SCOUR AT SELECTED BRIDGE SITES IN ALABAMA, 1991-94

By J.B. Atkins and T.S. Hedgecock

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BRUCE BABBITT, Secretary

U.S. GEOLOGICAL SURVEY

Gordon P. Eaton, Director

For further information, please write to

District Chief
U.S. Geological Survey
2350 Fairlane Dr., Suite 120
Montgomery, AL 36116

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CONTENTS

ILLUSTRATIONS

TABLES

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ABSTRACT

Scour data were collected at 15 sites on streams in Alabama during high flow conditions. The recurrence intervals of the streamflows ranged from less than 2 to 10 years. Scour depths measured near bridge piers ranged from 0.3 to 5.8 feet. The Colorado State University (CSU) local scour equation recommended in the Federal Highway Administration Hydraulic Engineering Circular No. 18 was used to estimate scour depths at the study sites. Estimated scour depths based on the CSU equation ranged from 2.5 to 12.7 feet with residuals (measured scour depth minus estimated scour depth) ranging from -8.1 to -1.4 feet. A comparison of the residuals with the estimated scour depths indicated that the CSU equation overestimated the measured scour depths throughout the range of measured data by an average of 434 percent.

INTRODUCTION

Scour results from the erosive action of flowing water which excavates and transports material from the streambed and streambank. Scour around bridges can cause the bridge piers or bridge abutments to be exposed or undermined and has resulted in more bridge failures in recent history than all other causes (Murillo, 1987). Knowledge of the amount of potential scour around bridges is important in the design and maintenance of bridge structures.

Scour around bridges can result from any one or combination of three interrelated components.

(1) **General scour** - progressive degradation or lowering of the streambed through natural or human-induced processes. Degradation progressing downstream generally results from increased discharge, decreased bedload, or decreased bed-material size. Upstream degradation is generally caused by an increased water-surface slope (Galay, 1983). Lateral erosion caused by a shift in the flow or meander pattern is included with general scour.

(2) **Contraction scour** - 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.

(3) **Local scour** - erosion caused by local disturbances in the flow, such as vortices and eddies near piers, abutments, and debris piles (Butch, 1991). Local pier scour as discussed in the report will hereafter be referred to as scour depth.

Empirical equations have been developed to compute contraction scour and local scour at bridges. Most of these equations are based on scale-model laboratory experiments and have not been field verified due to the lack of onsite scour data. As a result, application of these empirical equations to actual bridge sites can provide a wide range of estimated scour depths. Bridge designers and inspectors need more onsite scour data to validate estimated scour depths.

The need for reliable information and equations to estimate scour depths has resulted in efforts to collect scour data during high flow conditions or floods. Scour depths measured during high flow conditions or floods are a result of unique sites and flow conditions that are more complex and varied as compared with flows produced in a laboratory. In recent years, studies by 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 scour prediction equations (Landers, 1992).

The U.S. Geological Survey (USGS), in cooperation with the Alabama Department of Transportation, began a study of scour around bridges in 1990. The objectives of the study were to collect scour data during high flow conditions and to evaluate the usefulness of available scour estimation equations for estimating scour.

Purpose and Scope

This report summarizes scour data collected at 15 study sites during high flow conditions on streams in Alabama from 1991 to 1994. The methods used to collect scour data are briefly described and the bridge geometry, hydraulic characteristics, and scour measurements at each site are summarized. Data collected and presented in the report include pier shape and width; median bed-material diameter; flow velocity, flow depth, angle of flow to piers; and measured scour depths at piers. Scour estimates calculated using the local-scour estimation equation were graphically and statistically compared to the measured scour depths to evaluate the applicability of equations to streams in Alabama. One existing scour estimation equation was evaluated at the 15 study sites and the results were compared with measured data.

Bridge Site Descriptions

Scour data presented in this report were collected at 15 selected bridge sites in Ala. (fig. 1; table 1). Drainage areas at the bridge sites ranged from 112 to 1,480 square miles.

Selection of bridge-scour sites was based on data from USGS streamflow gaging stations and a number of factors. These factors included: (1) various types of stream channels and streambed materials; (2) location of sites at or near USGS gaging stations to facilitate data collection and assess channel stability; (3) accessibility during high-flow conditions; (4) location and type of bridge piers; (5) bridge design that would facilitate the use of a small recording fathometer and scour data collection; (6) avoidance of factors that might complicate or hinder scour measurement; and (7) safety considerations for data-collection personnel.

Methods of Study

Onsite surveys were made at the selected sites to obtain detailed location, cross-section, bridge geometry, and bed-material data. Cross sections were obtained during low flow conditions along the upstream and downstream sides of each bridge to establish existing conditions. Reference marks and stationing were established on the bridge handrails for vertical and horizontal control. Bed-material samples were collected to determine the representative size and gradation of streambed during low flow conditions as outlined by Guy and Norman (1970) which were assumed to represent streambed conditions during high flow. The bed-material samples were analyzed using methods described by Guy (1969) and collected upstream from the bridge and at the bridge site. The median bed-material diameters were averaged to obtain a representative median bed-material diameter at each site.

Cross sections of the upstream sides of bridges were measured during high flow conditions either by sounding with a lead weight or with an Eagle Model Mach 1 Graph recording fathometer. These cross section measurements were plotted to determine the location and depth of scour holes and included

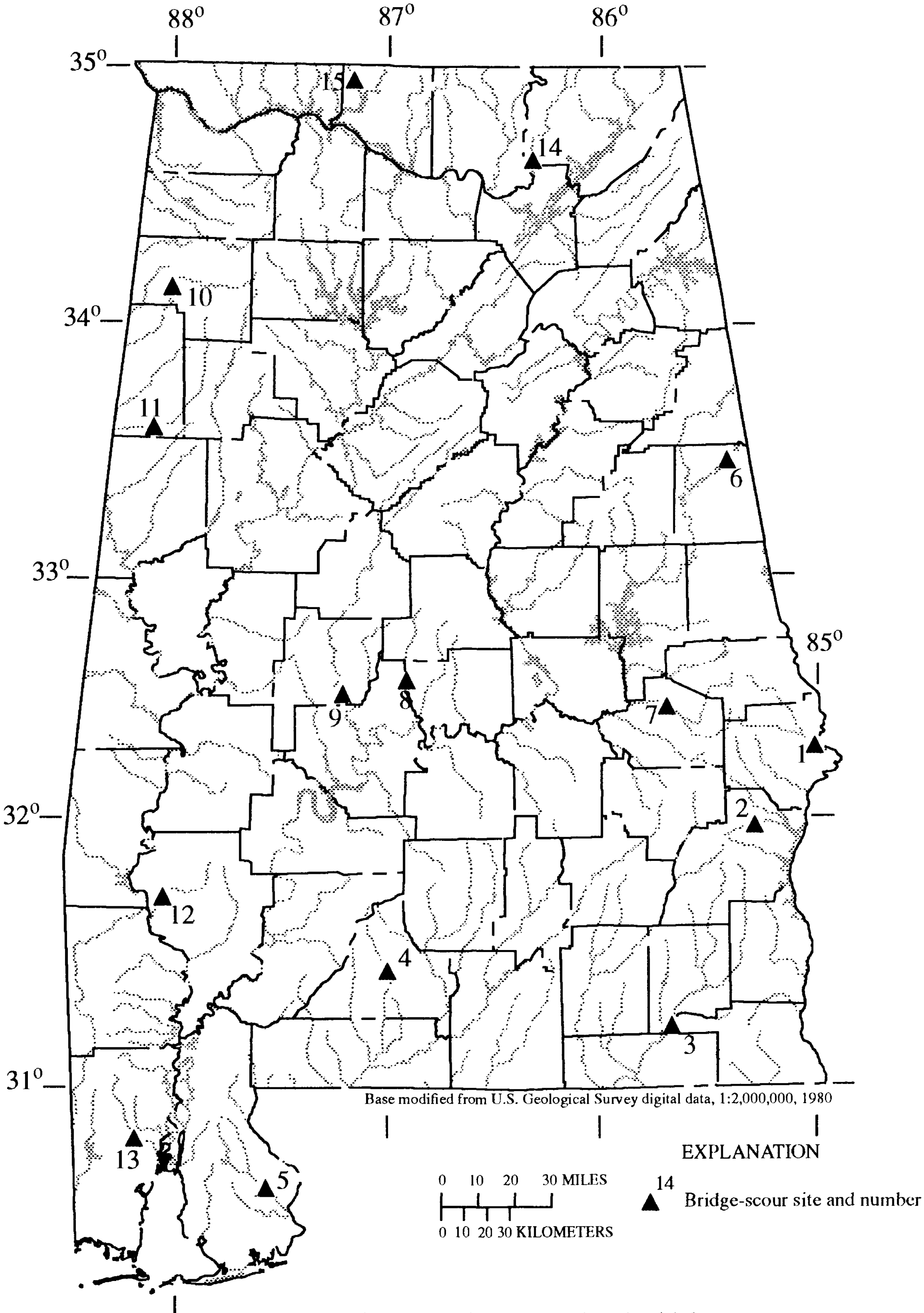

Figure 1. Location of bridge-scour sites in Alabama.

Table 1. Selected bridge sites in Alabama where scour data were collected

Site number	Station number	Site name and location	Drainage area, in square miles
1	02342500	Uchee Creek at State Highway 165 near Fort Mitchell, Russell County, Ala.	322
2	02342933	South Fork Cowikee Creek at county road 79 near Batesville, Barbour County, Ala.	112
3	02361175	Choctawhatchee River at State Highway 12 near Wicksburg, Houston County, Ala.	917
4	02374450	Murder Creek at county road 20 near Evergreen, Conecuh County, Ala.	114
5	02377570	Styx River at county road 87 near Elsanor, Baldwin County, Ala.	192
6	02413300	Little Tallapoosa River at county road 82 near Newell, Randolph County, Ala.	406
7	02419000	Uphapee Creek at State Highway 81 near Tuskegee, Macon County, Ala.	333
8	02422500	Mulberry Creek at county road 52 at Jones, Dallas County, Ala.	203
9	02424590	Cahaba River at county road 6 near Suttle, Perry County, Ala.	1,480
10	02437885	Buttahatchee River at county road 42 at Hamilton, Marion County, Ala.	244
11	02442500	Luxapallila Creek at State Highway 17 at Millport, Lamar County, Ala.	247
12	02469800	Satilpa Creek at State Highway 84 near Coffeeville, Clarke County, Ala.	164
13	02471001	Chickasaw Creek at State Highway 158 near Kushla, Mobile County, Ala.	125
14	03574500	Paint Rock River at U.S. Highway 72 near Woodville, Jackson County, Ala.	320
15	03585300	Sugar Creek on State Highway 99 near Good Springs, Limestone County, Ala.	152

streambed elevations at or on either side of the bridge or the bridge piers. The fathometers produced continuous soundings and the use of lead weights produced discrete soundings of the cross sections. Plots of bridge geometry and cross sections of the streambed prepared from these soundings provided comparisons that demonstrate the results of scour processes for various hydraulic and geometric conditions. The depth of a scour hole was calculated as the difference between the elevations of the projected channel cross section across the scour hole and lowest measured channel-bed elevation of the hole (Landers and Mueller, 1993). The projected channel cross section represents the streambed at the pier location without any pier scour. 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 as described by Rantz and others (1982). The velocity variable used in existing local-scour estimation equations is the average velocity of a vertical section immediately upstream from a pier. If velocities could not be measured immediately upstream from a pier, average velocity at the pier was calculated as the average of representative velocities in the vertical sections on each side of the pier.

MEASURED SCOUR DEPTHS

Scour measurements were obtained during high flow conditions at the 15 bridge scour sites with recurrence intervals of the measured discharges ranging from less than 2 to 10 years (table 2). Recurrence intervals of the measured discharges were determined using procedures and information described by Atkins (1996). Discharge measurements made at the 15 bridge scour sites resulted in 24 measurements of local scour ranging from 0.3 to 5.8 feet in depth (table 3). The approach-flow depth ranged from 5.1 to 28.6 feet, approach-flow velocity ranged from 1.5 to 6.8 feet per second, angle of flow to pier ranged from 0 to 60 degrees, and median bed-material diameter ranged from 0.00111 to 0.0282 feet.

Scour variables such as pier width, median bed-material diameter, approach-flow depth, approach-flow velocity, angle of flow to pier, and pier width normal to flow were plotted against the measured scour depths to examine the relation the scour variables have with the measured scour depths (figs. 2-7). Correlation coefficients for each of the scour variables were also computed to examine the strength of their association with measured scour depths. The figures indicate that angle of flow to the pier had a high correlation (0.87) with the amount of measured scour (table 4). The correlation coefficient of 0.82 for normal pier width to flow and measured scour also indicated a strong association between the two variables. The high correlations seemed to verify studies which have shown that as pier width increases, scour depth increases because as the angle of flow to the pier increases, the pier width that is normal to the flow also increases (Richardson and others, 1993). However, a strong correlation between two variables does not actually provide evidence for causal relationship between the two variables, but merely indicates a measure of observed co-variation between the two variables (Helsel and Hirsch, 1992). Also, because the correlation coefficients are based on a limited amount of data (24 points), the maximum scour depth has significant influence on correlation coefficients such as those computed for measured scour versus normal pier width and angle of flow (figs. 6 and 7). If the maximum scour depth were excluded from these correlations, the correlation coefficients would decrease (0.31 for measured scour versus normal pier width and 0.63 for measured scour versus angle of flow).

Table 2. Summary of discharge data at selected bridge sites in Alabama
[<, less than; ft^3/s, cubic feet per second]

Site number (figure 1)	Date of measurement	Measured discharge (ft^3/s)	Recurrence interval (years)
1	12-17-92	3,020	<2
2	1-13-92	2,810	<2
3	3-03-94	6,070	<2
4	2-18-92	1,110	<2
5	1-31-91	4,180	2
6	12-17-92	5,770	<2
7	12-17-92	3,600	<2
8	12-17-92	4,050	<2
9	1-22-93	14,700	<2
10	3-23-93	10,000	<2
11	2-20-91	11,100	10
12	2-19-92	1,640	<2
13	1-31-91	4,160	2
14	4-22-92	3,230	<2
15	3-10-92	11,900	3

Table 3. Summary of scour, pier geometry, and hydraulic data collected at study sites with measured scour depths
[ft, feet; ft/s, feet per second]

Site number	Date of measurement	Measured scour depth (ft)	Distance from left abutment (ft)	Median bed material diameter (ft)	Pier data				Hydraulic data at scour hole section		
					Type	Shape	Width (ft)	Width normal to flow (ft)	Approach-flow depth (ft)	Approach-flow velocity (ft/s)	Flow angle (degrees)
1	12-17-92	2.0	300	0.01215	group	square	3.5	4.3	5.1	4.4	15
2	1-13-92	.8	144	.00137	single	square	3.0	3.0	12.2	3.8	0
3	3-03-94	2.1	488	.00216	group	square	2.5	3.1	7.7	2.6	15
3	3-03-94	1.6	588	.00216	group	square	2.5	3.1	12.3	1.8	15
4	2-18-92	1.1	133	.00111	group	square	1.3	1.3	10.1	2.1	0
5	1-31-91	1.2	270	.00179	group	square	1.2	2.3	12.6	3.4	15
5	1-31-91	2.6	320	.00179	group	square	1.2	3.4	10.8	2.4	30
6	12-17-92	.4	95	.01367	single	square	2.0	2.0	10.7	3.2	0
6	12-17-92	.7	172	.01367	single	square	2.0	2.0	11.0	3.7	0
7	12-17-92	1.3	379	.00560	single	square	2.7	2.7	7.3	4.2	0
7	12-17-92	2.0	425	.00560	single	square	2.7	2.7	6.3	3.3	0
8	12-17-92	5.8	73	.00162	single	square	3.0	15.4	9.8	4.1	60
9	1-22-93	1.2	183	.00429	single	square	3.0	7.3	28.6	3.0	15
10	3-23-93	.3	89	.00985	group	square	2.0	2.0	13.7	1.5	0

Table 3. Summary of scour, pier geometry, and hydraulic data collected at study sites with measured scour depths--Continued
[ft, feet; ft/s, feet per second]

Site number	Date of measurement	Measured scour depth (ft)	Distance from left abutment (ft)	Median bed material diameter (ft)	Pier data				Hydraulic data at scour hole section		
					Type	Shape	Width (ft)	Width normal to flow (ft)	Approach-flow depth (ft)	Approach-flow velocity (ft/s)	Flow angle (degrees)
10	3-23-93	1.1	129	0.00985	group	square	2.0	2.0	16.2	6.8	0
10	3-23-93	2.0	179	.00985	group	square	2.0	2.0	14.4	5.3	0
11	2-20-91	.5	49	.01658	single	square	2.0	2.0	10.4	4.3	0
11	2-20-91	1.0	108	.01658	single	square	2.0	2.0	12.8	3.6	0
12	2-19-92	1.1	101	.00947	group	cylinder	2.3	5.8	16.7	2.1	15
13	1-31-91	.3	134	.00148	group	square	1.3	1.3	16.0	3.9	0
14	4-22-92	.4	150	.02820	group	square	3.0	3.0	12.4	1.9	0
14	4-22-92	1.2	218	.02820	group	square	3.0	3.5	10.3	1.9	15
15	3-10-92	.9	75	.01688	group	square	1.5	1.5	13.9	3.4	0
15	3-10-92	1.0	115	.01688	group	square	1.5	1.5	16.1	5.4	0

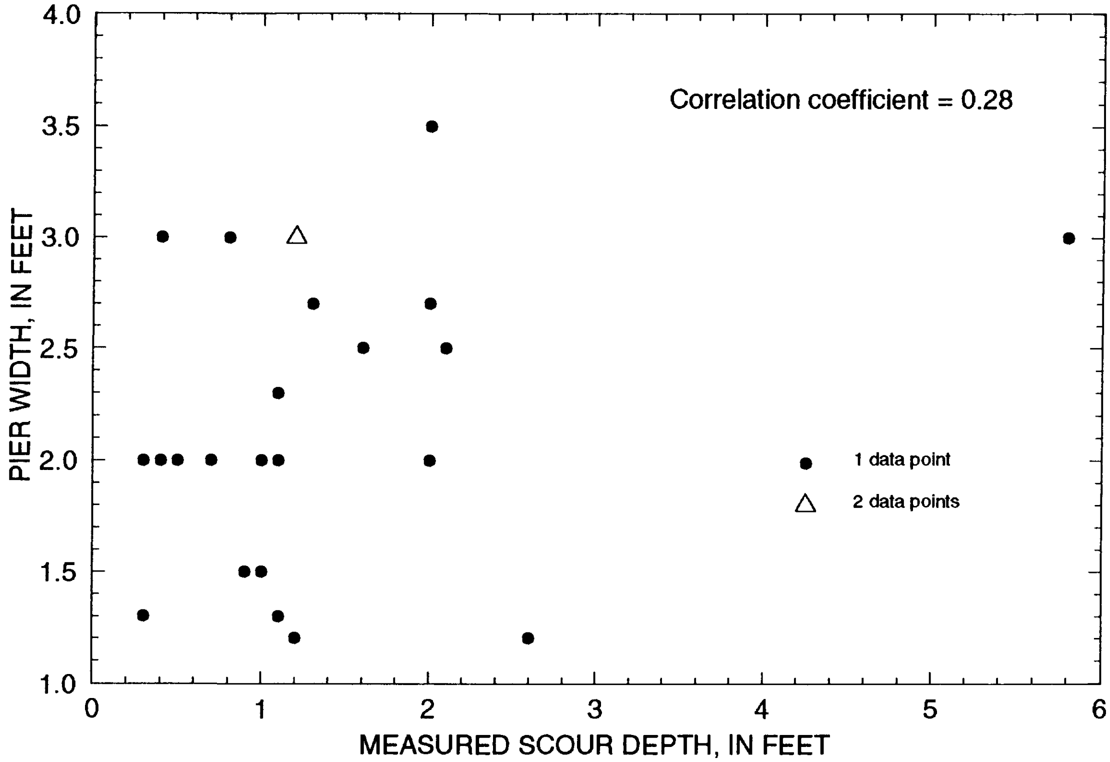

Figure 2. Relation between pier width and measured scour depth for selected bridge sites in Alabama.

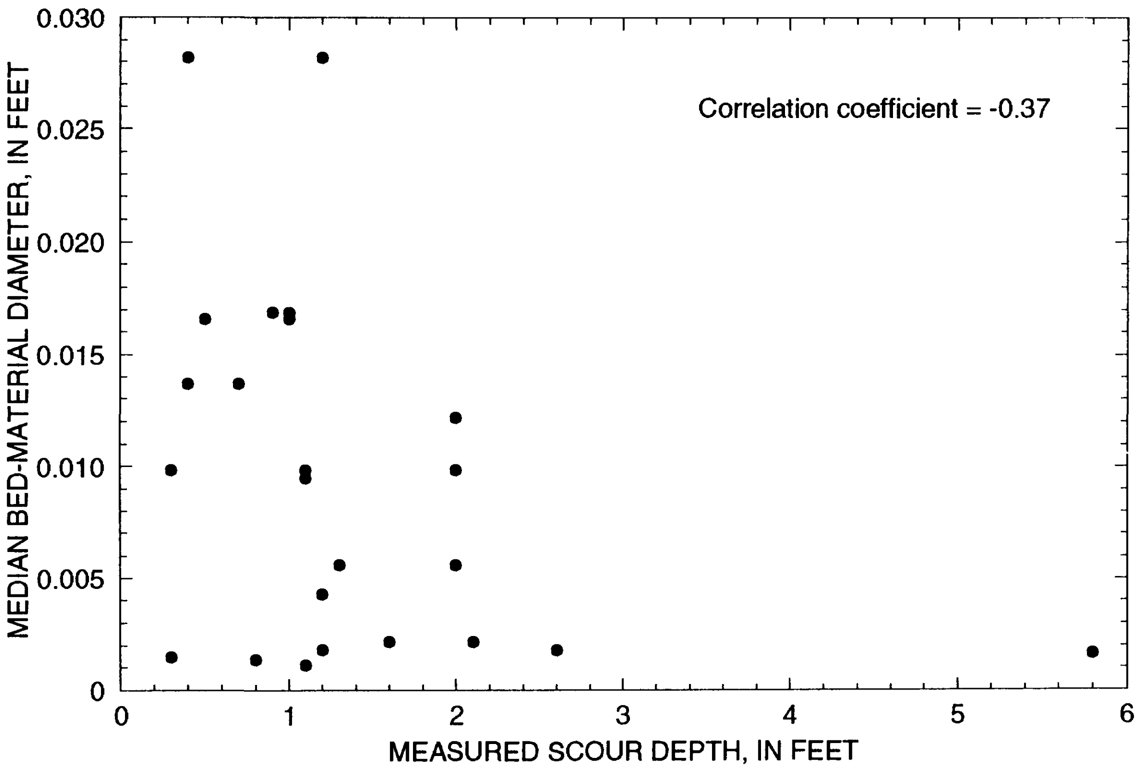

Figure 3. Relation between median bed-material diameter and measured scour depth for selected bridge sites in Alabama.

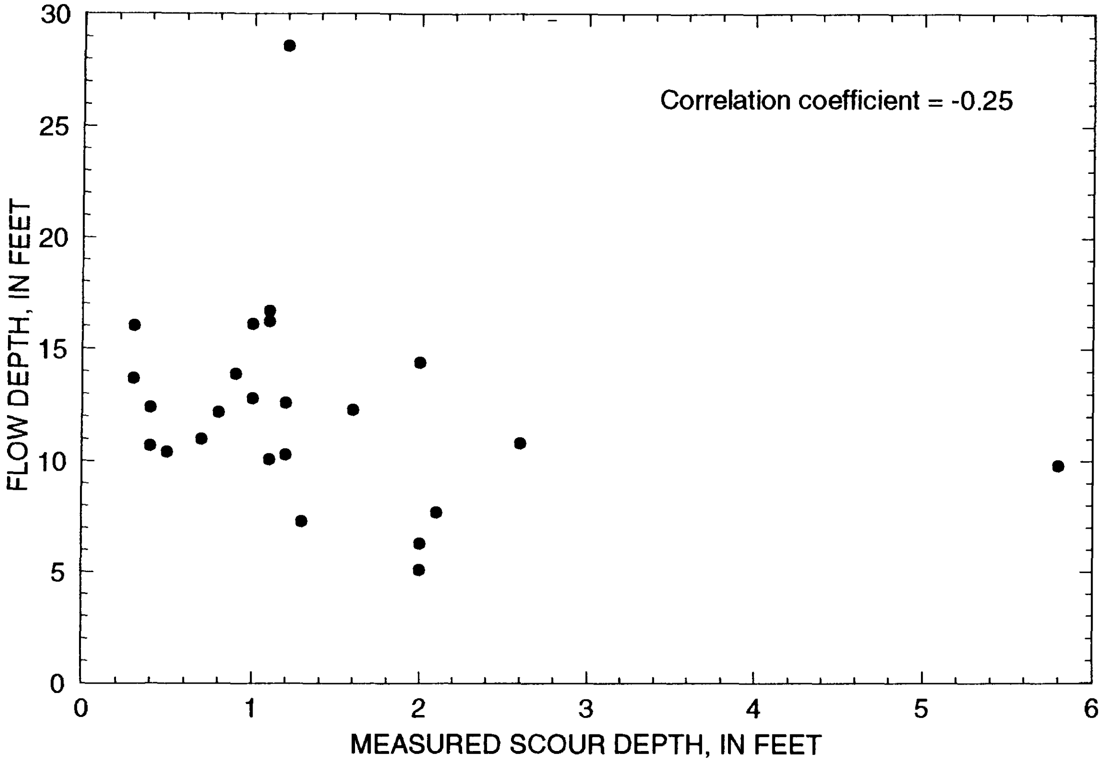

Figure 4. Relation between flow depth and measured scour depth for selected bridge sites in Alabama

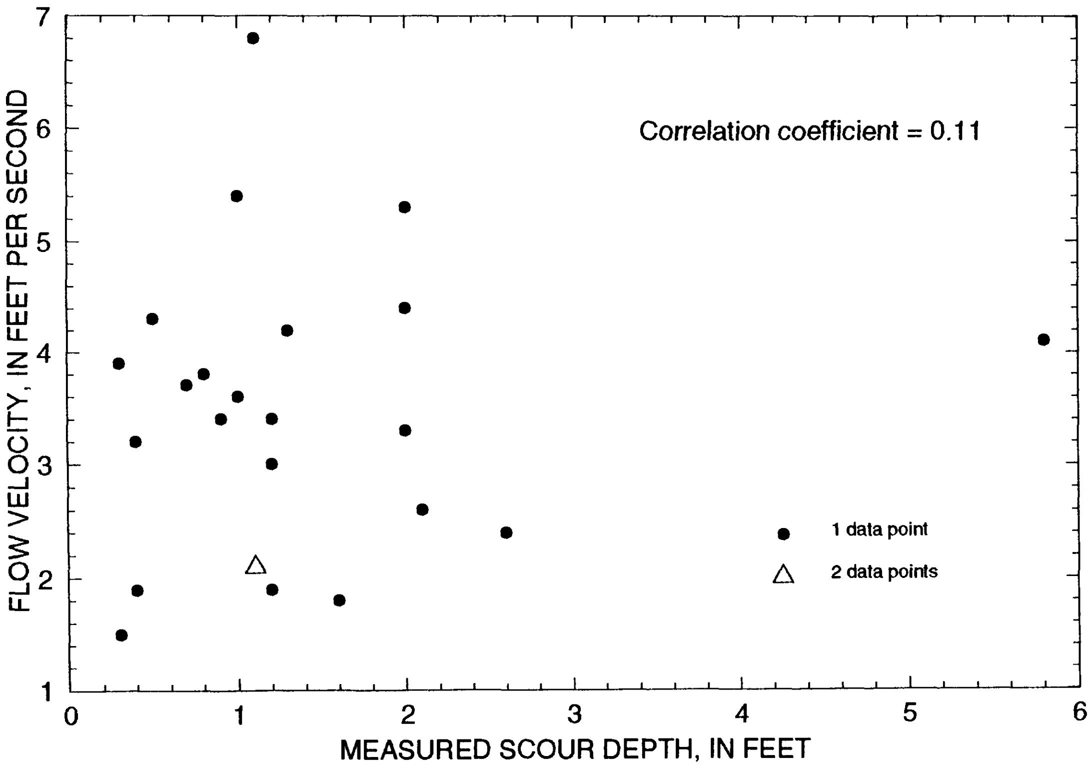

Figure 5. Relation between flow velocity and measured scour depth for selected bridge sites in Alabama.

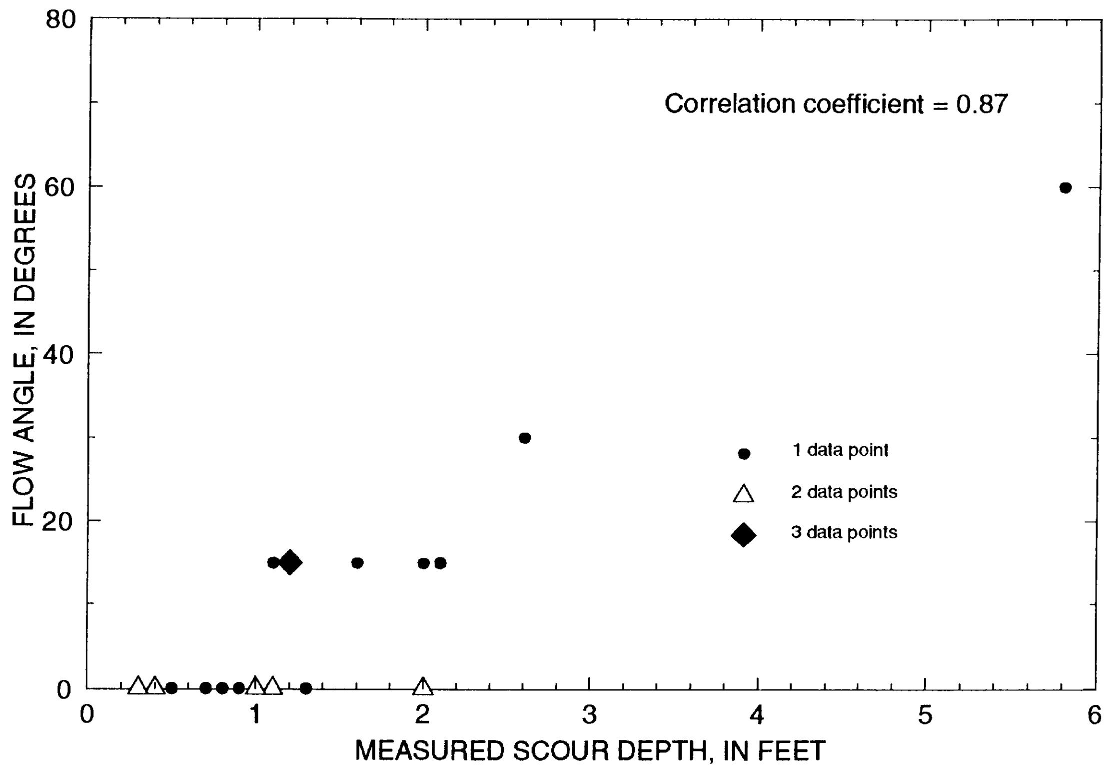

Figure 6. Relation between angle of flow to pier and measured scour depth for selected bridge sites in Alabama.

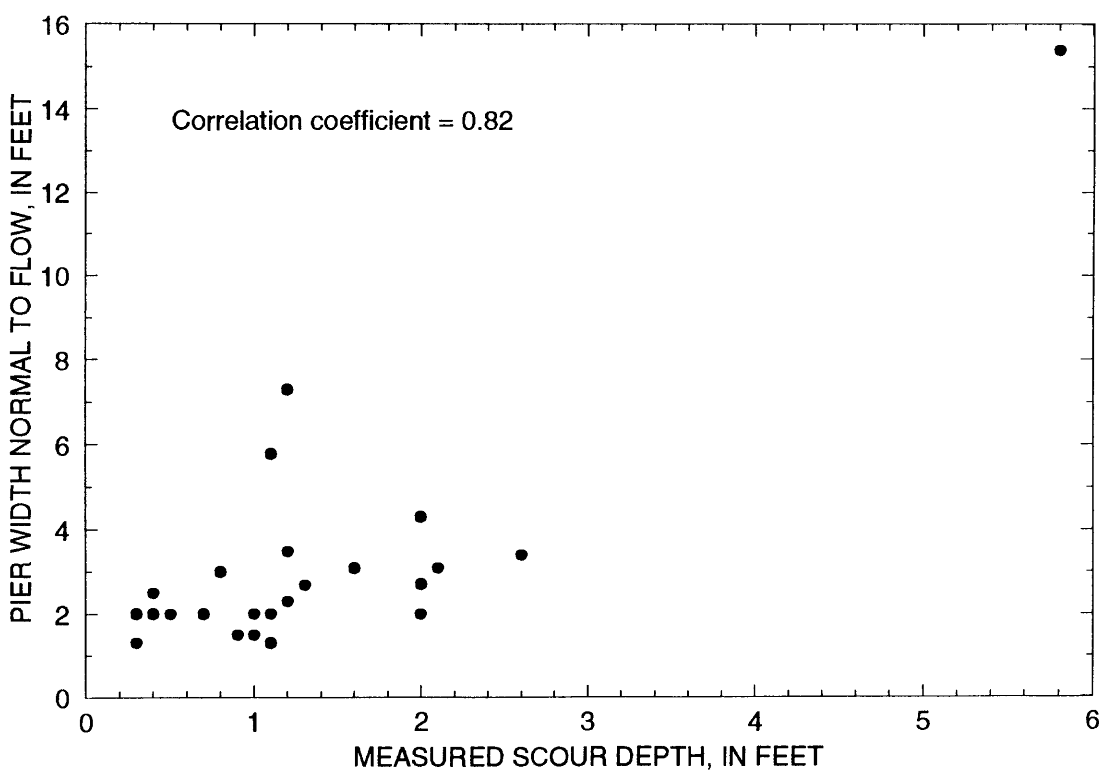

Figure 7. Relation between pier width normal to flow and measured scour depth for selected bridge sites in Alabama.

Table 4. Relation of scour variables to measured scour depths

Scour variable	Correlation coefficient
Pier width	0.28
Median bed-material diameter	-.37
Flow depth	-.25
Flow velocity	.11
Angle of flow to pier	.87
Pier width normal to flow	.82

ESTIMATED SCOUR DEPTHS

Many pier scour estimation equations have been published; however, only the equation used by the Alabama Department of Transportation and currently (1996) recommended by FHWA in Hydraulic Engineering Circular No. 18 (Richardson and others, 1993) was selected for comparison with measured scour data in Alabama. The equation which was developed by Colorado State University and will be hereafter referred to as the CSU equation, is:

$$Y_s = 2.0 Y_1 K_1 K_2 K_3 \left(\frac{a}{Y_1}\right)^{0.65} (F)^{0.43} \quad (1)$$

where

Y_s is scour depth, in feet;

a is pier width, in feet;

K_1 is correction factor for pier-nose shape from table 5;

K_2 is correction factor for approach flow angle from table 6;

K_3 is correction factor for bed condition from table 7;

Y_1 is depth of approach flow depth directly upstream of pier, in feet;

F is the Froude number defined as $V_1/\left(gY_1\right)^{0.5}$: where V_1 is the mean velocity of the approach flow upstream of the pier, in feet per second; g is the acceleration of gravity in feet per second squared; and Y_1 as defined above.

The measured scour depths and estimated scour depths from equation (1) are listed in table 8 and plotted against each other in figure 8. Estimated scour depths ranged from 2.5 to 12.7 feet with a mean estimated scour depth of 5.3 feet.

Box plots summarizing the distribution of the measured and estimated scour depths are shown in figure 9. Box plots indicate the center, spread, skewness, and the presence of extreme outlier values in a sample data set and are also useful in comparing different data sets. A box plot consists of a center line which represents the median that splits a rectangle defined by upper (75th percentile) and lower (25th percentile) quartiles. The box height is equal to the interquartile range (upper quartile minus lower quartile) and is a measure of the spread or variation of the data. Vertical lines at the top and at the bottom of the box extend to observations which are equal to the last observation within one step beyond either end of the box. A step is equal to 1.5 times the height of the box (the interquartile range). Observations between one and two steps from the box in either direction are plotted individually with an asterisk and represent values outside of the normal range because outside values occur fewer than once in 100 times for data for a normal distribution. Observations farther than two steps beyond the box in either direction are plotted individually with a small circle and represent values far outside of the normal range because these values occur fewer than once in 300,000 times for a normal distribution (Helsel and Hirsch, 1992). The summary statistics associated with the box plots are listed in table 9.

Table 5. Pier-shape correction factor (K_1) for the HEC-18 equation (from Richardson and others, 1993)

Shape of pier nose	K_1
Square nose	1.1
Round nose	1.0
Circular cylinder	1.0
Sharp nose	.9
Group of cylinders	1.0

Table 6. Approach flow-angle correction factor (K_2) for the HEC-18 equation (from Richardson and others, 1993)

[L, pier length, in feet; a, pier width, in feet]

Approach flow angle (degrees)	L/a=4	L/a=8	L/a=12
0	1.0	1.0	1.0
15	1.5	2.0	2.5
30	2.0	2.75	3.5
45	2.3	3.3	4.3
90	2.5	3.9	5.0

Table 7. Bed-condition correction factor (K_3) for the HEC-18 equation (from Richardson and others, 1993)

[N/A, not applicable]

Bed condition	Dune height (H) (feet)	K_3
Clear-water scour	N/A	1.1
Plane bed and antidune flow	N/A	1.1
Small dunes	10>H>2	1.1
Medium dunes	30>H>10	1.1 to 1.2
Large dunes	H>30	1.3

Table 8. Measured scour depths and estimated scour depths using the CSU equation

Site number	Distance from left abutment (feet)	Measured scour depth (feet)	Estimated scour depth (feet)
1	300	2.0	8.3
2	144	.8	5.8
3	488	2.1	5.7
3	588	1.6	5.1
4	133	1.1	2.5
5	270	1.2	4.2
5	320	2.6	4.7
6	95	.4	4.1
6	172	.7	4.4
7	379	1.3	5.3
7	425	2.0	4.7
8	73	5.8	12.7
9	183	1.2	9.3
10	89	.3	3.0
10	129	1.1	6.0
10	179	2.0	5.3
11	49	.5	4.6
11	108	1.0	4.4
12	101	1.1	6.3
13	134	.3	3.1
14	150	.4	3.8
14	218	1.2	5.7
15	75	.9	3.6
15	115	1.0	4.5

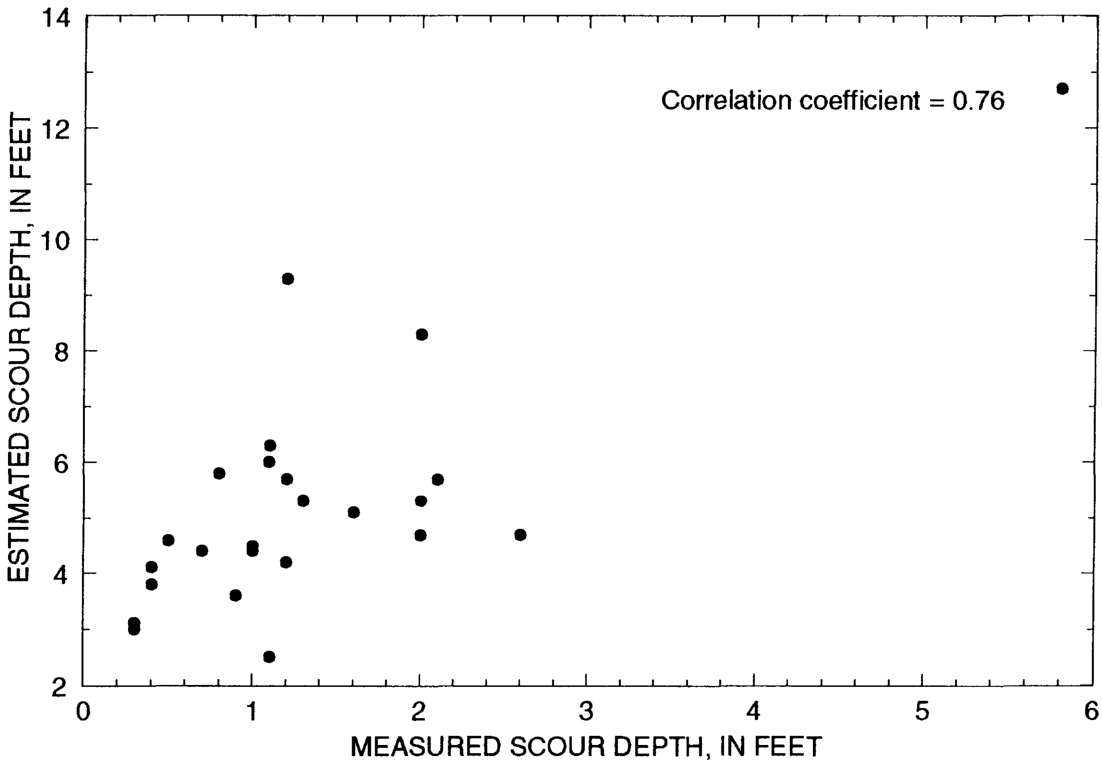

Figure 8. Relation between scour depth estimated by the CSU equation and measured scour depth for selected bridge sites in Alabama.

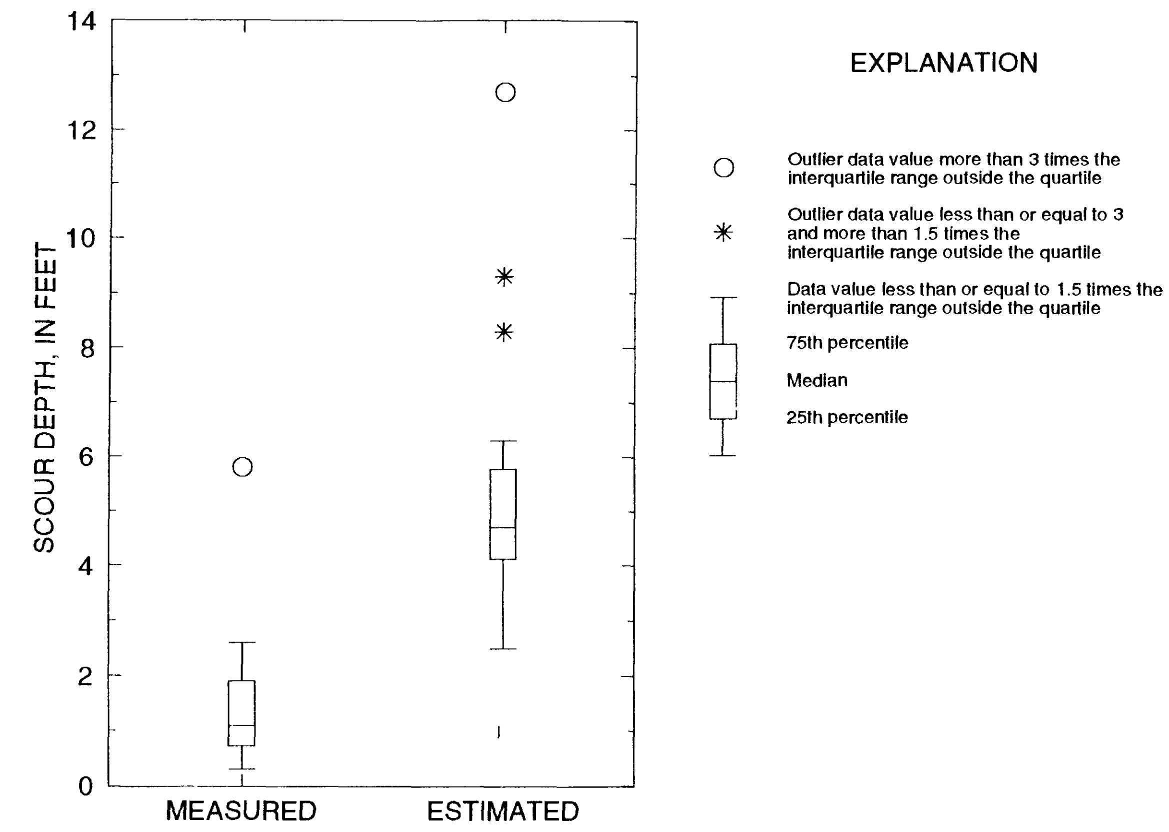

Figure 9. Boxplots of the distribution of measured scour depths and scour depths estimated by the CSU equation for selected bridge sites in Alabama.

Table 9. Statistics of measured and estimated scour depths

Statistic	Measured scour (feet)	Estimated scour (feet)
Mean	1.4	5.2
Minimum	.3	2.5
Maximum	5.8	12.7
Median	1.1	4.7
Lower quartile	.7	4.1
Upper quartile	1.9	5.8
Interquartile range	1.2	1.7

Each statistic computed for the estimated scour depth was greater than the corresponding statistic for measured scour depth. The central statistics (mean and median) for the estimated scour depths were nearly 4 times greater than those for the measured scour depths. The spread (interquartile range) of the estimated scour depths was 1.4 times greater than the spread of the measured scour depths. Based on the Wilcoxon Signed-Ranks test, the median of the estimated scour depths was statistically different from the median of the measured scour depths at a 0.05 level of significance.

Estimated scour depths were plotted against the residuals (measured scour depth minus estimated scour depth) to determine if any bias existed in the estimates (fig. 10). The residuals ranged from -8.1 to -1.4 feet with a mean residual of -3.9 feet. Large negative residuals indicated that the CSU equation significantly overestimated the measured scour depths throughout the range of measured data. The estimated scour depths were significantly higher than the measured scour depths by as much as 933 percent and by an average of 434 percent.

SUMMARY

Scour data were collected at 15 bridge sites in Alabama. Data collected consisted of pier geometry, bed-material particle-size data, and hydraulic characteristics during selected high flow conditions. Fathometer soundings and manual soundings were used to obtain streambed cross sections at the upstream sides of bridges from which scour depths near bridge piers could be determined. Data collected during this study resulted in 24 sets of scour data from 15 discharge measurements. The recurrence intervals of the discharges ranged from less than 2 to 10 years. Measured scour depths ranged from 0.3 to 5.8 feet. Approach-flow depth ranged from 5.1 to 28.6 feet, approach-flow velocity ranged from 1.5 to 6.8 feet per second, and angle of flow to piers ranged from 0 to 60 degrees. Median bed-material diameter ranged from 0.00111 to 0.0282 feet. The scour variables were plotted against the measured scour depths to examine the relation the scour variables have with the measured scour depths. The figures indicated that angle of flow to the pier and normal pier width had high associations with measured scour depths (correlation coefficients of 0.87 and 0.82, respectively).

Estimated scour depths using the CSU scour equation recommended by the Federal Highway Administration in its Hydraulic Engineering Circular No. 18 were compared to the measured scour depths. The estimated scour depths based on the CSU equation ranged 2.5 to 12.7 feet and the mean and median estimated scour depths were nearly 4 times greater than the mean and median measured scour depths. The residuals (measured scour depth minus estimated scour depth) ranged from -8.1 to -1.4 feet. A plot of the residuals against the estimated scour depths indicated that the equation overestimated the measured scour depths. The estimated scour depths were as much as 933 percent and averaged 434 percent higher than the measured scour depths.

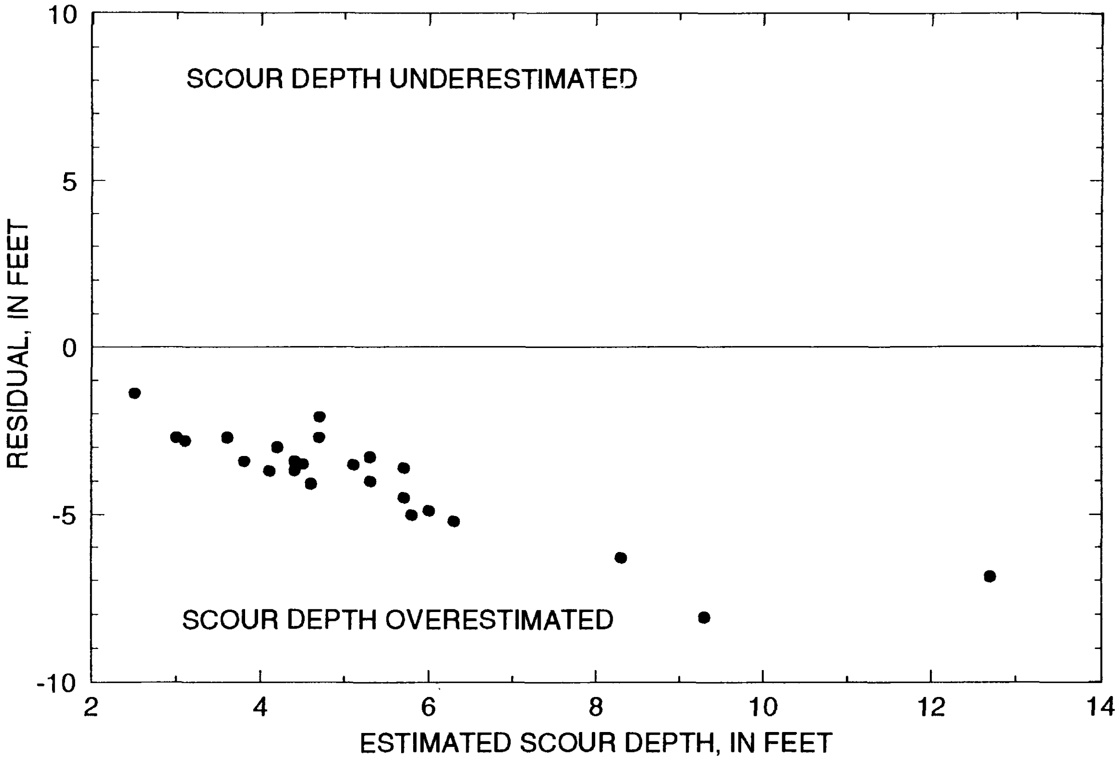

Figure 10. Relation between estimated scour depth and the residual (measured scour depth minus the estimated scour depth) for selected bridge sites in Alabama.

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