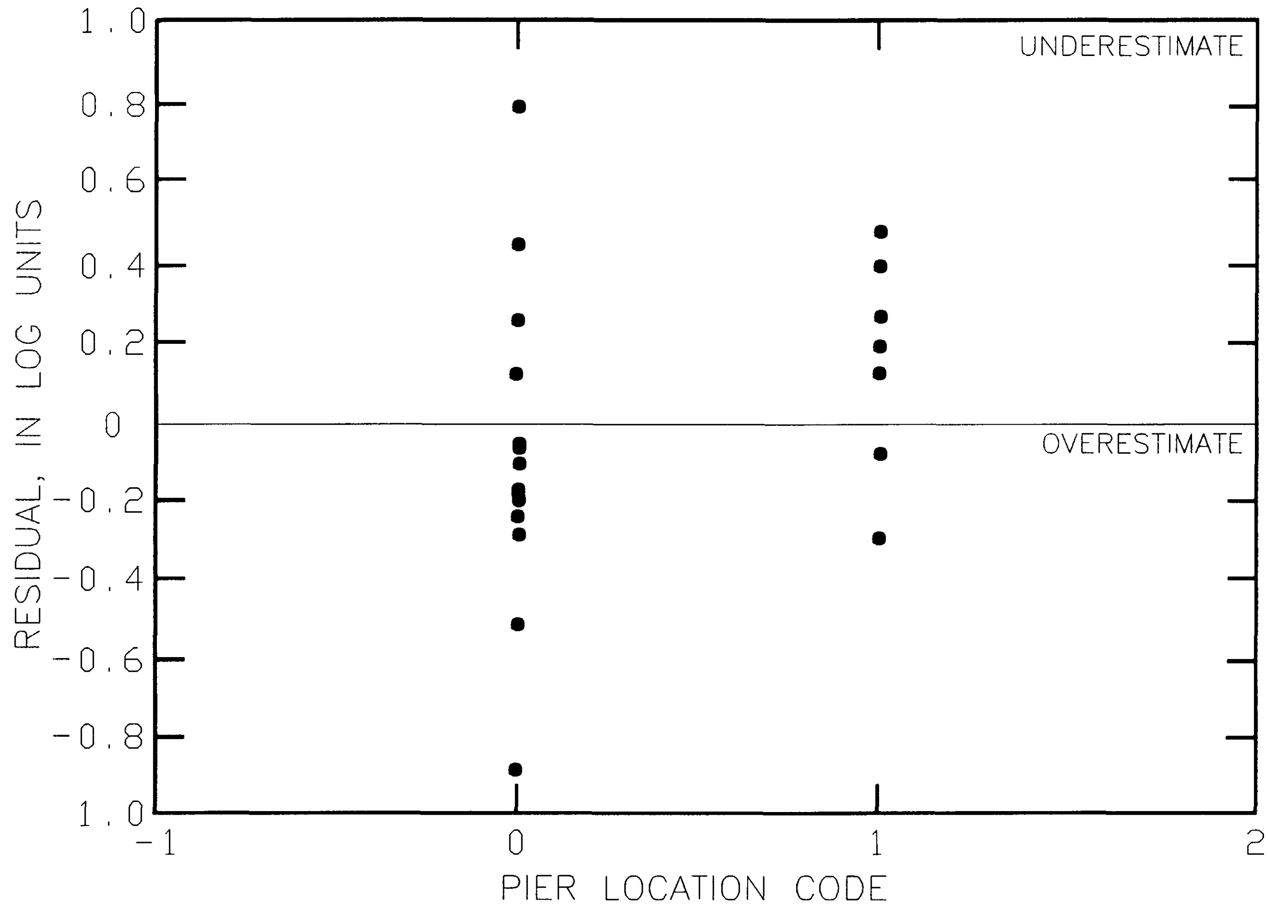

Figure 15.--Relation between pier location code and residual from multiple-linear regression analysis.

significant violations of the assumptions for multiple-linear regression. Scour depths determined using the multiple-linear regression equation should not be compared with depths determined using other equations in table 3. The regression equation was derived from the data and will inherently provide better estimates of scour depth for that data than the other equations which were based on different data sets.

SUMMARY

Local-scour data were collected at 12 sites in Arkansas, 6 of which were at streamflow-gaging stations. Data collected consists of bed-material particle-size data, pier geometry, and hydraulic characteristics during selected flood events. Historic station records and data collected during this study produced 22 sets of scour data during 14 flood events. The recurrence intervals of the high floods ranged from 3 to 100 years. Scour holes ranged from 2.3 to 16.0 ft in depth.

Five local-scour equations were evaluated to determine their usefulness in estimating scour depths at the 12 study sites where scour was measured. The equations were those developed by (1) Laursen, (2) Chitale, (3) Carstens, (4) Froehlich, and (5) Colorado State University. The interquartile range of estimated scour depths using the Froehlich and the Colorado State University equations were closest to the interquartile range of the measured scour depths. Froehlich's equation was the only equation that produced a median estimated scour depth statistically equal to the median of the measured scour depth at a 0.05 level of significance. The residuals of estimated scour depths were plotted against the estimated scour depths to evaluate bias. Residuals for depths estimated using the Laursen, Chitale, and Colorado State University equations indicated that the us of these equations overestimated the larger measured scour depths. The use of Carstens' equation consistently underestimated scour depths. Residuals of the estimated scour depths using Froehlich's equation indicated no significant bias in the estimated scour depths.

The 22 sets of data were used in a multiple-linear regression analysis. The variables were log-transformed because the distribution of the measured scour depths were skewed to the right. Analysis of bridge geometry, hydraulic, and channel-bed particle size factors used in the five selected equations indicated median bed-material diameter and average velocity were significant at the 0.05 level. Results of the analysis indicated that a variable identifying the location of the pier was needed. A pier location code was used to identify whether a pier is located in the main channel, or on the flood plain. The pier location code was statistically significant at the 0.05 level and was included in the multiple-linear regression equation. The resulting equation had an average standard error of estimate of plus or minus 42 percent on the limited data base in Arkansas.

REFERENCES

Anderson, A.G., 1974, Scour at bridge waterways--A review: Washington,D.C., U.S. Federal Highway Administration RD-75-89, 29 p.

Butch, G.K., 1991, Measurement of bridge scour at selected sites in New York, excluding Long Island: U.S. Geological Survey Water-Resources Investigations Report 91-4083, 17 p.

Fenneman, N.M., 1938, Physiography of eastern United States: New York, McGraw-Hill Book Co., 714 p.

Froehlich, D.C., 1988, Analysis of onsite measurements of scour at piers: Proceedings of the American Society of Civil Engineers, p. 534-539.

Galay, V.J., 1983, Causes of river bed degradation: Water Resources Research, v. 19, no. 5, p. 1057-1090.

Guy, H.P., 1969, Laboratory theory and methods for sediment analysis: U.S. Geological Survey Techniques of Water-Resources Investigations, book 5, chapter C1, 58 p.

Guy, H.P., and Norman, V.W., 1970, Field methods for measurement of fluvial sediment: U.S. Geological Survey Techniques of Water-Resources Investigations, book 3, chapter 2, 59 p.

Hopkins, G.R., Vance, R.W., and Kasraie, B., 1980, Scour around bridge piers: Washington, D.C., U.S. Federal Highway Administration RD-79-103, 131 p.

Interagency Advisory Committee on Water Data, 1982, Guidelines for determining floodflow frequency: U.S. Geological Survey Bulletin 17B, 28 p.

Jarrett, R.D., and Boyle, J.M., 1986, Pilot study for collection of bridge-scour data: U.S. Geological Survey Water-Resources Investigations Report 86-4030, 89 p.

Laursen, E.M., 1958, Scour at bridge crossings: Iowa Highway Research Board Bulletin 8, 53 p.

----- 1962, Scour at bridge crossings: Transactions of the American Society of Civil Engineers, v. 127, pt I, no. 3294, p. 166-209.

Laursen, E.M., and Toch, Arthur, 1953, A generalized model study of scour around bridge piers and abutments, in Minnesota International Hydraulics Convention, Minneapolis, 1953, Proceedings, International Association for Hydraulic Research and Hydraulics Division and American Society of Civil Engineers, p. 123-131.

National Cooperative Highway Research Program, 1970, Scour at bridge waterways: National Research Board Synthesis of Highway Practice 5, 37 p.

Neely, B.L., Jr., 1987, Magnitude and frequency of floods in Arkansas: U.S. Geological Survey Water-Resources Investigations Report 86-4335, 51 p.

Neill, C.R., 1970, River-bed scour--A review for bridge engineers: Ottawa, Canadian Good Roads Association Technical Publication 23, 37 p.

----- ed., 1973, Guide to bridge hydraulics: Toronto, University of Toronto Press, 191 p.

Norman, V.W., 1975, Scour at selected bridge sites in Alaska: U.S. Geological Survey Water-Resources Investigations Report 32-75, 160 p.

Rantz, S.E., and others, 1982, Measurement and computation of streamflow--volume 1, Measurement of stage and discharge: U.S. Geological Survey Water-Supply Paper 2175, 284 p.

Richardson, E.V., and Richardson, J.R., 1989, Bridge scour: Proceedings of the bridge scour symposium: U.S. Federal Highway Administration RD-90-035, p. 1-42.

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