Scour at Bridges on Selected Streams in Arkansas

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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 laboratory studies have produced many equations that can be used to estimate local scour at piers. The results of a study to collect scour data at selected bridges in Arkansas are described, the application of several of these local-scour equations to scour at the bridge sites studied is evaluated, and an equation for estimating scour on the basis of data collected at these sites is presented. Scour data were collected at 12 sites on nine streams in Arkansas during 14 floods. The recurrence intervals of the floods 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 ranged in depth from 0.70 to 4.88 m (2.3 to 16.0 ft). 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 had an interquartile range similar in magnitude to the interquartile range of the measured scour depths. A multiple linear regression equation was derived from scour data for the 12 sites. The independent variables are mean 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 ±42 percent.

One of the major concerns in the design of a new bridge or the evaluation of an existing bridge is the susceptibility of the bridge piers to scour. Three types of scour can occur at a bridge: general, contraction, and local. General scour is the progressive degradation or lowering of the streambed through natural or human-induced processes. Channel degradation generally results from increased discharge, decreased bed-load, or decreased bed-material size (*1*). Lateral erosion caused by a shift in the flow or meander pattern is also considered as 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 (*2*).

Many 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. When these equations are applied to actual bridge sites, a wide range of estimated scour depths commonly result. One equation may estimate little or no scour at a bridge pier, and another may overestimate 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, several federal and state agencies have been involved in collecting 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 (a) collect scour data during flood events, (b) evaluate the usefulness of selected scour equations for estimating local scour, and (c) develop an equation from local scour data collected on Arkansas streams. The scour data collected as part of this study also will be included in the national data base for a study conducted by the USGS and FHWA in 1992.

PURPOSE AND SCOPE

This paper summarizes scour data collected at 12 study sites during 14 high-flow events on 9 streams in Arkansas (Figure 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 paper include (a) pier type and width; (b) flow velocity, depth, and angle; and (c) median bed-material diameter. Existing local-scour equations were selected and 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 with the scour measurements.

METHODS OF STUDY

AHTD supplied a list of 72 bridges with known scour problems, and 21 sites were selected for additional data collection. The sites were evaluated on the basis of potential for local scour to occur at the bridge and the degree of difficulty in obtaining the scour data.

At the 21 sites, cross sections were obtained along the upstream and downstream sides of the bridge to establish ex-

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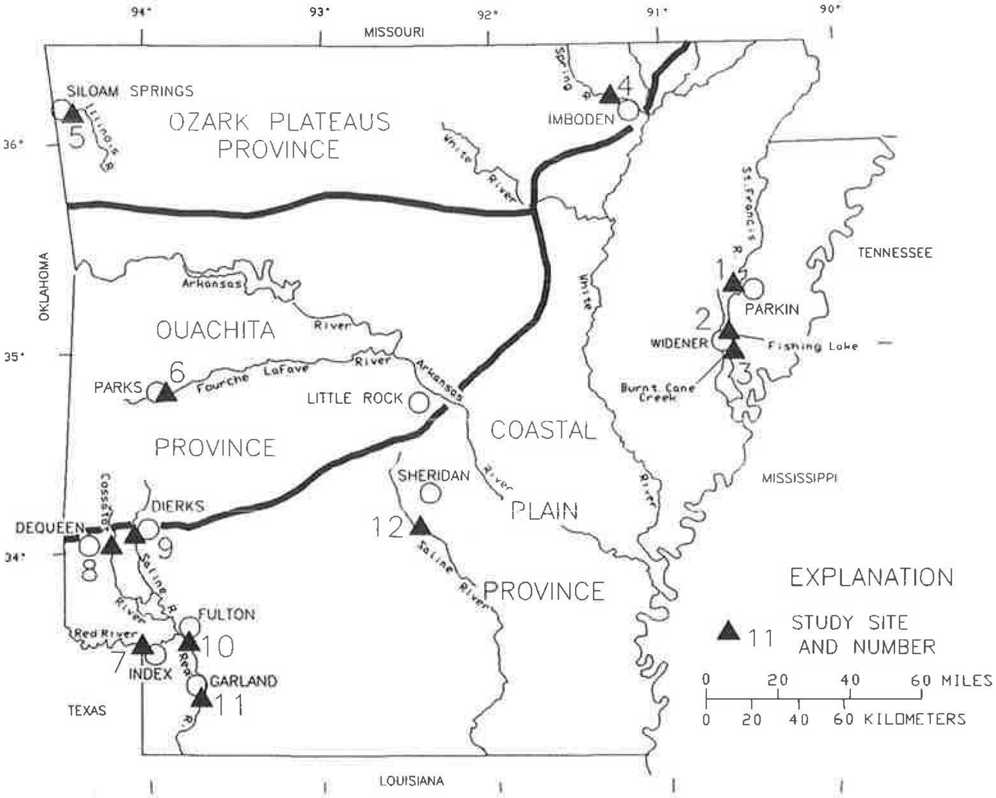

FIGURE 1 **Location of study sites and physiographic provinces in Arkansas (7).**

isting 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 (*3*). The bed-material samples were analyzed using methods described by Guy (*4*). Cross sections were measured during high flows and were plotted to determine the location and depth of the local 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 measured channel-bed elevation. For purposes of this paper, the depth of a local scour hole was calculated as the difference between the elevation of the projected channel-bed cross section across the scour hole to the lowest measured channel-bed elevation of the hole. 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-bed cross section at the scour hole.

Discharge and velocity were determined using standard streamflow-gauging procedures described by Rantz et al. (*5*). 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.

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 three additional sites on the Red River in southeastern Arkansas during the May 1990 flood. The 12 sites at which scour data were collected are given in Table 1. Six of the study sites are at streamflow-gauging 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 paper.

The 12 study sites are located in three physiographic provinces (Figure 1): the Coastal Plain Province in the southeastern half of Arkansas, the Ouachita Province in west-central Arkansas, and the Ozark Plateaus Province in northwest and north-central Arkansas (*7*). 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 and the Ozark Plateaus provinces, which are underlain by consolidated rocks consisting mostly of limestone, dolomite, sandstone, and shale. The composition of the bed material at these sites consists primarily of coarse gravel and coarse to fine sands.

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

TABLE 1 Summary of Discharge Data at Bridge Sites in Arkansas

Site number	Station number	Station name and location	Drainage area (km^2)	Date of measurement	Measured discharge (m^3/s)	Recurrence interval (years)[a]
1	[b]07047800	St. Francis River at State Highway 64 at Parkin	--(c)	12-28-87	[d]527	25
2	07047908	Fishing Lake at State Highway 70 near Widener	--(c)	12-27-87	484	--(c)
3	07047909	Burnt Cane Creek at State Highway 50 near Widener	--(c)	12-26-87	572	--(c)
4	[b]07069500	Spring River at U.S. Highway 62 at Imboden	[e]3,064	5-23-57	1,260	4
5	07195400	Illinois River at State Highway 161 near Siloam Springs	1,318	11-19-85	688	3
6	07261440	Fourche LaFave River at State Highway 28 near Parks	658	5-03-90	949	6
7	[b]07337000	Red River at U.S. Highway 71 at Index	124,398	5-09-90	7,420	[f]100
8	[b]07340500	Cossatot River at U.S. Highway 71 near DeQueen	932	1-30-69	1,830	12
9	[b]07341000	Saline River at U.S. Highway 70 near Dierks	313	5-06-61 5-13-68	796 1,592	10 80
10	07341500	Red River at Interstate 30 at Fulton	135,550	5-12-90	7,280	--(c)
11	7342000	Red River at U.S. Highway 82 at Garland	136,428	5-14-90	6,290	--(c)
12	[b]07363200	Saline River at U.S. Highway 167 near Sheridan	2,908	2-01-69 12-29-87	1,900 1,460	20 9

[a] Recurrence interval from Neely (1987) (6).
[b] U.S. Geological Survey streamflow-gaging station.
[c] Indeterminate.
[d] 1 m^3/s = 35.31 ft^3/s.
[e] 1 km = 0.62 m.
[f] Record furnished by U.S. Army Corps of Engineers, Little Rock District.

ranged from 313 km^2 (121 mi^2) for the Saline River at U.S. Highway 70 near Dierks to 136 428 km^2 (52,675 mi^2) for the Red River at US-82 at Garland. At sites where the recurrence intervals of the measured floods were determined, the intervals ranged from 3 years for the Illinois River at US-16 near Siloam Springs to 100 years for the Red River at US-71 at Index. 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.

MEASURED SCOUR DEPTHS

Review of previous measurements made at the six streamflow-gauging stations and measurements made during this study resulted in 22 sets of data describing local scour holes ranging in depth from 0.70 to 4.88 m (2.3 to 16.0 ft) (Table 2). The deepest of these scour holes (4.88 m) was measured during the flood on May 13, 1968, at the US-70 crossing of the Saline River near Dierks just minutes before the failure of a bridge pier. The scour undermined the pier and caused the pier and part of the bridge deck to be lowered by about 0.6 m (2 ft), creating a dangerous road hazard and resulting in the immediate closure of the bridge to traffic.

It should be noted that it was not possible to determine if this scour hole was a result of local scour or a combination of local scour and contraction scour; thus, it was considered to be from local scour only. It is important to determine whether a scour hole develops under live-bed or clear-water conditions. Under live-bed conditions, bed-material is supplied to the hole and scour will occur only if the rate of removal of bed-material exceeds the rate of supply. Clear-water conditions exist if no bed material is supplied to the scour hole. Neill developed an equation to compute the critical velocity necessary to move bed material so live-bed conditions may exist. From these computations, clear-water conditions existed only at Sites 5, 6, and 9 (Table 2).

Scour depths greater than 3.05 m (10 ft) were measured at several sites in the Red River basin during severe flooding in May 1990. Comparison of cross-section data collected before the May 1990 flood and cross-section data collected near the peak of the flood at the US-71, Interstate 30, and US-82 crossings indicates that contraction and local scour processes were prevalent. Scouring at these sites was similar to the scouring at the I-30 bridge shown in Figure 2. The main channel bed at I-30 was lowered 4.57 to 6.10 m (15 to 20 ft), and local scour holes of 2.65 and 4.45 m (8.7 and 14.6 ft) were measured at Stations 176.78 and 238.35 m (580 and 782 ft) from the left abutment. At Station 140.21 (460 ft), the channel bed elevation was approximately the same as the elevation of the bottom of the pier located at Station 118.57 (389 ft).

TABLE 2 Summary of Scour, Pier Geometry, and Hydraulic Data Collected at Study Sites with Measured Scour Depths

						Pier data				Hydraulic data at scour hole section		
Site number	Date of measurement	Measured scour depth (m)	Estimated error of scour depth (±m)	Distance from left abutment (m)	Median bed material diameter (mm)	Type of nose	Width (m)	Width normal to flow (m)	Location code[a]	Flow depth (m)	Average velocity (m/s)	Flow angle (degrees)
1	12-28-87	[b]0.85	0.3	91.4	[c]0.18	square	0.94	0.94	0	9.11	[d]0.76	0
2	12-27-87	1.22	0.3	64.0	0.33	square	0.91	0.91	0	9.45	1.25	0
3	12-26-87	1.92	0.2	101.2	0.28	round	0.46	0.46	1	3.78	1.01	0
3	12-26-87	1.46	0.2	67.0	0.28	round	1.83	1.83	0	8.75	1.28	0
4	5-23-57	1.00	0.2	140.2	3.90	square	1.40	1.40	0	7.25	1.40	0
5	11-19-85	[e]0.98	0.2	233.5	17.00	square	1.22	1.22	0	5.97	0.91	0
5	11-19-85	[e]0.70	0.2	256.0	17.00	square	1.22	1.22	0	5.09	1.10	0
6	5-03-90	[e]1.00	0.2	76.5	21.00	square	2.59	6.46	1	2.38	0.97	37
6	5-03-90	0.94	0.2	100.9	21.00	sharp	0.91	0.91	0	6.10	2.38	0
7	5-09-90	2.32	0.3	219.4	0.12	round	2.13	2.13	0	12.31	2.65	11
7	5-09-90	3.41	0.3	286.5	0.12	round	2.13	2.13	0	13.04	3.90	8
8	1-30-69	1.04	0.2	61.3	0.11	sharp	1.37	1.37	0	6.28	1.31	0
9	5-06-61	1.22	0.2	109.7	18.00	square	0.79	0.79	0	5.79	1.55	0
9	5-13-68	4.88	0.1	36.58	18.00	square	0.79	0.79	1	2.68	3.47	0
9	5-13-68	1.65	0.1	109.73	18.00	square	0.79	0.79	0	6.46	3.35	0
10	5-12-90	4.45	0.3	176.78	0.18	sharp	2.13	2.13	0	10.76	2.90	0
10	5-12-90	2.65	0.3	238.35	0.18	sharp	1.98	1.98	1	8.14	0.73	0
11	5-14-90	4.39	0.3	210.31	0.32	round	3.05	3.05	0	11.73	1.89	0
11	5-14-90	1.80	0.3	271.27	0.32	round	3.05	3.05	0	13.47	2.35	14
11	5-14-90	3.26	0.3	395.02	0.32	round	3.05	3.05	1	9.11	1.46	0
12	2-01-69	1.49	0.2	20.12	0.30	round	0.43	0.43	1	2.56	0.98	23
12	12-29-87	1.52	0.1	55.17	0.30	square	1.16	1.16	1	3.20	0.52	0

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

[b] 1 m = 3.28 feet.

[c] 1mm = 0.003281 feet.

[d] 1m/s = 3.28 feet per second.

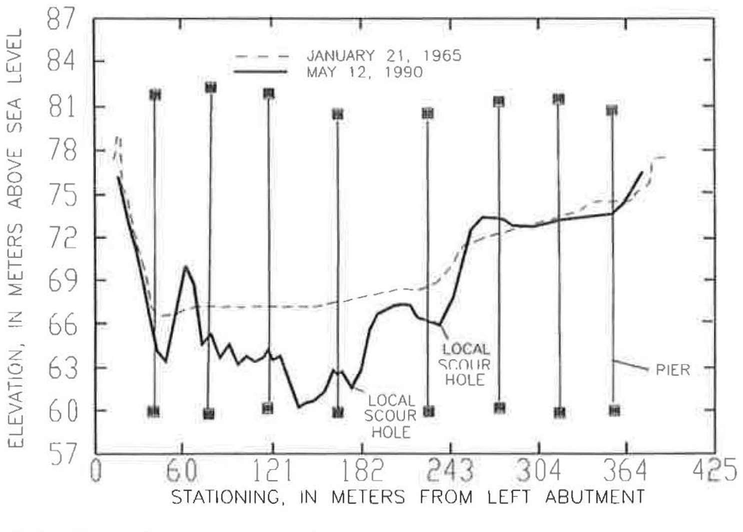

FIGURE 2 Channel cross sections based on data from bridge plans (January 21, 1965) and channel cross section measurements during flood of Red River at I-30 at Fulton, Arkansas (Site 10) along upstream side of bridge (May 12, 1990).

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 Laursen, Chitale, Carstens, Froehlich, and Colorado State University (CSU)—Equations 1 through 5, respectively. The Laursen, Chitale, and Carstens equations are two-variable equations developed from laboratory studies on scour around bridge piers conducted before 1970. The Froehlich and CSU equations are six-variable equations developed since 1987 on larger data bases.

During the 1950s, Laursen 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 1970s.

Chitale's equation is one of the first equations to use the 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.

As of 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.

Many other local scour equations exist (*8*), but only the five listed were evaluated as part of this study. These five equations were applied to all of the data collected, and no differentiation was made as to whether the scour holes were derived from live-bed or clear-water conditions. Of the five, the Laursen and Froehlich equations were developed from live-bed scour data, the Chitale and Carstens equations from clear-water scour data, and the CSU equation from both.

These equations were developed for design purposes. They are not a regression "best fit" of their respective data sets; instead, they encompass the data that allow for a factor of safety in the design and analysis of bridge structures. As an example, the Froehlich equation uses a factor of safety of one pier width for design purposes.

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:

$$D = 1.5B^{0.7}\,H^{0.3} \tag{1}$$

where

D = local scour depth measured from ambient bed elevation (m),
B = width of pier (m), and
H = flow depth at nose of pier, excluding local scour depth (m).

The Laursen equation was transcribed from its graphical form by Neill (*9*) on the basis of Laursen's basic design curve for a square-nosed pier aligned with the flow, as reported by Laursen and Toch (*10*) and Laursen (*11,12*).

- Chitale equation—1962:

$$D = H[6.65(F) - 5.49(F)^2 - 0.51] \tag{2}$$

where

F = Froude number,
= $V/(gH)^{0.5}$,
V = velocity of flow at end of pier (m/sec), and
g = acceleration of gravity (m/sec^2).

- Carstens equation—1966:

$$D = B\left(0.546\{[(N_s)^2 - 1.64]/[(N_s)^2 - 5.02]\}^{0.83}\right) \tag{3}$$

where

$N_s = V/[(s - 1)gD_m]^{0.5}$,
s = specific gravity of sand
= 2.65, and
D_m = median bed-material diameter (m).

- Froehlich equation—1987:

$$D = B[0.32\O(B/B')^{0.62}(H/B)^{0.46}(F)^{0.20}(B/D_m)^{0.08} + 1] \tag{4}$$

where

$\O$ = pier shape correction factor,
B' = pier width projected normal to flow,
= $B \cos \alpha + L \sin \alpha$,
α = flow angle (degrees),
= 0 for pier aligned with flow, and
L = length of pier (m).

- CSU equation—1990:

$$D = H[2.0K_1K_2(B/H)^{0.65}(F)^{0.43}] \tag{5}$$

where K_1 is the pier shape correction factor and K_2 is the flow angle correction factor.

The measured scour and estimated local-scour depths calculated using each of these equations are given in Table 3. The pier-shape factors used with the Froehlich and CSU equations are given in the following table:

	Pier-Shape Factor	
Pier Type	*Froelich ($\O$)*	*CSU (K_1)*
Square nose	1.3	1.1
Round nose	1.0	1.0
Sharp nose	0.7	0.9

TABLE 3 Measured Scour Depths and Scour Depths Estimated Using Various Equations

		Estimated scour depth calculated using indicated equation (meters)					
Site number	Measured scour depth (meters)	Laursen equation	Chitale equation	Carstens equation	Froehlich equation	Colorado State Universtiy equation	Multiple-linear regression equation (this study)
1	[a]0.8	2.8	--	0.1	2.2	1.6	1.1
2	1.2	2.8	2.4	0.5	2.3	1.9	1.5
3	1.9	1.3	1.6	0.5	1.2	0.9	2.1
3	1.5	4.4	2.7	1.0	3.4	2.7	1.5
4	1.0	3.4	3.2	0.8	2.8	2.5	1.2
5	1.0	3.0	1.2	--	2.2	1.9	0.7
5	0.7	2.8	2.0	--	2.1	3.0	0.8
6	1.0	3.8	1.4	--	4.6	5.6	1.2
6	0.9	2.4	6.2	0.6	1.4	1.9	1.4
7	2.3	5.4	9.5	1.2	4.6	4.3	2.8
7	3.4	5.5	14.7	1.2	4.9	5.1	3.6
8	1.0	3.2	2.8	0.8	2.3	2.0	1.7
9	1.2	2.2	3.6	0.8	1.6	1.8	1.1
9	4.9	1.7	4.0	0.5	1.5	2.3	3.0
9	1.6	2.2	8.5	0.5	1.8	2.5	1.8
10	4.4	5.2	9.9	1.2	5.1	4.4	2.8
10	2.6	4.5	--	1.1	3.1	4.0	1.8
11	4.4	6.9	5.7	1.7	5.6	4.6	1.9
11	1.8	7.1	8.3	1.7	5.9	5.2	2.3
11	3.3	6.3	3.6	1.7	5.3	4.0	2.6
12	1.5	1.1	1.4	0.2	0.8	0.8	2.0
12	1.5	2.4	0.2	0.7	2.1	1.3	1.3

[a] 1 m = 3.28 feet.

[--, scour not estimated]

The flow-angle factors used with the CSU equation are given in Table 4.

A method that can be used to summarize the distribution of the estimated scour depths presented in Table 3 is the boxplot. A boxplot displays the symmetry of the distribution of data while using numerical measures of the central tendency and location to provide variability and concentration of data in the tails of the distribution. 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 depth 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 4 Flow-Angle Factors Used with CSU Equation for Estimating Scour Depth

	Flow-angle factor (K_2)		
Flow angle (degrees)	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

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

The interquartile range and median were computed for each data set to compare the distribution of the estimated scour depths to 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 5, the interquartile range of the measured scour depths is 1.48 m (4.85 ft). The interquartile ranges for values estimated using the Carstens and CSU equations were the next lowest and highest values at 0.67 and 2.33 m (2.20 and 7.65 ft), respectively. The median of the measured scour depths was 1.51 m (4.95 ft). The medians of the scour depths estimated using the Froehlich and Carstens equations were 2.30 and 0.79 m (7.54 and 2.60 ft), respectively. The median of the scour depths estimated using the CSU data was 2.51 (8.25 ft).

Results of a correlation analysis between measured scour depths and estimated scour depths are presented in Table 6. The strongest relation between measured and estimated scour depths was for depths estimated using the CSU equation, with a correlation coefficient of 0.53; this was followed by Chitale's equation, with a correlation coefficient of 0.46. The analysis also indicated that (a) depths estimated using the Chitale equation were only moderately correlated with depths esti-

TABLE 5 Statistical Characteristics of Measured and Estimated Scour Depths

		Estimated scour depth calculated using indicated equation (meters)					
Statistical characteristic	Measured scour (meters)	Laursen equation	Chitale equation	Carstens equation	Froehlich equation	Colorado State University equation	Multiple-linear regression equation (this study)
Mean	[a]2.01	3.66	4.66	0.85	3.03	2.93	1.83
Minimum	0.70	1.10	0.21	0.06	0.80	0.79	0.73
Maximum	4.88	7.13	14.72	1.68	5.90	5.55	3.60
Median	1.51	3.11	3.41	0.79	2.30	2.51	1.75
25th percentile	1.00	2.29	1.80	0.49	1.70	1.81	1.20
75th percentile	2.48	4.88	7.25	1.16	4.60	4.14	2.16

[a] 1 m = 3.28 feet.

mated using the other equations, (b) 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 (c) there are significant relations among scour depths estimated using the Laursen, Carstens, Froehlich, and CSU equations.

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 characteristics of bridge geometry, hydraulics, and channel bed were significant on these Arkansas streams. Variables used in the equations and included in the regression analysis are presented 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 3.

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 were 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 on the banks of the main channel are classified as being on the flood plain. This characteristic was included in the analysis because (a) a large scour hole 4.88 m (16.0 ft) in depth on the flood plain of the Saline River at US-70 crossing was a very influential data point in the initial analysis and was significantly underestimated using any of the five equations, and (b) a scour hole 1.65 m (5.4 ft) in depth was measured at a pier in the main channel during this flood and was overestimated by three of the 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 River, two scour holes of nearly equal depth (about 1 m, or 3 ft) developed: one in the main channel and one on the flood plain. The existing equations yielded significantly different estimated

TABLE 6 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	0.31	0.46	0.37	0.41	0.53	0.83
Laursen equation		.51	.94	.97	.89	.29
Chitale equation			.51	.49	.76	.53
Carstens equation				.92	.83	.28
Froehlich equation					.90	.32
Colorado State University equation						.52

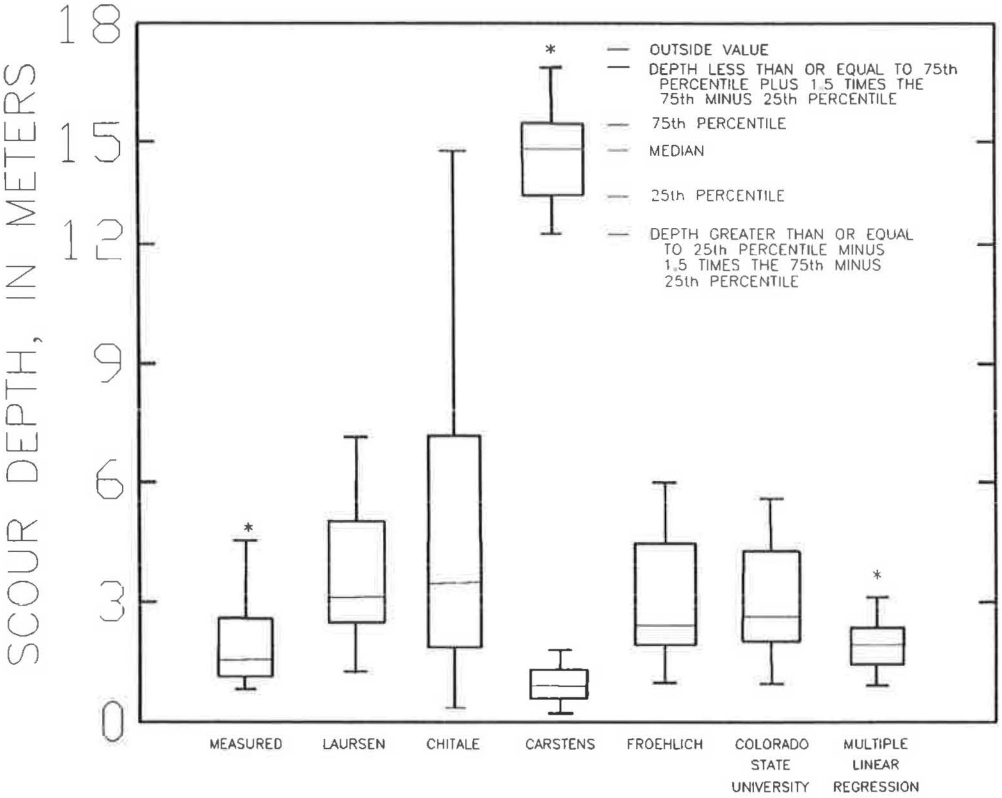

FIGURE 3 Boxplots of distribution of measured and estimated scour depths on data collected in Arkansas.

depths at these two scour holes. For example, the CSU equation indicated an estimated 1.9 m (6.3 ft) of scour in the main channel and 5.6 m (18.2 ft) of scour on the flood plain.

To determine if a significant relationship 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 1 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 significance of the pier location factor may be due to the effect of armoring on the bed of the main channel; nearly clear-water scour conditions in the flood plains; and fine, low-cohesion bed materials on the flood plain. 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.

Usually little or no bed material is supplied to a scour hole on a flood plain in comparison with a scour hole in the main channel, thus clear-water scour conditions may be approximated. These conditions would then result in greater scour depths on the flood plain under similar flow conditions.

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

$$D = 0.827(D_m)^{-0.117}(V)^{0.684}e^{0.476(c)} \qquad (6)$$

where

D_m = median bed-material diameter (m),
V = average velocity (m/sec), and
c = pier location code.

The average standard error of estimate of the multiple linear regression equation is ±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 is 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, along with the distribution of estimated depths based on the other equations.

Application of the regression equation is limited to sites with a median bed-material diameter between 0.11 and 21.00 mm (0.00036 and 0.0689 ft) and an average velocity of 0.52 to 3.90 m/sec (1.7 to 12.8 ft/sec). This equation is a regression equation that best fits the data set and has no factor of safety for design purposes. 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 those data than the other equations, which were based on different data sets.

SUMMARY

Local-channel scour data were collected at 12 sites on streams in Arkansas, 6 of which were at streamflow-gauging stations. Data collected consist 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 floods ranged from 3 to 100 years. Scour holes ranged from 0.70 to 4.88 m (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 Laursen, Chitale, Carstens, Froehlich, and CSU. The interquartile range of estimated scour depths using the Carstens and the CSU equations were closest to the interquartile range of the measured 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 a ±42 percent average standard error of estimate on the limited data base in Arkansas.

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