Scour at Bridge Sites in Delaware, Maryland, and Virginia

By Donald C. Hayes

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CONVERSION FACTORS

Multiply	By	To obtain
	Length	
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter
	Flow	
foot per second (ft/s)	0.3048	meter per second
cubic foot per second (ft^3/s)	0.02832	cubic meter per second

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Abstract

Scour data were obtained from discharge measurements to develop and evaluate the reliability of constriction-scour and local-scour equations for rivers in Delaware, Maryland, and Virginia. No independent constriction-scour or local-scour equations were developed from the data because no significant relation was determined between measured scour and streamflow, streambed, and bridge characteristics. Two existing equations were evaluated for prediction of constriction scour and 14 existing equations were evaluated for prediction of local scour.

Constriction-scour data were obtained from historical stream discharge measurements, field surveys, and bridge plans at nine bridge sites in the three-State area. Constriction scour was computed by subtracting the average-streambed elevation in the constricted reach from an uncontracted-channel reference elevation. Hydraulic conditions were estimated for the measurements with the greatest discharges by use of the Water-Surface Profile computation model.

Measured and calculated constriction-scour data were used to evaluate the reliability of Laursen's clear-water constriction-scour equation and Laursen's live-bed constriction-scour equation. Laursen's clear-water constriction-scour equation underestimated 21 of 23 scour measurements made at three sites. A sensitivity analysis showed that the equation is extremely sensitive to estimates of the channel-bottom width. Reduction in estimates of bottom width by one-third resulted in predictions of constriction scour slightly greater than measured values for all scour measurements. Laursen's live-bed constriction-scour equation underestimated 10 of 14 scour measurements made at one site. The error between measured and predicted constriction scour was less than 1.0 ft (feet) for 12 measurements and less than 0.5 ft for 8 measurements.

Local-scour data were obtained from stream discharge measurements, field surveys, and bridge plans at 15 bridge sites in the three-State area. The reliability of 14 local-scour equations were evaluated. From visual inspection of the plotted data, the Colorado State University, Froehlich design, Laursen, and Mississippi pier-scour equations appeared to be the best predictors of local scour. The Colorado State University equation underestimated 11 scour depths in clear-water scour conditions by a maximum of 2.4 ft, and underestimated 3 scour depth in live-bed scour conditions by a maximum of 1.3 ft. The Froehlich design equation underestimated two scour depth in clear-water scour conditions by a maximum of 1.2 ft, and underestimated one scour depth in live-bed scour conditions by a maximum of 0.4 ft. Laursen's equation overestimated the maximum scour depth in clear-water scour conditions by approximately one-half pier width or approximately 1.5 ft, and overestimated the maximum scour depth in live-bed scour conditions by approximately one-pier width or approximately 3 ft. The Mississippi equation underestimated six scour depths in clear-water scour conditions by a maximum of 1.2 ft, and

underestimated one scour depth in live-bed scour conditions by 1.6 ft. In both clear-water and live-bed scour conditions, the upper limit for the depth of scour to pier-width ratio for all local scour measurements was 2.1.

An accurate pier-approach velocity is necessary to use many local pier-scour equations for bridge design. Velocity data from all the discharge measurements reviewed for this investigation were used to develop a design curve to estimate pier-approach velocity from mean cross-sectional velocity. A least-squares regression and offset were used to envelop the velocity data.

INTRODUCTION

Scour at bridge sites can result in damage to bridges and ultimately cause bridge failure. Thus scour is a prime concern to officials and agencies responsible for the integrity of bridges and the safety of the traveling public. Scour data from 9 bridge sites in Delaware, Maryland, and Virginia were analyzed to evaluate the reliability of 2 existing constriction-scour equations, and field measurements from 15 bridge sites in the three-State area were analyzed to evaluate the reliability of 14 existing local-scour equations.

Numerous equations have been developed to predict scour depths, but the estimates of scour depths vary over a wide range for the same set of conditions (Highway Research Board, 1970; Melville, 1975; Norman, 1975; Chang, 1980; Hopkins and others, 1980; Jones, 1984; Jarrett and Boyle, 1986; and Froehlich, 1988). Most of these equations are based on theoretical approaches and laboratory measurements and have not been validated by field measurements. Uncertainty as to which equations are applicable for a given set of conditions has emphasized the need for field measurements. Accurate and complete field measurements of scour are difficult to obtain because of streamflow patterns that occur at bridges during floods, inability to get skilled personnel to bridge sites during floods, and problems associated with existing measuring equipment (Davis, 1984). Collection and analysis of field-scour data, however, is perhaps the only convincing way to improve bridge-scour prediction equations (Highway Research Board, 1970; Hopkins and others, 1980; and Jones, 1984) and improve the knowledge of scour processes.

In 1988, the U.S. Geological Survey (USGS), in cooperation with the Delaware Department of Transportation, the Maryland Department of Transportation, and the Virginia Department of Transportation, began a study in the three-State area as part of a National program to improve bridge-scour-prediction equations by collection of bridge-scour data.

This study is one of the first cooperative studies between the three-State area and the USGS to develop methods for collecting field measurements to evaluate scour at bridges (Hayes, 1993), and to develop methods for monitoring streambed elevations at potential scour locations (Hayes, 1995). All 50 States have begun studies that focus on bridge scour, and as many as 23 States have cooperative programs with the USGS to collect bridge-scour data to improve scour prediction equations. In addition, nine States have cooperative programs with the USGS to develop methods to monitor scour. The USGS, in cooperation with the Federal Highway Administration, developed a National Bridge-Scour Data Base (Landers and Mueller, in press) in which most of the data collected in these studies are available.

Purpose and Scope

This report presents a description of streamflow data and streambed and bridge characteristics at bridge sites in Delaware, Maryland, and Virginia and an evaluation of bridge-scour prediction equations. Information obtained from historical discharge measurements at nine bridge sites in the three-State area is used in conjunction with hydraulic computations to evaluate the relation of streamflow data and streambed and bridge characteristics to constriction scour. Constriction-scour values calculated from field data are compared to constriction-scour values calculated from existing constriction-scour-prediction equations. Information obtained from local-scour measurements at 15 bridge sites in the three-State area is used to evaluate the relation of streamflow data and streambed and bridge characteristics to local scour. Local-scour values measured in the field are compared to local-scour values calculated from existing local-scour-prediction equations. Additionally, velocity data from historical discharge measurements are presented to improve bridge design.

Description of Study Sites

Nine bridge sites were selected from the USGS streamflow-gaging network in the three-State area for analysis of constriction scour. Four of these sites were selected for measuring local scour during high streamflows. Eleven additional bridge sites were selected for analysis of local scour. One of these additional bridge sites had previous USGS streamflow-gaging information and another site was an active streamflow-gaging station operated by the State of Virginia. The remaining nine bridge sites had no previous streamflow-gaging information. The locations of the bridge-scour study sites are listed in table 1 and shown in figures 1 and 2. Criteria used in site selection are described in Hayes (1993). Background information on each bridge and characteristics of the stream are contained in the National Bridge-Scour Data Base, (Landers and Mueller, in press). Selected pier and stream characteristics are given in table 2.

Acknowledgments

Personnel from the Departments of Transportation in Delaware, Maryland, and Virginia are gratefully acknowledged for their assistance in providing copies of bridge inventories, site recommendations, bridge plans, and technical advice, and for removing debris from bridge sites selected for this study. Roy Trent and Sterling Jones of the Federal Highway Administration also are acknowledged for their technical advice.

SCOUR

Total scour of a channel can be described by three primary components—constriction scour, local scour, and general scour. The primary components of scour are not completely independent; however, separating total scour into these primary components is necessary in studying the causes of scour and in designing scour-resistant bridges. Design engineers can predict the magnitude of each component and combine the results to estimate the total scour at a site (Froehlich, 1991).

Constriction scour is the lowering of the stream bed because of increased flow velocities and bed-shear stress caused by a reduced cross-sectional area. Constriction scour normally occurs during high flows

Table 1. Location of bridge-scour study sites in Delaware, Maryland, and Virginia

[DE, Delaware State Highway; MD, Maryland State Highway; VA, Virginia State Highway; US, Federal Highway; A, bridge-scour measurements for analysis of local scour; H, historical discharge measurements for analysis of constriction scour; and latitude and longitude are reported in degrees (°), minutes ('), seconds (")]

Station number	Name	Latitude	Longitude	Bridge number	Road	Data type
01483530	Leipsic River at Leipsic, Del.	391444	0753105	2-12B	DE 9	A
01484702	Assawoman Bay near Fenwick Island, Del.	382720	0750400	437	DE 54	A
01490750	Choptank River near Goldsboro, Md.	390200	0754500	5002	MD 287	A
01581700	Winters Run near Benson, Md.	393112	0762224	12065	US 1	H
01625880	South River at Lyndhurst, Va.	380245	0785635	6071	VA 664	A
01633050	North Fork Shenandoah River near Mt. Jackson, Va.	384656	0783603	6312	VA 7	A
01639500	Big Pipe Creek at Bruceville, Md.	393645	0771410	6035	MD 194	A,H
01649500	Northeast Branch Anacostia River at Riverdale, Md.	385737	0765534	16069	MD 410	H
01673000	Pamunkey River near Hanover, Va.	374603	0771957	6918	VA 614	A,H
02027000	Tye River near Lovingston, Va.	374255	0785855	1017	VA 56	A
02039550	Bush River near Rice, Va.	371642	0782104	1031	US 460	A
02044280	Little Nottoway River near Blackstone, Va.	370516	0780323	6171	VA 603	A
02047000	Nottoway River near Sebrell, Va.	364613	0770959	6111	VA 653	A,H
02076000	Dan River at South Boston, Va.	364137	0785409	1900	US 501	A
03076500	Youghiogheny River at Friendsville, Md.	393913	0792431	11011	MD 42	A,H
03164000	New River near Galax, Va.	363850	0805845	1007	VA 94	H
03166700	Reed Creek near Wytheville, Va.	365647	0810132	6189	VA 649	A
03167500	Big Reed Island Creek near Allisonia, Va.	365320	0804340	N80A	VA 693	H
03208500	Russell Fork at Haysi, Va.	371225	0821745	1042	VA 63	H
03487990	North Fork Holston River near North Holston, Va.	365429	0814208	6042	VA 633	A

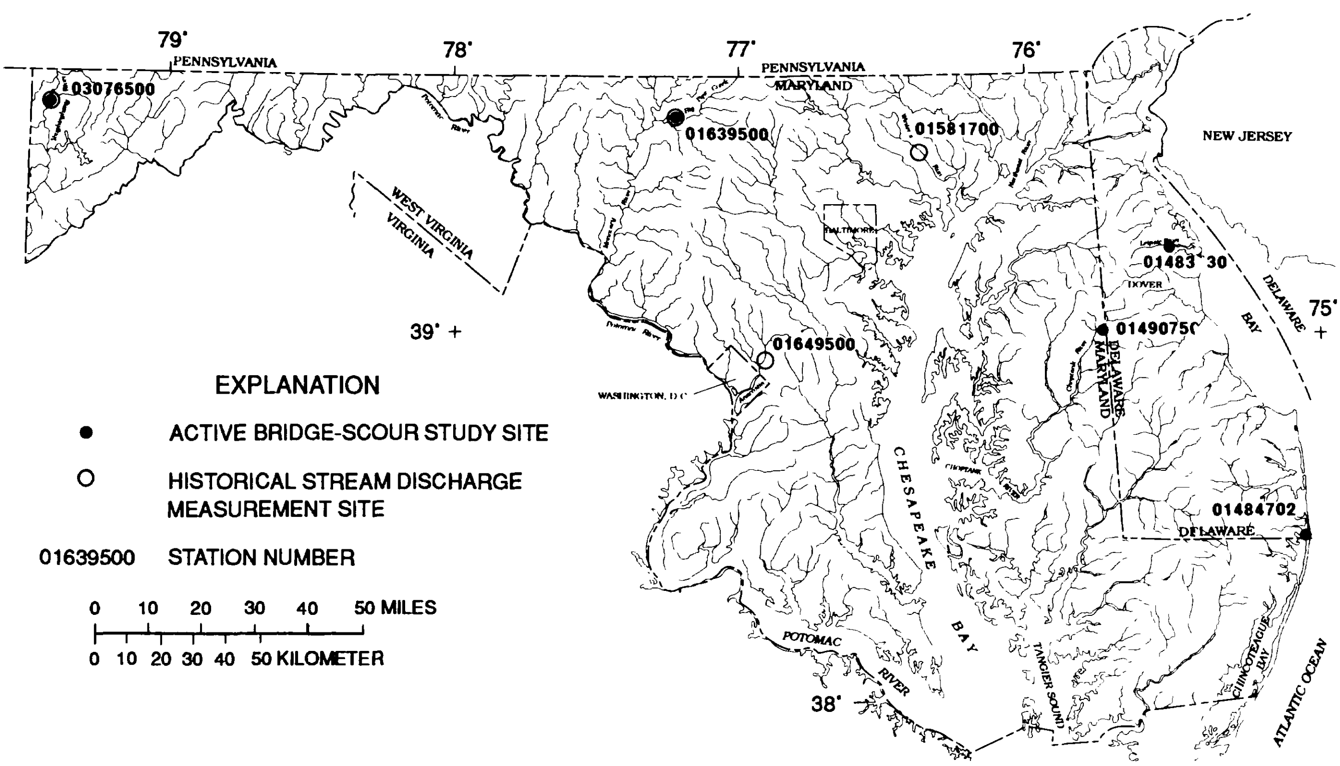

Figure 1. Location of bridge-scour study sites in Delaware and Maryland.

Table 2. Characteristics of bridge piers and streambeds at bridge-scour study sites in Delaware, Maryland, and Virginia

[Slope, the streambed slope in the vicinity of the bridge; D_{95}, grain size of which 95 percent of the material is smaller; D_{84}, grain size of which 84 percent of the material is smaller; D_{50}, grain size of which 50 percent of the material is smaller; D_{16}, grain size of which 16 percent of the material is smaller; ft, foot; mm, millimeters; --, not determined]

Station number	Number of piers	Pier nose shape	Slope (ft/ft)	Pier width (ft)	D_{95} (mm)	D_{84} (mm)	D_{50} (mm)	D_{16} (mm)	Gradation coefficient
01483530	4	round	--	1.25	8.0	1.4	0.4	0.06	4.8
01484702	10	round	--	2.5	.65	.37	.18	.09	2.0
01490750	3	square	--	4.0	2.6	.94	.38	.18	2.3
01581700	--	--	--	--	225	120	68	34	1.9
01625880	3	round	.0016	2.0	112	82	46	19	2.1
01633050	5	round	.0013	3.2	24	15	8	.62	4.9
01639500	3	round	.0016	4.0	160	76	22	13	2.4
01649500	1	square	.0030	5.0	51	30	20	12	1.6
01673000	3	round	.00012	3.0	2.8	1.6	.7	.32	2.2
02027000	3	round	.0029	2.0	250	170	72	33	2.3
02039550	4	round	.0011	2.5	10.5	4.8	.92	.29	4.1
02044280	3	round	.002	2.25	1.9	1.3	.69	.35	1.9
02047000	3	round	.00016	2.9	4.0	2.0	.74	.35	2.4
02076000	2	round	.00025	3.17	.77	.46	.28	.14	1.8
03076500	2	sharp	.005	5.0	350	233	108	68	1.9
03164000	--	--	.001	--	200	90	23	9.2	3.1
03166700	2	round	.0001	2.0	130	84	55	38	1.5
03167500	--	--	.0024	--	210	110	47	26	2.1
03208500	--	--	.0037	--	470	220	74	25	3.0
03487990	3	round	.001	2.0	180	75	37	18	2.0

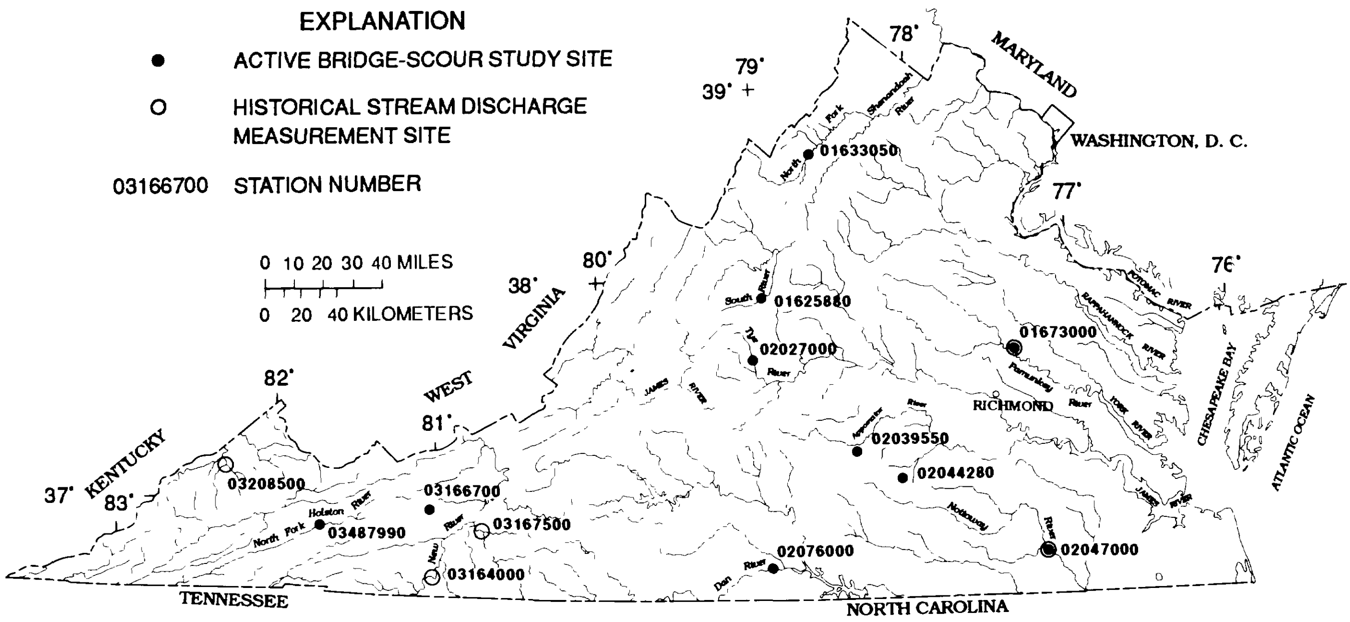

Figure 2. Location of bridge-scour study sites in Virginia.

and within a short distance (from upstream to downstream of the constriction).

Local scour is the erosion of the stream bed because of flow disturbances caused by obstructions in the streamflow. These obstructions create vortexes in the flow that remove streambed material in the vicinity of the obstruction.

General scour is the lowering (degradation) of the entire stream bed (normally along a defined length of stream) by changes in channel controls, sediment supply, or stream form. Dam construction, gravel mining, and stream channelization are examples of actions that can result in changes in channel controls, sediment supply, and stream form. General scour can occur whether a bridge is present or not. General scour is not studied in this report.

Scour can be classified as either clear-water scour or live-bed scour as determined by the sediment-transport conditions in the stream. Clear-water scour occurs when minimal streambed material is transported in the approach flow to the bridge site and the primary streambed material transported at the bridge site is the material being scoured. Live-bed scour occurs when streambed material is continuously transported in the approach flow to the bridge site and the streambed material transported at the bridge site consists of the material transported from upstream and the material being scoured (Mueller and others, 1994).

Constriction Scour

Constriction scour normally occurs when the flow area of a stream is reduced by either artificial obstructions or natural obstructions. Bridges, bridge embankments, and natural constrictions or narrowing of the channel are examples of obstructions that can reduce the cross-sectional area of the stream channel. A reduced flow area causes increased velocities and bed-shear stress in the constriction, thereby, increasing the erosion capabilities of the flow (Richardson and others, 1993).

Constriction scour can be defined as either clear-water scour or live-bed scour, depending on the sediment-transport conditions of the flow in the approach section of the stream. In this report, Laursen's equation for critical velocity (Richardson and others, 1993, p. 31) is used to define sediment-transport conditions as either clear water or live bed. For streambed material with a specific gravity equal to 2.65, Laursen's equation for critical velocity is

$$V_c = 10.95 (y_1)^{\frac{1}{6}} (D_{50})^{\frac{1}{3}} , \qquad (1)$$

where V_c is the critical velocity which will transport streambed material of size D_{50} and smaller, in feet per second; y_1 is the depth of flow in the approach section, in feet; and D_{50} is the median grain size of the streambed material, in feet. Sediment-transport conditions are defined by the flow conditions in the main channel and overbank area at the approach section. For mean velocities less than V_c, the sediment-transport conditions are considered clear water, and clear-water scour may exist. For mean velocities equal to or greater than V_c, the sediment-transport conditions are considered live bed, and live-bed scour may exist. Bed-material movement in sediment with nonuniform sizes, however, does not usually begin at a specific critical-shear stress as defined by V_c. In this investigation, measurements with mean velocities bordering V_c were analyzed for both clear-water and live-bed sediment-transport conditions.

During floods where there is flow in the overbank area of a stream, live-bed sediment-transport conditions may exist in the main channel with clear-water sediment-transport conditions in the overbank area. Sediment-transport conditions are complicated at the bridge if the flow in the overbank area is returned to the main channel upstream of the constriction. In this report, sediment-transport conditions are defined by the flow conditions in the main channel at the approach section.

Determination and Analysis of Constriction-Scour Data

Detailed measurements of constriction-scour data and streamflow characteristics are extremely difficult to obtain during high flows, especially at the approach and exit sections of bridges. Current field data, however, can be used in conjunction with historical data, through computer simulation, to estimate the streamflow characteristics needed to define or validate constriction-scour equations.

The depth of constriction scour is the difference in average-streambed elevations with and without the constriction in place and is defined generally as the difference between average-streambed elevations of the contracted and uncontracted sections (Landers and Mueller, 1993). The preferred method for computing the reference elevation for uncontracted conditions is by passing a line through the average-streambed elevations of the uncontracted sections upstream and downstream of the bridge. Historical streambed elevations on the uncontracted sections of the bridge was not available and could not be estimated accurately for historical discharge measurements. The reference elevation, therefore, was defined as the average-streambed elevation prior to bridge construction, and the depth of constriction scour was defined as the difference between the reference elevation and the average-streambed elevation during the discharge measurement with the bridge in place.

Once a site was selected for study, bridge plans and historical discharge measurements made at the bridge since construction were obtained. Cross-sectional data from the bridge plans and discharge measurements were plotted and adjusted to consistent horizontal and vertical datums. Background information on site selection, field survey, and streambed material sampling are contained in Hayes (1993).

The average-streambed elevation was determined by computing a weighted average-streambed elevation for an active-bed section at the bridge. The active-bed section is the minimum streambed section that contains flow during medium and high flows. A weighted average-streambed elevation was computed for all discharge measurements where the stream width encompassed the active-bed section. The weighted average-streambed elevation was computed in a manner similar to discharge computations in a standard USGS discharge measurement (Buchanan and Somers, 1969). The streambed elevation for each vertical within the active-bed section was multiplied by half the distance between adjacent verticals and summed. End sections were modified by estimating the streambed elevation at the end of the active-bed section by prorating from the adjacent verticals and by multiplying this streambed elevation by half the width to the next vertical within the active-bed section. The total was then divided by the width of the active-bed section. The reference elevation was computed in the same manner except the average-streambed elevation of the bridge section during uncontracted conditions was determined from preconstruction contours obtained from the bridge plans. If preconstruction contours were not available, the highest average-streambed elevation computed from discharge measurements was used as the reference elevation.

Plots of the average-streambed elevations with time were visually reviewed for trends. Trends in the data indicate changes in stream conditions, resulting from general scour or fill. Data from periods of time where trends exist were eliminated. Data from periods of time where no trends exist were reviewed and retained if appropriate vertical datums could be applied.

The depth of constriction scour was calculated as the difference between the reference elevation and the average-streambed elevation of the bridge section during discharge measurements. Some scour attributed to constriction scour computed in this manner is due to other factors not directly associated with the constriction, such as bed mobilization or local scour. The errors associated with computation of the constriction scour, however, should be minor compared to the total error associated with each measurement.

The streamflow, streambed, and bridge characteristics necessary to analyze constriction scour were obtained from historical discharge measurements made at the bridge, field surveys, and computer simulations of hydraulics during flood conditions. Mean velocity, maximum vertical-average velocity, and streamflow depths were obtained directly from discharge measurements. Bridge construction information was obtained from the bridge plans and verified during the field survey. Frequency of occurrence of streambed material sizes were determined from samples obtained during the field survey. The gradation coefficient is the geometric standard deviation of the streambed material sizes or $(D_{84}/D_{16})^{0.5}$. The streambed material size statistics presented in table 2 are composites of the samples obtained from the streambed along three parallel transects at the approach section and do not include sample data obtained from either bank.

Cross-section information obtained in the field survey was used to calibrate the Water-Surface Profile (WSPRO) computation model (Shearman, 1990). The WSPRO flow model was calibrated for bank-full stages and greater using data from approach and exit cross sections collected during the field survey along with discharge, stage, and the bridge cross section from historical discharge measurements. The model was calibrated by varying the roughness coefficients (Manning's n-values) estimated during the field survey until the model surface-water profile approximated the stage from the historical discharge measurement. An average n-value from all calibration model runs was selected for the computational model runs. Final model runs were made for the same discharges after substituting the bridge cross section determined from the bridge plans. Mean velocities, conveyance, geometric constriction ratio, and channel constriction ratio between the approach and bridge section were estimated by the WSPRO model. Mean depths were calculated as the difference between the water-surface elevation from the WSPRO output and the average-streambed elevation of the main channel at the approach and bridge sections. Sediment-transport conditions were determined by comparing V_c (calculated from eq. 1 using the mean depth at the approach section) with the mean velocity at the approach section. For mean velocities greater than $0.8V_c$, live-bed sediment-transport conditions were assumed. For mean velocities less than V_c, clear-water sediment-transport conditions were assumed. For mean velocities between $0.8V_c$ and V_c, both clear-water and live-bed sediment-transport conditions were assumed.

Nine bridge sites were initially selected for collection and analysis of constriction-scour data, (table 1) with a total of 680 historical discharge measurements made at the existing bridges. Five of the initial nine bridge sites were eliminated during the analysis. Winters Run near Benson, Md., was eliminated because of extensive channel modification and stabilization during bridge construction. Nottoway River near Sebrell, Va., was eliminated because the analysis showed that no constriction existed at the bridge and the channel developed 2 ft of general scour since bridge construction. New River near Galax, Va., was eliminated because scour was limited by bedrock. Big Reed Island Creek near Allisonia, Va., was eliminated because the analysis showed that no constriction existed at the bridge. Russell Fork at Haysi, Va., was eliminated because the stage elevations at the gage could not be tied to the stage elevations at the bridge or exit cross section for the historical discharge measurements.

Hydraulic data obtained from the discharge measurements and computed by the WSPRO simulations, and measured and predicted constriction scour at four sites are listed in table 3. The greatest measured discharges (approximately bank-full stage and greater) were analyzed for constriction scour. Clear-water sediment-transport conditions as defined by equation 1 existed for all measurements at three sites, Big Pipe Creek near Bruceville, Md., Northeast

Table 3. Hydraulic data from discharge measurements and Water-Surface Profile model, and measured and predicted constriction scour at bridge-scour study sites in Delaware, Maryland, and Virginia

[ft, foot; ft^3/s, cubic foot per second; ft/s, foot per second; C, clear-water; L, live-bed; --, not determined; for information on Laursen's equation, see "Constriction Scour"]

Station number	Measurement number	Date	Discharge (ft^3/s)	Mean velocity (ft/s)	Maximum vertical-average velocity (ft/s)	Sediment-transport conditions	Measured constriction scour (ft)	Laursen's clear-water scour (ft)	Laursen's live-bed scour (ft)
01639500	13	12-30-48	2,300	4.05	5.71	C	3.4	0.6	--
01639500	14	01-05-49	1,800	3.86	5.18	C	3.6	.4	--
01639500	242	03-19-75	1,940	3.86	5.36	C	2.4	.0	--
01639500	217	06-23-72	3,490	3.78	5.50	C	3.5	1.4	--
01639500	248	09-25-75	3,850	4.69	7.21	C	2.1	1.9	--
01639500	370	10-23-90	2,660	4.04	5.58	C	2.7	.9	--
01639500	371	10-23-90	2,630	3.61	5.58	C	2.7	1.1	--
01649500	28	04-20-40	2,320	3.48	6.96	C	.9	.0	--
01649500	29	04-20-40	1,940	3.45	6.60	C	.7	.0	--
01649500	55	08-09-42	2,950	3.74	7.22	C	1.0	.2	--
01649500	100	07-27-45	2,350	3.37	6.98	C	1.1	.0	--
01649500	101	07-27-45	2,100	3.26	6.80	C	1.0	.0	--
01649500	193	04-27-52	1,950	3.42	7.56	C	1.1	.0	--
01649500	392	04-13-61	2,060	4.82	8.22	C	3.1	--	--
01649500	483	08-25-67	3,050	6.62	8.44	C	.1	2.8	--
01673000	324	08-25-69	15,800	2.62	4.36	L	7.0	--	6.2
01673000	339	06-01-71	9,390	2.18	3.96	L	4.6	--	3.7
01673000	344	10-29-71	9,610	2.22	4.11	L	4.4	--	3.9
01673000	351	06-25-72	18,100	2.93	4.71	L	7.4	--	6.5
01673000	374	03-21-75	11,000	2.61	4.62	L	2.8	--	4.1
01673000	432	04-19-83	7,880	1.96	3.98	L	2.5	--	3.0
01673000	453	08-20-85	11,800	2.50	4.85	L	4.1	--	3.8
01673000	485	05-31-90	14,800	2.84	5.20	L	1.9	--	5.4
01673000	492	01-14-91	7,650	1.81	3.68	L	2.8	--	2.9
01673000	526	04-12-93	8,960	1.94	3.78	L	3.5	--	3.3
01673000	527	04-13-93	8,230	1.78	3.80	L	3.4	--	3.3
01673000	529	04-19-93	8,840	1.92	3.70	L	3.6	--	3.5
01673000	537	11-30-93	11,700	2.38	4.80	L	4.3	--	4.3
01673000	539	03-31-94	19,300	2.99	5.48	L	6.9	--	6.3
03076500	123	02-03-50	3,240	4.53	5.50	C	.6	.0	--
03076500	192	01-11-57	3,470	4.44	5.72	C	1.0	.0	--
03076500	275	05-08-67	5,030	6.07	7.76	C	1.0	.0	--
03076500	305	09-14-71	4,200	5.58	6.96	C	.7	.0	--
03076500	359	02-25-77	3,860	5.10	6.70	C	.8	.0	--
03076500	428	11-05-85	12,800	10.00	11.9	C	.1	2.4	--
03076500	451	07-13-90	7,500	7.50	9.07	C	1.0	.5	--
03076500	467	04-01-93	4,820	5.62	7.08	C	.5	.0	--

Table 3. Hydraulic data from discharge measurements and Water-Surface Profile model, and measured and predicted constriction scour at bridge-scour study sites in Delaware, Maryland, and Virginia—Continued

[ft, foot; ft^3/s, cubic foot per second; ft/s, foot per second; variables determined by WSPRO computer model simulation (Shearman, 1990); --, not determined]

Approach section bottom width (ft)	Approach section depth (ft)	Approach section mean velocity (ft/s)	Approach section convey-ance (ft^3/s)	Bridge section bottom width (ft)	Bridge section depth (ft)	Bridge section mean velocity (ft/s)	Bridge section convey-ance (ft^3/s)	Geo-metric constric-tion ratio	Channel constric-tion ratio
90	6.23	4.35	53,723	60	5.89	4.16	60,348	0.0	0.0
90	5.20	4.18	39,556	60	4.67	4.50	37,945	.0	.0
90	6.01	3.83	50,510	60	5.73	3.65	57,141	.0	.0
90	8.43	4.43	87,776	60	8.28	3.63	129,033	.118	.005
90	8.84	4.40	97,659	60	8.70	3.72	144,806	.181	.018
90	6.87	4.51	63,222	60	6.60	4.01	76,546	.0	.0
90	6.62	4.65	59,418	60	6.28	4.31	68,833	.0	.0
80	8.92	2.45	157,122	40	6.55	3.52	87,992	.209	.061
80	8.00	2.31	131,407	40	5.62	3.39	70,488	.181	.073
80	10.42	2.61	203,275	40	8.05	3.69	119,679	.251	.032
80	9.07	2.43	161,307	40	6.70	3.49	91,036	.214	.056
80	8.56	2.32	146,794	40	6.20	3.35	81,266	.199	.068
80	7.77	2.40	125,422	40	5.37	3.56	66,107	.174	.075
80	--	3.40	81,119	40	--	--	--	--	--
80	8.12	3.57	134,835	40	5.34	5.59	65,628	.180	.076
150	23.44	2.85	1,339,000	140	22.89	3.66	1,162,221	.288	.112
150	19.26	2.38	770,784	140	18.79	2.85	756,719	.288	.041
150	19.50	2.38	799,260	140	19.02	2.87	778,012	.288	.046
150	23.83	3.18	1,397,466	140	23.23	4.11	1,198,556	.288	.116
150	19.86	2.63	845,254	140	19.36	3.20	810,026	.288	.055
150	18.22	2.22	647,731	140	17.75	2.59	664,736	.288	.012
150	19.38	2.96	784,449	140	18.84	3.57	761,882	.288	.043
150	21.97	2.97	1,125,405	140	21.41	3.75	1,009,232	.288	.092
150	17.93	2.22	614,822	140	17.46	2.58	639,949	.289	.003
150	18.58	2.43	688,797	140	18.09	2.87	694,509	.288	.022
150	18.57	2.23	688,643	140	18.11	2.63	695,832	.288	.022
150	18.95	2.31	732,922	140	18.48	2.75	728,775	.288	.033
150	20.14	2.73	826,757	140	19.62	3.34	834,493	.288	.060
150	23.35	3.50	1,325,089	140	22.71	4.52	1,142,626	.288	.111
173	5.01	4.11	80,990	90	4.51	4.63	68,816	.080	.0
173	5.20	4.23	86,196	90	4.68	4.78	73,119	.086	.0
173	6.08	5.17	112,501	90	5.05	6.43	82,631	.104	.0
173	5.62	4.70	98,539	90	4.88	5.55	78,378	.095	.0
173	5.37	4.54	91,201	90	4.65	5.35	72,469	.088	.0
173	10.30	7.34	280,222	90	9.05	9.13	211,770	.170	.009
173	7.57	6.05	164,506	90	6.45	7.50	122,954	.136	.0
173	6.02	5.01	110,760	90	5.19	5.99	86,497	.106	.0

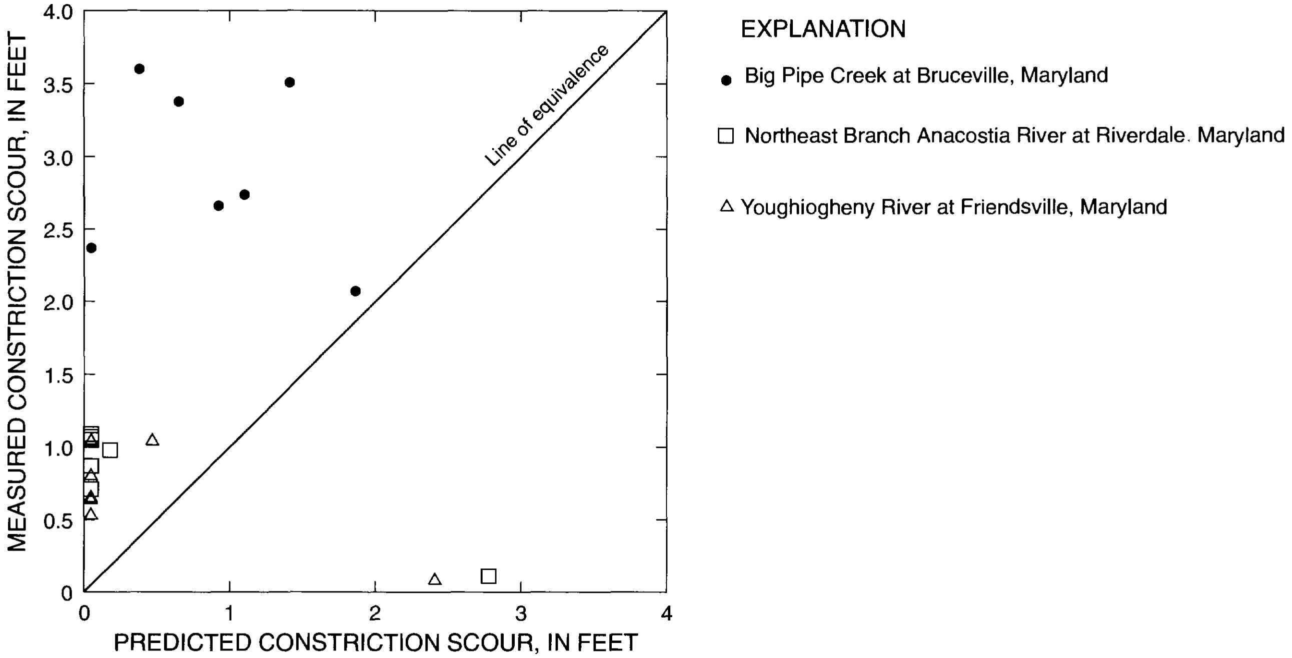

Figure 3. Relation of measured constriction scour to predicted constriction scour for clear-water scour conditions at bridge-scour study sites in Maryland.

Branch Anacostia River at Riverdale, Md., and Youghiogheny River at Friendsville, Md. Constriction scour at these three sites were analyzed together.

Comparison of Measured and Predicted Constriction Scour

Laursen's clear-water scour equation (eq. 2), which is currently (1996) recommend by the Federal Highway Administration, was used as modified by Richardson and others (1993, p. 35) for prediction of constriction scour in clear-water sediment-transport conditions, as follows:

$$y_{sc} = 0.13\, y_1 \left[\frac{Q}{(1.25\, D_{50})^{\frac{1}{3}}\ (y_1)^{\frac{7}{6}}\ W} \right]^{\frac{6}{7}} - y_1 , \quad (2)$$

where y_{sc} is depth of constriction scour, in feet; y_1 is depth of flow at the approach section, in feet; Q is discharge through the bridge, in cubic feet per second; D_{50} is the median grain size of the streambed material, in feet; and W is the channel-bottom width at the bridge section minus affected pier widths, in feet. The relation between measured and predicted constriction scour from equation 2 is shown in figure 3. All scour measurements were underestimated except for two. All the constriction-scour measurements for the Northeast Branch Anacostia River and the Youghiogheny River sites were less than 1.1 ft, which approximates the scour measurement accuracy and, therefore, has limited value for this analysis. The Northeast Branch Anacostia River had one measured constriction scour of 3.1 ft; however, flow conditions for that measurement could not be modeled at the approach section and the predictive equation could not be used. The two scour measurements that were not underestimated had the least measured scour, and were obtained during the greatest measured discharges at each site. One measurement was on the Northeast Branch Anacostia River and one measurement was on the Youghiogheny River.

Scour prediction equations are developed so that the equation line envelops, or encloses, all measured data. An equation should predict the maximum expected scour, which is equal or greater than any measured scour. Plotted points should fall on or below the line of equivalence shown in figure 3. Plotted points above this line indicate more scour has occurred than predicted by equation 2, which could cause failure of the bridge if the equation had been used for bridge design. Plotted points far below the line indicate increased construction cost because of overdesign of the bridge.

A sensitivity analysis showed that equation 2 is extremely sensitive to changes in the value of the channel-bottom width at the bridge. The definition of the channel-bottom width is not exact and cannot be accurately measured in the field. Reduction of the bottom width by one-third for each value listed in table 3 gave predicted constriction-scour values greater than the measured values and appeared to give the best results for these sites. However, modification of equation 2 is not recommended because of the limited data available for this study.

There was no relation among ratios of streamflow characteristics at the approach section and bridge section to measured constriction scour. Ratios developed from streamflow characteristics also were tested, such as the ratio of bed-shear stress at the approach section to the bridge section and the ratio of the maximum velocity to the mean velocity at the bridge section. Several plots showed relations similar to those in figure 3; however, none of the relations showed improvements to equation 2.

Live-bed sediment-transport conditions existed for all measurements at the Pamunkey River near Hanover, Va., site. Laursen's live-bed scour equation (eq. 3), which is recommended by the Federal Highway Administration, was used as modified by Richardson and others (1993, p. 33) for prediction of constriction scour in live-bed sediment-transport conditions:

$$y_{sc} = y_1 \left[\frac{Q_2}{Q_1}\right]^{\frac{6}{7}} \left[\frac{W_1}{W_2}\right]^k - y_1 , \qquad (3)$$

where y_{sc} is the depth of constriction scour, in feet; y_1 is the average depth in the main channel at the approach section, in feet; Q_2 is the flow in the contracted channel at the bridge section, in cubic feet per second; Q_1 is the flow transporting sediment in main channel at the approach section, in cubic feet per second; W_1 is the bottom width of the main channel at the approach section, in feet; W_2 is the bottom width of the contracted channel at the bridge section, in feet; and k is a dimensionless exponent dependent upon the mode of streambed material transport (k is 0.64 for the measurements at the Pamunkey River site).

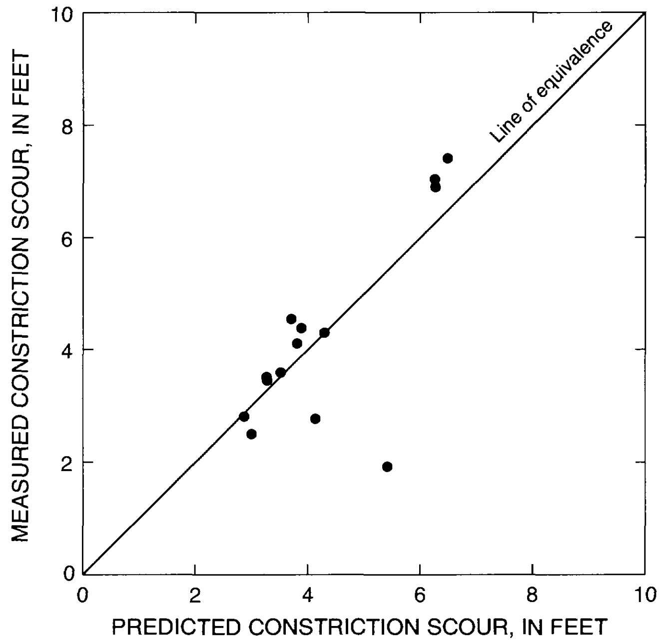

Figure 4. Relation of measured constriction scour to predicted constriction scour for live-bed scour conditions at Pamunkey River near Hanover, Virginia.

The relation between measured and predicted constriction scour from equation 3 is shown in figure 4. The equation underestimated constriction scour for 10 measurements and overestimated constriction scour for 4 measurements. The error between measured and predicted constriction scour was less than 1.0 ft for all 10 measurements that were underestimated. The predicted values that overestimated the measured values did not overestimate by large amounts. The error between measured and predicted constriction scour was less than 0.5 ft for 8 of the 14 measurements.

Although the equation does not envelop the data, it appears to predict live-bed constriction scour well. The slight underprediction of the data is within the accuracy of the measurements. As stated previously, the measured constriction scour may be greater than the actual constriction scour because of the method used in determining the reference elevation and because of factors not associated with the constriction. No significant relation was determined among ratios of streamflow characteristics at the approach section and bridge section to measured constriction scour, and no improvements were applied to equation 3.

Local Scour

Local scour normally occurs when the flow at a point in a stream is restricted by either artificial or natural obstructions. Bridge piers and bridge-foundation piles are examples of artificial obstructions. Debris accumulations and ice jams are examples of natural obstructions. The existence of a pier in the streamflow results in the creation of two types of vortexes, the horseshoe vortex and the wake vortex. The horseshoe vortex is caused by the pileup of water on the upstream side of the pier. The downward force causes an acceleration of the flow and increased bed-shear stress at the nose of the pier, resulting in removal of the streambed material around the base of the pier. The wake vortex is caused by the flow streamlines rejoining after being separated by a pier. The angular acceleration of the flow at the downstream end of a pier also results in removal of material from the base of the pier (Richardson and others, 1993).

Similar to constriction scour, local scour also can be defined as either clear-water scour or live-bed scour, depending on the sediment-transport conditions of the flow approaching the pier. Laursen's equation for critical velocity (eq. 1) is used to define sediment-transport conditions as either clear water or live bed. For mean velocities less than V_c, the sediment-transport conditions are considered clear water, and clear-water scour may exist. For mean velocities equal to or greater than V_c, the sediment-transport conditions are considered live-bed, and live-bed scour may exist. Measurements with mean velocities bordering V_c are analyzed for both clear-water and live-bed sediment-transport conditions because of the nonuniform sizes of the streambed material.

Determination and Analysis of Local-Scour Data

Problems associated with measuring streambed profiles and velocities around bridge piers during floods, and the interaction of complex streamflow patterns with alluvial streambed materials, make accurate field data difficult to obtain. Background information on site selection, data collection, and accuracy of local-scour data used in this investigation are described in Hayes (1993).

The depth of local scour is the difference in streambed level with and without the pier present, and is determined by measuring the distance from a reference surface to the streambed in the vicinity of the pier. The reference surface used in this report is the concurrent-ambient streambed level, or the extended line of the streambed if the pier were removed. Use of the concurrent-ambient streambed level reduces the probability of including amounts of constriction scour or general scour in the local-scour measurement and allows local scour to be analyzed separately from the other components of total scour (Landers and Mueller, 1993).

The streambed profile (compiled during scour measurements) and bridge cross sections were plotted for analysis. Separate analyses were conducted when a fathometer and sounding weight were used to determine the streambed profile during a flood event. The greatest determination of local scour from both analyses at each pier was chosen as the representative local scour for the flow conditions.

The concurrent-ambient bed level was determined in the vicinity of each pier for each measurement. Local scour was determined by measuring the maximum vertical distance from the concurrent-ambient bed level to the streambed. The measured scour was considered the maximum local scour for that cross section, pier location, and flow condition. Because of equipment limitations, the cross section may not pass through the area of greatest scour, and the measured scour may not be maximum local scour at the pier for concurrent flow conditions.

Mean velocity, approach velocity, approach angles, streamflow depths, and water temperature were obtained directly from the discharge measurements. Pier width, length, and shape were obtained from the bridge plans and verified during the field survey. The streambed material size statistics presented in table 2 are composites of the samples obtained in the streambed along three parallel transects at the approach section and do not include sample data obtained at either bank or near the piers.

Total depth is the maximum depth measured at each pier and includes all scour. Approach velocity is the average of the vertical-average velocities from each side of the pier, outside the influence of the pier (normally 2.5 pier diameters). The preferred approach velocity is the vertical average velocity measured in front of the pier, outside the influence of the pier, but this velocity could not be measured because of equipment limitations.

The critical velocity (V_c) was calculated for local scour from equation 1, except y_1 is the depth of flow at the pier using the reference bed elevation (total depth minus local scour), to represent the approach flow depth. Sediment-transport conditions were classified using the mean velocity from the discharge measurement rather than the mean velocity estimated for the approach section from the WSPRO program. Local-scour measurements were analyzed as clear-water scour for mean velocities less than V_c, and analyzed as live-bed scour for mean velocities greater than $0.8V_c$. Local-scour measurements were analyzed as both clear-water and live-bed scour for mean velocities between $0.8V_c$ and V_c.

Fifteen sites were initially selected for collection and analysis of local-scour data (table 1). No scour or streamflow data were collected at North Fork Shenandoah River near Mount Jackson, Va., because of logistic factors. At the remaining 14 sites, 252 measurements of local scour were made at 42 piers. Data were not analyzed for the right pier (pier 1) at the Nottoway River near Sebrell, Va., because exposed piles and submerged debris limited the depth of local scour. The measured local scour, predicted local scour, and additional data for each measurement are listed in table 4 (at the back of this report). Many of the local-scour measurements do not represent the active-scour process (observed scour or fill that is the result of current hydraulic conditions), or they are multiple measurements made at the same pier during the same flood event. Measurements were removed from the analysis using one or more of the guidelines discussed later in this section. These guidelines are similar to guidelines used in current scour studies by the USGS (M.N. Landers and D.S. Mueller, U.S. Geological Survey, written commun., 1995). A total of 140 measurements were removed, with 112 measurements of local scour remaining for this analysis.

Multiple scour measurements made during the same flood event at a given pier are important in studying the scour process; however, for the purpose of this report, these scour measurements are not independent and may exhibit serial correlation. When multiple measurements were made during the same flood event at a given pier, the measurement with the maximum bed-shear stress at the pier was selected as representative of local scour for that flood. The scour measurement with the maximum bed-shear stress has the greatest probability of being sampled during the active-scour process.

Local-scour measurements were eliminated when the measured scour was less than the estimated accuracy limit of 0.5 ft (Hayes, 1993) because of uncertainty of the measurement. In addition, local-scour measurements were eliminated when the approach velocity was 0, or when the total depth to local-scour ratio was less than 1.5, because these measurements may represent remanent scour holes and may not be the result of the active-scour process.

Local-scour measurements with approach velocities less than 0.4 V_c were reviewed closely. These measurements were removed when the local scour to pier width-ratio was less than 0.9, the total depth to local-scour ratio was less than 2.0, or the local-scour to D_{50} ratio was less than 2.0. These measurements also may represent remanent scour holes and may not be the result of the active-scour process.

Piers that are not aligned with the flow at high stages increase the complexity of the analysis. Locating and measuring the maximum scour with available equipment at piers skewed to the flow was not possible. Sites were specifically selected for this investigation where the skew angle of the pier was less than 5 degrees; therefore, no measurements were removed because of pier skew.

Multiple regression analysis was used to determine if significant relations exist between measured local scour and streamflow, streambed, and bridge characteristics. No significant relation was determined from these tests. Several investigations have reported upper limits for the depth of scour to pier-width ratio. The upper limit for the ratio ranges from 2.3 to 3.0 from information compiled by Richardson and others (1993). In this investigation, the upper limit for the depth of scour to pier-width ratio for all local-scour measurements was 2.1.

Many equations have been developed for predicting local scour at bridge piers. Thirteen commonly used equations are available for use in the National Bridge Scour Data Base (Landers and Mueller, in press). One additional equation was obtained from Wilson (1995). Predictions of local scour were computed using these equations and the streamflow, streambed, and bridge characteristics collected from discharge measurements, bridge plans, and field surveys. The remaining 112 local-scour measurements were plotted with the predicted local scour from each of the 14 equations to determine the most reliable equations for the selected sites and field conditions. Clear-water and live-bed scour conditions were plotted separately. Measured and predicted local scour for 89 measurements were analyzed as clear-water scour. Measured and predicted local scour for 23 measurements were analyzed as live-bed scour.

Comparison of Measured and Predicted Local Scour

No valid statistical test is available to determine the most reliable equation because the equations are designed normally to envelop data and predict the maximum local scour. Preferably, the measured local scour would never be greater than the predicted local scour, and the difference between the maximum measured local scour and predicted local scour would be minimal. The plots of measured scour with predicted scour were visually inspected and equations that consistently underpredicted the measured local scour were eliminated. The Colorado State University equation, the Froehlich design equation, the Laursen equation, and the Mississippi equation appeared to produce the best estimates of local scour.

The Colorado State University pier-scour equation was developed from laboratory experiments and limited field data for both clear-water and live-bed scour conditions, and is recommended by the Federal Highway Administration (Richardson and others, 1993). The equation as reported in the National Bridge Scour Data Base (Landers and Mueller, in press) is

$$y_{sp} = 2.0\, y_o K_1 K_2 K_3 \left(\frac{b}{y_o}\right)^{0.65} (F_o)^{0.43} , \qquad (4)$$

where y_{sp} is the depth of local pier scour, in feet; y_o is the depth of flow just upstream from the bridge pier, excluding local scour, in feet; K_1 is a coefficient based on the shape of the nose of the pier, dimensionless; K_2 is a coefficient based on the ratio of the pier length to pier width and the angle of the approach flow referenced to the bridge pier, dimensionless; K_3 is a coefficient based on streambed conditions, dimensionless; b is pier width, in feet; and F_o is the Froude number of the flow just upstream from the pier, dimensionless.

The relation between measured and predicted local scour from equation 4 is shown in figure 5. The equation underestimates local scour for 11 measurements in clear-water scour conditions and 3 measurements in live-bed scour conditions; however, all except 3 of the clear-water scour measurements and 2 of the live-bed scour measurements were underestimated by less than 0.5 ft. Equation 4 underestimated local scour by a maximum of 2.4 ft for clear-water scour conditions and 1.3 ft for live-bed scour conditions.

The Froehlich pier-scour design equation was developed from field measurements with sustained high flows for live-bed scour conditions only (Froehlich, 1988); however, prediction of local-scour depths for clear-water scour conditions also were tested. The equation as reported in the National Bridge Scour Data Base (Landers and Mueller, in press) is

$$y_{sp} = 0.32\, b\, \phi \left(\frac{b'}{b}\right)^{0.62} \left(\frac{y_o}{b}\right)^{0.46} (F_o)^{0.2} \left(\frac{b}{D_{50}}\right)^{0.08} + b, \qquad (5)$$

where y_{sp} is the depth of local-pier scour, in feet; b is pier width, in feet; ϕ is a coefficient based on the shape of the nose of the pier, dimensionless; b' is the width of the bridge pier projected normal to the approach flow, in feet; y_o is the depth of flow just upstream from the bridge pier, excluding local scour, in feet; F_o is the Froude number of the flow just upstream from the pier, dimensionless; and D_{50} is the median grain size of the streambed material, in feet.

The relation between measured and predicted local scour from equation 5 is shown in figure 5. The equation underestimates local scour for two measurements in clear-water scour conditions and one measurement in live-bed scour conditions. Equation 5 underestimated local scour by a maximum of 1.2 ft for clear-water scour conditions and 0.4 ft for live-bed scour conditions.

Laursen developed a pier-scour equation from his constriction-scour equation for live-bed sediment-transport conditions with additional analysis from flume experiments; however, prediction of local-scour depths for clear-water scour conditions also were tested. The equation as reported in the National Bridge Scour Data Base (Landers and Mueller, in press) is

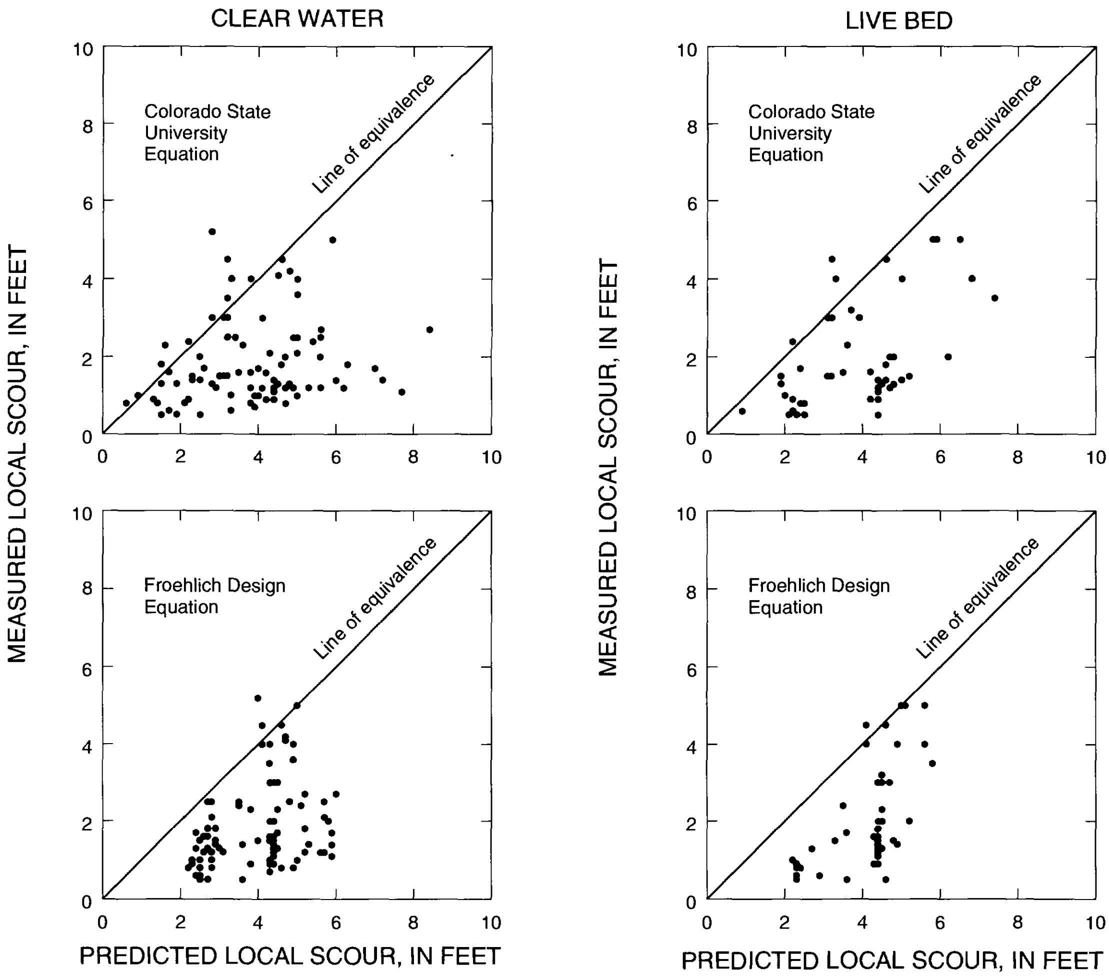

Figure 5. Relation of measured local scour to predicted local scour using the Colorado State University equation and Froehlich design equation for clear-water and live-bed scour conditions at bridge-scour study sites in Delaware, Maryland, and Virginia.

$$\frac{b}{y_o} = 5.5\left(\frac{y_{sp}}{y_o}\right)\left(\left[\left(\frac{1}{11.5}\right)\left(\frac{y_{sp}}{y_o}\right)+1\right]^{1.70}-1\right), \qquad (6)$$

where b is pier width, in feet; y_o is the depth of flow just upstream from the bridge pier, excluding local scour, in feet; and y_{sp} is the depth of local pier scour, in feet. Laursen reported that the skew between the pier and streamflow, coupled with the length-width ratio of the pier was the most important aspect of the pier geometry. The local-scour depth computed in equation 6 must be corrected for skew, as follows:

$$y_{sp} = K_{\alpha L}\, y_{sp} \ , \qquad (7)$$

where $K_{\alpha L}$ is a coefficient based on the skew of the bridge pier to the streamflow. Laursen also reported that the shape of the pier was important if the pier is aligned with the flow, and the correction to depth of scour computed in equation 6 for pier shape is

$$y_{sp} = K_{S1}\, y_{sp} \ , \qquad (8)$$

where K_{S1} is a coefficient based on the shape of the pier nose.

The relation between measured and predicted local scour from equations 6 and 8 is shown in figure 6. Equation 7 was not used because there was no skew between the piers and streamflow. The equations did not underestimate local scour for any measurements in clear-water scour conditions or in live-bed scour

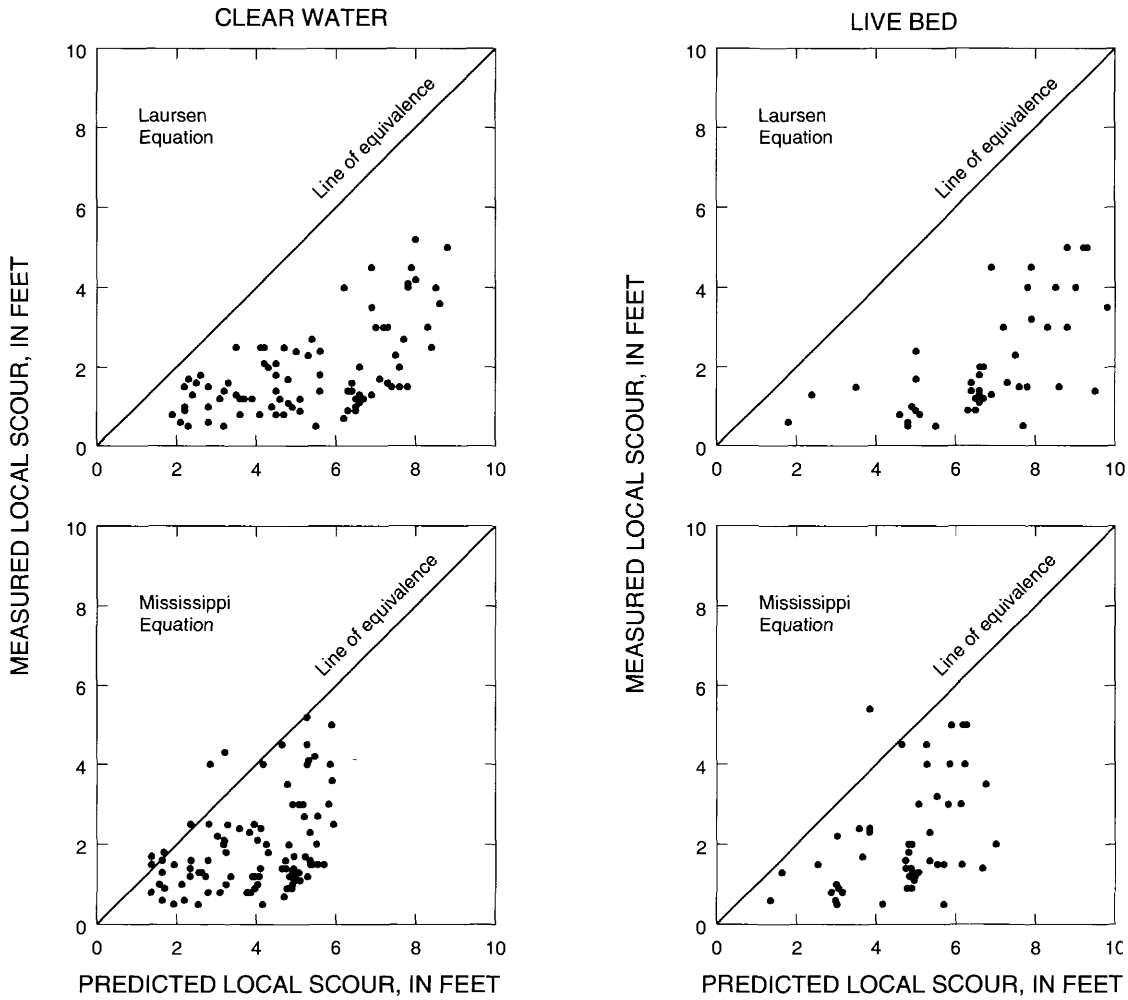

Figure 6. Relation of measured local scour to predicted local scour using the Laursen equation and Mississippi equation for clear-water and live-bed scour conditions at bridge-scour study sites in Delaware, Maryland, and Virginia.

conditions. The equations overestimated the maximum measured scour in clear-water conditions by approximately one-half pier width (approximately 1.5 ft), and overestimated the maximum measured scour in live-bed scour conditions by approximately one-pier width (approximately 3 ft). In both clear-water and live-bed scour conditions, the greater the measured scour, the greater the average overestimate of scour.

Wilson (1995), developed an envelope-curve equation using 190 measurements of local scour obtained from 22 bridge sites in Mississippi. Seventeen local-scour measurements were obtained during clear-water scour conditions and 173 local-scour measurements were obtained during live-bed scour conditions. The median grain size of the streambed material (D_{50}) ranged from 0.28 to 7.51 mm at the 22 bridge sites. The equation (not reported in the National Bridge Scour Data Base) modified from Wilson (1995) is

$$\frac{y_{sp}}{b} = 0.9\left(\frac{y_o}{b}\right)^{0.4}, \tag{9}$$

where y_{sp} is the depth of local pier scour, in feet; b is the pier width normal to the flow, in feet; and y_o is the depth of flow just upstream from the bridge pier, excluding local scour, in feet.

The relation between measured and predicted local scour from equation 9 is shown in figure 6. The equation underestimates local scour for six measurements in clear-water scour conditions and one

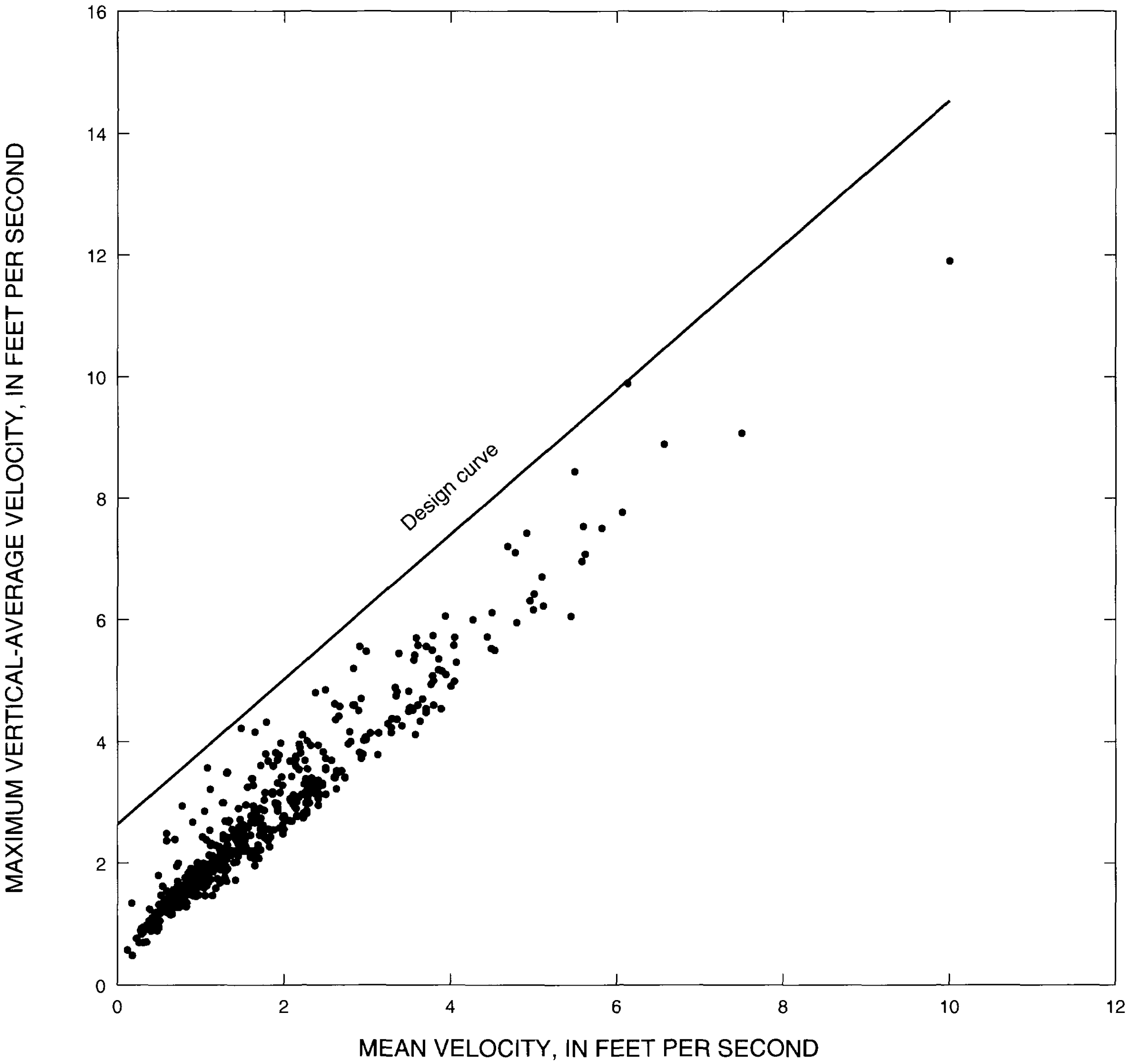

Figure 7. Relation of mean velocity to maximum vertical-average velocity for the main channel at bridge-scour study sites in Delaware, Maryland, and Virginia. (Data obtained from stream discharge measurements.)

measurement in live-bed scour conditions; however, all except two of the clear-water scour measurements and the one live-bed scour measurement were under-estimated by less than 0.5 ft. Equation 9 under-estimated local scour by a maximum of 1.2 ft for clear-water scour conditions and 1.6 ft for live-bed scour conditions.

Approach Velocity Estimates for Bridge Design

Knowledge and data are available to estimate the mean velocity at a bridge-design site for a specified design streamflow with sufficient confidence that major inaccuracies can be avoided. Confidence is less for an accurate estimate of the approach velocity at a given pier for the design flow. An accurate pier-approach velocity is necessary to use many local pier-scour equations (Landers and Mueller, in press). Data collected or acquired for this investigation was used to determine a better estimate of the pier-approach velocity.

Velocity data were collected from 579 discharge measurements made in Delaware, Maryland, and Virginia and reviewed for this investigation. Mean velocity and the maximum vertical-average velocity were selected from each discharge measurement and plotted. A design curve was developed by computing a least-squares regression of the data and adding an offset of 2.0 ft/s to envelop the points (fig. 7). The pier design approach velocity and the maximum vertical-average velocity are assumed to be interchangeable for the design curve to be useful, and the design mean velocity and measured mean velocity also are assumed to be interchangeable. The design curve can be used to estimate the pier-approach velocity for piers in the main channel or at any pier that may be affected by lateral migration of the channel. The equation for the design curve is

$$V_{app} = 2.64 + 1.19\ V_{mean} \quad , \qquad (10)$$

where V_{app} is the pier design approach velocity, in feet per second; and V_{mean} is the design mean velocity, in feet per second for the main channel. The equation or curve is not recommended for design mean velocities greater than 10 ft/s.

SUMMARY

Scour at bridge sites can result in damage to bridges and ultimately cause bridge failure. Thus scour is a prime concern to officials and agencies responsible for the integrity of bridges and the safety of the traveling public. Scour data from 9 bridge sites in Delaware, Maryland, and Virginia were analyzed to evaluate the reliability of 2 existing constriction-scour equations, and field measurements from 15 bridge sites in the three-State area were analyzed to evaluate the reliability of 14 existing local-scour equations.

Streamflow data and streambed and bridge characteristics necessary to analyze constriction scour were obtained from historical discharge measurements, field surveys, and computer simulation of hydraulic conditions during floods. No independent constriction-scour equations were developed from analysis of the data. Laursen's clear-water scour equation was evaluated using 23 measurements from three sites. The equation underestimated constriction scour in all but two of the measurements. A sensitivity analysis indicates that the equation is extremely sensitive to variations in channel-bottom width, a variable which is difficult to accurately determine. Reduction of the channel-bottom width by one-third of the value determined in the field survey gave predicted constriction-scour values greater than the measured values and appeared to give the best results for these sites. Laursen's live-bed scour equation was evaluated using 14 measurements from one site. The equation underestimated constriction scour for 10 measurements and overestimated constriction scour for 4 measurements. The error between measured and predicted constriction scour was less than 1.0 ft for all 10 measurements that were underestimated. For 8 of the 14 measurements, the error was less than 0.5 ft.

Streamflow data and streambed and bridge characteristics necessary to analyze local scour were obtained from discharge measurements made at the bridge, field surveys, and bridge plans. No independent equations were developed from the data. The reliability of 13 equations in the National Bridge Scour Data Base and 1 equation from another publication were evaluated for application in the three-State area. From the visual inspections of the plotted data, the Colorado State University equation, the Froehlich design equation, the Laursen equation, and the Mississippi equation appeared to be the best predictors of local scour.

The Colorado State University pier-scour equation was developed to predict local scour in clear-water and live-bed scour conditions. The equation underestimated local scour for 11 measurements in clear-water scour conditions and 3 measurements in live-bed scour conditions; however, all except 3 of the clear-water scour measurements and 2 of the live-bed scour measurements were underestimated by less than 0.5 ft. The Colorado State University pier-scour equation underestimated local scour by a maximum of 2.4 ft for clear-water scour conditions and 1.3 ft for live-bed scour conditions.

The Froehlich pier-scour design equation was developed to predict local scour in live-bed scour conditions; however, it was tested in both clear-water and live-bed scour conditions. The equation underestimated local scour for two measurements in clear-water scour conditions and one measurement in live-bed scour conditions. The Froehlich pier-scour design equation underestimated local scour by a maximum of 1.2 ft for clear-water scour conditions and 0.4 ft for live-bed scour conditions.

The Laursen pier-scour equation was developed to predict local scour in live-bed scour conditions; however, it was tested in both clear-water and live-bed scour conditions. The equation overestimated the maximum measured scour in clear-water conditions by approximately one-half pier width or approximately 1.5 ft, and overestimated the maximum measured scour in live-bed scour conditions by approximately one-pier width or approximately 3 ft.

In both clear-water and live-bed scour conditions, the difference between measured value and predicted value was greater with increasing measured local scour.

The Mississippi pier-scour equation was developed to predict local scour in clear-water and live-bed scour conditions. The equation underestimated local scour for six measurements in clear-water scour conditions and one measurement in live-bed scour conditions; however, all except two of the clear-water scour measurements and the one live-bed scour measurement were underestimated by less than 0.5 ft. The Mississippi pier-scour equation underestimated local scour by a maximum of 1.2 ft for clear-water scour conditions and 1.6 ft for live-bed scour conditions

Several investigations have reported upper limits for the depth of scour to pier-width ratio that range from 2.3 to 3.0. In both clear-water and live-bed scour conditions, the upper limit for the depth of scour to pier-width ratio for all local-scour measurements in this study was 2.1.

Mean velocity and maximum vertical-average velocity were collected from 579 discharge measurements used in this investigation. A design curve for estimating pier-approach velocity from mean cross-sectional velocity was developed by computing a least-squares regression of the data and adding an offset of 2.0 ft/s. The design curve can be used to estimate the approach velocity of piers in the main channel or at any pier that may be affected by lateral migration of the channel.

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Table 4. Measurement data and predictions of local scour at bridge-scour study sites in Delaware, Maryland, and Virginia

EXPLANATION OF CODES

Sediment-transport conditions

C Clear water

B Clear water but also analyzed as live bed

L Live bed

Remarks

Reason for elimination

E1 No scour measured

E2 Multiple measurements at pier during same flood

E3 Measured scour is less than 0.5 ft

E4 Measured approach velocity is 0

E5 Ratio of total depth to measured scour is less than 1.5

E6 Ratio of measured approach velocity to critical velocity is less than 0.4 and ratio of measured scour to pier diameter is less than 0.9

E7 Ratio of measured approach velocity to critical velocity is less than 0.4 and ratio of total depth to measured scour is less than 2.0

Table 4. Measurement data and predictions of local scour at bridge-scour study sites in Delaware, Maryland, and Virginia—Continued

[ft, foot; ft^3/s, cubic foot per second; ft/s, foot per second; --, not determined]

Station number	Measurement number	Date	Pier designation	Pier diameter (ft)	Pier nose shape	Discharge (ft^3/s)	Mean velocity (ft/s)	Approach velocity (ft/s)
01483530	1	112888	C2	1.25	Square	4,920	1.65	1.82
01483530	2	111590	C2	1.25	Square	4,090	1.53	2.22
01483530	3	120290	C2	1.25	Square	3,600	1.20	1.33
01483530	4	120290	C2	1.25	Square	4,600	2.00	2.18
01483530	5	120490	C2	1.25	Square	4,000	1.29	1.42
01483530	6	100791	C2	1.25	Square	4,830	1.70	1.60
01483530	7	061092	C2	1.25	Square	4,480	1.70	1.65
01483530	8	061092	C2	1.25	Square	3,530	1.83	1.62
01483530	9	061092	C2	1.25	Square	3,440	1.65	1.52
01483530	1	112888	C3	1.25	Square	4,920	1.65	1.73
01483530	2	111590	C3	1.25	Square	4,090	1.53	1.74
01483530	3	120290	C3	1.25	Square	3,600	1.20	1.00
01483530	4	120290	C3	1.25	Square	4,600	2.00	1.74
01483530	5	120490	C3	1.25	Square	4,000	1.29	1.30
01483530	6	100791	C3	1.25	Square	4,830	1.70	1.64
01483530	7	061092	C3	1.25	Square	4,480	1.70	1.72
01483530	8	061092	C3	1.25	Square	3,530	1.83	1.72
01483530	9	061092	C3	1.25	Square	3,440	1.65	1.60
01484702	1	092491	B	2.5	Round	4,000	1.05	.32
01484702	2	060892	B	2.5	Round	5,140	1.42	.56
01484702	3	060892	B	2.5	Round	4,850	1.31	.45
01484702	1	092491	C	2.5	Round	4,000	1.05	.88
01484702	2	060892	C	2.5	Round	5,140	1.42	1.08
01484702	3	060892	C	2.5	Round	4,850	1.31	.84
01484702	1	092491	D	2.5	Round	4,000	1.05	1.05
01484702	2	060892	D	2.5	Round	5,140	1.42	1.36
01484702	3	060892	D	2.5	Round	4,850	1.31	1.24
01484702	1	092491	E	2.5	Round	4,000	1.05	1.13
01484702	2	060892	E	2.5	Round	5,140	1.42	1.55
01484702	3	060892	E	2.5	Round	4,850	1.31	1.58
01484702	1	092491	F	2.5	Round	4,000	1.05	1.42
01484702	2	060892	F	2.5	Round	5,140	1.42	1.67
01484702	3	060892	F	2.5	Round	4,850	1.31	1.62
01484702	1	092491	G	2.5	Round	4,000	1.05	.92
01484702	2	060892	G	2.5	Round	5,140	1.42	1.25
01484702	3	060892	G	2.5	Round	4,850	1.31	1.04
01484702	1	092491	H	2.5	Round	4,000	1.05	.53
01484702	2	060892	H	2.5	Round	5,140	1.42	.80
01484702	3	060892	H	2.5	Round	4,850	1.31	.60
01484702	1	092491	I	2.5	Round	4,000	1.05	.28
01484702	2	060892	I	2.5	Round	5,140	1.42	.72
01484702	3	060892	I	2.5	Round	4,850	1.31	.50
01484702	1	092491	J	2.5	Round	4,000	1.05	.18
01484702	2	060892	J	2.5	Round	5,140	1.42	.54
01484702	3	060892	J	2.5	Round	4,850	1.31	.15
01484702	1	092491	K	2.5	Round	4,000	1.05	.07
01484702	2	060892	K	2.5	Round	5,140	1.42	.18
01484702	3	060892	K	2.5	Round	4,850	1.31	.0
01490750	1	022389	Left	4.0	Square	671	1.02	2.18
01490750	2	032589	Left	4.0	Square	2,120	1.60	2.53

Table 4. Measurement data and predictions of local scour at bridge-scour study sites in Delaware, Maryland, and Virginia—Continued

[ft, foot; ft^3/s, cubic foot per second; ft/s, foot per second; --, not determined]

Critical velocity (ft/s)	Sediment-transport conditions	Total depth (ft)	Measured local scour (ft)	Local scour (ft) predicted by indicated equation: Colorado State University equation	Froehlich design equation	Laursen equation	Mississippi equation	Remarks
0.87	L	15.4	0.5	2.3	2.3	4.8	3.0	--
.88	L	17.3	.8	2.5	2.4	5.1	3.2	--
.87	L	15.7	1.0	2.0	2.2	4.9	3.0	E2
.85	L	13.9	.8	2.4	2.3	4.6	2.9	--
.86	L	15.5	1.0	2.0	2.2	4.9	3.0	--
.87	L	15.2	.5	2.1	2.3	4.8	3.0	--
.86	L	15.0	.6	2.2	2.3	4.8	3.0	--
.85	L	13.9	.7	2.1	2.2	4.6	2.9	E2
.83	L	12.3	.5	2.0	2.2	4.3	2.8	E2
--	--	17.9	--	2.3	2.3	5.2	3.3	E1
.85	L	13.2	.3	2.2	2.2	4.5	2.9	E3
--	--	18.2	--	1.8	2.2	5.3	3.3	E1
--	--	17.5	--	2.3	2.3	5.2	3.2	E1
--	--	19.3	--	2.0	2.3	5.4	3.4	E1
--	--	18.0	--	2.2	2.3	5.2	3.3	E1
--	--	17.4	--	2.2	2.3	5.1	3.2	E1
.87	L	16.2	.9	2.2	2.3	5.0	3.1	--
--	--	14.9	--	2.1	2.3	4.8	3.0	E1
--	--	5.5	--	1.3	3.2	3.7	3.1	E1
--	--	4.9	--	1.7	3.2	3.5	2.9	E1
--	--	4.0	--	1.5	3.1	3.1	2.7	E1
1.29	B	10.4	2.4	2.2	3.5	5.0	3.6	--
1.30	L	10.1	1.7	2.4	3.6	5.0	3.6	--
1.32	B	10.2	1.1	2.2	3.5	5.0	3.8	E2
--	--	13.8	--	2.5	3.7	5.8	4.5	E1
--	--	15.5	--	2.8	3.8	6.2	4.6	E1
--	--	14.2	--	2.7	3.7	5.9	4.5	E1
1.52	C	26.2	5.2	2.8	4.0	8.0	5.3	--
1.52	B	25.5	4.5	3.2	4.1	7.9	5.3	E2
1.52	B	25.5	4.5	3.2	4.1	7.9	5.3	--
1.53	C	23.4	1.5	3.1	4.0	7.6	5.4	--
1.52	B	25.0	4.0	3.3	4.1	7.8	5.3	--
1.52	B	24.8	4.0	3.3	4.1	7.8	5.2	E2
1.37	C	12.6	1.4	2.3	3.6	5.6	4.1	--
--	--	13.1	--	2.7	3.7	5.7	4.4	E1
1.38	B	12.2	.5	2.5	3.6	5.5	4.2	--
1.12	B	3.8	.4	1.6	3.2	3.0	2.5	E3
1.12	L	4.9	1.5	1.9	3.3	3.5	2.5	--
1.12	L	4.8	1.5	1.7	3.2	3.4	2.5	E2
.86	L	.9	.2	1.0	2.8	1.5	1.4	E3
.75	L	1.0	.7	1.5	2.9	1.5	1.0	E5
.84	L	.9	.3	1.3	2.9	1.5	1.3	E3
.86	L	1.3	.6	.9	2.9	1.8	1.4	--
.62	L	1.3	1.2	1.4	2.9	1.8	.6	E5
.88	L	1.2	.4	.8	2.8	1.7	1.4	E3
.88	L	1.2	.4	.6	2.8	1.7	1.4	E3
.62	L	1.1	1.0	.8	2.8	1.6	.6	E5
.86	L	1.0	.3	--	--	1.5	1.4	E3
1.34	C	6.2	4.0	--	--	--	2.8	--
1.52	L	10.1	5.4	--	--	--	3.8	--

Table 4. Measurement data and predictions of local scour at bridge-scour study sites in Delaware, Maryland, and Virginia—Continued

[ft, foot; ft^3/s, cubic foot per second; ft/s, foot per second; --, not determined]

Station number	Measure-ment number	Date	Pier designation	Pier diameter (ft)	Pier nose shape	Discharge (ft^3/s)	Mean velocity (ft/s)	Approach velocity (ft/s)
01490750	3	072891	Left	4.0	Square	866	1.11	2.52
01490750	1	022389	Center	4.0	Square	671	1.02	.29
01490750	2	032589	Center	4.0	Square	2,120	1.60	1.36
01490750	3	072891	Center	4.0	Square	866	1.11	.71
01490750	1	022389	Right	4.0	Square	671	1.02	.90
01490750	2	032589	Right	4.0	Square	2,120	1.60	1.89
01490750	3	072891	Right	4.0	Square	866	1.11	1.04
01625880	1	102590	1	2.0	Round	219	.90	.12
01625880	2	112392	1	2.0	Round	309	1.26	.60
01625880	3	030493	1	2.0	Round	412	1.49	.52
01625880	4	030593	1	2.0	Round	1,480	1.65	.60
01625880	5	030893	1	2.0	Round	340	1.33	.97
01625880	1	102590	2	2.0	Round	219	.90	1.65
01625880	2	112392	2	2.0	Round	309	1.26	2.74
01625880	3	030493	2	2.0	Round	412	1.49	3.89
01625880	4	030593	2	2.0	Round	1,480	1.65	2.76
01625880	5	030893	2	2.0	Round	340	1.33	2.25
01625880	1	102590	3	2.0	Round	219	.90	.53
01625880	2	112392	3	2.0	Round	309	1.26	.25
01625880	3	030493	3	2.0	Round	412	1.49	.58
01625880	4	030593	3	2.0	Round	1,480	1.65	1.21
01625880	5	030893	3	2.0	Round	340	1.33	.25
01639500	217	062372	1	4.0	Round	3,490	3.78	2.64
01639500	248	092575	1	4.0	Round	3,850	4.69	4.28
01639500	312	041683	1	4.0	Round	829	2.93	.0
01639500	366	052990	1	4.0	Round	1,310	3.36	.0
01639500	370	102390	1	4.0	Round	2,660	4.04	1.31
01639500	371	102390	1	4.0	Round	2,630	3.61	1.40
01639500	217	062372	2	4.0	Round	3,490	3.78	3.72
01639500	248	092575	2	4.0	Round	3,850	4.69	5.20
01639500	312	041683	2	4.0	Round	829	2.93	2.96
01639500	366	052990	2	4.0	Round	1,310	3.36	3.32
01639500	370	102390	2	4.0	Round	2,660	4.04	5.39
01639500	371	102390	2	4.0	Round	2,630	3.61	5.26
01639500	217	062372	3	4.0	Round	3,490	3.78	.0
01639500	248	092575	3	4.0	Round	3,850	4.69	.18
01639500	312	041683	3	4.0	Round	829	2.93	.0
01639500	366	052990	3	4.0	Round	1,310	3.36	--
01639500	370	102390	3	4.0	Round	2,660	4.04	.0
01639500	371	102390	3	4.0	Round	2,630	3.61	.0
01673000	485	053190	1	3.0	Round	14,770	2.84	1.87
01673000	486	060490	1	3.0	Round	1,920	.83	.33
01673000	491	011291	1	3.0	Round	4,230	1.47	1.10
01673000	492	011491	1	3.0	Round	7,650	1.81	2.50
01673000	493	011791	1	3.0	Round	3,210	1.18	.38
01673000	495	040191	1	3.0	Round	5,890	1.56	.74
01673000	496	040291	1	3.0	Round	2,390	1.00	.36
01673000	499	070891	1	3.0	Round	3,850	1.34	.36
01673000	500	070991	1	3.0	Round	809	.65	.90
01673000	507	022692	1	3.0	Round	964	.72	.05

Table 4. Measurement data and predictions of local scour at bridge-scour study sites in Delaware, Maryland, and Virginia—Continued

[ft, foot; ft³/s, cubic foot per second; ft/s, foot per second; --, not determined]

Critical velocity (ft/s)	Sediment-transport conditions	Total depth (ft)	Measured local scour (ft)	Local scour (ft) predicted by indicated equation: Colorado State University equation	Froehlich design equation	Laursen equation	Mississippi equation	Remarks
1.41	C	7.3	4.3	--	--	--	3.2	--
1.24	B	3.6	2.2	--	--	--	2.4	E7
1.52	L	7.1	2.4	--	--	--	3.8	--
1.40	C	4.9	2.0	--	--	--	3.2	--
1.33	C	3.7	1.6	--	--	--	2.8	--
1.52	L	7.0	2.3	--	--	--	3.8	--
1.38	B	4.8	2.2	--	--	--	3.0	--
5.82	C	1.8	.8	.6	2.2	1.9	1.4	--
5.72	C	2.1	1.2	1.3	2.3	2.0	1.3	E7
7.18	C	4.6	1.1	1.4	2.4	3.0	2.2	E2
7.57	C	6.1	1.3	1.5	2.4	3.5	2.6	--
5.82	C	2.5	1.5	1.6	2.3	2.0	1.4	E7
5.92	C	3.1	2.0	2.1	2.4	2.5	1.4	E6
5.82	C	2.7	1.7	2.6	2.4	2.3	1.4	--
7.31	C	6.4	2.5	3.4	2.7	3.5	2.4	--
7.62	C	7.6	2.6	3.0	2.7	3.9	2.6	E6
6.54	C	3.8	1.8	2.5	2.5	2.7	1.8	E2
6.36	C	2.6	.9	1.3	2.3	2.2	1.7	--
6.16	C	2.4	1.0	.9	2.3	2.2	1.6	--
--	--	3.7	--	1.4	2.4	2.7	2.3	E1
7.85	C	6.8	0.8	2.1	2.5	3.6	2.8	--
5.92	C	2.0	.9	.9	2.2	2.0	1.4	E2
8.67	C	11.6	1.2	4.9	5.2	6.7	5.3	--
8.43	C	10.2	1.4	6.0	5.3	6.3	4.9	--
--	--	--	--	--	--	--	--	E1
--	--	2.7	--	--	--	--	--	E1
--	--	8.6	--	--	--	--	--	E1
--	--	4.7	--	--	--	--	--	E1
7.82	C	8.0	2.4	5.4	5.1	5.6	4.1	--
7.95	C	8.0	1.8	6.3	5.2	5.6	4.3	--
7.54	C	5.3	.8	4.7	4.9	4.5	3.8	--
7.75	C	6.3	1.0	5.0	5.0	4.9	4.0	--
7.77	C	6.6	1.2	6.2	5.2	5.1	4.1	--
8.37	C	10.1	1.7	6.5	5.3	6.3	4.8	E2
--	--	--	--	--	--	--	--	E1
7.62	C	5.6	.8	1.4	4.6	4.7	3.9	--
--	--	--	--	--	--	--	--	E1
--	--	--	--	--	--	--	--	E1
6.47	C	2.3	.5	--	--	2.5	2.6	E4
5.96	C	1.6	.5	--	--	3.0	2.2	E4
2.44	L	26.3	3.0	3.9	4.7	8.8	6.1	--
2.19	C	15.7	3.5	1.7	4.0	6.8	4.7	E6
--	--	17.3	--	3.0	4.3	7.1	5.4	E1
--	--	22.4	--	4.4	4.7	8.1	6.0	E1
2.26	C	17.7	2.8	1.9	4.1	7.2	5.1	E6
2.33	C	19.8	2.0	2.5	4.3	7.6	5.5	--
2.25	C	16.2	1.6	1.8	4.0	6.9	5.1	E2
--	--	17.1	--	1.8	4.0	7.1	5.4	E1
--	--	9.7	--	2.5	4.0	5.3	4.3	E1
--	--	7.2	--	.7	3.5	4.6	3.8	E1

Table 4. Measurement data and predictions of local scour at bridge-scour study sites in Delaware, Maryland, and Virginia—Continued

[ft, foot; ft³/s, cubic foot per second; ft/s, foot per second; --, not determined]

Station number	Measure-ment number	Date	Pier designation	Pier diameter (ft)	Pier nose shape	Discharge (ft^3/s)	Mean velocity (ft/s)	Approach velocity (ft/s)
01673000	508	022792	1	3.0	Round	3,630	1.29	0.54
01673000	509	022892	1	3.0	Round	4,000	1.27	.74
01673000	510	030292	1	3.0	Round	1,230	.85	.16
01673000	515	090492	1	3.0	Round	2,380	1.38	.58
01673000	518	121292	1	3.0	Round	4,760	1.63	1.13
01673000	519	121392	1	3.0	Round	7,060	1.90	1.25
01673000	520	121492	1	3.0	Round	7,270	1.87	1.20
01673000	521	121592	1	3.0	Round	5,930	1.62	.82
01673000	522	121792	1	3.0	Round	956	.91	.38
01673000	523	011193	1	3.0	Round	6,100	1.79	1.07
01673000	524	011293	1	3.0	Round	6,140	1.72	.95
01673000	525	011393	1	3.0	Round	4,510	1.45	.70
01673000	526	041293	1	3.0	Round	8,960	1.94	1.16
01673000	527	041393	1	3.0	Round	8,230	1.78	1.08
01673000	528	041593	1	3.0	Round	2,540	.98	.52
01673000	529	041993	1	3.0	Round	8,840	1.92	1.08
01673000	530	042293	1	3.0	Round	3,390	1.37	.57
01673000	537	113093	1	3.0	Round	11,700	2.38	1.47
01673000	539	033194	1	3.0	Round	19,300	2.99	2.53
01673000	485	053190	2	3.0	Round	14,770	2.84	4.56
01673000	486	060490	2	3.0	Round	1,920	.83	1.36
01673000	491	011291	2	3.0	Round	4,230	1.47	2.20
01673000	492	011491	2	3.0	Round	7,650	1.81	3.16
01673000	493	011791	2	3.0	Round	3,210	1.18	1.93
01673000	495	040191	2	3.0	Round	5,890	1.56	2.72
01673000	496	040291	2	3.0	Round	2,390	1.00	1.55
01673000	499	070891	2	3.0	Round	3,850	1.34	2.27
01673000	500	070991	2	3.0	Round	809	.65	1.08
01673000	507	022692	2	3.0	Round	964	.72	1.26
01673000	508	022792	2	3.0	Round	3,630	1.29	2.22
01673000	509	022892	2	3.0	Round	4,000	1.27	1.72
01673000	510	030292	2	3.0	Round	1,230	.85	1.24
01673000	515	090492	2	3.0	Round	2,380	1.38	2.11
01673000	518	121292	2	3.0	Round	4,760	1.63	2.74
01673000	519	121392	2	3.0	Round	7,060	1.90	3.18
01673000	520	121492	2	3.0	Round	7,270	1.87	3.31
01673000	521	121592	2	3.0	Round	5,930	1.62	3.01
01673000	522	121792	2	3.0	Round	956	.91	1.10
01673000	523	011193	2	3.0	Round	6,100	1.79	2.84
01673000	524	011293	2	3.0	Round	6,140	1.72	3.08
01673000	525	011393	2	3.0	Round	4,510	1.45	2.44
01673000	526	041293	2	3.0	Round	8,960	1.94	3.34
01673000	527	041393	2	3.0	Round	8,230	1.78	3.22
01673000	528	041593	2	3.0	Round	2,540	.98	1.55
01673000	529	041993	2	3.0	Round	8,840	1.92	3.26
01673000	530	042293	2	3.0	Round	3,390	1.37	1.85
01673000	537	113093	2	3.0	Round	11,700	2.38	3.88
01673000	539	033194	2	3.0	Round	19,300	2.99	3.99
01673000	485	053190	3	3.0	Round	14,770	2.84	1.73
01673000	486	060490	3	3.0	Round	1,920	.83	.33

Table 4. Measurement data and predictions of local scour at bridge-scour study sites in Delaware, Maryland, and Virginia—Continued

[ft, foot; ft^3/s, cubic foot per second; ft/s, foot per second; --, not determined]

Critical velocity (ft/s)	Sediment-transport conditions	Total depth (ft)	Measured local scour (ft)	Local scour (ft) predicted by indicated equation: Colorado State University equation	Froehlich design equation	Laursen equation	Mississippi equation	Remarks
2.23	C	16.6	3.0	2.2	4.1	7.0	4.9	E6
--	--	15.5	--	2.5	4.2	6.8	5.2	E1
--	--	7.5	--	1.2	3.7	4.7	3.9	E1
2.03	C	11.7	4.0	2.1	4.0	5.9	3.9	E6
2.24	C	16.8	2.6	3.0	4.3	7.0	5.0	E2
2.33	B	19.5	1.5	3.2	4.4	7.6	5.5	--
2.33	C	20.0	2.0	3.1	4.4	7.7	5.5	E2
2.33	C	18.8	1.2	2.6	4.3	7.4	5.5	E2
1.96	C	7.5	1.2	1.7	3.8	4.7	3.6	E2
2.31	C	18.5	1.5	3.0	4.3	7.4	5.4	--
2.33	C	19.3	1.3	2.8	4.3	7.5	5.5	E2
2.30	C	17.5	1.0	2.4	4.2	7.2	5.3	E2
2.36	B	20.8	1.5	3.1	4.4	7.8	5.7	--
2.37	C	21.0	1.5	3.0	4.4	7.9	5.7	E2
2.14	C	13.2	2.5	2.1	4.0	6.2	4.5	E2
2.38	B	23.4	3.0	3.1	4.5	8.3	5.8	--
2.18	C	13.5	1.5	2.2	4.0	6.3	4.7	E2
2.42	B	22.5	.0	3.8	4.5	8.2	6.0	E1
2.52	L	30.2	1.4	5.0	4.9	9.5	6.7	--
2.44	L	28.7	5.0	5.8	5.1	9.2	6.2	--
2.20	C	16.0	3.5	3.2	4.3	6.9	4.8	--
2.29	C	18.3	2.1	4.0	4.5	7.3	5.3	E2
2.40	C	24.0	2.5	4.9	4.8	8.4	5.9	--
2.24	C	17.4	3.3	3.8	4.5	7.2	5.0	E2
2.30	C	20.4	4.1	4.5	4.7	7.8	5.3	--
2.22	C	17.5	4.0	3.4	4.4	7.2	4.9	E2
2.27	C	18.2	3.0	4.1	4.5	7.3	5.2	--
2.06	C	10.9	2.3	2.8	4.1	5.7	4.1	E2
2.06	C	10.2	1.7	2.9	4.1	5.5	4.1	E2
2.28	C	17.3	1.7	4.0	4.5	7.1	5.2	--
2.31	C	18.9	2.0	3.6	4.5	7.5	5.4	E2
2.06	C	11.0	2.5	2.9	4.1	5.7	4.1	E2
2.07	C	12.9	4.0	3.8	4.3	6.2	4.2	--
2.25	C	19.6	5.0	4.5	4.6	7.6	5.1	E2
2.17	B	16.2	4.5	4.6	4.6	6.9	4.6	--
2.36	C	22.8	3.5	4.9	4.8	8.2	5.7	E2
2.32	C	22.0	4.5	4.7	4.7	8.1	5.5	E2
1.96	C	9.9	3.5	2.7	4.1	5.4	3.7	E2
2.29	C	21.3	5.1	4.6	4.7	7.9	5.3	E2
2.32	C	21.7	4.2	4.8	4.7	8.0	5.5	--
2.28	C	20.0	4.5	4.3	4.6	7.7	5.2	E2
2.39	B	24.6	4.0	5.0	4.9	8.5	5.8	--
2.39	C	24.4	3.5	4.9	4.8	8.5	5.9	E2
2.20	C	16.3	3.5	3.4	4.4	6.9	4.8	E2
2.40	C	24.8	3.6	5.0	4.9	8.6	5.9	--
2.22	C	16.3	3.0	3.7	4.4	6.9	4.9	E2
2.40	B	26.1	5.0	5.9	5.0	8.8	5.9	--
2.58	L	34.5	2.0	6.2	5.2	10.1	7.0	--
2.33	L	21.2	3.2	3.7	4.5	7.9	5.5	--
2.00	C	9.5	2.3	1.6	3.8	5.3	3.8	--

Table 4. Measurement data and predictions of local scour at bridge-scour study sites in Delaware, Maryland, and Virginia—Continued

[ft, foot; ft^3/s, cubic foot per second; ft/s, foot per second; --, not determined]

Station number	Measure-ment number	Date	Pier designation	Pier diameter (ft)	Pier nose shape	Discharge (ft^3/s)	Mean velocity (ft/s)	Approach velocity (ft/s)
01673000	491	011291	3	3.0	Round	4,230	1.47	0.92
01673000	492	011491	3	3.0	Round	7,650	1.81	1.25
01673000	493	011791	3	3.0	Round	3,210	1.18	.14
01673000	495	040191	3	3.0	Round	5,890	1.56	.43
01673000	496	040291	3	3.0	Round	2,390	1.00	.12
01673000	499	070891	3	3.0	Round	3,850	1.34	.15
01673000	500	070991	3	3.0	Round	809	.65	.03
01673000	507	022692	3	3.0	Round	964	.72	.0
01673000	508	022792	3	3.0	Round	3,630	1.29	1.05
01673000	509	022892	3	3.0	Round	4,000	1.27	.28
01673000	510	030292	3	3.0	Round	1,230	.85	.00
01673000	515	090492	3	3.0	Round	2,380	1.38	.35
01673000	518	121292	3	3.0	Round	4,760	1.63	.70
01673000	519	121392	3	3.0	Round	7,060	1.90	1.21
01673000	520	121492	3	3.0	Round	7,270	1.87	1.30
01673000	521	121592	3	3.0	Round	5,930	1.62	1.02
01673000	522	121792	3	3.0	Round	956	.91	.29
01673000	523	011193	3	3.0	Round	6,100	1.79	.95
01673000	524	011293	3	3.0	Round	6,140	1.72	1.01
01673000	525	011393	3	3.0	Round	4,510	1.45	.58
01673000	526	041293	3	3.0	Round	8,960	1.94	1.56
01673000	527	041393	3	3.0	Round	8,230	1.78	1.35
01673000	528	041593	3	3.0	Round	2,540	.98	.16
01673000	529	041993	3	3.0	Round	8,840	1.92	1.70
01673000	530	042293	3	3.0	Round	3,390	1.37	.13
01673000	537	113093	3	3.0	Round	11,700	2.38	2.14
01673000	539	033194	3	3.0	Round	19,300	2.99	2.94
02027000	1	050389	2	2.0	Round	866	4.27	1.84
02027000	2	050789	2	2.0	Round	1,250	4.92	5.10
02027000	3	042292	2	2.0	Sharp	3,070	6.13	5.22
02027000	1	050389	3	2.0	Round	866	4.27	4.05
02027000	2	050789	3	2.0	Round	1,250	4.92	5.31
02027000	3	042292	3	2.0	Round	3,070	6.13	8.50
02039550	1	052990	1	2.5	Round	340	.59	.0
02039550	2	052990	1	2.5	Round	539	.77	.0
02039550	1	052990	2	2.5	Round	340	.59	.66
02039550	2	052990	2	2.5	Round	539	.77	2.10
02039550	1	052990	3	2.5	Round	340	.59	.0
02039550	2	052990	3	2.5	Round	539	.77	.0
02039550	1	052990	4	2.5	Round	340	.59	.0
02039550	2	052990	4	2.5	Round	539	.77	.0
02044280	1	050289	1	2.25	Round	737	1.11	2.15
02044280	2	082490	1	2.25	Round	721	1.31	2.25
02044280	3	082490	1	2.25	Round	470	1.04	2.10
02044280	4	032991	1	2.25	Round	163	.69	1.26
02044280	5	032991	1	2.25	Round	340	1.32	1.70
02044280	6	032991	1	2.25	Round	656	1.08	1.72
02044280	7	080791	1	2.25	Round	123	.59	.61
02044280	1	050289	2	2.25	Round	737	1.11	.62
02044280	2	082490	2	2.25	Round	721	1.31	1.06

Table 4. Measurement data and predictions of local scour at bridge-scour study sites in Delaware, Maryland, and Virginia—Continued

[ft, foot; ft³/s, cubic foot per second; ft/s, foot per second; --, not determined]

Critical velocity (ft/s)	Sediment-transport conditions	Total depth (ft)	Measured local scour (ft)	Local scour (ft) predicted by indicated equation				Remarks
				Colorado State University equation	Froehlich design equation	Laursen equation	Mississippi equation	
--	--	11.7	--	2.6	4.1	5.9	4.6	E1
--	--	16.0	--	3.1	4.3	6.9	5.3	E1
--	--	10.5	--	1.1	3.7	5.6	4.5	E1
--	--	14.2	--	1.9	4.0	6.5	5.0	E1
--	--	9.0	--	1.0	3.7	5.1	4.2	E1
--	--	11.5	--	1.2	3.8	5.8	4.6	E1
--	--	3.9	--	.5	3.4	3.4	3.0	E1
--	--	3.3	--	--	--	--	2.8	E1
--	--	10.0	--	2.7	4.1	5.4	4.4	E1
--	--	12.3	--	1.6	3.9	6.0	4.8	E1
--	--	3.7	--	--	--	3.3	2.9	E1
--	--	9.3	--	1.7	3.8	5.2	4.2	E1
2.10	C	14.0	4.5	2.4	4.1	6.4	4.3	E6
2.26	B	16.5	1.6	3.1	4.3	7.0	5.1	E2
2.25	B	17.5	3.0	3.2	4.4	7.2	5.1	--
2.26	C	16.9	2.0	2.9	4.3	7.1	5.1	E2
1.50	C	3.0	1.7	1.3	3.5	2.9	1.9	E7
2.23	B	15.6	1.8	2.7	4.2	6.8	5.0	E2
2.22	C	16.4	3.0	2.8	4.3	7.0	4.9	--
2.17	C	14.6	2.8	2.2	4.1	6.6	4.7	E6
2.30	B	18.1	1.6	3.5	4.4	7.3	5.3	--
2.30	C	18.4	2.0	3.3	4.4	7.4	5.3	E2
2.03	C	10.4	2.5	1.2	3.7	5.5	4.0	E2
2.30	B	18.9	2.3	3.6	4.5	7.5	5.4	--
2.13	C	10.9	.5	1.1	3.7	5.7	4.4	E2
2.36	L	19.9	.5	4.4	4.6	7.7	5.7	--
2.44	L	25.0	1.5	5.2	4.8	8.6	6.2	--
6.37	C	1.5	.8	2.0	2.3	1.7	1.2	E7
7.32	C	2.2	.6	3.3	2.5	2.1	1.6	--
8.49	C	5.5	1.6	3.8	2.6	3.3	2.4	--
8.12	C	4.0	1.0	3.3	2.5	2.8	2.1	--
8.45	C	5.0	1.2	3.8	2.6	3.1	2.3	--
9.14	C	8.6	2.5	5.0	2.8	4.1	2.8	--
1.93	C	4.0	.7	--	--	3.1	2.5	E4
1.95	C	4.6	1.0	--	--	3.3	2.6	E4
2.10	C	7.9	2.3	1.9	3.3	4.4	3.1	E6
2.15	C	8.9	2.5	3.2	3.5	4.7	3.3	--
1.86	C	3.8	1.1	--	--	3.0	2.3	E4
1.96	C	4.8	1.1	--	--	3.4	2.6	E4
1.97	C	4.7	.9	--	--	3.4	2.7	E4
2.01	C	5.5	1.2	--	--	3.7	2.8	E4
1.83	C	5.6	1.3	2.8	3.0	3.5	2.6	--
1.86	C	5.9	1.2	2.9	3.1	3.6	2.7	--
1.84	C	5.1	.7	2.8	3.0	3.3	2.6	E2
1.55	C	2.9	1.3	2.0	2.8	2.5	1.8	E2
1.74	C	4.6	1.4	2.5	2.9	3.2	2.3	--
1.81	C	5.3	1.2	2.5	3.0	3.4	2.6	E2
1.61	C	2.5	.5	1.5	2.7	2.3	1.9	--
1.52	C	3.2	1.8	1.5	2.7	2.6	1.7	--
1.28	L	2.9	2.4	1.9	2.8	2.5	1.1	E5

Table 4. Measurement data and predictions of local scour at bridge-scour study sites in Delaware, Maryland, and Virginia—Continued

[ft, foot; ft³/s, cubic foot per second; ft/s, foot per second; --, not determined]

Station number	Measurement number	Date	Pier designation	Pier diameter (ft)	Pier nose shape	Discharge (ft³/s)	Mean velocity (ft/s)	Approach velocity (ft/s)
02044280	3	082490	2	2.25	Round	470	1.04	0.0
02044280	4	032991	2	2.25	Round	163	.69	--
02044280	5	032991	2	2.25	Round	340	1.32	--
02044280	6	032991	2	2.25	Round	656	1.08	.15
02044280	7	080791	2	2.25	Round	123	.59	--
02044280	1	050289	3	2.25	Round	737	1.11	.79
02044280	2	082490	3	2.25	Round	721	1.31	1.06
02044280	3	082490	3	2.25	Round	470	1.04	.62
02044280	4	032991	3	2.25	Round	163	.69	--
02044280	5	032991	3	2.25	Round	340	1.32	--
02044280	6	032991	3	2.25	Round	656	1.08	1.63
02044280	7	080791	3	2.25	Round	123	.59	--
02047000	456	081090	2	2.9	Round	2,100	1.00	1.47
02047000	457	082390	2	2.9	Round	335	.44	.59
02047000	458	082790	2	2.9	Round	5,450	1.76	2.41
02047000	459	083090	2	2.9	Round	1,580	.83	1.00
02047000	460	111590	2	2.9	Round	476	.53	.66
02047000	461	011491	2	2.9	Round	4,940	1.60	2.31
02047000	462	011591	2	2.9	Round	6,130	1.92	2.64
02047000	463	011691	2	2.9	Round	7,130	2.09	2.97
02047000	464	011891	2	2.9	Round	6,620	1.98	2.62
02047000	465	012091	2	2.9	Round	3,160	1.17	1.61
02047000	466	013191	2	2.9	Round	1,150	.80	1.18
02047000	467	022291	2	2.9	Round	1,060	.80	1.23
02047000	468	040491	2	2.9	Round	7,750	2.20	3.26
02047000	469	040591	2	2.9	Round	6,740	2.14	3.42
02047000	470	040891	2	2.9	Round	1,830	.95	1.20
02047000	474	081491	2	2.9	Round	1,120	.75	1.10
02047000	477	013092	2	2.9	Round	1,180	.84	1.27
02047000	478	030592	2	2.9	Round	1,050	.78	1.09
02047000	479	030992	2	2.9	Round	3,420	1.33	1.90
02047000	480	031092	2	2.9	Round	4,420	1.49	2.40
02047000	481	031192	2	2.9	Round	5,310	1.63	2.62
02047000	482	031292	2	2.9	Round	6,660	1.92	3.03
02047000	483	031692	2	2.9	Round	3,380	1.24	1.86
02047000	484	051492	2	2.9	Round	696	.68	1.01
02047000	485	061692	2	2.9	Round	382	.48	.56
02047000	490	031193	2	2.9	Round	8,840	2.28	3.69
02047000	491	031593	2	2.9	Round	4,660	1.51	2.16
02047000	492	031693	2	2.9	Round	5,731	1.77	2.90
02047000	493	031793	2	2.9	Round	7,760	2.14	3.28
02047000	494	031893	2	2.9	Round	8,680	2.32	3.66
02047000	495	031993	2	2.9	Round	7,590	2.07	3.45
02047000	496	032293	2	2.9	Round	4,350	1.47	2.38
02047000	497	040193	2	2.9	Round	8,140	2.19	3.56
02047000	498	040593	2	2.9	Round	3,600	1.39	1.89
02047000	456	081090	3	2.9	Round	2,100	1.00	.74
02047000	457	082390	3	2.9	Round	335	.44	.77
02047000	458	082790	3	2.9	Round	5,450	1.76	2.37
02047000	459	083090	3	2.9	Round	1,580	.83	1.44

Table 4. Measurement data and predictions of local scour at bridge-scour study sites in Delaware, Maryland, and Virginia—Continued

[ft, foot; ft³/s, cubic foot per second; ft/s, foot per second; --, not determined]

Critical velocity (ft/s)	Sediment-transport conditions	Total depth (ft)	Measured local scour (ft)	Local scour (ft) predicted by indicated equation: Colorado State University equation	Froehlich design equation	Laursen equation	Mississippi equation	Remarks
.00	L	2.4	2.4	--	--	2.3	--	E5
--	--	--	--	--	--	--	--	E1
--	--	--	--	--	--	--	--	E1
1.53	C	3.2	1.7	.8	2.6	2.6	1.7	E7
--	--	--	--	--	--	--	--	E1
1.50	C	2.9	1.6	1.7	2.7	2.5	1.6	--
1.50	B	2.6	1.3	1.9	2.7	2.4	1.6	--
1.32	C	2.0	1.4	1.4	2.6	2.1	1.2	E5
--	--	--	--	--	--	--	--	E1
--	--	--	--	--	--	--	--	E1
1.61	C	3.5	1.5	2.3	2.9	2.8	1.9	--
--	--	--	--	--	--	--	--	E1
2.11	C	9.1	.4	3.0	4.0	5.1	4.0	E3
--	--	--	--	--	--	--	--	E1
2.28	C	15.0	1.0	4.0	4.3	6.5	4.9	--
2.11	C	9.8	1.1	2.6	3.9	5.3	4.0	E2
--	--	--	--	--	--	--	--	E1
2.20	C	13.2	1.9	3.8	4.2	6.1	4.5	E2
2.27	B	14.8	1.2	4.1	4.3	6.5	4.8	E2
2.29	B	15.5	1.1	4.4	4.4	6.6	5.0	--
2.29	B	16.0	1.5	4.2	4.4	6.8	5.0	E2
2.19	C	12.4	1.5	3.3	4.1	5.9	4.4	E2
--	--	--	--	--	--	--	--	E1
--	--	--	--	--	--	--	--	E1
2.31	B	16.5	1.2	4.6	4.5	6.9	5.1	E2
2.29	B	15.7	1.2	4.7	4.4	6.7	5.0	--
2.08	C	9.5	1.5	2.8	3.9	5.2	3.9	E2
--	--	--	--	--	--	--	--	E1
--	--	--	--	--	--	--	--	E1
--	--	--	--	--	--	--	--	E1
2.16	C	11.3	1.1	3.5	4.1	5.7	4.3	E2
2.21	C	12.6	1.0	3.9	4.2	6.0	4.5	E2
2.25	C	13.8	.8	4.1	4.3	6.3	4.8	E2
2.27	B	14.7	1.2	4.4	4.4	6.5	4.8	--
2.22	C	13.0	1.1	3.5	4.2	6.1	4.6	E2
--	--	--	--	--	--	--	--	E1
--	--	--	--	--	--	--	--	E1
2.31	B	16.5	1.3	4.8	4.5	6.9	5.1	--
2.26	C	14.4	1.1	3.8	4.3	6.4	4.8	E2
2.25	C	13.6	.8	4.3	4.3	6.2	4.7	E2
2.30	B	16.7	1.8	4.6	4.5	6.9	5.0	E2
2.28	L	15.9	2.0	4.8	4.5	6.7	4.9	--
2.30	B	16.9	2.0	4.7	4.5	6.9	5.0	E2
2.18	C	12.8	2.2	3.9	4.2	6.0	4.4	E2
2.26	B	15.4	2.0	4.7	4.4	6.6	4.8	--
2.21	C	13.4	1.8	3.5	4.2	6.2	4.5	E2
2.08	C	9.1	.9	2.2	3.8	5.1	4.0	--
--	--	--	--	--	--	--	--	E1
2.24	C	13.3	.7	3.9	4.3	6.2	4.7	--
2.05	C	8.2	.7	2.9	3.9	4.8	3.8	E2

Table 4. Measurement data and predictions of local scour at bridge-scour study sites in Delaware, Maryland, and Virginia—Continued

[ft, foot; ft^3/s, cubic foot per second; ft/s, foot per second; --, not determined]

Station number	Measurement number	Date	Pier designation	Pier diameter (ft)	Pier nose shape	Discharge (ft^3/s)	Mean velocity (ft/s)	Approach velocity (ft/s)
02047000	460	111590	3	2.9	Round	476	.53	0.70
02047000	461	011491	3	2.9	Round	4,940	1.60	2.22
02047000	462	011591	3	2.9	Round	6,130	1.92	2.53
02047000	463	011691	3	2.9	Round	7,130	2.09	2.80
02047000	464	011891	3	2.9	Round	6,620	1.98	2.56
02047000	465	012091	3	2.9	Round	3,160	1.17	1.47
02047000	466	013191	3	2.9	Round	1,150	.80	1.12
02047000	467	022291	3	2.9	Round	1,060	.80	1.10
02047000	468	040491	3	2.9	Round	7,750	2.20	3.03
02047000	469	040591	3	2.9	Round	6,740	2.14	2.81
02047000	470	040891	3	2.9	Round	1,830	.95	1.14
02047000	474	081491	3	2.9	Round	1,120	.75	1.00
02047000	477	013092	3	2.9	Round	1,180	.84	1.02
02047000	478	030592	3	2.9	Round	1,050	.78	.97
02047000	479	030992	3	2.9	Round	3,420	1.33	2.00
02047000	480	031092	3	2.9	Round	4,420	1.49	2.18
02047000	481	031192	3	2.9	Round	5,310	1.63	2.31
02047000	482	031292	3	2.9	Round	6,660	1.92	2.82
02047000	483	031692	3	2.9	Round	3,380	1.24	1.78
02047000	484	051492	3	2.9	Round	696	.68	.92
02047000	485	061692	3	2.9	Round	382	.48	.81
02047000	490	031193	3	2.9	Round	8,840	2.28	3.32
02047000	491	031593	3	2.9	Round	4,660	1.51	2.16
02047000	492	031693	3	2.9	Round	5,731	1.77	2.63
02047000	493	031793	3	2.9	Round	7,760	2.14	3.14
02047000	494	031893	3	2.9	Round	8,680	2.32	3.35
02047000	495	031993	3	2.9	Round	7,590	2.07	3.13
02047000	496	032293	3	2.9	Round	4,350	1.47	2.19
02047000	497	040193	3	2.9	Round	8,140	2.19	3.24
02047000	498	040593	3	2.9	Round	3,600	1.39	1.97
02076000	1	102490	1	3.2	Round	--	--	5.24
02076000	2	102590	1	3.2	Round	43,600	6.57	6.16
02076000	3	042290	1	3.2	Round	23,500	4.80	4.32
02076000	2	102590	2	3.2	Round	43,600	6.57	7.11
02076000	3	042292	2	3.2	Round	23,500	4.80	5.46
03076500	450	052990	B	5.0	Sharp	1,500	2.79	4.16
03076500	451	071390	B	5.0	Sharp	7,500	7.50	7.66
03076500	452	071690	B	5.0	Sharp	2,370	3.80	4.30
03076500	455	032191	B	5.0	Sharp	1,330	2.63	2.88
03076500	461	021892	B	5.0	Sharp	1,900	3.30	3.82
03076500	467	040193	B	5.0	Sharp	4,820	5.62	6.85
03076500	450	052990	C	5.0	Sharp	1,500	2.79	3.90
03076500	451	071390	C	5.0	Sharp	7,500	7.50	8.62
03076500	452	071690	C	5.0	Sharp	2,370	3.80	4.78
03076500	455	032191	C	5.0	Sharp	1,330	2.63	3.11
03076500	461	021892	C	5.0	Sharp	1,900	3.30	3.99
03076500	467	040193	C	5.0	Sharp	4,820	5.62	6.20
03166700	1	032991	1	2.0	Round	551	3.38	.11
03166700	2	060592	1	2.0	Round	5,980	5.49	1.78
03166700	3	032493	1	2.0	Round	4,590	4.78	1.45

Table 4. Measurement data and predictions of local scour at bridge-scour study sites in Delaware, Maryland, and Virginia—Continued

[ft, foot; ft^3/s, cubic foot per second; ft/s, foot per second; --, not determined]

Critical velocity (ft/s)	Sediment-transport conditions	Total depth (ft)	Measured local scour (ft)	Local scour (ft) predicted by indicated equation: Colorado State University equation	Froehlich design equation	Laursen equation	Mississippi equation	Remarks
--	--	--	--	--	--	--	--	E1
2.24	C	13.2	.6	3.8	4.2	6.1	4.7	E2
2.24	B	13.5	.8	4.0	4.3	6.2	4.7	E2
2.25	B	14.0	.9	4.2	4.3	6.3	4.8	--
2.27	B	14.4	.8	4.1	4.3	6.4	4.8	E2
2.18	C	11.6	1.0	3.1	4.1	5.7	4.4	E2
--	--	--	--	--	--	--	--	E1
--	--	--	--	--	--	--	--	E1
2.28	B	14.8	.9	4.4	4.4	6.5	4.9	--
2.25	B	14.0	1.1	4.2	4.3	6.3	4.7	E2
2.04	C	8.4	1.3	2.7	3.9	4.9	3.7	E2
--	--	--	--	--	--	--	--	E1
--	--	--	--	--	--	--	--	E1
--	--	--	--	--	--	--	--	E1
2.16	C	11.3	1.1	3.5	4.1	5.7	4.3	E2
2.21	C	12.6	1.0	3.7	4.2	6.0	4.5	E2
2.23	C	13.5	1.1	3.9	4.3	6.2	4.7	E2
2.25	B	14.4	1.6	4.2	4.3	6.4	4.7	--
2.18	C	12.0	1.2	3.4	4.1	5.8	4.4	E2
--	--	--	--	--	--	--	--	E1
--	--	--	--	--	--	--	--	E1
2.27	L	15.2	1.4	4.6	4.4	6.6	4.9	--
2.20	C	12.0	.6	3.7	4.2	5.8	4.5	E2
2.21	C	13.0	1.4	4.1	4.3	6.1	4.5	E2
2.25	B	14.3	1.4	4.4	4.4	6.4	4.7	--
2.26	L	15.2	1.8	4.6	4.4	6.6	4.8	--
2.27	B	15.2	1.5	4.5	4.4	6.6	4.9	E2
2.22	C	12.6	.6	3.7	4.2	6.0	4.6	E2
2.28	B	15.4	1.3	4.5	4.4	6.6	4.9	--
2.17	C	11.5	1.0	3.5	4.1	5.7	4.4	E2
1.84	L	20.5	3.5	6.2	5.3	8.0	5.6	E2
1.69	L	26.0	4.0	6.8	5.6	9.0	6.2	--
1.70	C	19.1	2.7	5.6	5.2	7.7	5.5	--
1.78	L	30.5	3.5	7.4	5.8	9.8	6.8	--
1.78	L	27.5	5.0	6.5	5.6	9.3	6.3	--
9.72	C	5.1	1.2	5.6	5.7	3.9	4.1	--
.66	C	7.9	1.1	7.7	5.9	4.8	5.1	--
9.84	C	5.4	1.2	5.7	5.7	4.0	4.2	E2
9.54	C	4.7	1.2	4.7	5.6	3.7	3.9	--
9.59	C	4.8	1.2	5.3	5.7	3.7	4.0	--
.26	C	6.8	1.4	7.2	5.9	4.5	4.6	--
9.59	C	6.1	2.5	5.6	5.7	4.2	4.0	--
.76	C	9.9	2.7	8.4	6.0	5.4	5.2	--
.16	C	7.4	2.3	6.2	5.8	4.7	4.5	E2
9.67	C	5.9	2.1	5.0	5.7	4.2	4.0	--
9.88	C	6.3	2.0	5.6	5.8	4.3	4.2	--
.53	C	8.0	1.7	7.0	5.9	4.8	4.9	--
--	--	1.5	--	.6	2.2	1.7	1.6	E1
8.67	C	9.6	2.0	2.6	2.6	4.3	3.1	E6
8.38	C	8.2	2.0	2.3	2.6	4.0	2.8	E6

Table 4. Measurement data and predictions of local scour at bridge-scour study sites in Delaware, Maryland, and Virginia—Continued

[ft, foot; ft^3/s, cubic foot per second; ft/s, foot per second; --, not determined]

Station number	Measurement number	Date	Pier designation	Pier diameter (ft)	Pier nose shape	Discharge (ft^3/s)	Mean velocity (ft/s)	Approach velocity (ft/s)
03166700	1	032991	2	2.0	Round	551	3.38	3.70
03166700	2	060592	2	2.0	Round	5,980	5.49	5.51
03166700	3	032493	2	2.0	Round	4,590	4.78	6.45
03487990	1	052990	1	2.0	Round	3,500	3.94	4.08
03487990	2	033091	1	2.0	Round	3,460	3.56	3.58
03487990	3	022692	1	2.0	Round	3,990	3.59	3.36
03487990	4	030493	1	2.0	Round	4,270	3.71	3.48
03487990	5	030493	1	2.0	Round	4,970	3.79	3.52
03487990	1	052990	2	2.0	Round	3,500	3.94	4.60
03487990	2	033091	2	2.0	Round	3,460	3.56	4.47
03487990	3	022692	2	2.0	Round	3,990	3.59	4.60
03487990	4	030493	2	2.0	Round	4,270	3.71	4.79
03487990	5	030493	2	2.0	Round	4,970	3.79	5.10
03487990	1	052990	3	2.0	Round	3,500	3.94	.37
03487990	2	033091	3	2.0	Round	3,460	3.56	.95
03487990	3	022692	3	2.0	Round	3,990	3.59	1.09
03487990	4	030493	3	2.0	Round	4,270	3.71	1.38
03487990	5	030493	3	2.0	Round	4,970	3.79	1.51

Table 4. Measurement data and predictions of local scour at bridge-scour study sites in Delaware, Maryland, and Virginia—Continued

[ft, foot; ft^3/s, cubic foot per second; ft/s, foot per second; --, not determined]

Critical velocity (ft/s)	Sediment-transport conditions	Total depth (ft)	Measured local scour (ft)	Local scour (ft) predicted by indicated equation				Remarks
				Colorado State University equation	Froehlich design equation	Laursen equation	Mississippi equation	
6.18	C	2.5	1.5	3.0	2.5	2.2	1.4	--
8.82	C	10.5	2.1	4.3	2.8	4.5	3.2	--
8.87	C	10.5	1.8	4.6	2.9	4.5	3.2	--
7.48	C	7.1	.2	3.5	2.7	3.7	3.0	E3
7.40	C	6.9	.4	3.3	2.7	3.7	2.9	E3
7.65	C	8.1	.2	3.3	2.7	4.0	3.1	E3
7.65	C	8.2	.3	3.4	2.7	4.0	3.1	E3
7.84	C	9.5	.3	3.5	2.8	4.3	3.3	E3
7.58	C	7.9	.4	3.8	2.7	3.9	3.0	E3
7.61	C	8.5	.8	3.8	2.8	4.1	3.1	--
7.77	C	9.7	1.0	3.9	2.8	4.4	3.2	--
7.83	C	9.9	.8	4.0	2.8	4.4	3.3	E2
7.89	C	10.7	1.2	4.1	2.8	4.6	3.4	--
6.61	C	3.5	.2	1.1	2.3	2.6	2.2	E3
6.61	C	3.9	.6	1.7	2.4	2.8	2.2	--
7.04	C	5.3	.5	1.9	2.5	3.2	2.6	--
7.04	C	5.2	.4	2.1	2.5	3.2	2.6	E3
7.20	C	5.9	.4	2.3	2.5	3.4	2.7	E3

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