Evaluation of Scour at Selected Bridge Sites in Indiana

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CONTENTS

CONTENTS

FIGURES

CONTENTS

FIGURES—Continued

CONTENTS

TABLES

CONTENTS

TABLES—Continued

CONTENTS

TABLES—Continued

CONTENTS

TABLES—Continued

CONVERSION FACTORS AND ABBREVIATIONS

Multiply	By	To Obtain
inch (in.)	25.4	millimeter
foot (ft)	0.3048	meter
mile (mi)	1.609	kilometer
square mile (mi^2)	2.590	square kilometer
cubic foot (ft^3)	0.02832	cubic meter
foot per second (ft/s)	0.3048	meter per second
cubic foot per second (ft^3/s)	0.02832	cubic meter per second
foot per mile (ft/mi)	0.1894	meter per kilometer

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

The following abbreviations are used in this report:

Abbreviation	Description
kHz	Kilohertz
mHz	Megahertz
mm	Millimeter

SYMBOLS

a A coefficient based on the ratio of the shear velocity (u_*) to the fall velocity (ω) in the uncontracted channel, used to compute live-bed contraction scour.

A_e Cross-sectional area of the flow obstructed by the embankment.

b Width of the pier.

b' Width of the pier projected normal to the approach flow for the Froehlich equation,
$b' = b\cos(\alpha) + L\sin(\alpha)$.

B_c Bottom width of the contracted section.

B_u Bottom width of the uncontracted (approach) section.

C Pier location code for the Arkansas equation (0 for piers in the main channel and 1 for piers on the overbanks).

d_{50} Median grain size of the bed material.

d_{84} 16th percentile of the grain size of the bed material.

$\mathbf{F}_a$ Froude number of the flow at the abutment for the Froehlich equation.

$\mathbf{F}_o$ Froude number of the flow just upstream from the pier or abutment.

$\mathbf{F}_p$ Pier Froude number used in the Shen-Maza equation, defined as $\frac{V_o}{\sqrt{gb}}$.

g Acceleration due to gravity.

k_s Grain roughness of the streambed, normally taken as the d_{84} of the bed material.

K A coefficient for the Ahmad equation that is a function of boundary geometry, abutment shape, width of the piers, shape of the piers, and angle of the approach flow. Range is from 1.7 to 2.0. For this study, it was assumed to be 1.8.

K_1 A coefficient for the CSU equation based on the shape of the pier nose (1.1 for a square nose; 1.0 for a round nose, a circular cylinder, or a group of cylinders; and 0.9 for a sharp nose).

K_2 A coefficient for the CSU equation based on the attack angle of the approach flow to the pier and the ratio of pier length (L) to pier width (b).

K_3 A coefficient for the CSU equation based on the bed condition (1.1 for clear-water scour, plane bed and antidunes, and small dunes of <10 ft; 1.1 to 1.2 for medium dunes of 10 to 30 ft; 1.3 for large dunes of >30 ft).

K_{sa} A coefficient for abutment shape (1.0 for a vertical abutment with square or rounded corners and a vertical embankment; 0.82 for a vertical abutment with wingwalls and a sloped embankment; and 0.55 for a spill-through abutment and a sloped embankment).

SYMBOLS—Continued

K_{S1} A coefficient for the Laursen equation based on the shape of the pier nose.

K_{aL} A coefficient for the Laursen equation based on the angle of the approach flow referenced to the pier.

K_{S2} A coefficient based on the shape of the pier nose for the Larras equation (1.0 for cylindrical piers and 1.4 for rectangular piers).

K_θ A coefficient based on the angle that an embankment is skewed to the direction of flow, $K_\theta = \left(\frac{\theta}{90}\right)^{0.13}$.

L Length of the pier.

l Length of an abutment, defined as, $\frac{A_e}{y_{oa}}$.

q Discharge per unit width just upstream from the pier.

Q_c Discharge in the part of the contracted channel represented by the specified bottom width.

Q_e Discharge obstructed by the embankment.

Q_u Discharge in the part of the uncontracted (approach) channel represented by the specified bottom width.

$\mathbf{R}_p$ Pier Reynolds number used in the Shen equation, defined as $\frac{V_o b}{\nu}$.

S Dimensionless slope of the energy grade line near the bridge, used to compute shear velocity for live-bed contraction scour.

u_* Shear velocity, defined as, $\sqrt{g y_u S}$.

ν Kinematic viscosity of water, used to compute the pier Reynolds number.

V_f Average velocity in the flow zone below the top of the footing.

V_o Velocity of the approach flow just upstream from the pier or abutment.

y_b Average depth of flow at the bridge before contraction scour.

y_f Distance from the streambed to the top of the footing.

y_o Depth of flow just upstream from the pier or abutment, excluding local scour.

y_{oa} Average depth of flow obstructed by the embankment for the Froehlich equation.

y_{sa} Depth of abutment scour below the ambient bed.

y_{sc} Depth of contraction scour below the existing bed.

y_{sp} Depth of pier scour below the ambient bed.

y_u Average depth of flow in the uncontracted (approach) channel.

SYMBOLS—Continued

ω Fall velocity of the median grain size of the bed material, used to compute live-bed contraction scour.

a Angle of the approach flow referenced to the bridge pier, in degrees, for the Froehlich equation.

ϕ A coefficient for the Froehlich equation based on the shape of the pier nose (1.3 for a square nose, 1.0 for a round nose, 0.7 for a sharp nose).

θ Angle an embankment is skewed to the direction of flow, in degrees; if an embankment points downstream $\theta<90^\circ$, if an embankment points upstream $\theta>90^\circ$ ($\theta=90^\circ$ if the embankment skew is 0°).

Evaluation of Scour at Selected Bridge Sites in Indiana

By Robert L. Miller *and* John T. Wilson

ABSTRACT

Twenty bridge sites in Indiana were evaluated during 1990-93 to determine (1) the extent of scour during floods, (2) streambed stability, (3) maximum historical scour, (4) estimates of potential scour resulting from the 100-year and 500-year floods, and (5) the utility of 14 published pier-scour equations for predicting the measured depths of scour and the maximum historical scour. The sites were selected to represent various geographic areas and a wide range of drainage areas within Indiana. In addition, the sites were selected to allow for stream soundings and velocity measurements during flooding and to ensure an adequate response time, open and safe workspace, and accessibility of the nose of the pier to measurements with sounding equipment.

Historical scour data were collected by means of geophysical methods and were used to evaluate the scour-computation procedures recommended by the U.S. Federal Highway Administration, as well as the use of 13 other published pier-scour equations. Geophysical data were collected with a ground-penetrating radar system and a tuned transducer. Data obtained from soil-boring logs in bridge-construction plans, from probing with a steel pipe, and from sediment cores were used to support the geophysical data.

Subsurface interfaces indicating possible scour holes were identified at 14 sites. These interfaces were used to evaluate 14 pier-scour equations. For this comparison, the authors assumed that the interpreted historical scour was associated with the peak historical discharge, except at three sites where the subsurface interfaces were identified before the peak historical discharge occurred. At these sites, the next largest historical peak discharge was used for the analysis. Hydraulic conditions for the peak historical discharges were estimated by use of WSPRO, a model for computing water-surface profiles.

Local scour from the effects of piers could not be separated from contraction scour because the geophysical data were insufficient to determine the lateral extent of the refilled scour holes. For the evaluation, the depths of contraction scour and pier scour were combined to determine a computed bed elevation that was compared to the historical bed elevation at the upstream end of the piers. Computed contraction scour appeared to be excessive at many sites, so the comparisons also were made without contraction scour. The results were combined with the results of a previous study, for a total of 38 observations. When contraction scour was included, most of the equations overestimated the historical scour. Accuracy increased when contraction scour was excluded, but the number of times

scour was underestimated also increased—an indication that the contraction-scour equation over predicts. None of the pier-scour equations accurately represented the historical scour at all the study sites.

Soundings were made periodically at all the sites and during flooding at some sites. These data indicate that scour is affected greatly by debris on piers and often is not uniquely related to discharge or depth. At several piers where debris piles were present, scour was identified at or near the pier through soundings made during low flow; however, measurements made during higher flows after debris removal indicated that the scour had not increased and that, in some cases, scour holes had refilled.

Streambed elevations determined during flood measurements were used to evaluate 14 pier-scour equations. Pier scour was computed with the hydraulic conditions estimated for the measured discharges. Contraction scour was not included in the analysis because contraction scour was not positively identified by the flood measurements and the periodic soundings. From 1 to 4 feet of scour was identified during the flood measurements at debris-free piers, and most of the pier-scour equations overestimated this scour. The lack of measured scour during the floods may be a result of the high frequency of the floods that were measured. Recurrence intervals of most of the measured discharges were less than 10 years; at these discharges, the hydraulic conditions may not be suitable to induce scour.

A comparison of velocities computed with WSPRO to velocities measured during floods indicates that WSPRO more accurately predicted velocities at piers in the main channel than at piers on the overbanks. Most of the computed velocities for the main channel were within 1 foot per second of the measured velocities, which ranged from less than 1 to 7 feet per second. In general, WSPRO overestimated at lower velocities and underestimated at higher velocities, but this trend was more distinct with velocities for the overbanks than for the main channel.

The potential scour resulting from the 100-year and 500-year peak discharge was computed according to the procedures recommended by the Federal Highway Administration. Contraction-scour and abutment-scour computations appear to be excessive at several sites; however, at high discharges, the potential exists for severe scouring. Additional data would be required for definitive conclusions.

On the basis of estimated historical peak discharges, flooding equal to or greater than the 100-year flood has occurred at five of the study sites. The identification and estimates of historical scour bed elevations do not indicate scouring of the extent predicted by the potential scour computations. Historical scour interfaces were estimated at three of these sites, and all of the interfaces were above the computed potential scour bed elevations.

INTRODUCTION

Scour of the streambed in the vicinity of bridge piers and abutments during floods has resulted in more bridge failures in the United States than all other causes of bridge failure in recent history (Murillo, 1987). The I-29 bridge over the Big Sioux River in Iowa failed because of scour in 1962, as did the I-64 bridge over the John Day River in Oregon in 1964. In 1985, 73 bridges were destroyed or damaged by scour resulting from floods in Pennsylvania, Virginia, and West Virginia. In 1987, 17 bridges in New York and New England were damaged or destroyed by scour, including the failure of the New York State Thruway bridge spanning Schoharie Creek that resulted in the loss of 10 lives (Harrison and Morris, 1991, p. 210).

In 1989, eight people were killed when the U.S. Route 51 bridge over the Hatchie River in Tennessee failed because of a lateral shift of the stream. In 1990, the Troy Avenue bridge over Buck Creek near Indianapolis, Ind., failed because of scour of the streambed. In central California, seven people died as the result of bridge failure on I-5 over Arroyo Pasajero near Coalinga due to flood waters. Damage to bridges resulting from scour of the streambed is a serious problem of national concern.

The U.S. Federal Highway Administration (1988) recommended that "Every bridge over an alluvial stream, whether existing or under design, should be evaluated as to its vulnerability to floods in order to determine the prudent measures to be taken for its protection." More than 35 equations for the prediction of scour around bridge piers, a significant number of abutment-scour equations, and several contraction-scour equations are published in the literature. Nearly all these equations are empirical and are based on laboratory data developed by use of flumes with uniform cohesionless bed materials under steady-flow conditions. Minimal field data have been collected to verify the applicability and accuracy of these equations for the ranges of soil conditions, streamflow conditions, and bridge designs throughout the United States (Richardson and others, 1991). Anderson (1974) showed that, for identical conditions, the scour predicted by various, pier-scour equations can differ by a factor of 6 or greater. The U.S. Federal Highway Administration (FHWA) has published two Hydraulic Engineering Circulars (Richardson and others, 1993; Lagasse and others, 1991) that provide guidance for evaluating scour and stream instabilities at highway stream crossings. Richardson and others (1993, p. 21) recommend the following:

> Adequate consideration must be given to the limitations and gaps in existing knowledge when using currently available formulas for estimating scour. **The designer needs to apply engineering judgment in comparing results obtained from scour computations with available hydrologic and hydraulic data to achieve a reasonable and prudent design.** Such data should include:
>
> a. Performance of existing structures during past floods,
>
> b. Effects of regulation and control of flood discharges,
>
> c. Hydrologic characteristics and flood history of the stream and similar streams, and
>
> d. Whether the bridge is structurally continuous.

Therefore, to improve the accuracy of scour computations at a site, published equations need to be evaluated and results from these equations need to be compared with field measurements at sites where hydraulic and geotechnical conditions are similar. Because scour holes often refill after the passage of a flood, simple bed surveys are not sufficient to determine the depth of scour holes that formed during previous floods. Geophysical techniques—such as ground-penetrating radar and continuous high-resolution subbottom seismic profiling—and onsite measurements during a flood must be used to delineate the scour holes formed by flooding. To verify the FHWA procedures for use in Indiana, the U.S. Geological Survey (USGS), in cooperation with the Indiana Department of Transportation (INDOT), evaluated the available published equations to provide information on 20 bridge sites.

Purpose and Scope

This report, the second in a series, continues the assessment of the ability of selected published scour-computation procedures to duplicate measured historical scour in Indiana. This report also assesses the ability of these procedures to duplicate scour measurements made during floods. Estimates of the potential scour resulting from the 100- and 500-year floods are computed by use of the recommended FWHA procedures.

Twenty sites were selected to represent various geographic areas and a wide range of drainage areas within Indiana. In addition, the sites were selected to allow for stream soundings and velocity measurements during flooding and to ensure adequate time to respond to floods, open and safe workspace, and accessibility of the nose of the pier to measurements with sounding equipment.

This information will assist INDOT and the FHWA in making decisions about the safety of the selected bridges and in determining whether the procedures used in this study are efficient and reliable for future bridge-scour investigations in Indiana.

APPROACH

Onsite measurements were made during flooding to document depth of scour and flow characteristics at the time of the measurement. High-water marks representing the river stage at the time of the measurement and the peak (if the stage were dropping) were set and surveyed to document the conditions needed for calibration of the surface-water flow model used in the analytical phase of the study. Soundings were made at selected times to document the changes to the channel bottom during the study.

The streambed in the vicinity of the bridge opening was surveyed by use of ground-penetrating radar and a tuned transducer. These data were used to locate old scour holes that had refilled. Sediment cores were collected along the upstream face of the bridge by use of a vibracoring technique. The area around each pier was probed to verify the interpretation of the geophysical surveys.

Valley cross sections and the bridge openings were surveyed, streambed material was collected and analyzed for grain-size distribution, and a review of the bridge plans for bridge characteristics was done. These data were applied to 14 scour-prediction equations to compute scour for the maximum historical and measured discharges. The results of the computations for the historical discharge were compared to the scour depths determined by use of geophysical techniques. The results for the measured discharges were compared to the soundings made at the time of the measurement. Potential scour was computed for the 100- and 500-year floods in accordance with guidelines in the FHWA procedures.

METHODS OF INVESTIGATION FOR DATA COLLECTION

The 20 study sites were selected (fig. 1) by field reconnaissance of all bridges in the State Highway System over streams with drainage areas greater than 300 mi^2 and of selected bridges where a drainage area upstream from the bridge was greater than 100 mi^2. The study sites were selected in consultation with INDOT. The bridge characteristics are listed in table 1.

Each bridge site was surveyed by use of a total station (electronic theodolite). Approach and exit cross sections were surveyed across the valley. Channel sections were surveyed to the water level. Elevations for the underwater part of the channel were established by use of a fathometer or by measurement of the water depth with a level rod and subtraction of water depth from water-surface elevation. Each bridge was surveyed to document its geometry, and roadways were surveyed where flow over the road might occur. Additional bridge and pier details were obtained from the bridge plans. The numbering of piers in this report is consistent with the bridge plans. The footings and their piles are drawn to depict what was shown on the bridge plans.

Stationing (horizontal distance) was marked on the upstream and downstream guardrail of each study bridge. Stationing began with zero on the left end of the bridge opening (looking downstream) at the left-most point of flow and ended at the right-most point of flow on the right end of the bridge.

Table 1. Bridge characteristics of study sites in Indiana
[S.R., State Road; U.S., U.S. Route; wing, wingwall; slope, sloping embankment]

Site number	Bridge name	County	Channel slope (foot per foot)	Bridge width (feet)	Abutment type	Main-channel footing	Skew of piers to deck (degrees)	Pier width minimum and maximum (feet)	Year built
1	S.R. 1 over St. Marys River at Fort Wayne	Allen	0.00018	87	Spill through	Spread	0	2.0	1968
2	S.R. 9 over Pigeon River at Howe	Lagrange	.00069	36.5	Spill through	Bent	15	2.0	1961
3	S.R. 11 over Flatrock River at Columbus	Bartholomew	.00050	46.7	Spill through	Piles	0	3.2–5.0	1926
4	S.R. 14 over Tippecanoe River at Winamac	Pulaski	.00012	28	Spill through	Piles	10	2.0–3.1	1952
5	S.R. 15 over Little Elkhart River at Bristol	Elkhart	.0013	44	Vertical/wing	Piles	15	2.0	1941
6	S.R. 19 over Wabash River at Peru	Miami	.00044	51.5	Spill through	Spread[1]	0	2.0–3.9	1983
7	S.R. 25 over Wildcat Creek at Lafayette	Tippecanoe	.00057	84.9	Spill through	Piles	30	2.0–3.2	1952
8	S.R. 32 over Wabash River at Perrysville	Fountain/Vermillion	.000094	34	Spill through[2]	Piles	0	3.0–7.1	1984
9	U.S. 35 over Kankakee River at Union Center	La Porte	.00011	44	Spill through	Bent	0	1.0	1970
10	U.S. 41 over Kankakee River at Schneider	Lake/Newton	.00015	30	Spill through	Piles	12	3.0	1954
11	S.R. 54 over Busseron Creek near Sullivan	Sullivan	.00045	38.8	Vertical/slope	Bent	0	2.0	1924
12	S.R. 57 over East Fork White River near Petersburg	Daviess/Pike	.00010	44	Spill through	Piles[3]	0	2.5–5.9	1972
13	S.R. 59 over Eel River north of Clay City	Clay	.00041	34	Spill through	Piles	0	2.0–3.9	1955
14	S.R. 63 over Little Vermillion River at Newport	Vermillion	.00066	40	Spill through	Spread	0	2.0	[4]1954
15	S.R. 101 over St. Joseph River at Saint Joe	DeKalb	.00023	31	Spill through	Spread	22	2.0	1963
16	S.R. 109 over White River at Anderson	Madison	.00041	65.5	Spill through	Spread	20	2.0–3.8	1948
17	S.R. 110 over Tippecanoe River near Mentone	Marshall/Fulton	.00031	28	Spill through	Piles	0	2.0	1957
18	S.R. 135 over Muscatatuck River at Millport	Jackson/Washington	.000050	30	Spill through	Piles[5]	0	2.2–3.7	1954
19	S.R. 157 over White River at Worthington	Greene	.00030	44	Spill through	Piles	10	2.0–3.0	1984
20	S.R. 163 over Wabash River at Clinton	Parke/Vermillion	.00010	30.2	Spill through	Piles	17	2.5–3.0	1963

[1]Set on bedrock.
[2]With spur dikes.
[3]Pier 2 at the left edge of channel is on a spread footing.
[4]Southbound lane built in 1976.
[5]Pier 3 at the left edge of channel is on a spread footing.

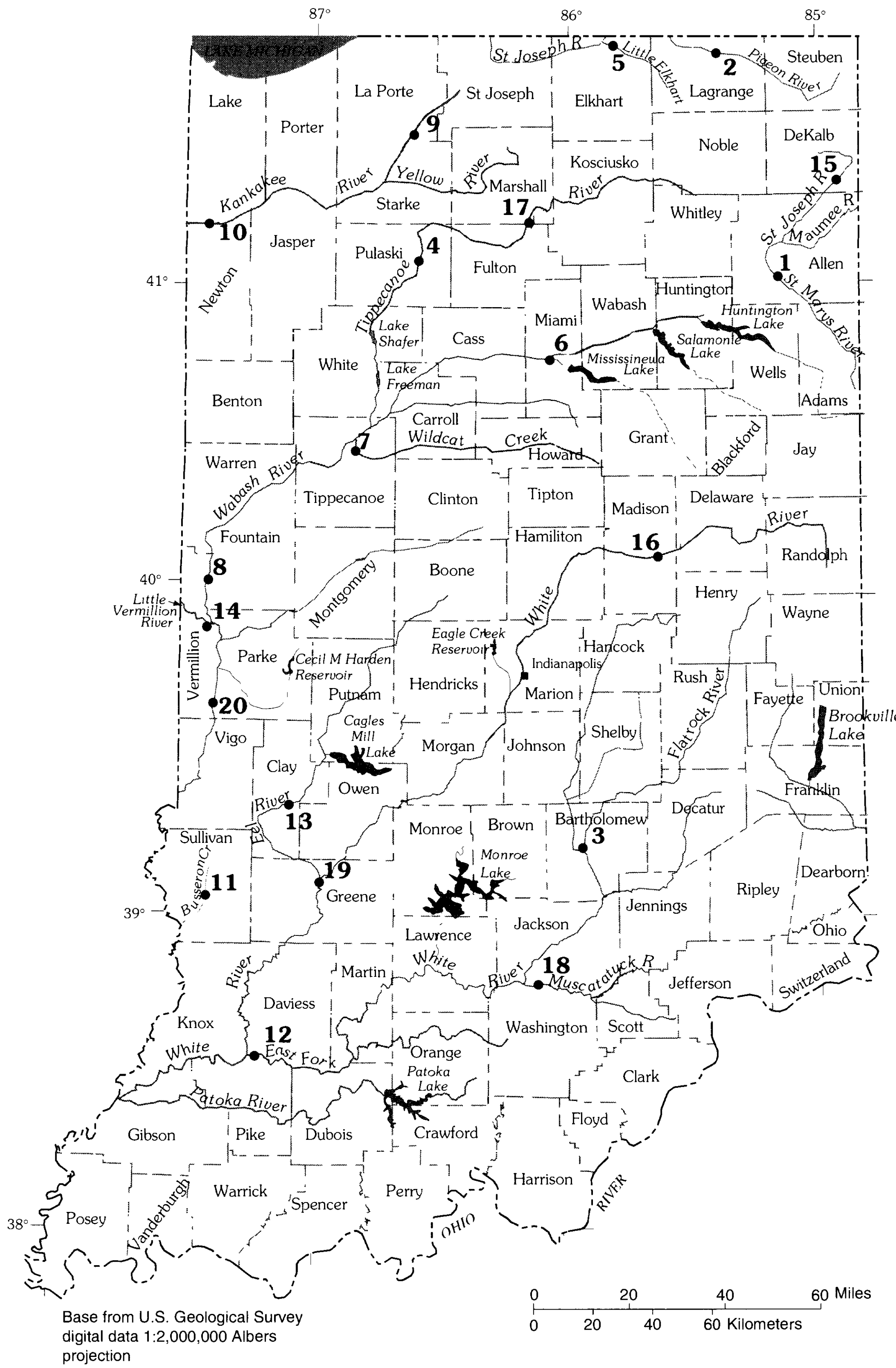


Figure 1. Location of study sites.

Figure 1. EXPLANATION

1) S.R. 1 over St. Marys River at Fort Wayne
2) S.R. 9 over Pigeon River at Howe
3) S.R. 11 over Flatrock River at Columbus
4) S.R. 14 over Tippecanoe River at Winamac
5) S.R. 15 over Little Elkhart River at Bristol
6) S.R. 19 over Wabash River at Peru
7) S.R. 25 over Wildcat Creek at Lafayette
8) S.R. 32 over Wabash River at Perrysville
9) U.S. 35 over Kankakee River at Union Center
10) U.S. 41 over Kankakee River at Schneider
11) S.R. 54 over Busseron Creek near Sullivan
12) S.R. 57 over East Fork White River near Petersburg
13) S.R. 59 over Eel River north of Clay City
14) S.R. 63 over Little Vermillion River at Newport
15) S.R. 101 over St. Joseph River at Saint Joe
16) S.R. 109 over White River at Anderson
17) S.R. 110 over Tippecanoe River near Mentone
18) S.R. 135 over Muscatatuck River at Millport
19) S.R. 157 over White River at Worthington
20) S.R. 163 over Wabash River at Clinton

The stationing of the bridge generally is shorter than the total bridge length from the bridge plans because the bridge length includes the entire abutment. Reference points were established on the upstream and downstream guardrail and were referenced to sea level.

The channel slope was measured from the most recent available versions of 1:24,000-scale USGS topographic quadrangle maps. The slope was computed by measuring the distance from the first contour crossing downstream from the bridge to the first contour crossing upstream from the bridge; the difference in elevation between the contours was divided by the measured distance.

Soundings were made on the upstream and downstream side of the bridge openings to establish channel-bottom elevations. One of two methods was used to measure the water depth: (1) Columbus sounding weights suspended by cable from the bridge deck or (2) level rod. The elevation of the water surface was established by a measurement from the reference point to the surface of the water. Channel-bottom elevations were computed by subtracting the water depth from the water-surface elevation.

Discharge measurements during floods were made by use of a Columbus weight and Price AA meter suspended by cable from the bridge deck. These measurements—referred to hereafter as "flood measurements"—document the water-surface elevation, velocity of the water at selected points, water depth at these points, angle of flow to the bridge deck measured at the water surface, station of the data points, and referenced conditions at the time of the measurement. Water-surface elevations were measured at the approach cross section and on the upstream and the downstream sides of the bridge for the water surface at the completion of the measurement and at the peak stage if the water level was falling.

At sites where flood measurements were made, the angle of flow approaching the pier was measured. At sites where flood measurements were not made, the angle of flow approaching the pier was estimated from the bridge plans and the quadrangle maps. During flood measurements, the cosine of the angle between the bridge deck and a line perpendicular to flow was documented by use of the USGS discharge-measurement sheet. The angle of flow as it approaches the bridge is derived from the cosine of the angle. The angle of flow as it approaches a pier is computed by subtracting the angle that a pier is skewed to the bridge (taken from the bridge plan) from the angle of flow as it approaches the bridge.

At each study site, a composite bed-material sample was made up from individual samples collected along the upstream face of the bridge at selected points across the main channel. Median grain sizes of the streambed were determined from grain-size analyses of these sediment samples. Composition of the bed material determined which sampler was used to collect the sample. In sand and gravel channels that could be waded, a BMH-53 piston sampler was used to collect samples. In channels consisting of sand and gravel that were too deep to wade, a US BM 54 cable and reel sampler with a spring-driven bucket was used. In channels with cobble- or boulder-size bed material, a clam bucket was used to collect the sample. The one exception was St. Marys River at Fort Wayne, where a sample was collected by wading and picking up cobbles at 0.5-ft intervals across the main channel at the upstream face of the bridge.

The grain size for the overbanks at each site was estimated from the soil-boring logs that accompanied the bridge plans. The one exception was Wildcat Creek at Lafayette, where the sample in the left overbank was collected with a shovel at randomly selected spots. At this site, each section between the piers was sampled separately to document the obvious variation in particle size.

Each bridge opening was surveyed with a ground-penetrating radar system (GPR) and (or) a tuned transducer to locate evidence of scour holes that may have refilled. These geophysical methods are described in Gorin and Haeni (1989). The GPR was used with 100-mHz antennae that transmit electromagnetic pulses into the subsurface. Ideally, this energy would be reflected from subsurface interfaces where electrical properties differ. The GPR technique was successful on the gravel bars and in water less than 4 ft deep. In water depths greater than 4 ft, however, the signal was rapidly attenuated in the water column because of high specific conductance of the water; no useful data were recorded. The data sometimes contained interference from debris, side echo, and point reflections.

The tuned transducer was used with a 3.5- to 7-kHz and a 14-kHz transducer to send and receive an acoustic signal. The acoustic signal is reflected from subsurface interfaces where acoustic impedances change. The transducer was suspended 6 to 12 in. below the water surface. This equipment was usable in water deeper than 4 ft. The data were sometimes obscured by the effects of side echo, debris, point reflections from cobbles and boulders, and multiple reflections.

The geophysical surveys were completed in the main channel of the bridge opening and around each pier. In shallow channels, investigators maneuvered the equipment around the piers and across the channel by wading. At locations too deep to wade, the antennae or the transducer was attached to a 16-ft flat-bottom boat and maneuvered around the piers and across the channel. Sections were recorded across the upstream and downstream side of the bridge, along each side of each main-channel pier, and along the upstream and downstream end of each main-channel pier. The piers on the overbanks were not surveyed. To support the geophysical data, investigators probed the area around each surveyed pier with a steel pipe (0.5-in. inside diameter) to locate subsurface interfaces.

These data were assessed to identify subsurface interfaces indicating that the bed had scoured at sometime and had subsequently refilled. Because GPR and tuned-transducer records indicate interfaces where the electrical and acoustic properties change, correct interpretation of the record is critical to ensure that construction fill or other changes in subbottom material are not interpreted as scour. The data were adequate for determining the approximate location and depth of the interface; however, the data were not of sufficient resolution for the mapping of the lateral extent of refilled scour holes or for the separation of pier scour from contraction scour.

Where possible, shallow cores were collected along the upstream side of the bridge opening to verify the geophysical interpretation. These cores were collected by use of a concrete vibrator attached to 3-in. diameter thin-walled aluminum irrigation pipe. The pipe was forced into the channel bottom by the vibration and by manually weighting the pipe. The coring was successful in sand and gravel. Penetration was stopped when cobbles or larger material were encountered.

The length of the cores ranged from 1 to 10 ft. The cores, however, were compacted as a result of the vibration, and the total depth penetrated was greater than the length of the core. To establish the elevation of an interface believed to represent scour and refilling, it was assumed that the loose bed material had compacted and that the deeper, undisturbed material had not.

HISTORICAL SCOUR, FLOOD MEASUREMENTS, AND ROUTINE SOUNDINGS BY SITE

In the following section of the report, historical scour data, flood-measurement data, and routine-sounding data are given in narrative and diagrammatic form for each site. The bridge numbers in the section headings are those assigned by INDOT; the abbreviation "S.R." stands for "State Road."

Bridge 3-02-5261B, S.R. 1 over St. Marys River at Fort Wayne, Indiana

This study site is approximately 110 mi northeast of Indianapolis (fig. 1) and is in an urban area of commercial structures and residences. The rolling basin drains agricultural and urban areas.

The channel approaching the bridge is fairly straight and directs the flow through the bridge parallel to the piers. The flood plain is approximately 1,500 ft wide. The banks are lined with trees and appear to be stable. The bed material is cobbles and small boulders, covered with a thin layer of sand and gravel in the pools and in reaches of low velocity.

Historical Scour Around Bridge Piers. The bridge opening was surveyed by use of the GPR. The record indicates a thin layer of loose bed material over a denser material. This bed composition is verified by the soil borings in the bridge plans (table 2, at back of report). The borings indicate sand and gravel over a hard, silty loam. The GPR record shows a fairly uniform layer of bed material and no evidence of scouring.

The bed material was too coarse to allow vibracoring or probing. Thus, the investigators collected bed-material samples by wading and measuring the material every 6 in. across the channel. The material is predominantly cobbles and boulders with sand and gravel filling in between.

Flood Measurement and Routine Soundings. A flood measurement was made on January 2, 1991, at a discharge of 9,580 ft^3/s. Routine soundings also were made on September 8, 1990, and June 4, 1992 (fig. 2). At piers 3 and 4, debris piles accumulated and were removed by some process during the study. No pier scour was detected. The channel bottom was stable; only small changes were detected in the soundings.

In a comparison of the bed elevation from the bridge plans with the soundings made during the study, some infilling was indicated upstream and downstream from pier 3. The most obvious cause of this infilling is the accumulation of debris around the pier. The channel bottom between pier 3 and the adjacent piers shows a small amount of infilling on the downstream side and a slight scouring on the upstream side.

Bridge 9-44-4381A, S.R. 9 over Pigeon River at Howe, Indiana

This study site is approximately 150 mi northeast of Indianapolis (fig. 1) and is a rural, wooded, rolling landscape. The basin is rolling to hilly and is predominantly agricultural.

The channel is meandering but directs the flow through the bridge parallel to the bents. At the site, the flood plain is approximately 1,000 ft wide and swampy. The banks and flood plains in the vicinity of the bridge are wooded. Both banks appear to be stable. The bed material is sand and gravel, with cobbles and boulders in the sections of high velocity.

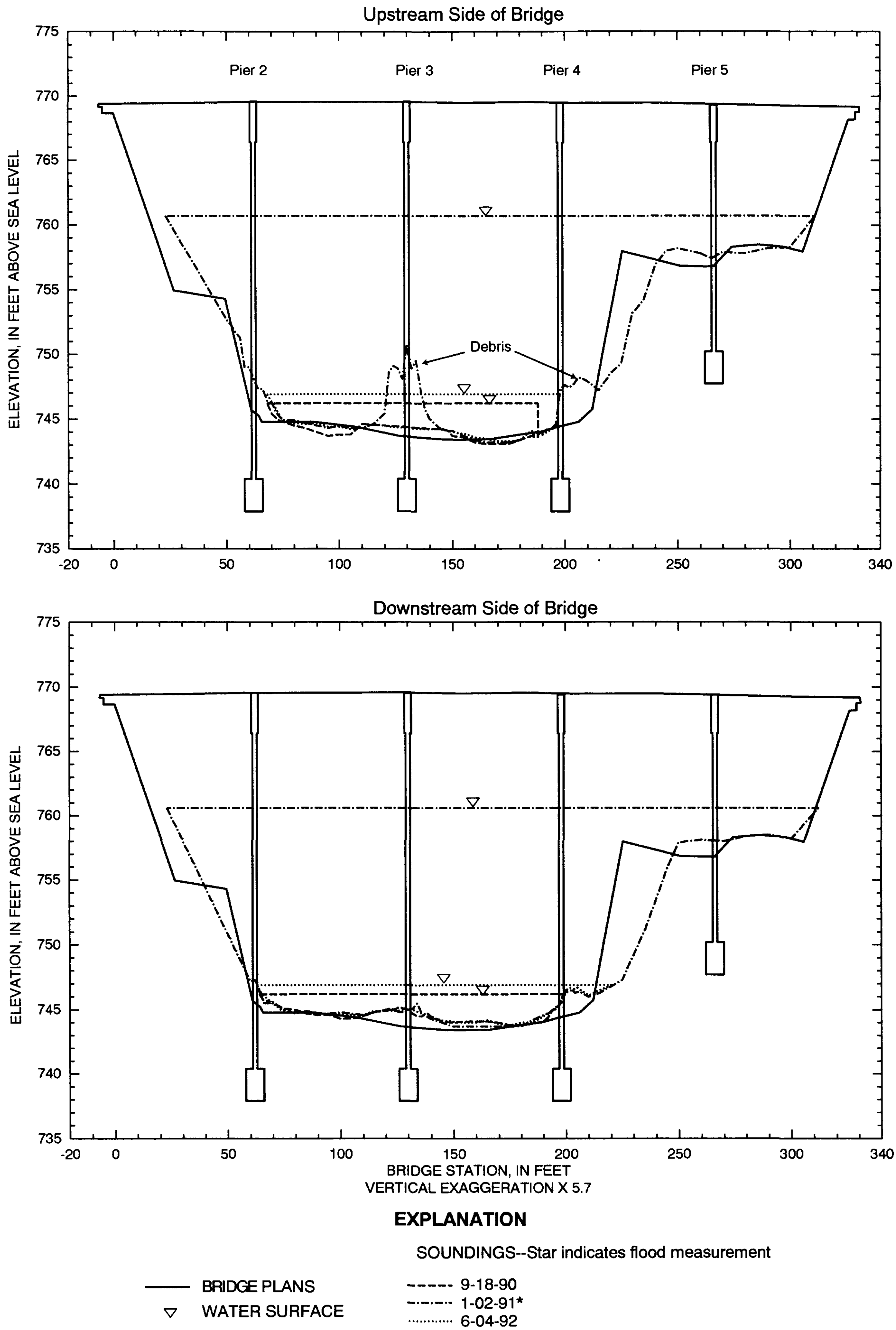


Figure 2. Cross sections showing bed elevations from bridge plans and soundings, State Road 1 over St. Marys River at Fort Wayne, Indiana.

Historical Scour Around Bridge Piers. The bridge opening was surveyed by use of the GPR and the tuned transducer. The GPR did not produce usable record. The tuned-transducer record indicates loose sand and gravel over a dense material containing cobbles or boulders. This loose layer is about 1 to 2 ft thick. The lowest elevation for the bottom of this interface, observed with the tuned transducer, was at an elevation of about 850 ft; this interface does not appear to be the result of local scour but tends to conform to the thalweg. Bridge-induced scour was not observed at this site.

The probing generally was limited to 1 to 2 ft of penetration because of the coarse bed material and hard subbottom. The deepest penetration was to an elevation of 851.5 ft at the upstream end of bent 2. The vibracoring penetrated to an elevation of 848.3 ft at this same point. The sediment cores (table 3, at back of report) and the probing verified the geophysical interpretations. The soil-boring logs from the bridge plans are summarized in table 4 (at back of the report).

Flood Measurement and Routine Soundings. A flood measurement was made on January 1, 1991, at a discharge of 1,100 ft^3/s. Routine soundings also were made on September 17, 1990, March 5, 1991, and June 3, 1992 (fig. 3). The bents remained free of debris during the study. Some shifting of the channel bottom is evident from the sounding plots. The measured cross sections differ from the bridge plans; however, the left bank and adjacent area is protected by riprap, is stable, and shows no sign of lateral movement. The right half of the bridge opening and the adjacent area appear to be less stable. This area is on the inside of a channel meander and is subject to cyclic deposition and erosion.

Bridge (11)31A-03-3039B, S.R. 11 over Flatrock River at Columbus, Indiana

This study site is approximately 40 mi south of Indianapolis (fig. 1) and is in an urban area of parks, commercial structures, and residences. The basin is rolling and predominantly agricultural.

The channel approaching the bridge is fairly straight and directs the flow through the bridge parallel to the piers. The flood plain is narrow, approximately 1,500 ft wide. The approach is confined by a railroad embankment along the left side of the flood plain and fill from a commercial building on the right.

The cross section downstream from the bridge has been altered; the park area on the left bank has been filled and regraded. Flow over the road will not rejoin the Flatrock River but will be diverted into the East Fork White River. The right bank has been filled with debris placed around a residence.

The banks upstream and downstream are lined with trees and appear to be stable. The bed material is sand and gravel.

Historical Scour Around Bridge Piers. The bridge opening was surveyed by use of the GPR and the tuned transducer. Both records indicate scouring at this site. Pier 3 is the only pier in the main channel. The area around this pier was probed, and four cores were collected (table 5, at back of report). Soil-boring logs were not available.

The geophysical record shows scour holes on both sides of the upstream end of pier 3 to an elevation of 600 ft and at a point 25 ft downstream to an elevation of 599 ft. These data are supported by results of probing; at a point 2 ft to the right and 2 ft to the left, the probe penetrated to elevations of 600.5 and 600.7 ft, respectively; at a point 3 ft downstream from the pier, the probe penetrated to an elevation of 598.4 ft.

Core 11-2 (table 5) penetrated to an elevation of 599.2 ft, where a firm surface was reached. The material collected in the core is very similar to the bed material on the surface, an indication that the bed may have scoured to bottom of the core and refilled. Core 11-3 (table 5) penetrated to an elevation of 598.6 ft, where a firm surface was reached. The lower 1.2 ft of material is consistent

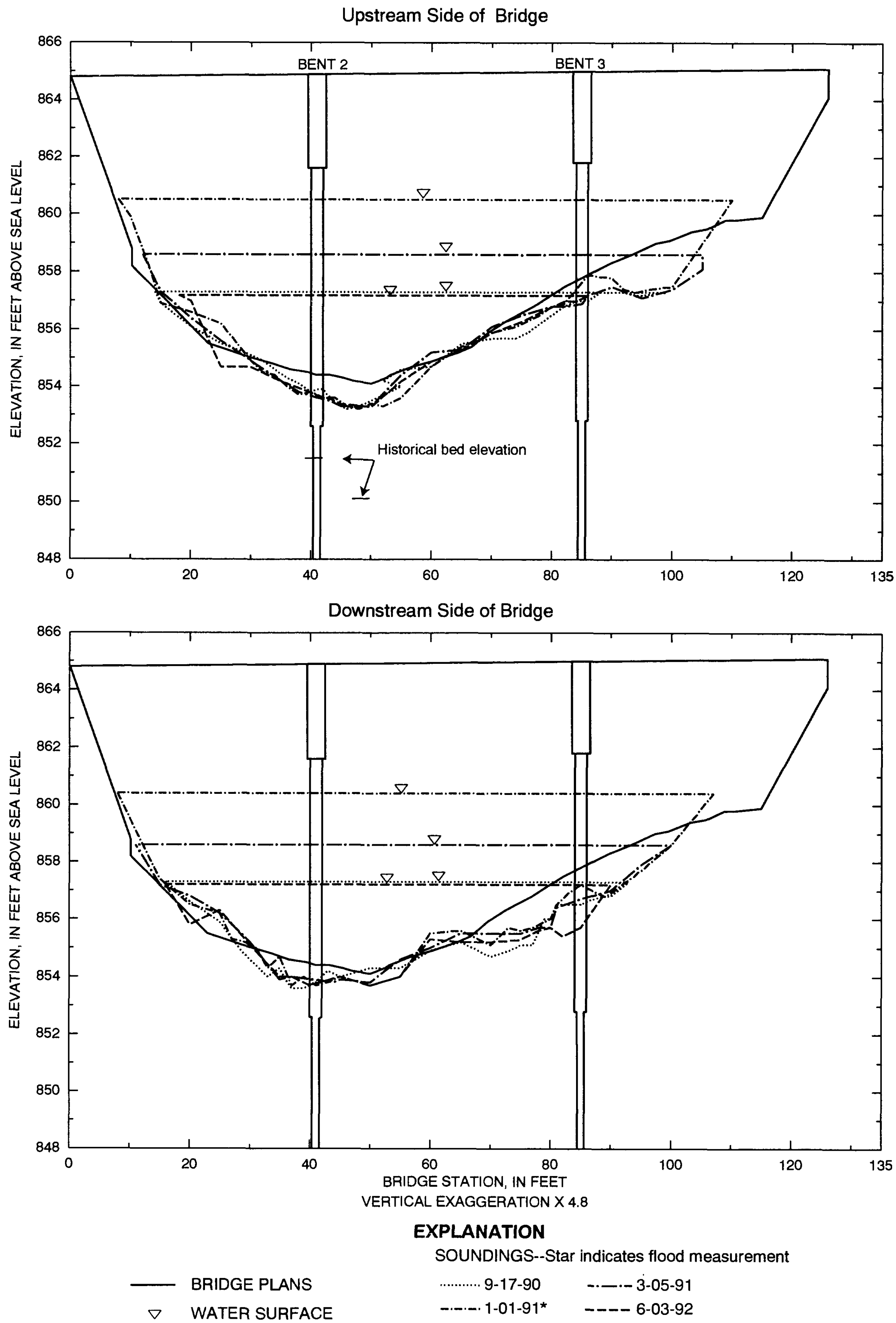


Figure 3. Cross sections showing bed elevations from bridge plans and soundings, State Road 9 over Pigeon River at Howe, Indiana.

with backfill from the construction of the bridge. The upper 0.7 ft is similar to the surface-bed material, an indication that the bed has scoured to an elevation of 599.9 ft.

Flood Measurement and Routine Soundings. A flood measurement was made on July 31, 1992, at a discharge of 3,460 ft^3/s. Routine soundings also were made on September 20, 1990, February 11, 1991, and June 10, 1992 (fig. 4). The piers remained free of debris during the study. Soundings indicate that changes in the bed elevations are due to the movement of bed material. The probing and sounding data indicate an item buried in the bed material at the upstream end of pier 3. This buried item is depicted as a spike in figure 4.

The soundings indicate some movement of bed material around pier 3. During the flood measurement, the scour was measured to an elevation of 600 ft at the upstream end of pier 3; this equals the maximum observed scour in the geophysical record at that point. These data may indicate that the measured flood lifted the loose material from an existing scour hole and did not create a new hole. At the downstream end of pier 3, the scour was measured at 601 ft, which was higher than the maximum scour observed in the geophysical record.

Bridge 14-66-3459A, S.R. 14 over Tippecanoe River at Winamac, Indiana

This study site is approximately 100 mi north of Indianapolis (fig. 1) and is in an urban area of commercial structures and residences. The basin is rolling to flat and is predominantly agricultural. The basin contains numerous small lakes that affect the peak flows; the upper 100 mi^2 is affected most.

The channel approaching the bridge is fairly straight and directs the flow through the bridge parallel to the piers. The flood plain is narrow, approximately 800 ft wide. The banks are lined with trees and appear to be stable. The bed material is sand and gravel.

Historical Scour Around Bridge Piers. The bridge opening was surveyed by use of the GPR and the tuned transducer. The GPR did not produce usable record. The tuned-transducer record indicates small scour holes at the right upstream corner and at the left downstream corner of pier 4. The right upstream corner is scoured to an elevation of about 674 ft; the left downstream corner is scoured to about 675 ft.

The probing penetration at pier 3 ranged from 1.4 to 9.2 ft. The lowest elevation reached by probing at pier 3 was 679.8 ft at a point 2 ft downstream from the downstream end of the pier. At pier 4, the penetration ranged from 0.2 to 2.7 ft. The lowest elevation reached was 674.2 ft at a point 3 ft to the right of the downstream end of pier 4. At pier 5, the penetration ranged from 1.9 to 6.8 ft. The lowest elevation reached was 672.1 ft at a point 4 ft left of the of the pier center.

Five cores (table 6, at back of report) were collected at this site. The only core collected in the vicinity of the observed scour was at pier 4. This core is believed to be within the area excavated during the pier construction and includes evidence of the backfilling. Soil-boring logs from the bridge plans are summarized in table 7 (at back of report).

Routine Soundings. Routine soundings were made on September 12, 1990, and March 4 and June 2, 1992 (fig. 5). No debris was observed within the bridge opening during the study. The channel bottom was fairly stable, showing some infilling in the left half of the opening during the study. A comparison of the bed elevations established from soundings to the design elevations from the bridge plans indicate some movement of bed material. The right half of the opening has scoured as much as 1 ft; the left half has scoured and filled but remains within about 1 ft of the original elevations. The scouring appears to be general movement of bed material.

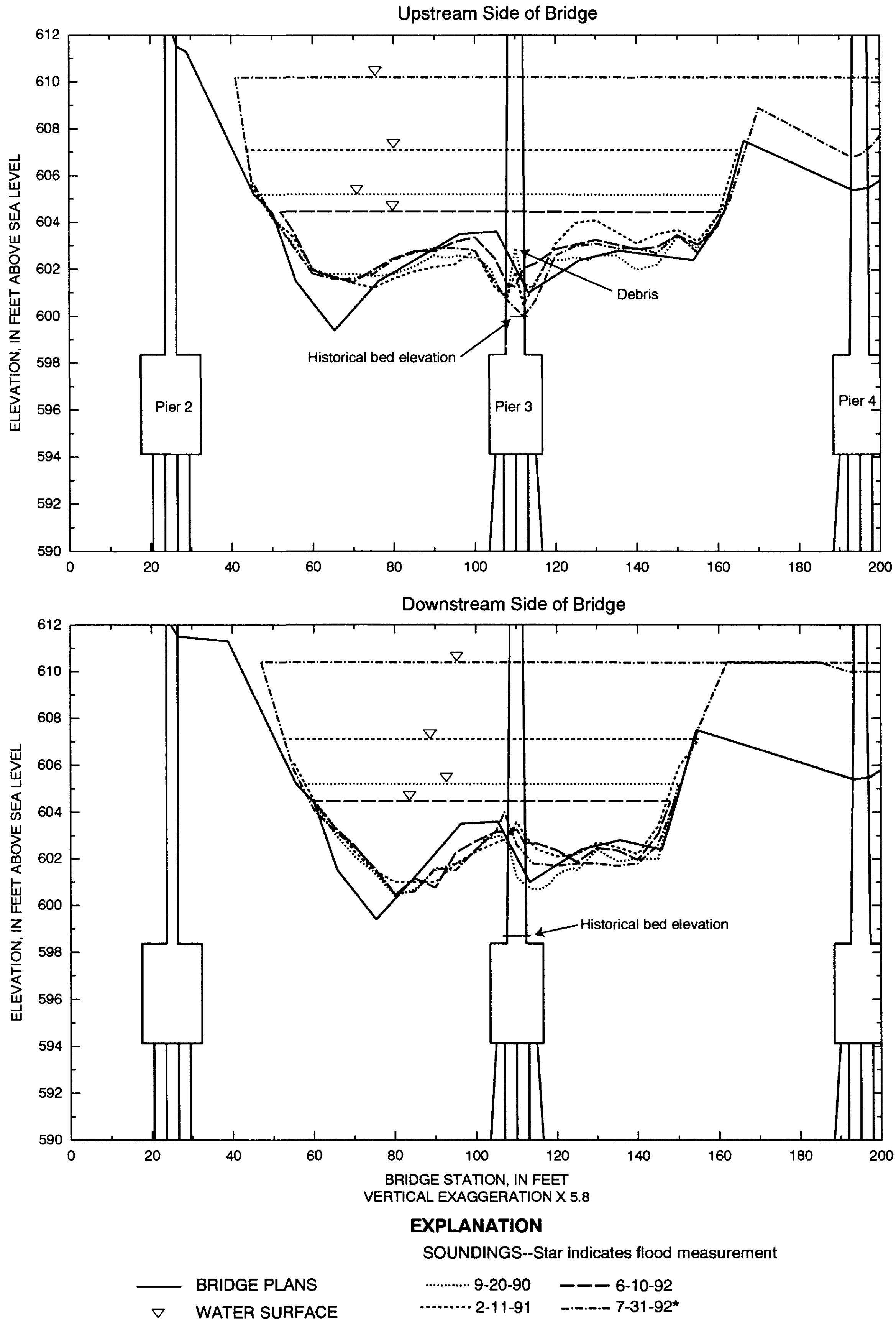


Figure 4. Cross sections showing bed elevations from bridge plans and soundings, State Road 11 over Flatrock River at Columbus, Indiana.

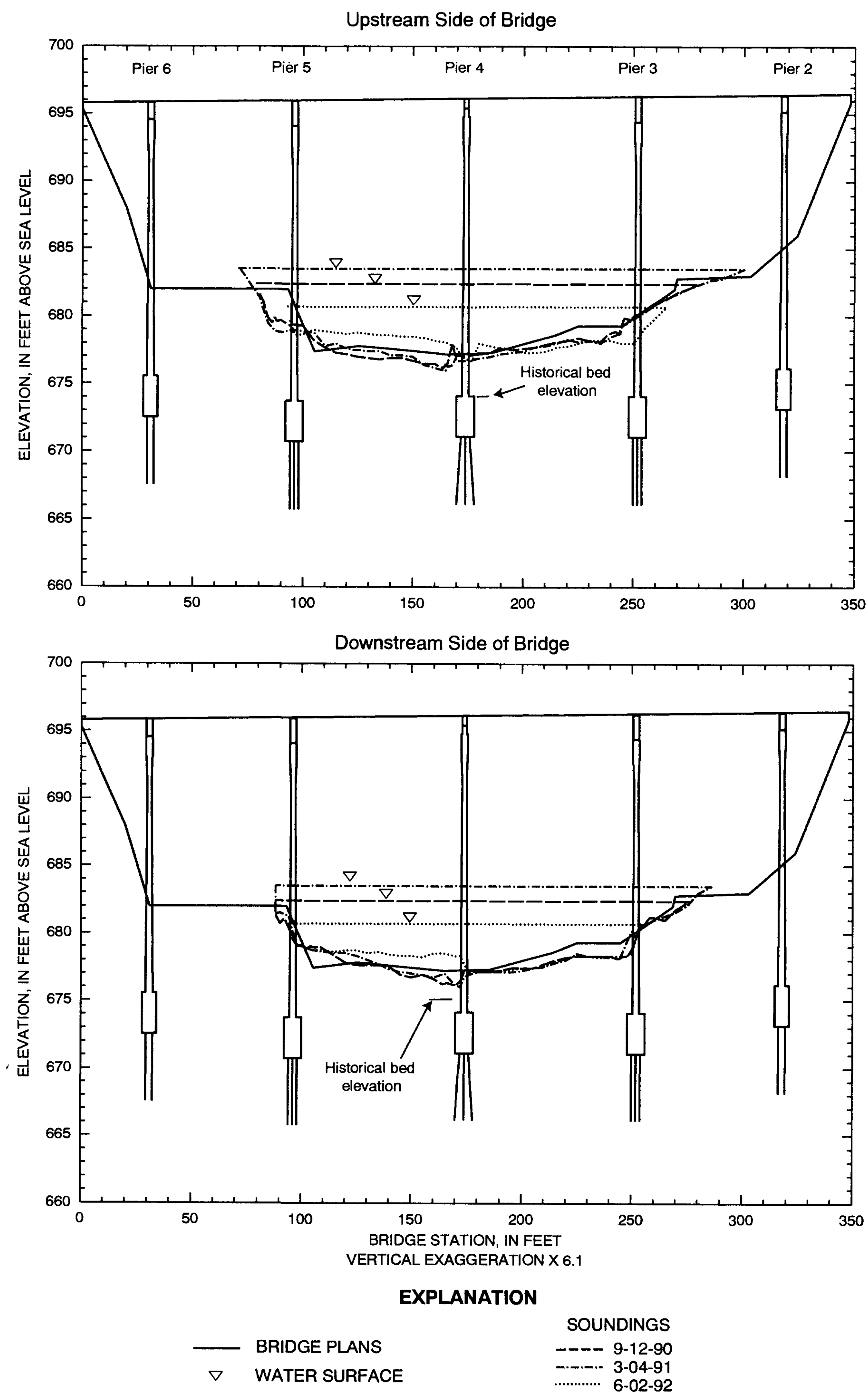


Figure 5. Cross sections showing bed elevations from bridge plans and soundings, State Road 14 over Tippecanoe River at Winamac, Indiana.

Bridge 15-20-1664A, S.R. 15 over Little Elkhart River at Bristol, Indiana

This study site is approximately 135 mi north of Indianapolis (fig. 1) and is in a residential urban area. The basin is rolling and drains agricultural and wooded areas. Small lakes are scattered throughout the basin.

The channel is meandering but directs the flow through the bridge opening parallel to the piers. The flood plain is narrow, approximately 800 ft wide. The banks are lined with trees and appear to be stable; the overbanks are wooded. The bed material is sand and gravel.

Historical Scour Around Bridge Piers. The bridge was surveyed by use of the GPR; the water was too shallow for the tuned transducer. Along the upstream face of the bridge, interfaces were detected between elevations of 739 and 743 ft. Along the downstream face, the interfaces ranged from 736 to 739 ft. One set of interfaces is below the present thalweg and may represent an old thalweg that has refilled.

Three cores (table 8, at back of report) were collected at the upstream face of the bridge—one at the upstream end of the pier and one at the midpoint between the pier and each abutment. Core 15-3 (table 8), collected between the pier and the right abutment, shows infilling with organic material from 740 to 743.9 ft; this is comparable to the geophysical record. The soil-boring logs from the bridge plans are summarized in table 9 (at back of report).

The probe, penetrated to an elevation of 739.5 ft at a point 2 ft upstream and in line with the left edge of the upstream end of the pier. The probing to this interface confirms the geophysical interpretation.

Routine Soundings. Routine soundings were made on December 12, 1990, March 5, 1991, and June 3, 1992. No debris was observed within the bridge opening during the study. The channel bottom was stable during the study; only slight movement of the bed material is evident in the soundings (fig. 6). A comparison of the soundings with the contour elevations shown on the bridge plans (dated July 1941) indicates some scouring of the bottom. The upstream side of the bridge is consistently lower than indicated on the plans. The plots on the downstream side of the bridge show very little movement of the bed material except for the thalweg, which is between the pier and the left abutment.

Bridge 19-52-6617, S.R. 19 over Wabash River at Peru, Indiana

This study site is approximately 70 mi north of Indianapolis (fig. 1) and is in an urban area of commercial structures. The basin is rolling to hilly and drains predominantly agricultural and wooded areas. Three flood-control reservoirs—Huntington Lake, Salamonie Lake, and Mississinewa Lake—are in this basin.

The channel in the vicinity of the bridge has been straightened and is confined by fill and retainer walls. The bridge spans the entire waterway; therefore, it is not a constriction to the flow of water. The flow through the bridge is parallel to the piers. The banks are riprap, grass, and concrete walls intermixed; there is a scattering of trees. The banks appear to be stable. The bed material is predominantly cobbles and boulders overlain by approximately 0.1 ft of sand and gravel.

Historical Scour Around Bridge Piers. The bridge was surveyed by use of the GPR and the tuned transducer. The GPR did not produce usable record. The tuned-transducer record indicates scour holes along the sides of both piers; evidence indicates these holes were caused by flow around debris. The bed material is too coarse to allow probing or vibracoring. At this site, the piers are set in bedrock covered with about 10 ft of erodible material. The elevation of bedrock is about 610 ft, according to the soil-boring logs from the bridge plans (table 10, at back of report).

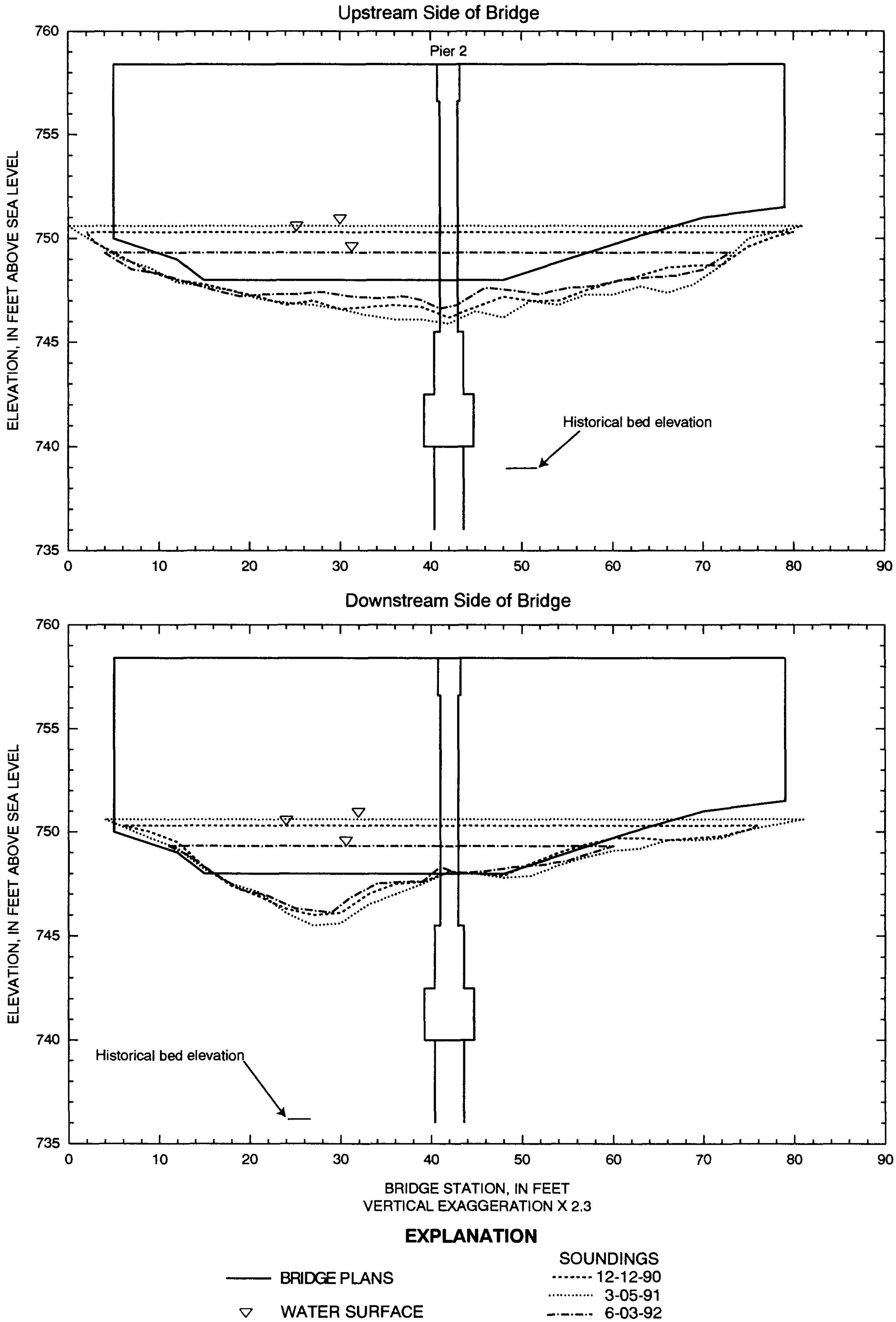


Figure 6. Cross sections showing bed elevations from bridge plans and soundings, State Road 15 over Little Elkhart River at Bristol, Indiana.

At pier 2, the geophysical record indicates a scour hole along both sides of the pier to an elevation of 618 ft. Some debris is visible in the geophysical record. Along the left side of the pier, the scouring of the channel bottom extends to a point about 75 ft upstream from the pier. At the upstream end of this scour, some debris or a point reflector is visible on the channel bottom. The deepest point of this scour is along the left side of the pier at a point one-third of the pier length upstream from the downstream end of the pier.

The scouring along the right side of pier 2 appears to extend to about the same depth, but the record is obscured by reflection from debris above the hole. This debris appears to be on the channel bottom. Along the right side, the scouring does not extend as far upstream as on the left side. The scouring appears to start about 25 ft upstream and extend to a point about halfway down the pier. The deepest part of the scour is at a point about one-third the length of the pier downstream from the upstream end of the pier.

At pier 3, scouring is evident along both sides of the pier. Along the left side of pier 3, at a point about 5 ft downstream from the upstream end, a hole with a bottom elevation of about 618 ft was observed (at the time of the survey, August 15, 1990). The geophysical record indicates little or no infilling. The hole was slightly deeper on the survey pass 20 ft left of the pier than it was on the pass 5 ft left of the pier. A debris pile was removed 2 days before the geophysical survey was done. Along the right side of pier 3 at a point 20 ft downstream from the upstream end, a hole was observed with a bottom elevation of about 619 ft. This hole was partly refilled. Debris was visible on the channel bottom from the area around the hole to a point several feet upstream from the pier. Because of the distance of the hole on the right and because debris was observed, the debris is assumed to be a significant factor in this scouring.

Routine Soundings. Routine soundings were made on September 19, 1990, March 6, 1991, and June 21, 1992. Large debris piles were recorded at pier 3 in all soundings (fig. 7). This debris was removed by INDOT, but more debris accumulated. Some debris was observed on pier 2, and soundings at the edges of this debris indicate scour and filling. Bed elevations are not available below the debris; however, the field observations indicate that the debris collected on the channel bottom and within the water column, forcing the flow to the outside of this debris. Around this debris, the deepest scour was along the edges.

The 1990 soundings indicate a hole with a bottom elevation of 618 ft adjacent to the debris at pier 3. Based on the geophysical survey, this is the maximum scour observed. This hole refilled after the debris was removed. The soundings indicate that the scouring follows the edge of debris and moves with the accumulation and removal of debris. The scour seems to be associated closely with the accumulation of debris and may not be attributed to the pier alone. Therefore, the pier-scour equations discussed later in this report may not be applicable to these observed holes because the equations do not consider debris. Soundings on the downstream face of the bridge indicate a stable channel bottom during the study. Based on the bed elevations from the bridge plans, the holes noted at the time of construction appear to have filled.

Bridge 25-79-3881, S.R. 25 over Wildcat Creek at Lafayette, Indiana

This study site is approximately 60 mi northwest of Indianapolis (fig. 1) and is in an urban area of commercial structures and residences. The basin is rolling to flat and drains predominantly agricultural areas.

The channel approaching the bridge curves sharply to the left and directs the flow through the bridge at an angle of 10° to 14° to the piers. The channel is filling with sand and gravel on the left side. Vegetation is growing on this gravel bar.

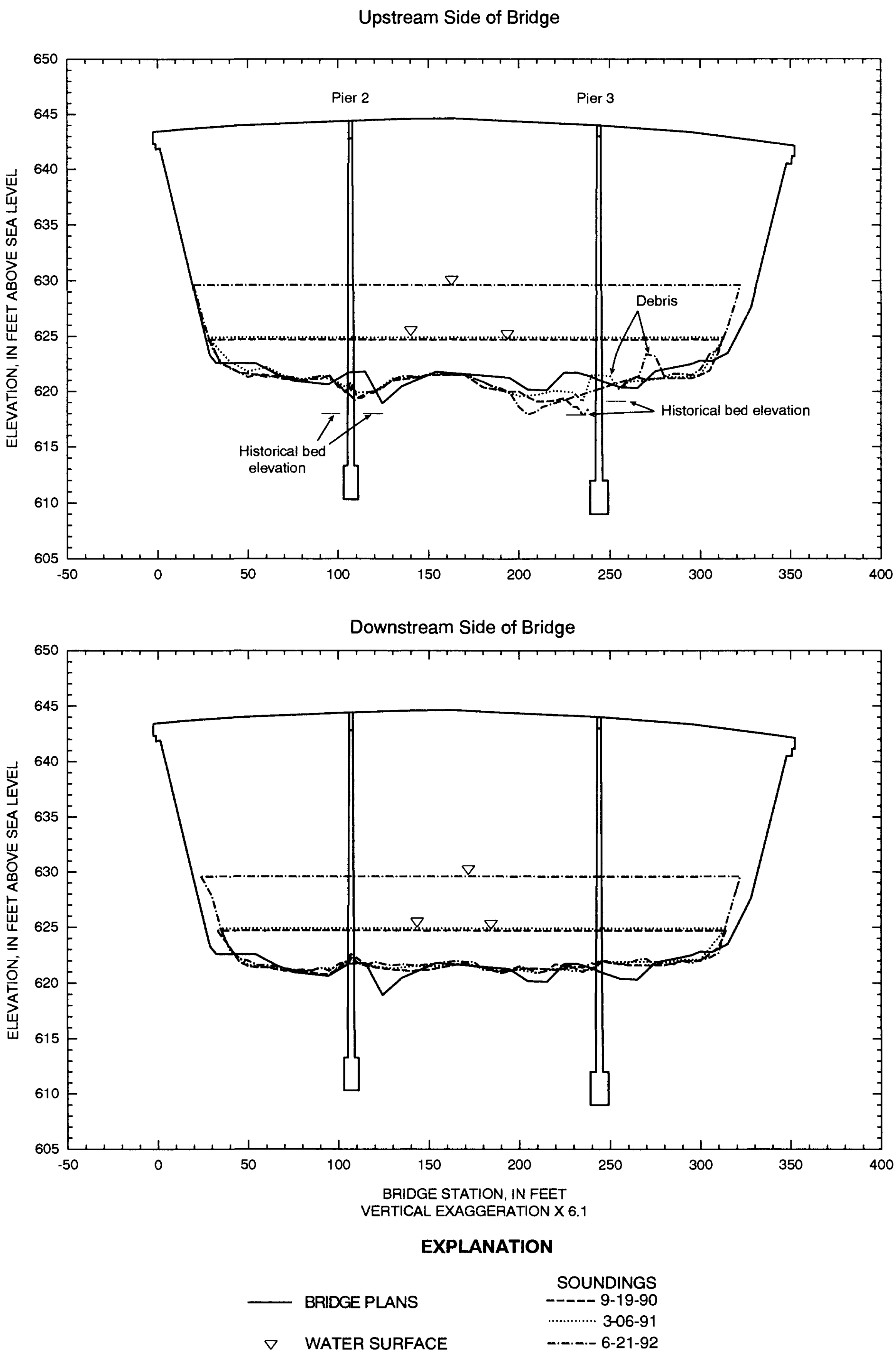


Figure 7. Cross sections showing bed elevations from bridge plans and soundings, State Road 19 over Wabash River at Peru, Indiana.

In the vicinity of the bridge opening adjacent to the low channel, gravel was mined from the gravel bar during this study. The flood plain is about 600 ft wide.

The banks of the main channel are lined with trees and appear to be stable, except for an area along the right bank about 300 ft upstream from the bridge opening. This area deflects the flow as it curves to the left and, as a result, is eroding. Pier 6 downstream from this area is surrounded by boulders. The bed material is sand, gravel, and cobbles.

Historical Scour Around Bridge Piers. The bridge was surveyed with the GPR and the tuned transducer. The GPR did not produce usable record. The tuned-transducer record shows an interface between the loose bed material and a firmer subbottom. Scour holes were not indicated at the upstream end of the piers within the low-water channel. The lowest point at which the interface was observed within the channel at the upstream face of the bridge was 515 ft. At the downstream face, the lowest point for this interface was 516 ft. Along the left side of pier 6 at a point about one-fourth of the pier length downstream from the upstream end, this interface dips to an elevation of 516 ft. This low point is believed to be the thalweg rather than local scour.

Three cores were collected at this site. The first core, collected at the upstream nose of pier 3, recovered silts, clays, and sand that were the result of infilling since the bridge was built. The second core was collected at the upstream end of pier 5; the third core was collected in the low-water channel. Neither of these cores was able to penetrate the coarse layer of the surface material; therefore, no meaningful sediments were collected. The logs of the cores are not shown. The soil-boring logs from the bridge plans are summarized in table 11 (at back of report).

The area around piers 5 and 6 was probed. The lowest point reached at pier 5, elevation 517.1 ft, was along the right side, one-fourth the length of the pier downstream from the upstream end. Results from probing are compatible with the geophysical interpretation. The lowest point reached around pier 6, elevation 516.8 ft, was at a point along the left side at the middle of the pier.

Flood Measurement and Routine Soundings. A flood measurement was made on July 14, 1992, at a discharge of 9,270 ft^3/s. Routine soundings also were made on September 5, 1990, March 4, 1991, and June 8, 1992 (fig. 8). During the period of the study, debris was not a problem at this site; small amounts of debris were removed when found during site visits. To the right of the thalweg, the channel bottom is stable, and the soundings indicate little change in bed elevation. In the left part of the low-water channel, however, the soundings indicate some change in bed elevation. Small scour holes are evident at the upstream nose of pier 5. At the time of the soundings on June 8, 1992, only a small hole with a bottom elevation of 522.0 ft was evident along the right side of this pier. In 1991, the hole had a bottom elevation of about 521.1 ft, deeper than any other soundings made at this pier. This hole developed sometime between September 5, 1990, and March 4, 1991 (a peak discharge of 16,900 ft^3/s occurred on December 31, 1990). The flood measurement of July 14, 1992, documents a hole with a bottom elevation of 521.7 ft. This measurement and the hole documented in 1991 are about 1.5 ft below the average bed elevation adjacent to the pier. The channel-bottom elevation from the bridge plans, however, is about 521.5 ft at this location. This elevation indicates that the holes have formed in material deposited after the bridge was built.

Gravel was mined from the gravel bar along the left side of pier 5 before the soundings made on June 8, 1992. Tire marks made from equipment used to remove the gravel were visible at the time of the soundings. Gravel was removed from the streambed, starting at the left side of this pier and extending about 100 ft left. The removal started

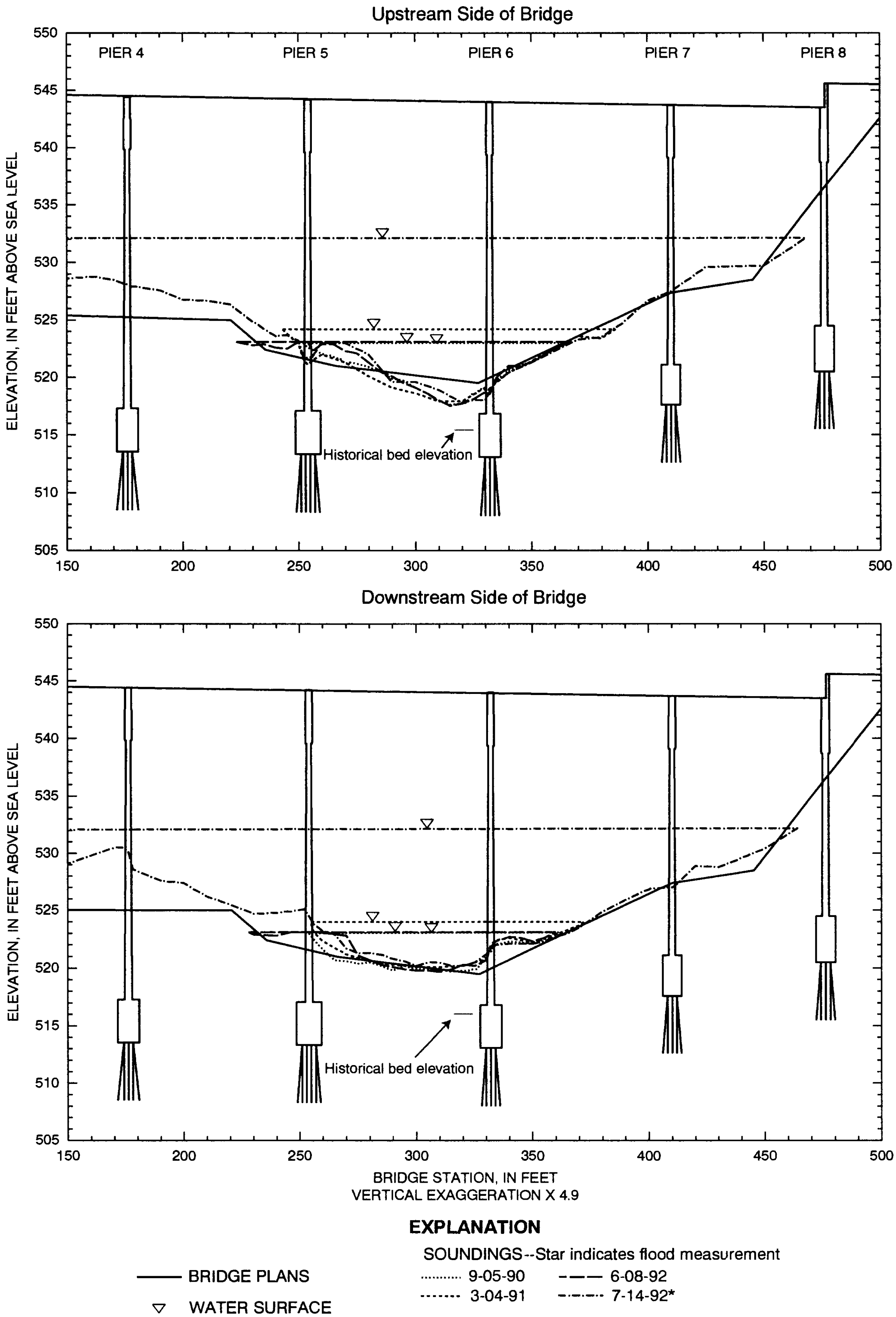


Figure 8. Cross sections showing bed elevations from bridge plans and soundings, State Road 25 over Wildcat Creek at Lafayette, Indiana.

about 50 ft upstream from the bridge and extended to a point about 100 ft downstream from the bridge. The site was not surveyed before the high-water measurement was made in July. The soundings made during the measurement matched the survey elevations at the beginning of the study, indicating that material had been deposited.

Bridge 32-83-6771A, S.R. 32 over Wabash River at Perrysville, Indiana

This study site is approximately 75 mi west of Indianapolis (fig. 1) and is in a rural area of cultivated land and residences. The basin is predominantly rolling to hilly and drains agricultural and wooded areas. Three flood-control reservoirs—Huntington Lake, Salamonie Lake, and Mississinewa Lake—are in this basin.

The channel approaching the bridge curves gradually to the left. The piers are skewed to the flow at a 15° angle. The flood plain is about 0.75 mi wide. The banks of the main channel are lined with trees and appear to be stable. The bed material is sand.

Historical Scour Around Bridge Piers. The bridge opening was surveyed by use of the tuned transducer. The water was too deep for the GPR. The pattern in the geophysical record is chaotic, indicating an unstable channel bottom with considerable scouring and infilling within and adjacent to the bridge opening. Areas approximately 40 ft downstream from the piers have scoured to an elevation of 460 ft. The bed has scoured to an elevation of 463 ft adjacent to a large debris pile on the upstream side of pier 6. The areas around the piers were probed to support the geophysical data, but the water was too deep for vibracoring at this site. The soil-boring logs from the bridge plans are summarized in table 12 (at back of report).

At pier 4, the geophysical record indicates that the channel bottom has scoured to an elevation of 464 ft at the downstream end of the pier. The record on the upstream end and along the sides is chaotic, and the interpretation is inconclusive. An interface is visible at about 468 ft at the upstream end of the pier, but the record is not adequate to assign this elevation to the bottom of a scour hole. The probing at this pier indicates loose material to an elevation of 464.1 ft at a point 5 ft downstream from the downstream end of the pier. The lowest elevation reached by probing along the sides was 462.6 ft at a point 6 ft left of the center of the pier. The lowest elevation reached by probing at the upstream end of the pier was 464.0 ft at a point 4 ft upstream from the end of the pier and 8 ft to the right of the upstream end of the pier.

At pier 5, the geophysical record indicates that the bed material has scoured to an elevation of 460 ft at the downstream end of the pier. The record on the upstream end and along the sides is chaotic, and the interpretation is difficult. The geophysical record shows an existing hole along the right side, 10 ft downstream from the upstream end of the pier. The bottom elevation is 467 ft, and the best estimation of the subbottom elevation is 465 ft. At a point 5 ft downstream from the downstream end, the probe penetrated to an elevation of 462.2 ft. At 16 ft left of the center of the pier, the probe penetrated to an elevation of 460.9 ft. Closer to pier 5, the probe hit the top of the footing. At 16 ft to the right of the upstream end of pier 5, the probe penetrated to an elevation of 463.8 ft. The bottom of the footing is 461.4 ft.

At the time of the geophysical survey, a large debris pile had formed on the upstream end of pier 6 and extended along the left side of the pier. Therefore, the survey followed the outside limits of this debris. At a point 10 ft to the right from the upstream end of pier 6, the record indicates scour to an elevation of 463 ft. At the downstream end of pier 6, the record indicates scouring to about 469 ft. At a point 8 ft to the right from the upstream end of pier 6, the probe penetrated to an elevation of 462.0 ft, consistent with the geophysical record. At 4 ft downstream from the downstream end of pier 6, the probe penetrated to an elevation of 466.4 ft, deeper than the interface detected in the geophysical record.

The soil boring from bridge plan logs (table 12) indicates that the bed material is loose to medium-dense sand to an elevation of 453 to 461 ft in the main channel. It is possible that the probe penetrated this loose layer and that the interface is not an indicator of past scouring. A geophysical cross section surveyed 500 ft upstream from the bridge opening, however, does not show the chaotic pattern seen in the bridge opening. The loose material indicated in the patterns within the bridge opening is limited to the upper few feet in the section surveyed 500 ft upstream. Therefore, the interfaces identified in the bridge opening are interpreted to be the result of past scouring.

Flood Measurement and Routine Soundings. A flood measurement was made on January 1, 1991, at a discharge of 78,700 ft^3/s. Routine soundings also were made on September 24, 1990; January 2, January 15, and February 13, 1991; and June 17, 1992 (fig. 9). Small amounts of debris accumulated and were removed by some process at pier 5.

A large debris pile was present at pier 6 throughout most of the study. This debris was removed between November 15 and November 22, 1991, under a maintenance contract administered by INDOT. This debris probably affected the scouring considerably. The debris was not present when the site was surveyed in June 1990 or when the soundings were made on June 17, 1992. The plot of these soundings shows deposition when compared to soundings when the debris was present. The sounding plots after the debris was collected show about 8 ft of scour along the right side of the pier. This scour developed between June 1990 and September 24, 1990. Streamflow record at Covington, about 5 mi upstream from this study site, indicates that a daily mean discharge of 29,400 ft^3/s occurred on August 23, 1990. This discharge was the highest flow recorded for this 4-month period, and is probable that the debris collected and that the scour occurred during this high-water event. The soundings during the January 1, 1991, flood and during the recession show no deepening or infilling of this scour hole; however, the bed elevation lowered about 3.5 ft between the deepest part of the scour hole and the adjacent pier to the right. Because the flow is skewed to the piers, the debris could have deflected the flow to this area.

At pier 5, a scour hole developed during the recession of the January 1991 flood. Soundings made on January 1, 1991, indicate that this hole was not present on the flood peak. The flow is skewed to this pier at about a 15° angle, flowing from left to right. The hole, however, is on the right side—the lee side—of the pier. Smaller holes are indicated on the soundings made on September 24, 1990, and June 17, 1992. The field notes from routine soundings indicate debris at this pier on September 24, 1990, January 15, 1991, and February 13, 1991, but the flood-measurement notes do not mention debris at this pier. These data tend to support the hypothesis that the scour is debris induced.

At pier 4, small scour holes are evident upstream from the pier. From the soundings, the elevation at the upstream end of this pier is higher than the original bottom elevation in the bridge plans. Though these holes appear to be typical scour holes, the process leading to their development may be deposition. A large hole adjacent to the right bank has been observed to form and refill. This hole is documented by the soundings on the upstream and downstream side of the bridge. Geophysical sections surveyed upstream and downstream from the bridge show no evidence of this hole. The data collected for this study are insufficient to develop an explanation for this hole.

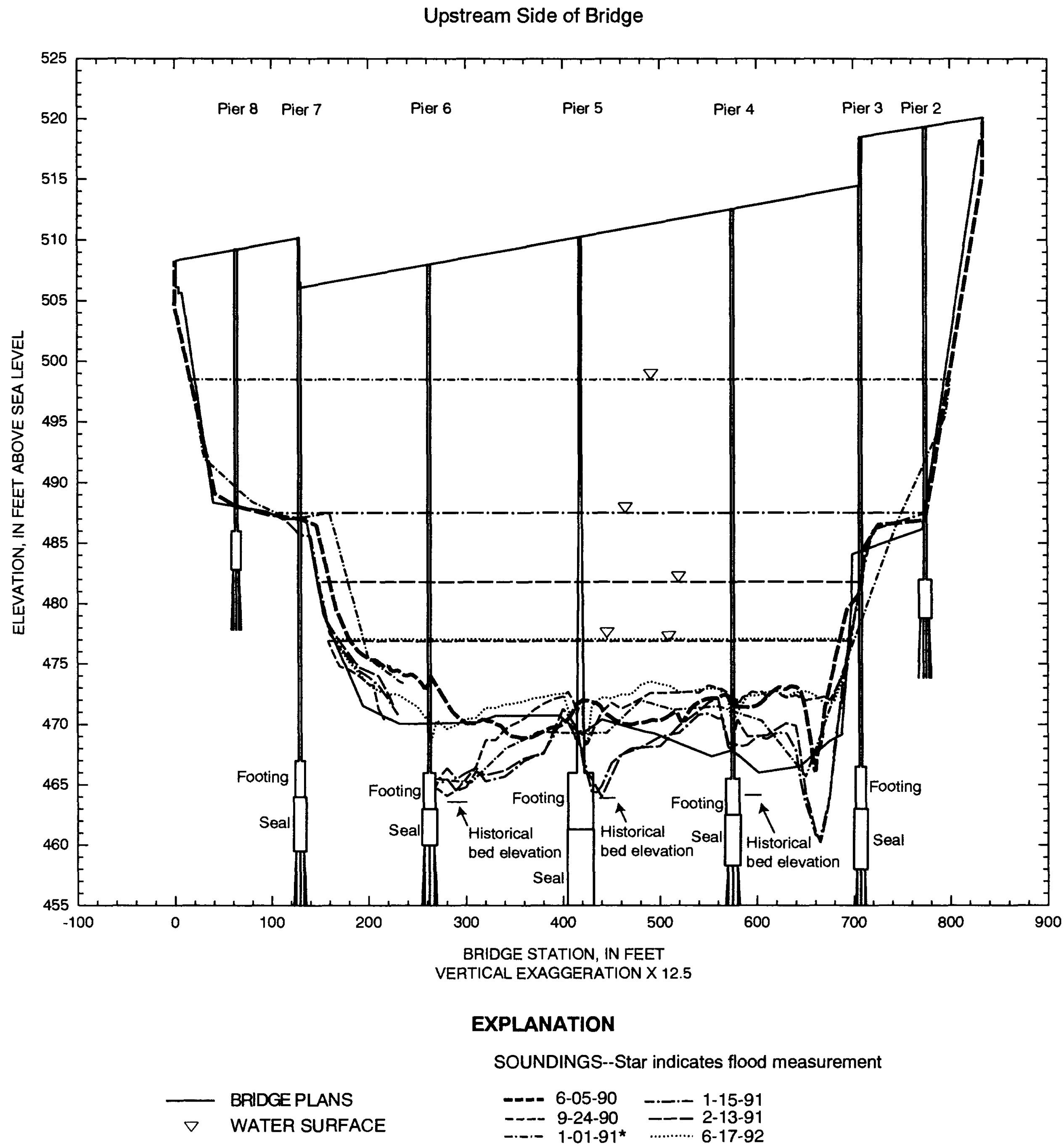


Figure 9a. Cross sections showing bed elevations from bridge plans and soundings, State Road 32 over Wabash River at Perrysville, Indiana.

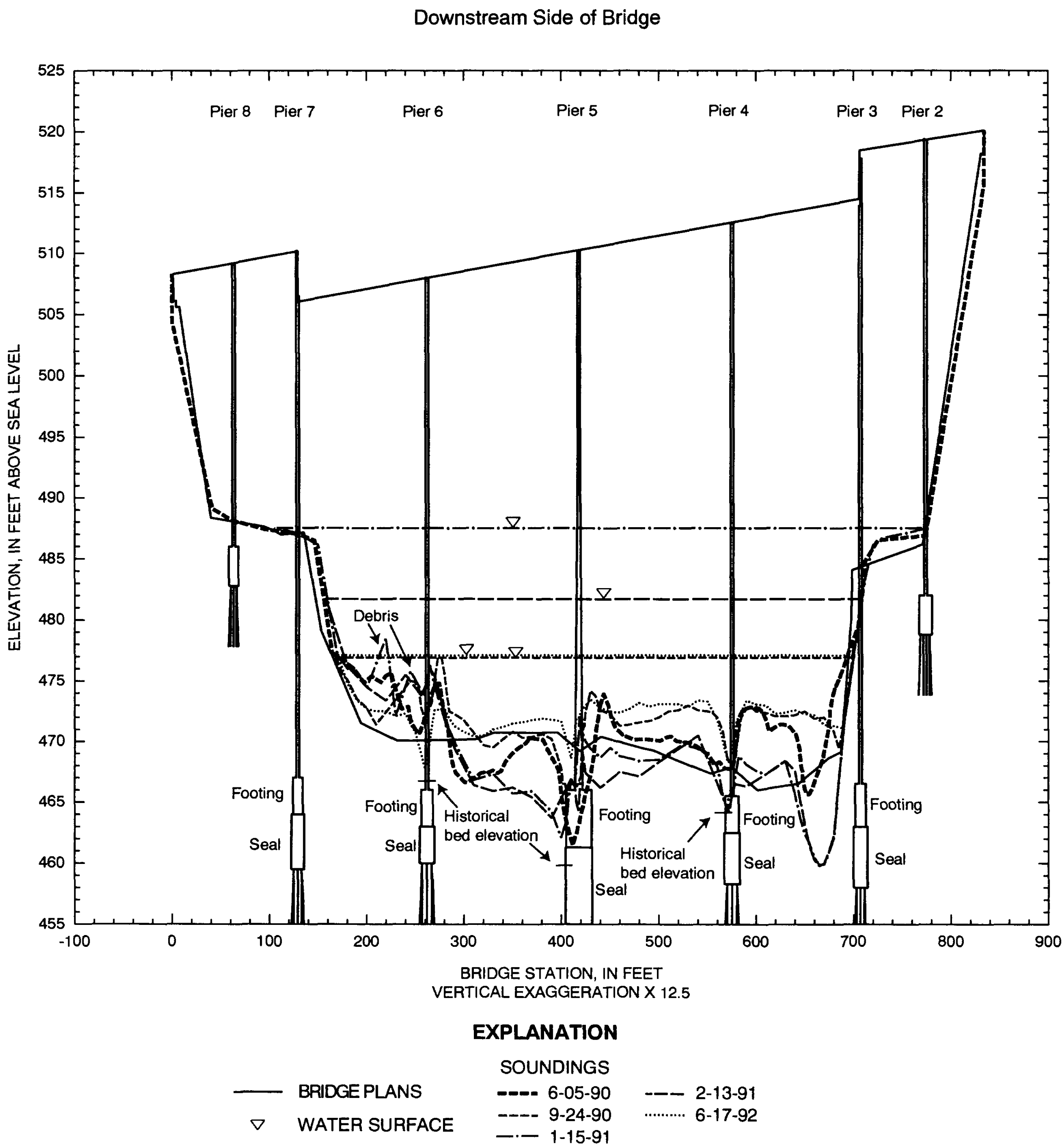


Figure 9b. Cross sections showing bed elevations from bridge plans and soundings, State Road 32 over Wabash River at Perrysville, Indiana--Continued.

On the downstream side of the bridge, the sounding plots show large scour holes at piers 4, 5, and 6 in the main channel. At pier 6, the bed elevations are all above the bed elevation shown in the bridge plans. One exception is the hole documented by the soundings made on June 17, 1992 (after the debris was removed). The plots show scour-shaped holes within the deposition on the left and deposition on the right. This area is on the inside of the meander and, given the debris conditions at this pier, appears to have been subjected to scour and deposition.

Along the left side of pier 5, the plots of the downstream soundings indicate scour holes as deep as the bottom of the footing; however, the footing is set on top of a seal. These holes appear to scour and fill as flow and (or) debris conditions vary. The deepest hole documented by the plots was in June 1990, when the bridge was surveyed. The hole filled about 4 ft, as inferred from the September 24, 1990, soundings and reappeared almost as deep, as inferred from the January 15, 1991, soundings that were made during the recession of the January 1, 1991, flood.

At pier 4, the sounding plots indicate conditions similar to those at the other piers. As indicated in the plots from routine soundings on January 15, 1991, and February 13, 1991, scour is evident on the left side of the pier to a point below the top of the footing. Soundings made at low-flow conditions indicate scour-shaped holes within deposition. As noted for the previous piers, deposition is shown for the right side of the pier.

The deepest scour recorded at pier 6 was at the right edge of the debris at the upstream side of the bridge. At pier 5, the deepest scour was at the downstream left corner. At pier 4, the deepest scour was at the downstream left corner. For the hole adjacent to the right bank, the deepest point measured was downstream. The scour at the piers does not relate to the highest flow. The scour at pier 6 seems to be debris controlled; at piers 4 and 5, the scour appears to have occurred during the recession. The hole along the right bank probably developed with the flood rise of January 1, 1991, but it may be the result of loose material being removed from a previous hole.

Bridge 35-46-5899, U.S. Route 35 over Kankakee River at Union Center, Indiana

This study site is approximately 125 mi northwest of Indianapolis (fig. 1) and is in a rural area of cultivated fields and residences. The basin is rolling to flat and drains predominantly agricultural areas.

The channel is dredged and uniform in shape, and it directs the flow through the bridge at an 8° angle to the bents. Along the channel are spoil banks that function as levees and contain the flow. The bridge spans from levee to levee and does not create a constriction to the flow. Both banks are lined with trees and appear to be stable. The bed material is sand.

Historical Scour Around Bridge Piers. The bridge opening was surveyed by use of the tuned transducer and the GPR. The GPR did not produce any usable record. The tuned transducer record, however, indicates soft material over a firmer subbottom; this soft material is believed to represent gradual infilling since the dredging and straightening of the channel was completed in 1917. The area around both bents was probed, and cores (table 13, at back of report) were collected at the upstream face of the bridge. The probe penetrated several feet, again indicating that the bottom is loose sand; this interpretation is supported by the cores. None of the data indicates that scouring has occurred at this site. The soil-boring logs from the bridge plans are summarized in table 14 at (back of report).

Flood Measurement and Routine Soundings. A flood measurement was made on January 1, 1991, at a discharge of 1,600 ft^3/s. Routine soundings also were made October 10, 1990, March 4, 1991, and June 2, 1992 (fig. 10). During the period of the study, debris was not a problem at this site (small amounts were removed when found during site visits). The sounding plots indicate movement of the bed material; however, no scour at the bents is apparent. The sounding plots for the flood measurement indicate infilling upstream and downstream from the bridge. The bed elevations are about the same as the elevations shown on the bridge plans.

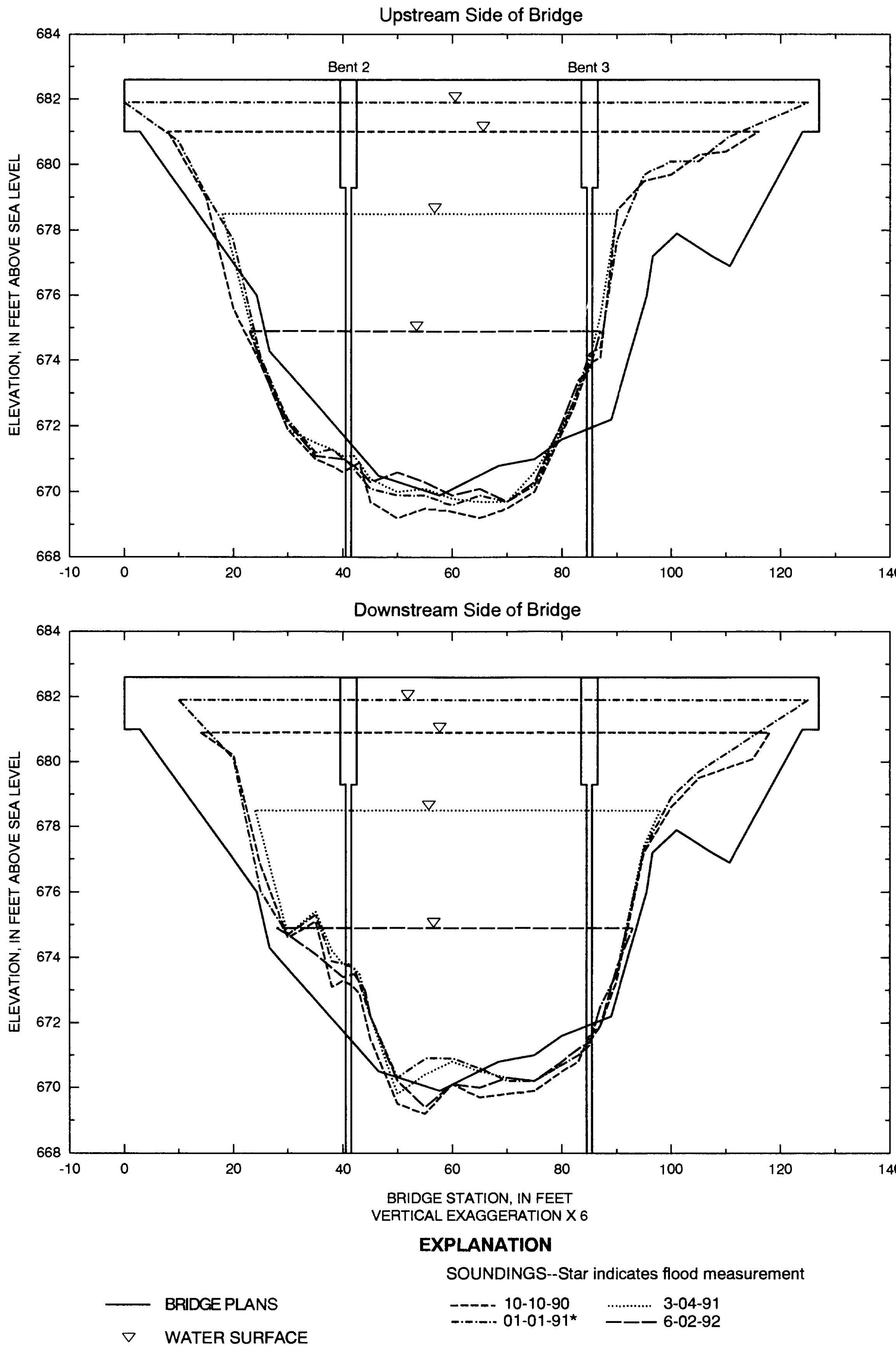


Figure 10. Cross sections showing bed elevations from bridge plans and soundings, U.S. Route 35 over Kankakee River at Union Center, Indiana.

Bridge 41-56-1489JB, U.S. Route 41 over Kankakee River at Schneider, Indiana

This study site is approximately 130 mi northwest of Indianapolis (fig. 1). The site is rural, consisting of low-lying wooded areas. The basin is predominantly flat and drains agricultural areas. The site consists of two bridges, a northbound single-span truss bridge upstream from a southbound bridge with two piers. Only the southbound bridge was studied.

The channel is dredged and uniform in shape. As it approaches the bridge, the channel curves to the left; the piers are skewed to the flow at an 11° angle. In places, the spoil banks function as levees. At this site, the spoil is set back from the channel, allowing some contraction. Along the downstream left bank, the flow expands into a low-lying swampy area. Both banks are lined with trees and appear to be stable. The bed material is sand.

Historical Scour Around Bridge Piers. The bridge opening was surveyed by use of the tuned transducer; the water was too deep for the GPR. The pattern in the geophysical record is chaotic, indicating an unstable channel bottom with considerable scouring and infilling within and adjacent to the bridge opening. Interfaces indicating scour and refilling are visible to an elevation of 615 ft. The upstream and downstream ends of both piers were probed. Cores were not collected at this site because of deep water. The soil-boring logs from the bridge plans are summarized in table 15 (at back of report).

At pier 2, an existing hole with a bottom elevation of 620 ft was recorded at the time of the geophysical survey. This hole is 8 ft downstream from the downstream end of pier 2. The geophysical record indicates about 1 ft of infilling in this hole. At a point 4 ft downstream from the downstream end, the channel bottom was 619.9 ft, and the probe penetrated to an elevation of 615.5 ft, where it hit a firm surface. At the upstream end of pier 2, the patterns in the geophysical record are chaotic, and no discernible scour hole is evident. The probe penetrated to an elevation of 619.7 ft at a point 3 ft to the right of the upstream end of pier 2.

At pier 3, a hole with a bottom elevation of 619 ft was identified at the time of the geophysical survey (August 7,1990). This hole is 5 ft upstream and 5 ft to the right of the pier. Debris obscured the record at the upstream end where the geophysical record identified a refilled hole along the left side of the pier; the subbottom elevation ranged from 615 to 617 ft. The probing record (November 14, 1990) indicates the bottom elevation to be 617.3 ft, with a subbottom elevation of 614.7 ft that is 5 ft upstream from the pier's upstream end. This was the deepest point of the observed scour. Data from the USGS gage on the Kankakee River at Shelby, 6 mi upstream, indicate that an annual peak discharge of 5,150 ft^3/s was recorded on August 23, 1990. This discharge would account for the change in bottom elevations between August 7 and November 14.

Flood Measurement and Routine Soundings. A flood measurement was made on January 2, 1991, at a discharge of 6,160 ft^3/s. Routine soundings also were made on September 12, 1990, March 5, 1991, and June 1, 1992 (fig. 11). Debris was always present on the channel bottom at pier 3, and the accuracy of the soundings was affected by this debris. Scour and deposition are evident in the sounding plots. On the upstream side of pier 3, a scour hole approximately 6 ft deep was present at the beginning of the study. During the flood of January 2, 1991, the hole deepened. The soundings made on March 5, 1991, indicated that this hole was still open; the hole filled about 4.5 ft between March 5, 1991, and June 1, 1992. A comparison of the soundings during the study and the bed elevations on the bridge plans shows that deposition on the bed upstream of pier 2 totaled 2 to 3 ft. The sounding plots show small scour-shaped holes in this deposition.

The plots show a large scour hole on the downstream end of pier 2. This hole was present at the beginning of the study and remained fairly constant during the flood on January 2, 1991. The plots of the last soundings from June 1, 1992, show about 1.5 ft of deposition in this hole. The streambed between the piers scoured and filled during the study by as much as 4 ft.

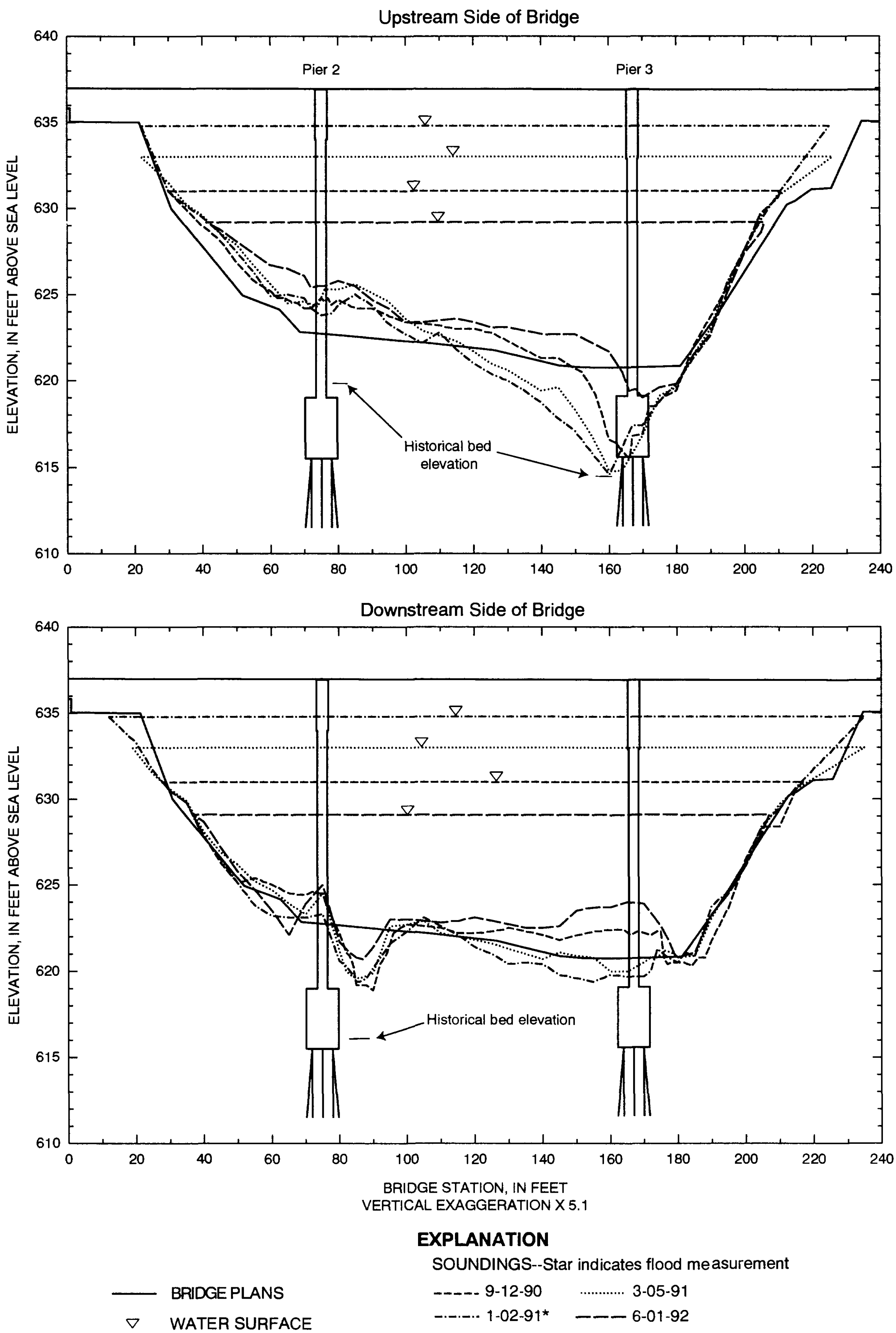


Figure 11. Cross sections showing bed elevations from bridge plans and soundings, U.S. Route 41 (southbound lane) over Kankakee River at Schneider, Indiana.

Bridge 54-77-343A, S.R. 54 over Busseron Creek near Sullivan, Indiana

This study site is approximately 90 mi southwest of Indianapolis (fig. 1). The site is rural, consisting of wooded and agricultural areas. The basin is rolling and drains agricultural and surface-mined areas.

The channel is dredged and uniform in shape and directs the flow through the bridge parallel to the bents. The flood plain is approximately 4,000 ft wide. During times of high flow, water bypasses through a relief bridge about 0.5 mi east of the study bridge. The banks are lined with trees and appear to be stable. The bed material is sand and coal fines.

Historical Scour Around Bridge Piers. The bridge opening was surveyed by use of the GPR; the water was too shallow for the tuned transducer. The GPR record indicates scouring along the upstream left side of bent 3 to an elevation of 437.0 ft. Based on the bridge plans, this elevation indicates about 3.5 ft of scour. The GPR record is not conclusive regarding scouring within the channel or around bent 2. Soil-boring logs were not available.

Three cores (table 16, at back of report) were collected at this site. They indicate scouring to an elevation of 437.4 ft at the upstream end of bent 3, 438.0 ft at a point midway between bents 2 and 3, and 436.2 ft at a point 2 ft left from the upstream end of bent 2. This is compatible with the GPR record.

The deepest point reached by probing at the upstream end of bent 2 was 437.7 ft, 2 ft left from the bent. The probe penetrated to an elevation of 438.2 ft, 6 ft left from the bent. The deepest point reached by probing at the upstream end of bent 3 was 437.8 ft, at a point 2 ft upstream from the center of the bent. The probing on the downstream end indicated loose material to an elevation of 438.0 ft and 438.4 ft. The data from the GPR record, cores, and probing indicate that contraction scour (the general lowering of the streambed from the effects of bridge contracting the flow) may have occurred to an elevation of 438.0 ft. Small scour holes have developed at both bents. Based on the geophysical and coring record, the lowest elevation detected at these holes was 436 ft at bent 2 and 437 ft at bent 3.

Flood Measurement and Routine Soundings. A flood measurement was made on January 5, 1993, at a discharge of 1,270 ft^3/s. Routine soundings also were made on December 10, 1990, February 12, 1991, and June 11, 1992 (fig. 12). During the period of the study, debris was not a problem at this site; small amounts of debris were removed when found during the site visits. At the time the site was surveyed, small scour holes were present at the upstream side of both bents. These holes changed little during the study. The sounding plots of the downstream side show changes in bed elevations of about 1.5 ft in some places.

Bridge 57-63-6013, S.R. 57 over East Fork White River near Petersburg, Indiana

This study site is approximately 110 mi southwest of Indianapolis (fig. 1). The site is rural, consisting of agricultural areas and residences. The basin ranges from hilly to gently rolling and drains predominantly agricultural and wooded areas. One flood-control reservoir—Monroe Lake—is in the basin.

The channel approaching the bridge curves to the right but directs the flow through the bridge parallel to the piers. The flood plain is about 2 mi wide. The banks are wooded and appear to be stable. The bed material is sand and gravel. The piers in the main channel are protected by broken concrete and construction debris.

Historical Scour Around Bridge Piers. The bridge opening was surveyed by use of the GPR and the tuned transducer. The record from the GPR was inconclusive. The tuned-transducer record indicates considerable scour and refilling between piers 3 and 4. At the beginning of the study, a debris pile was removed from pier 3;

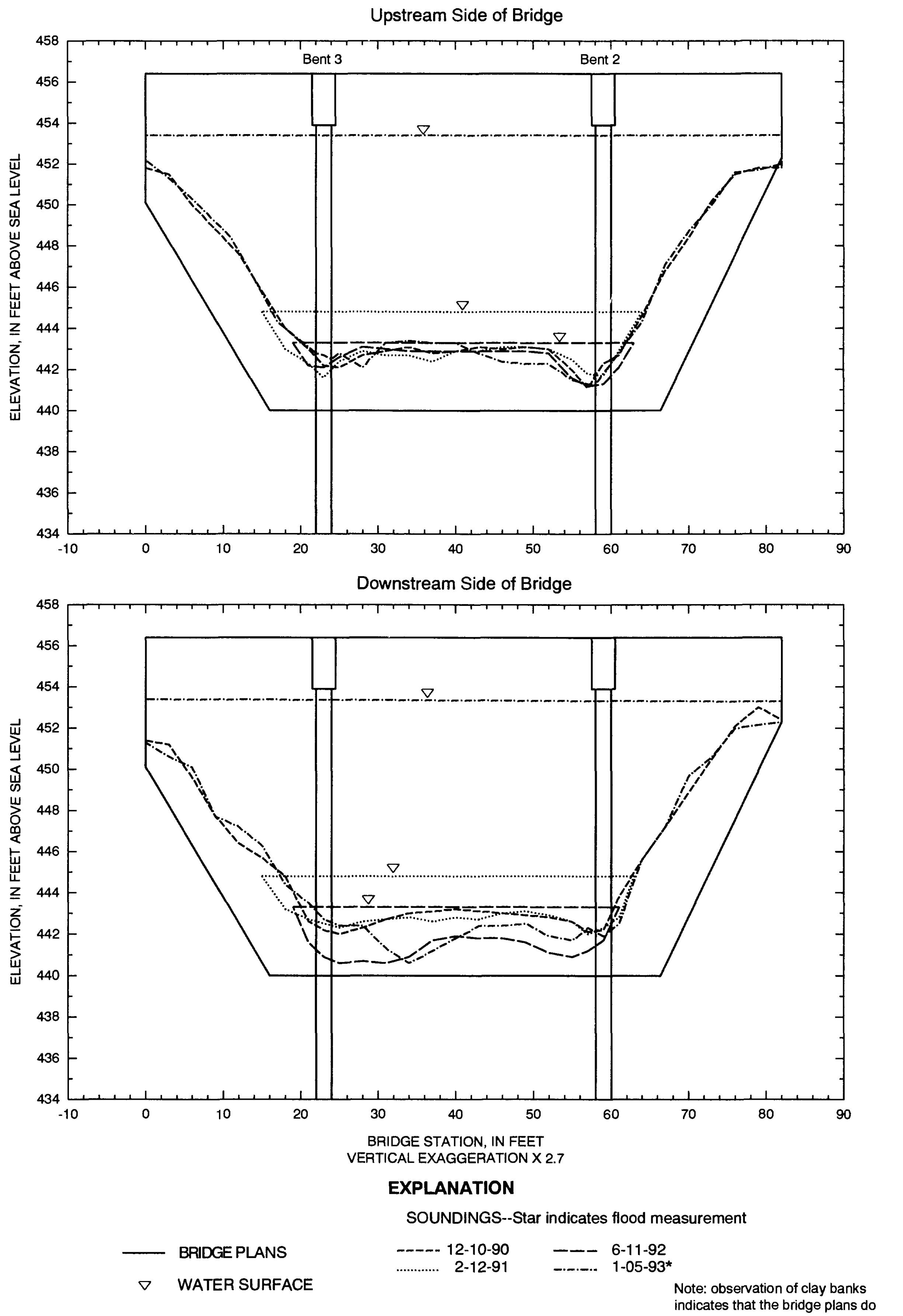


Figure 12. Cross sections showing bed elevations from bridge plans and soundings, State Road 54 over Busseron Creek near Sullivan, Indiana.

the plots from the soundings at that time show large holes between piers 3 and 4. During the flooding in January 1991, these holes filled, as can be seen in the geophysical record. Because pier 2 is armored with broken concrete and pier 3 was surrounded with debris through the course of the study, this site was not probed or vibracored. The soil-boring logs from the bridge plans are summarized in table 17 (at back of report).

The geophysical record indicates a firm bottom from a point 35 ft left from pier 3 to the left edge of the low-water channel. No scour is evident along this area. The area along the left side of the pier has a large debris pile, and, based on the streambed elevations from the bridge plans, has filled about 2 to 5 ft. Along the right side of this pier, the record indicates about 5 ft of infilling from a point one-third the length of the pier downstream from the upstream end to a point 10 ft downstream from the pier.

Scour is visible along the upstream left corner of pier 3 to an elevation of 394 ft. Between the pier and the right edge of the low-water channel, scour is visible to an elevation of 390 ft at the upstream face of the bridge and about 389 ft at the downstream face. Soundings collected from September 1990 show the bottom elevation to be 394 ft upstream and 393 ft downstream. These areas refilled to an elevation of about 400 ft during the flood in January 1991.

Flood Measurement and Routine Soundings. Flood measurements were made on January 2, and January 4, 1991, at discharges of 31,500 and 33,500 ft^3/s, respectively. Routine soundings also were made on September 10, 1990, February 12, 1991, and June 15, 1992 (fig. 13). At the beginning of the study, a large debris pile was lodged in front of and along the left side of pier 3. Most of this debris was removed before the discharge measurements were made. Debris, however, remained embedded in the channel bottom at this pier. During the study, some debris was deposited at the upstream end of this pier, eventually building up into a small pile.

Comparison of sounding plots to bed elevations from the bridge plans indicates that infilling has occurred around pier 3. The bed elevation between piers 2 and 3 has remained stable during the life of this bridge. Between piers 3 and 4, considerable scour and deposition has occurred. A scour hole as deep as 8 ft was present between these piers at the beginning of the study. During the flood of January 1991, this hole filled in. As the debris collected again, this hole redeveloped—as evidenced in the soundings from June 15, 1992. This hole is probably debris induced. The deepest scour was on the downstream side of the bridge. The bed elevations and subbottom elevations established through the geophysical surveys indicate that this hole is associated with the bridge rather than the thalweg.

Bridge 59-11-1728A, S.R. 59 over Eel River North of Clay City, Indiana

This study site is approximately 60 mi southwest of Indianapolis (fig. 1). The site is rural, consisting of agricultural areas and residences. The basin ranges from hilly to gently rolling and drains predominantly agricultural and wooded areas. One flood-control reservoir—Cagles Mill Lake—is in the basin.

The channel approaching the bridge curves to the right and flows through the bridge opening parallel to piers 1 and 2. Piers 3 and 4 are skewed to the flow at a 20° angle. The flood plain is about 1.5 mi wide. The banks are wooded and, adjacent to the bridge, they appear to be stable. In places, however, the banks are free of vegetation and are slumping into the channel. The bed material is sand and gravel.

Historical Scour Around Bridge Piers. The bridge opening was surveyed by use of the GPR and the tuned transducer. The record from the tuned transducer was inconclusive. The record from the GPR shows interfaces at an elevation of 524 ft. The area around piers 2 and 3 were probed,

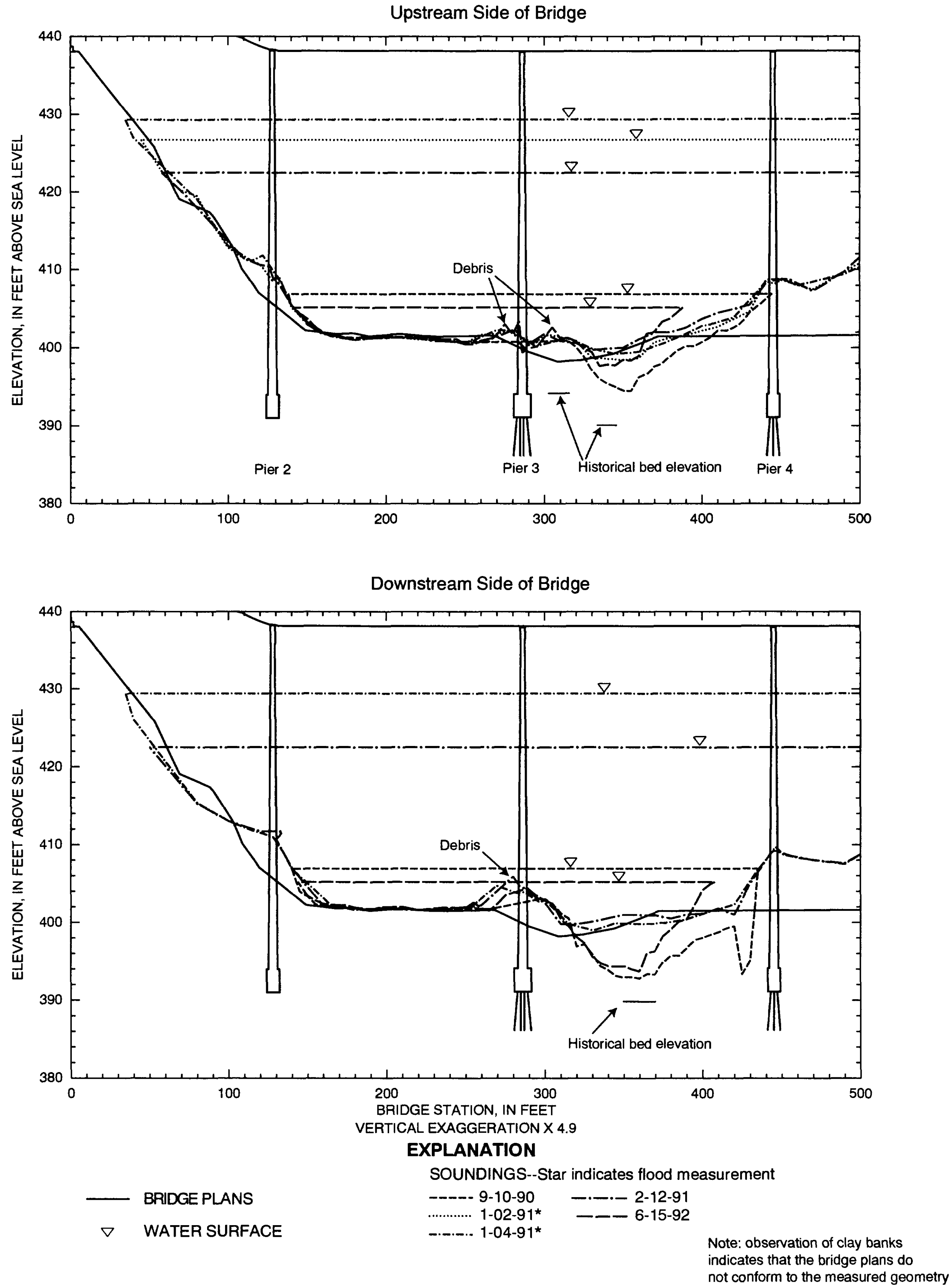


Figure 13. Cross sections showing bed elevations from bridge plans and soundings, State Road 57 over East Fork White River near Petersburg, Indiana.

and five cores (table 18, at back of report) were collected along the upstream face of the bridge. The soil-boring logs from the bridge plans are summarized in table 19 (at back of report).

The record from along the right side of pier 2 showed an interface at an elevation of 529 ft at a point 3 ft upstream from the upstream end. The lowest elevation reached by probing was 531.5 ft, 1 ft right of the upstream end of the pier; this elevation is comparable to that of the interface in the GPR record.

The record from along the right side of pier 3 showed an interface at an elevation of 529 ft about 3 ft upstream from the upstream end. At a point one-fourth the length of the pier, upstream from the downstream end, the elevation of this interface was at 529 ft. The lowest elevation reached by probing along the right side was 527.8, at a point 2 ft right of the center of the pier.

Along the left side of pier 3, interfaces were visible to an elevation of 524 ft. Along the left side of the pier, at the upstream end, an interface was visible at an elevation of 529 ft. Farther to the left, an interface was visible at 524 ft. Another interface was visible at an elevation of 526 ft at two points along the side of the pier. The probe penetrated to 525.2 ft at a point 5 ft left of the midpoint of the pier and of 526.8 ft at a point 2 ft upstream of the pier. At the downstream end of the pier, an interface was visible at 527 ft. Farther to the left, an interface was visible at 524 ft.

Flood Measurement and Routine Soundings. A flood measurement was made on November 13, 1993, at a discharge of 9,100 ft^3/s. Routine soundings also were made on October 17, 1990, February 13, 1991, and June 12, 1992 (fig. 14). During the period of the study, debris was not a problem at this site; small amounts were removed when found during site visits. The sounding plots from the upstream and downstream side of the bridge show 1- to 2-ft changes of bed elevations in places. These changes may represent typical bed movement for this sand and gravel channel. The sounding plots from the upstream side of the bridge during the flood measurement show a scour hole along the left side of pier 3. The flow is skewed to this pier at about a 15° angle. Data gathered during the geophysical surveys indicate that the thalweg had scoured during this flood event.

Bridges 63-83-3561B and 63-83-3561JA, S.R. 63 over Little Vermillion River at Newport, Indiana

This study site is approximately 75 mi west of Indianapolis (fig. 1). Two bridges are at this site, a northbound bridge downstream from a southbound bridge. The site is rural, consisting of cultivated fields and wooded areas. The basin is rolling and drains predominantly agricultural and wooded areas.

The channel approaching the bridge curves to the right but directs the flow through the bridge parallel to the piers. The flood plain is about 0.5 mi wide. The banks are wooded and appear to be stable. A mound of material along the left downstream bank functions as a levee and affects the flow. The bed material is sand and gravel.

Historical Scour Around Bridge Piers. The bridge was surveyed by use of the GPR and the tuned transducer. The GPR produced a usable record in shallow water, and the tuned transducer produced a usable record in the deeper water. The areas around all piers were probed. Cores (table 20, at back of report) were collected on the upstream side of the upstream bridge. Scour was detected at piers 2 and 3 of the upstream bridge and pier 2 of the downstream bridge. The soil-boring logs from the bridge plans are summarized in table 21 (at back of report).

The record obtained by use of the tuned transducer at pier 3 of the upstream bridge indicates that the bed has scoured to an elevation of 485 ft at the upstream end. The closest point probed to this location was 6 ft downstream from and 2 ft left of the upstream end, where the probe penetrated to an elevation of 484.9 ft, verifying the geophysical

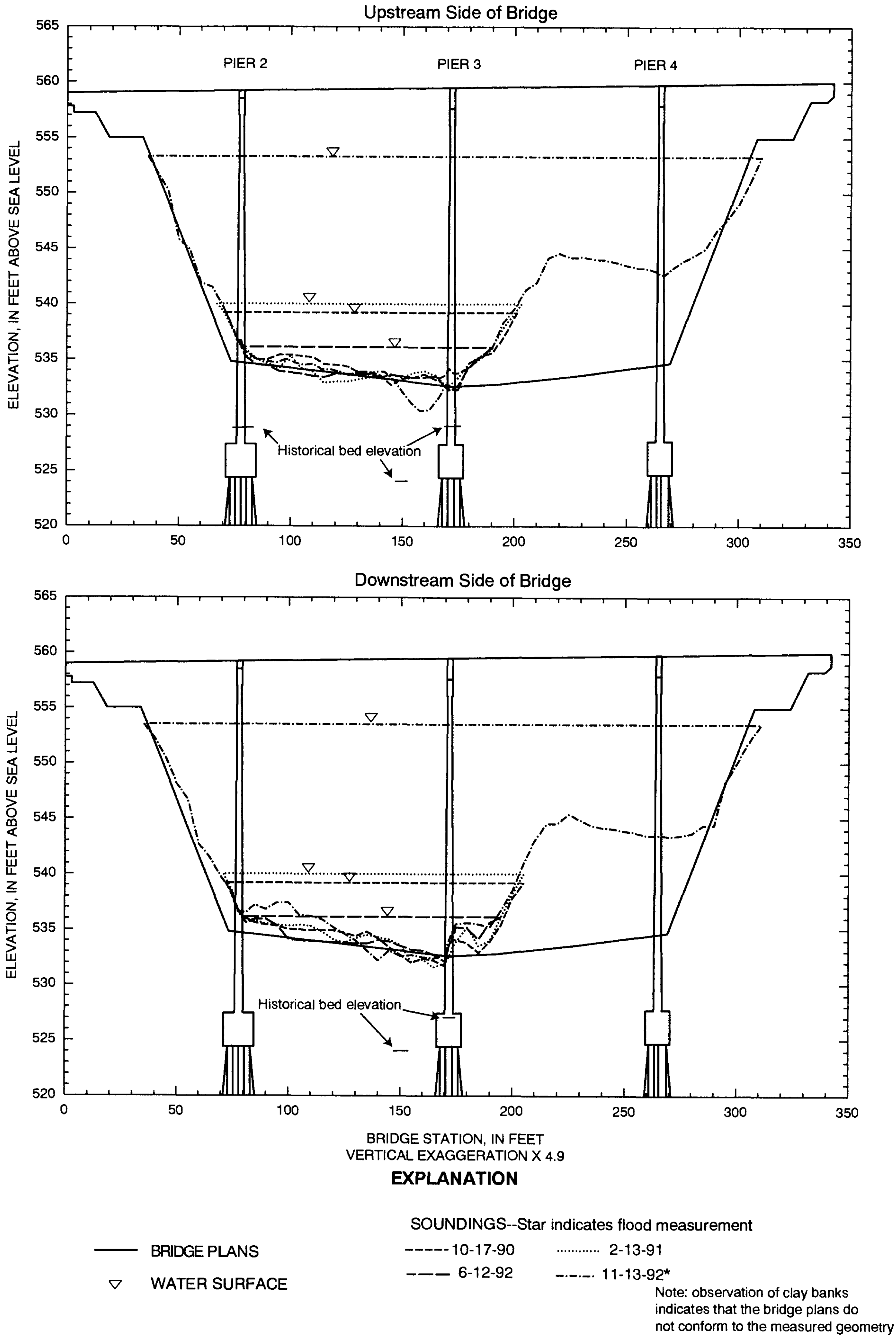


Figure 14. Cross sections showing bed elevations from bridge plans and soundings, State Road 59 over Eel River north of Clay City, Indiana.

record. The core collected 1.5 ft upstream and 1.5 ft to the right from the upstream end includes sand and gravel over a gray clay layer to an elevation of 484.7 ft, again verifying the geophysical record at this pier.

Cores from the upstream end of pier 2 under the upstream bridge indicate that this pier has scoured to an elevation of 488 ft where a blue clay layer is present. A cobble layer overlain by sand and gravel is evident in the cores above this clay layer. The area adjacent to this pier was not covered by the geophysical survey. The area was dry at the time of the GPR survey and was too shallow at the time of the survey for the tuned transducer.

The record obtained by use of the GPR at pier 3 of the downstream bridge indicates that the bed has scoured to an elevation of 487 ft upstream from and along the left side of the pier. The lowest elevation reached by probing was 487.0 ft at a point 25 ft left of the upstream end of the pier and 487.5 ft at a point 8 ft left of the upstream end of pier 3. These data agree with the geophysical record. Cores were not collected at the downstream bridge.

Flood Measurement and Routine Soundings. A flood measurement was made on November 12, 1992, at a discharge of 4,550 ft^3/s. Routine soundings also were made on December 11, 1990, February 14, 1991, and June 11, 1992 (fig. 15). During the period of the study, debris was not a problem at this site; small amounts of debris were removed when found during site visits. The sounding plots made from the downstream side of the bridge show a fairly stable channel bottom. The elevation of these soundings are about the same as the design elevation shown on the bridge plans.

The sounding plots made from the upstream side indicate a large scour hole at the upstream end of pier 3. This hole was present at the beginning of the study and was about 4.5 ft below the bed elevations from the bridge plans. This hole deepened about 1 ft between May 1990 and December 1990 and then remained stable through the remainder of the study. The bed elevations between piers 2 and 3 shifted as much as 4 ft during the study.

The soundings made on February 14, 1991, documented a scour hole with a bottom elevation of 489 ft at a point 7 ft left of the upstream end of pier 2. The sediment cores indicate that this pier has scoured to an elevation of 488 ft in the past.

Bridge 101-17-5096A, S.R. 101 over St. Joseph River at Saint Joe, Indiana

This study site is approximately 145 mi northeast of Indianapolis (fig. 1). The site is rural, consisting of cultivated fields and wooded areas. The basin is rolling and drains predominantly agricultural and wooded areas.

The channel approaching the bridge is straight, but the piers are skewed to the flow at an angle of 4° to 31°. The flood plain is about 0.5 mi wide. The banks are wooded and appear to be stable. The bed material is sand and gravel; a cobble layer armors the center of the channel.

Historical Scour Around Bridge Piers. The bridge opening was surveyed by use of the GPR and the tuned transducer. The record from the tuned transducer was inconclusive. The GPR record, however, shows interfaces to an elevation of about 778 ft. Piers 2 and 3 are in the main channel and were probed; four cores (table 22, at back of report) were collected at this site. The soil-boring logs from the bridge plans are summarized in table 23 (at back of report).

Two cores upstream from pier 2 included the interface between the sand and gravel and the silty loam. Core 1 was collected 3.2 ft upstream from the center line of the pier; the interface elevation is 783.4 ft. Core 2 was collected 3.3 ft upstream from and 0.6 ft left of the upstream end; the interface elevation is 781.6 ft. Because the interface is sloping, these cores must have been on the side, not the bottom, of a hole. The results of probing at this pier are compatible with the coring results. The probe penetrated to an elevation of 782.8 ft at a point 2 ft upstream from the pier and to 779.5 ft at a point 2 ft left of the upstream end. These data indicate a scour hole along the left upstream side of pier 2 to an elevation of at least 779.5 ft.

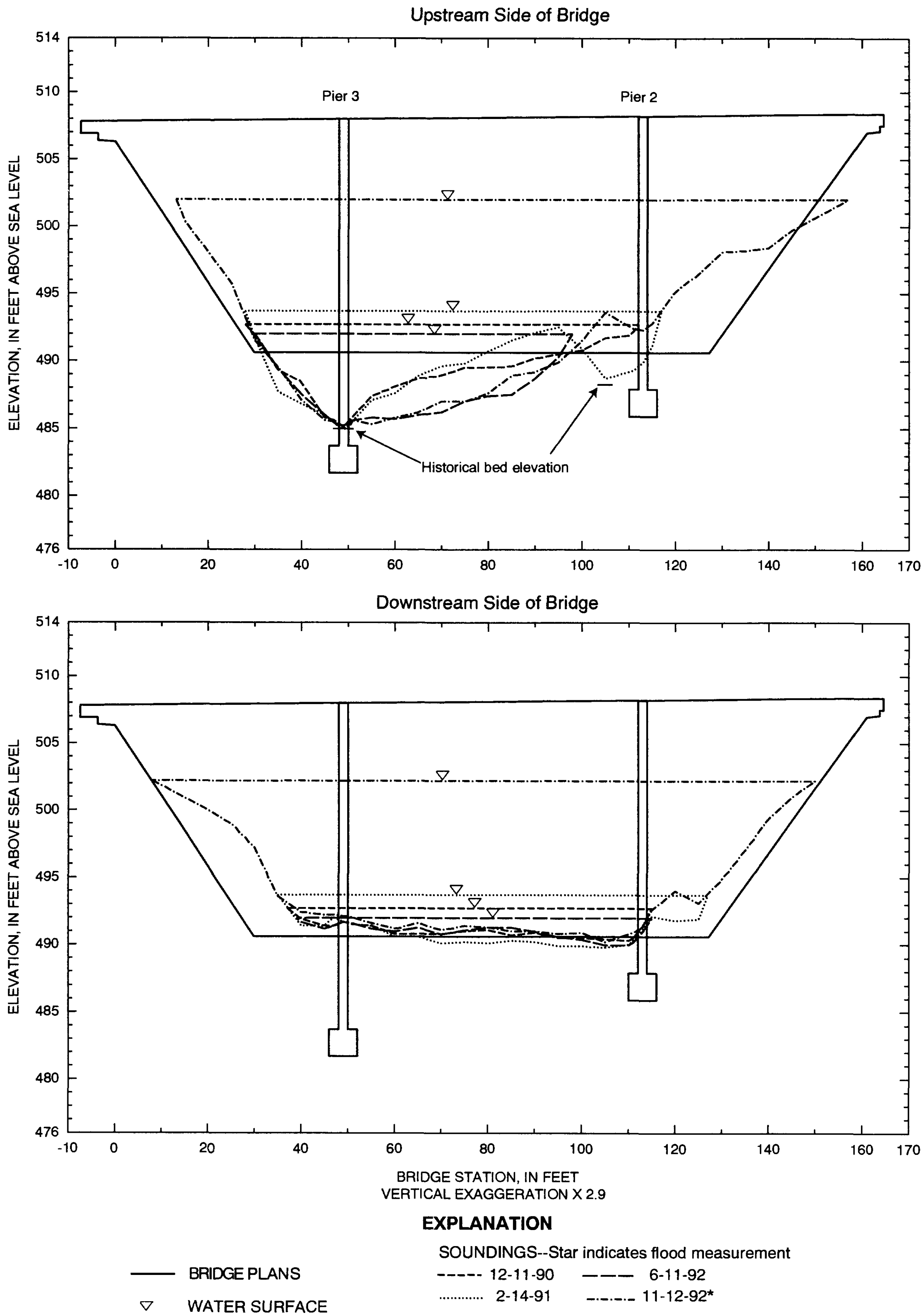


Figure 15. Cross sections showing bed elevations from bridge plans and soundings, State Road 63 (southbound lane) over Little Vermillion River at Newport, Indiana.

A possible scour hole, with a bottom elevation of 779 ft, is indicated at a point 8 ft upstream from and 3 ft to the right of pier 3. Interference from a point reflector leaves doubt as to the validity of this interface. A core collected 3 ft upstream from the upstream end indicates no scouring at that point. Between pier 3 and the right bank, an interface was visible; the lowest elevation observed was 778 ft. This interface is interpreted to be an old channel that has filled with sand and gravel. The probing located loose material to an elevation of 779.9 ft at a point 2 ft left of the upstream end of pier 3. In addition, the lowest point probed at this pier—elevation 778.3—was at a point 2 ft downstream from the downstream end. At pier 3, therefore, the deepest scour at the upstream end appears to be 779.9 ft.

Flood Measurement and Routine Soundings. A flood measurement was made on January 2, 1991, at a discharge of 6,220 ft^3/s. Routine soundings also were made on September 8, 1990, March 5, 1991, and June 5, 1992 (fig. 16). During the period of the study, debris was not a problem at this site; small amounts of debris were removed when found during site visits. The sounding plots indicate a stable channel bottom. The bed elevations established during the study are slightly above the bed elevations from the bridge plans. The coring record indicates scouring and refilling at piers 2 and 3.

Bridge (9)109-48-3727A, S.R. 109 over White River at Anderson, Indiana

This study site is approximately 35 mi northeast of Indianapolis (fig. 1) and is in an urban area of commercial structures and residences. The basin is rolling and drains predominantly agricultural areas.

The channel approaching the bridge is straight, but the piers are skewed to the flow at an angle of 8° to 20°. The flood plain is about 800 ft wide; the left overbank has been filled, and a shopping center and parking lot occupy most of the flood plain. The banks are wooded and appear to be stable. The bed material is cobble.

Historical Scour Around Bridge Piers. The bridge was surveyed by use of the GPR and the tuned transducer. The record from the tuned transducer was inconclusive. The record from the GPR shows interfaces to an elevation as low as 824 ft. The area around piers 5 and 6 were probed; however, the penetration was limited because of the coarse bed material. Cores were not collected. The soil-boring logs from the bridge plans are summarized in table 24 (at back of report).

In the geophysical record, visible interfaces indicate that the dense material at pier 6 and between piers 5 and 6 may have scoured to an elevation as low as 824 ft and subsequently refilled. The record indicates a possible scour hole along the upstream face of the bridge at the end of pier 6 that has scoured to an elevation of 824 ft and refilled. At a point 25 ft upstream from the upstream end of pier 6, the interface was observed at an elevation of 827 ft. At a point six-tenths the length of the pier downstream from the upstream end of pier 6, along the left side the interface, an elevation of 824 ft was observed. The bottom of the footing at pier 6 is 825.5 ft.

Flood Measurement and Routine Soundings. A flood measurement was made on January 1, 1991, at a discharge of 7,700 ft^3/s. Routine soundings also were made on September 25, 1990, March 6, 1991, and June 16, 1992 (fig. 17). During the period of the study, debris was not a problem at this site; small amounts of debris were removed when found during site visits. The sounding plots indicate that the channel bottom was fairly stable during the time of the study. The bed elevations established during the study are about the same as the bed elevations from the bridge plans. The geophysical surveys, however, indicate that scouring at pier 6 reached the bottom of the footings at some time in the past.

Bridge 110-25-4126A, S.R. 110 over Tippecanoe River near Mentone, Indiana

This study site is 105 mi north of Indianapolis (fig. 1). The site is rural, consisting of residences and wooded areas. The basin is rolling and drains

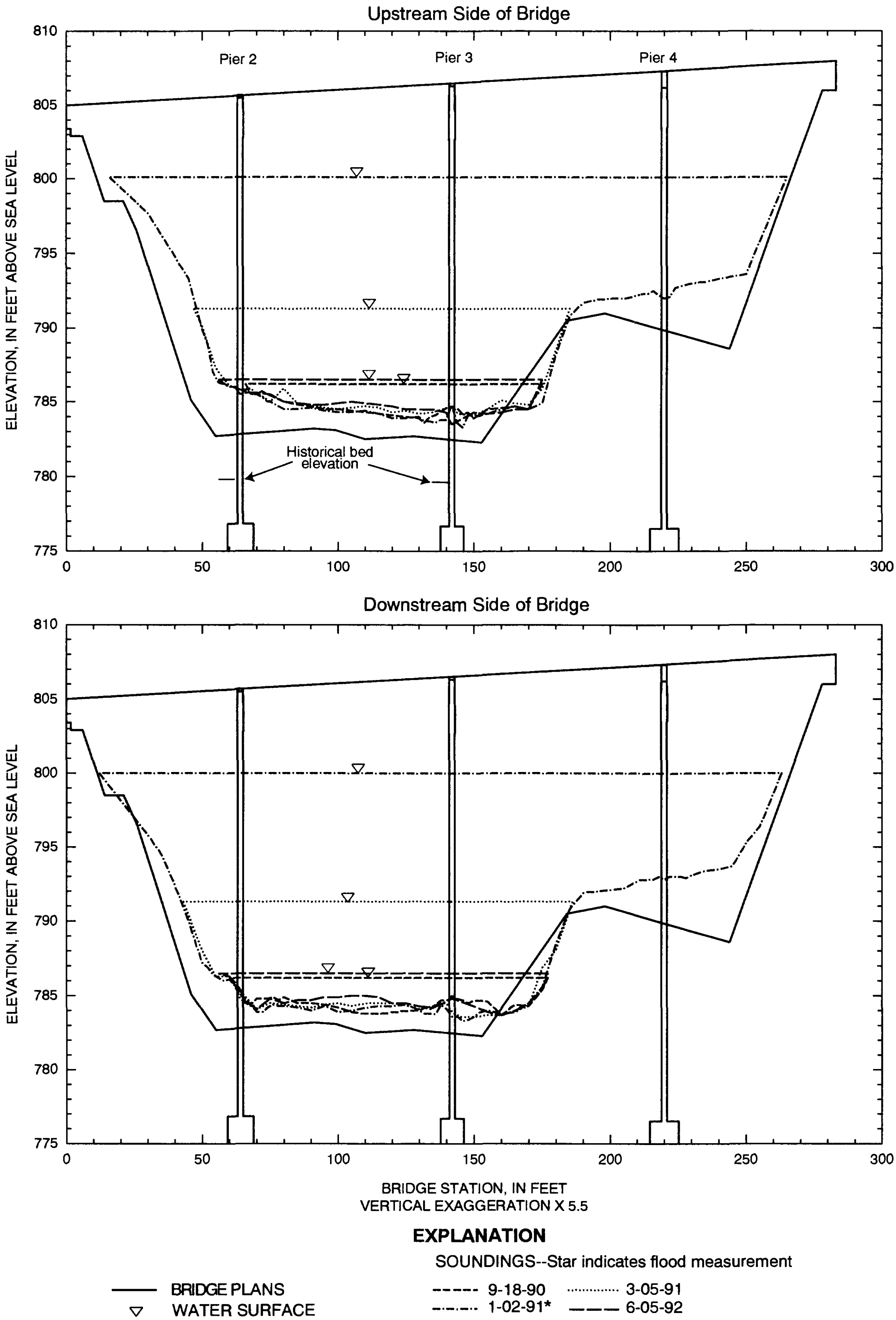


Figure 16. Cross sections showing bed elevations from bridge plans and soundings, State Road 101 over St. Joseph River at Saint Joe, Indiana.

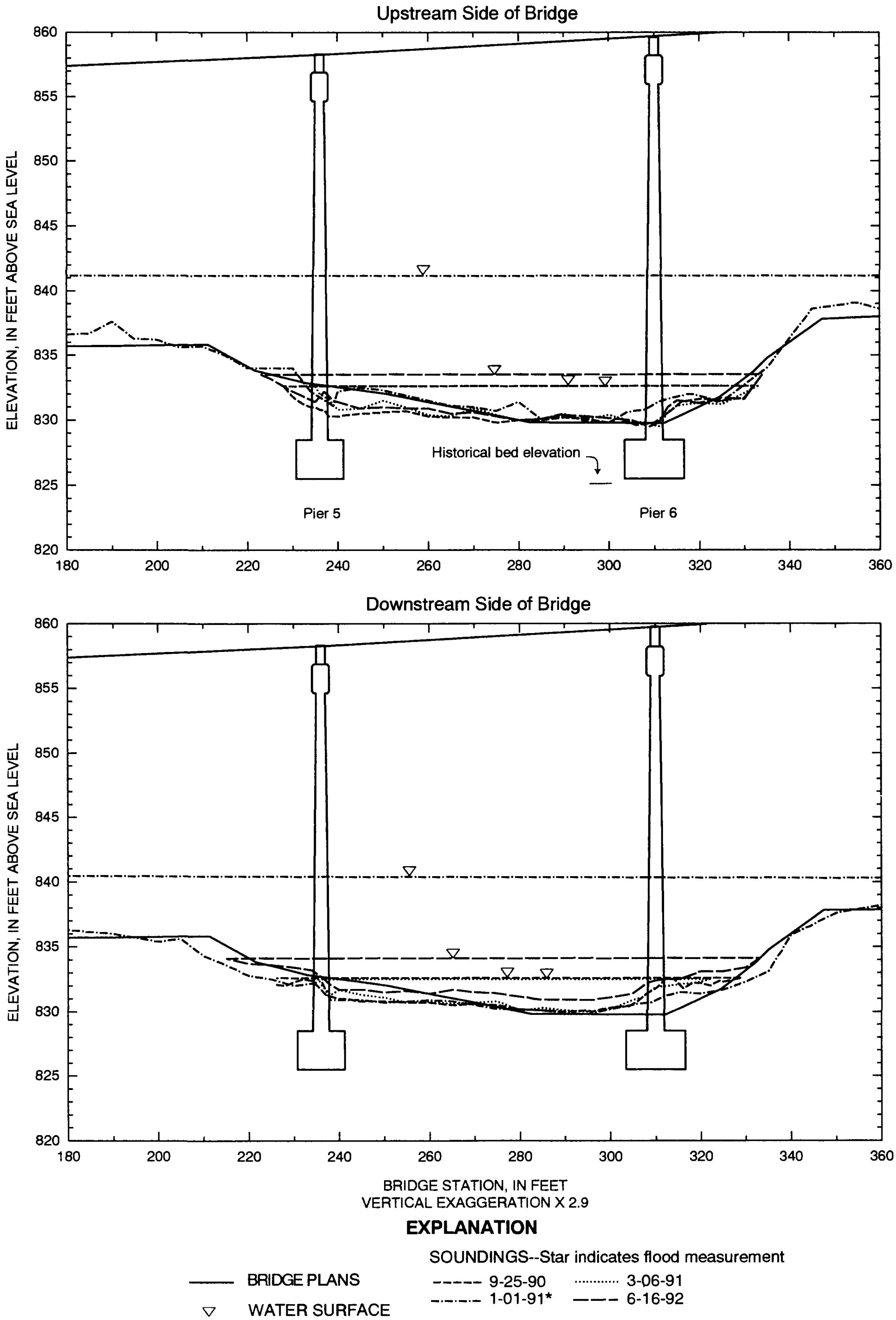


Figure 17. Cross sections showing bed elevations from bridge plans and soundings, State Road 109 over White River at Anderson, Indiana.

predominantly agricultural and wooded areas. The basin has numerous small lakes that affect the peak flow, especially the upper 100 mi^2.

The channel approaching the bridge is straight and directs the flow through the bridge, parallel to the piers. The flood plain is about 0.25 mi wide. The banks are wooded and appear to be stable. The left overbank is low lying and swampy upstream and downstream from the bridge. The bed material is sand and gravel.

Historical Scour Around Bridge Piers. The bridge opening was surveyed by use of the GPR and the tuned transducer. The record from the GPR was inconclusive. The record from the tuned transducer shows interfaces to elevations as low as 749 ft. The areas around piers 3 and 4 were probed, and six cores (table 25, at back of report) were collected along the upstream face of the bridge opening. The soil-boring logs from the bridge plans are summarized in table 26 (at back of report).

At pier 3, the geophysical record indicates scouring along the left side. The interface is at an elevation of about 751 ft at the upstream end and about 749 ft at the downstream end of the pier. The probing at pier 3 penetrated to an elevation of 751.6 ft at the upstream end and 751.2 ft at a point 4 ft left of the downstream end. A core collected at the upstream end includes sand and gravel mixed with organic material, an indication of infilling; the elevation at the bottom of the core was 749.7 ft.

At pier 4, a small hole is indicated under a surface layer of sand and gravel at the upstream end. The interface extends about three-fourths of the length of the pier along the right side of the pier. The lowest elevation at the upstream end is 750 ft; the lowest elevation along the side of the pier is about 751 ft. The results of probing are compatible with the geophysical record. The bottom of the probed hole at the upstream end was 750.1 ft; at the midpoint along the side of the pier, the bottom of the probed hole was 750.3 ft. A core from the upstream end of the pier includes sand and gravel mixed with organic material, an indication of infilling; the elevation at the scour interface is 751.2 ft.

Routine Soundings. Soundings were made on December 11, 1990, March 4, 1991, and June 18, 1992 (fig. 18). During the period of the study, debris was not a problem at this site; small amounts of debris were removed when found during site visits. The sounding plots indicate that the channel bottom was fairly stable during the study. The bed elevations measured during the study are about the same as the bed elevations from the bridge plans. A small hole about 1.5 ft deep has developed on the downstream side of pier 3. The geophysical and probing data indicate that this hole deepened to an elevation of 749 ft at some time in the past.

Bridge 135-88-3939A, S.R. 135 over Muscatatuck River at Millport, Indiana

This study site is approximately 80 mi south of Indianapolis (fig. 1). The site is rural, consisting of agricultural areas and residences. The basin is rolling to hilly and drains predominantly agricultural and wooded areas. The lower part of the basin is characterized by wide, flat overbanks that allow for unusually large amounts of storage during flooding.

The channel approaching the bridge is straight and directs the flow through the bridge, parallel to the piers. The flood plain is about 1 mi wide. The banks are wooded and appear to be stable. The bed material is sand and gravel. The left pier is partially protected by riprap.

Historical Scour Around Bridge Piers. The bridge was surveyed by use of the GPR and the tuned transducer. Both systems produced usable record. The bridge opening was surveyed in October 1990 and again in October 1992 after a major flood in August 1992. The record indicates some infilling around both piers in the main channel. No scouring was detected at this location. Cores were not collected at this site because of the deep water. The soil-boring logs from the bridge plans are summarized in table 27 (at back of report).

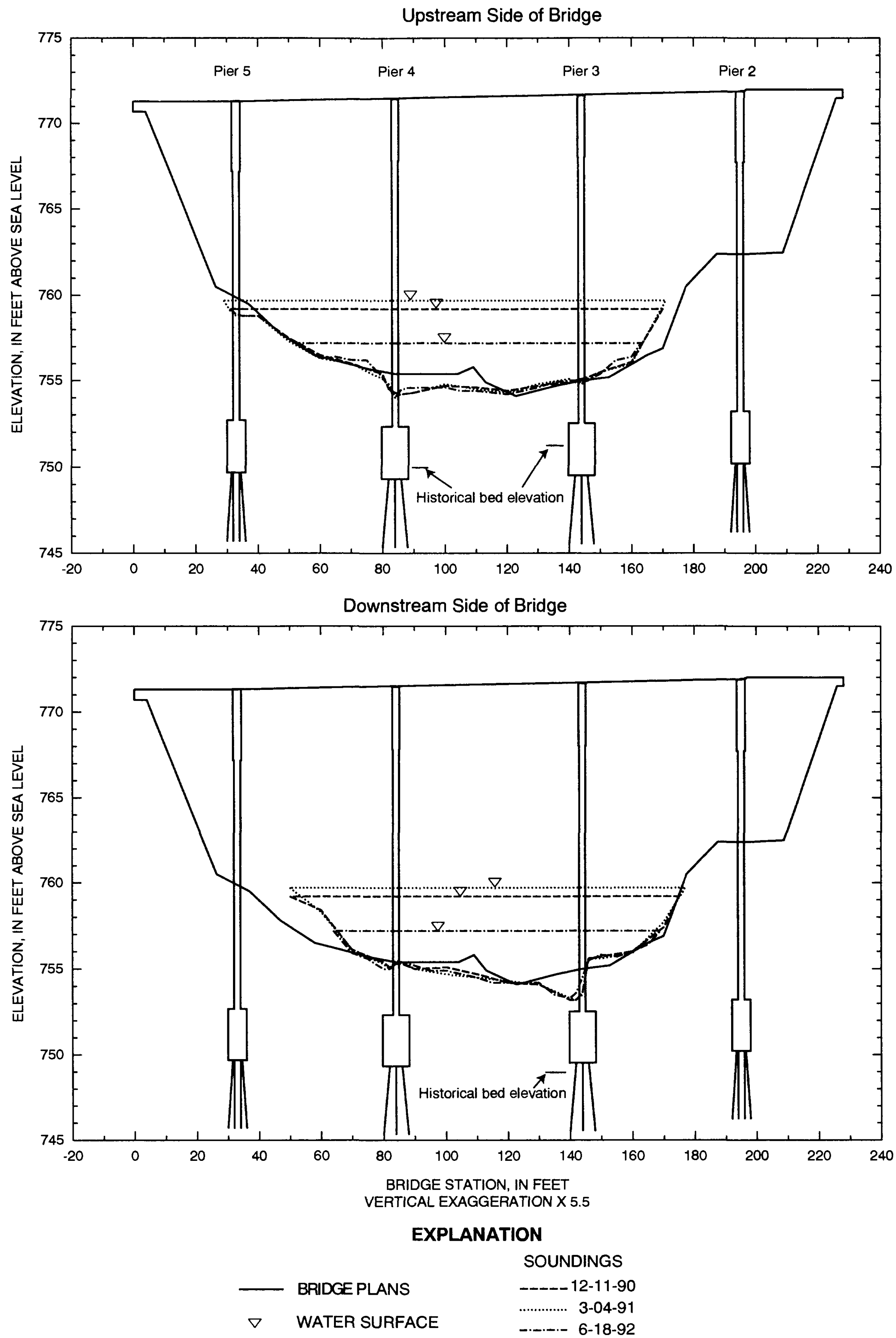


Figure 18. Cross sections showing bed elevations from bridge plans and soundings, State Road 110 over Tippecanoe River near Mentone, Indiana.

The areas around piers 3 and 4 were probed. At pier 3, the bed elevation ranged from 495.5 to 501.4 ft. Based on the contour map from the bridge plans, the bed elevation at the time of construction ranged from 495 to 498 ft. These elevations indicate some infilling. At this pier, the lowest elevation reached by probing was 488.0 ft at a point 2 ft to the right of the center of the pier. At pier 4, the bed elevation ranged from 495.4 to 500.2 ft. The bed elevation based on the contour map from the bridge plans was 495 to 496 ft, an indication of some infilling. At this pier, the lowest elevation reached by probing was 483.7 ft; the probe penetrated the natural sand layer and was stopped at the clay layer indicated on the soil-boring log.

Flood Measurement and Routine Soundings. A flood measurement was made on August 9, 1992, at a discharge of 7,160 ft^3/s. Routine soundings also were made on September 21, 1990, February 11, 1991, and June 16, 1992 (fig. 19). During the period of the study, debris was not a problem at this site; small amounts of debris were removed when found during site visits. The sounding plots indicate a stable channel bottom. The bed elevations established during the study are about the same as the bed elevations of the bridge plans. No scouring was observed at this site.

Bridge 157-28-6589, S.R. 157 over White River at Worthington, Indiana

This study site is approximately 65 mi southwest of Indianapolis (fig. 1). The site is rural, consisting of agricultural areas and residences. The basin is rolling and drains predominantly agricultural and wooded areas.

The channel approaching the bridge is straight, but the piers are skewed to the flow at an angle of 0° to 6°. The flood plain is about 1 mi wide. The banks are wooded and appear to be stable. The bed material is sand and gravel. Two flood-control reservoirs—Cagles Mill Lake and Eagle Creek Reservoir—are in the basin.

Historical Scour Around Bridge Piers. The bridge opening was surveyed by use of the GPR and the tuned transducer. The record from the GPR was inconclusive. Pier 5 is within the low-water channel, and the area around this pier was probed to support the geophysical survey. Cores were not collected at this site. The soil-boring log from the bridge plans is summarized in table 28 (at back of report).

In the beginning of the study, a large debris pile was removed from the upstream end of pier 5; however, considerable debris was still imbedded in the channel around this pier. At the time of the geophysical survey, some debris had collected on the upstream end and along the sides of the pier.

Infilling is evident along the upstream side of the bridge opening within the low-water channel. The geophysical record does not detect scouring at the upstream end of the pier. Scouring, however, is evident along the left side of the debris to an elevation of 480 ft. This geophysical evidence of scour is supported by the probing. At a point 6 ft left of and 4 ft downstream from the upstream end of pier 5, the probe penetrated to an elevation of 479.9 ft. Any evidence of scouring along the right side of the pier is obscured by a channel-bottom multiple reflection. The probe, however, penetrated to an elevation of 473.0 ft at a point 7 ft to the right and 2 ft downstream from the upstream end.

On the downstream side of the pier, infilling and scouring are evident. The geophysical record indicates that the deepest scouring is along the right bank, to an elevation of 475 ft. Along the left side of the pier, scouring is evident to an elevation of 483 ft. The record below this point is obscured by a channel-bottom multiple reflection. The probe penetrated to an elevation of 483.5 ft, at a point 2 ft left of the downstream end.

Along the right side of the pier, the geophysical record indicates scouring to an elevation of 484 ft. This interface drops to an elevation of 477 ft at a point 20 ft to the right of the pier. The probe penetrated to an elevation of 482.4 ft at a point 2 ft to the right of the downstream end and 479.3 ft at a point 6 ft to the right of the pier.

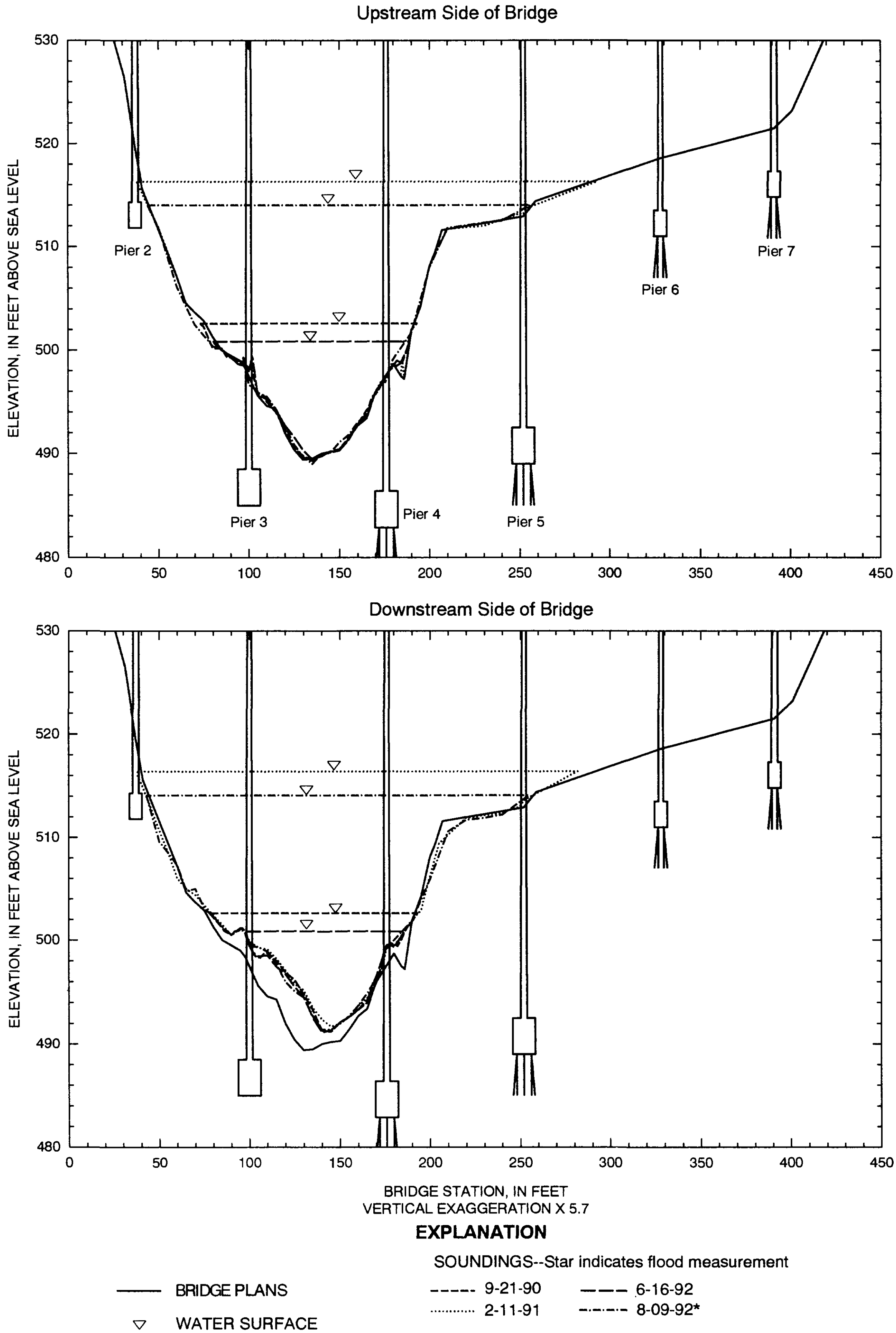


Figure 19. Cross sections showing bed elevations from bridge plans and soundings, State Road 135 over Muscatatuck River at Millport, Indiana.

Flood Measurement and Routine Soundings. A flood measurement was made on January 3, 1991, at a discharge of 43,400 ft^3/s (road overflow not measured). Routine soundings also were made on September 10, 1990, February 12, 1991, and June 9, 1992 (fig. 20). A large debris pile was lodged on the upstream side of pier 5. Most of the debris was removed prior to the soundings made on September 10, 1990. Debris, however, was left embedded in the channel bottom which formed a new debris pile that continued to grow during the study.

At the beginning of the study, large holes were present on both sides of the downstream end of pier 5. These holes filled prior to or during the flood of January 3, 1991. It is believed that debris caused the scouring and that the holes refilled after the debris was removed. The hole on the right side returned between February 12, 1991, and June 9, 1992. Again, this hole is believed to result from the collection of debris on this pier. Smaller holes are evident at the outside edge of the debris pile at the upstream side of the bridge.

Some deposition is evident between piers 4 and 5. This area tended to scour and refill during the study. The overall effect, however, was some infilling within the main channel. The soundings adjacent to pier 4 indicate that some scour has occurred, moving the bank to a more stable slope than the sharp edge shown on the construction plans. During the study, this area was stable.

Bridge 163-83-5325A, S.R. 163 over Wabash River at Clinton, Indiana

This study site is approximately 70 mi west of Indianapolis (fig. 1) and is in urban area of commercial structures and residences. The basin is predominantly rolling to hilly and drains agricultural and wooded areas. Four flood-control reservoirs—Huntington Lake, Salamonie Lake, Mississinewa Lake, and Cecil M. Harden Reservoir—are in this basin.

The channel approaching the bridge is straight, but the piers are skewed to the flow at an angle of 1° to 15°. The flood plain is about 1 mi wide but is bounded by a levee in the left overbank, confining the flow to a width of about 1,200 ft. The banks of the main channel are lined with trees and appear to be stable. The bed material is sand.

Historical Scour Around Bridge Piers. The bridge was surveyed by use of the tuned transducer; the water was too deep for the GPR. The record did not show evidence of scouring. The areas around piers 2, 3, and 4 were probed. The data indicate some infilling around the piers. Vibracoring was not attempted at this site because of deep water. The soil-boring logs from the bridge plans are summarized in table 29 (at back of report).

Based on the probing, the bed elevation around pier 2 ranged from 447.6 to 451.3 ft, about the same as the elevation indicated on the construction plans. The lowest elevation probed was 443.3 ft at a point 2 ft left of the upstream end. The findings from the probing are compatible with the elevation of the loose fine to medium gravel layer indicated in the soil-boring log 2 (table 29).

Based on the probing, the bed elevation around pier 3 ranged from 452.3 to 455.0 ft. The construction plans show a bed elevation ranging from 443 ft to 443.5 ft. This difference indicates infilling at this pier. The lowest elevation reached by probing was 444.4 ft at a point 2 ft to the right of the center of the pier; the probing results indicate that the infilling is loose material. The probing at this pier also indicates debris along the channel bottom.

Based on the probing, the bed elevation around pier 4 ranged from 450.8 to 455.3 ft. The construction plans show a bed elevation of about 447 ft. This difference indicates infilling at this pier. The lowest elevation reached by probing was 441.4 ft at a point 2 ft left of the center of the pier. The soil-boring log indicates loose material to an elevation of 424.0 ft. Therefore, none of the data collected at this site indicates scour.

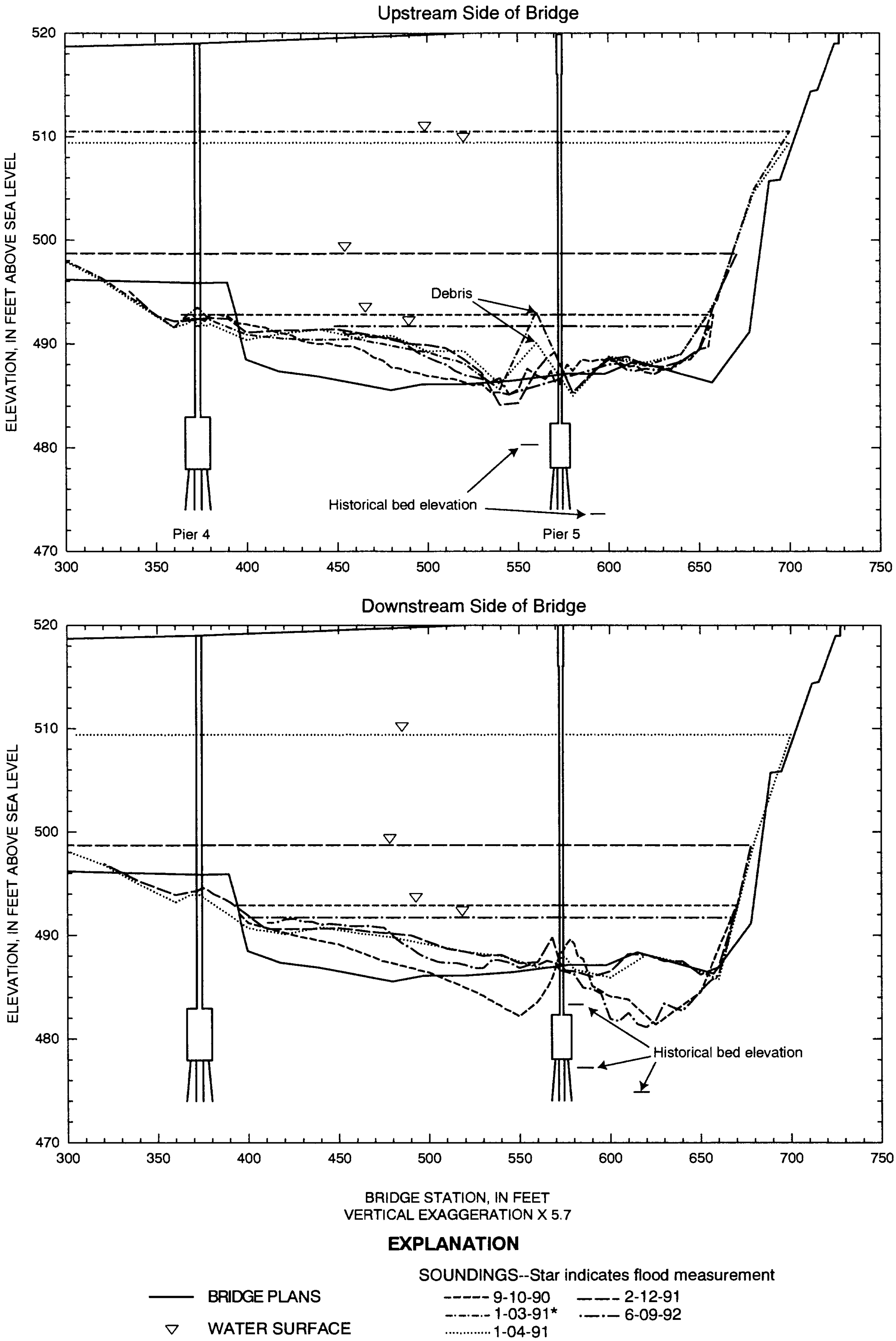


Figure 20. Cross sections showing bed elevations from bridge plans and soundings, State Road 157 over White River at Worthington, Indiana.

Flood Measurement and Routine Soundings. A flood measurement was made on January 3, 1991, at a discharge of 98,200 ft^3/s. Routine soundings also were made on September 11, 1990, January 15, 1991, February 13, 1991, and June 10, 1992 (fig. 21). Some surface debris was removed during the site visits. Debris, however, was always present below the water surface at pier 3. Debris also was present in small quantities on the channel bottom at pier 4. Scouring was not evident at either of these piers.

The channel bottom was fairly stable during the study. Differences between measured elevations and channel elevations from the bridge plans indicate some deposition in the left part of the main channel. The thalweg from the bridge plans is consistent with the elevations measured during the soundings. No scouring was observed at this site.

MODELING TECHNIQUES

Description of Scour Equations

The contraction-, pier-, and abutment-scour equations used in this study to compute the potential scour resulting from the 100- and 500-year peak discharges are those currently recommended by the FHWA (Richardson and others, 1993). Additional selected pier-scour equations evaluated for how well they reproduce measured historical scour are the same 13 equations evaluated in Mueller and others (1994), except for one additional equation developed from measurements of scour in Arkansas (Southard, 1992). The 14 pier-scour equations also were evaluated for how well they reproduce streambed elevations determined from flood measurements. The notation for variables used for presentation of the equations in this report is consistent with the notation used in Mueller and others (1994), which may differ from that in the original published equations. The variables are defined in the text the first time they are presented and in a listing of symbols that follows the table of contents. Some of the equations are dimensionless and can be used with any units, as long as those units are consistent. If equation variables require specific units, the units are defined with the equation in which they are required.

Contraction-Scour Equations

Contraction scour is the removal of bed material from the bridge opening as a result of increased velocity and shear stress on the bed caused by a contraction of the flow area. Contraction of the flow area by highway embankments encroaching onto the flood plain and (or) bridge abutments projecting into the main channel is the most common cause of contraction scour (Richardson and others, 1993). Contraction scour is classified as either live-bed or clear-water scour. Live-bed scour occurs when bed material is in transport upstream from the contracted section. With live-bed scour, the sediment transported from a scour hole consists of bed material removed from the scour hole as well as bedload transported into the scour hole. Clear-water scour occurs when bed material is not in transport upstream from the contracted section. The only material being transported from the scour hole is the bed material being scoured. Separate equations have been developed to estimate scour for these two conditions. As a general rule, the live-bed scour equation has been applied to the main channel of the bridge opening and the clear-water scour equation has been applied to the overbanks. Specific conditions at each site, however, should be considered before applying an equation. For example, loose sediments in the overbanks of a bridge opening may indicate live-bed scour rather than clear-water scour. A summary of the contraction-scour equations used in this report follows; details on the development of these equations are given in Mueller and others (1994, p. 38).

Live-Bed Scour

The live-bed contraction-scour equation currently recommended by FHWA is a modified version of an equation developed by Laursen (1960). The modified Laursen live-bed scour equation has been applied to the main-channel part of the bridge openings for the historical scour analyses and for the computation of potential scour.

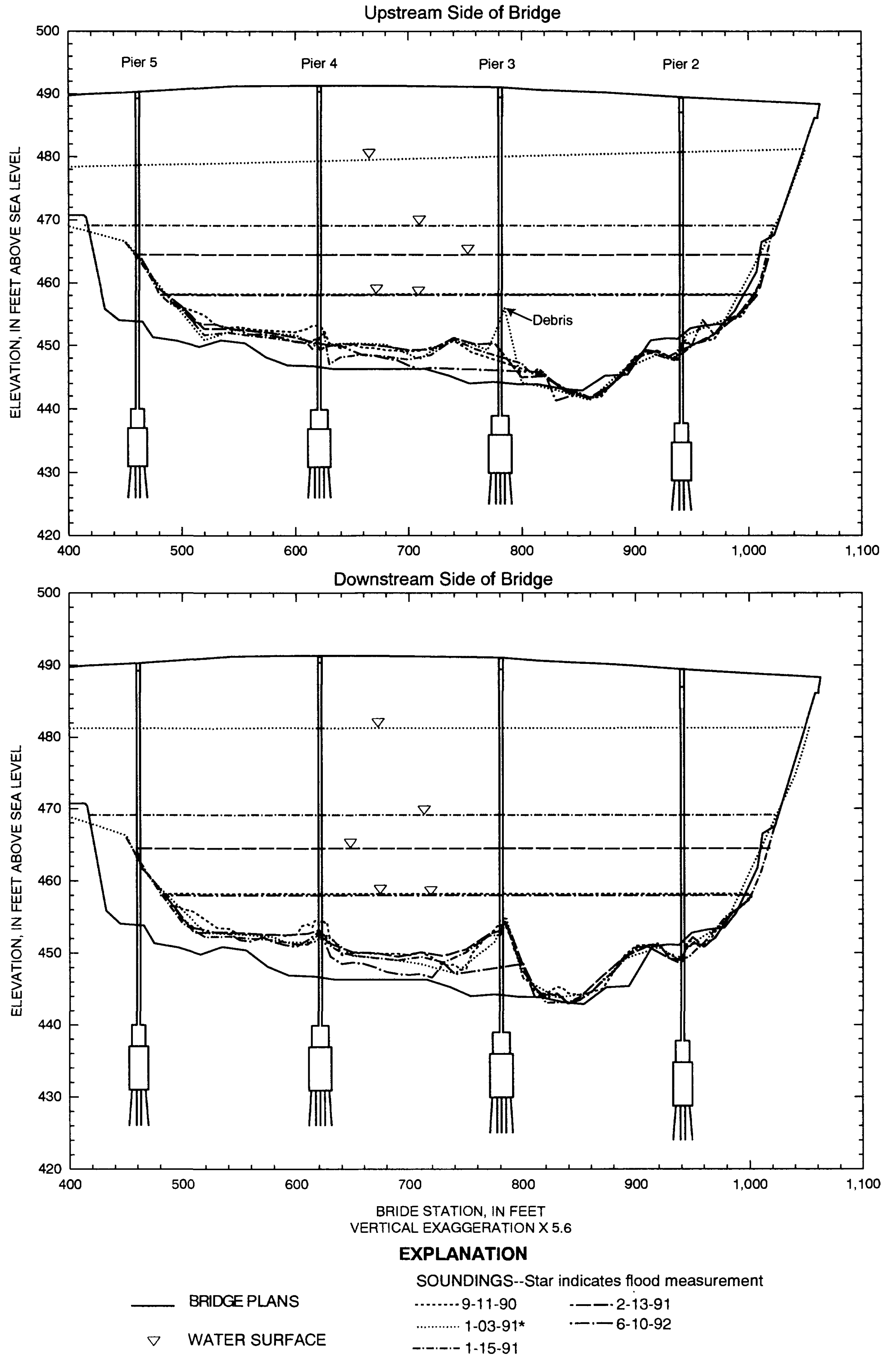


Figure 21. Cross sections showing bed elevations from bridge plans and soundings, State Road 163 over Wabash River at Clinton, Indiana.

The modified Laursen equation differs from earlier versions of the equation in that the ratio of Manning's roughness coefficient has been eliminated. The Laursen live-bed contraction-scour equation used in this study is

$$y_{sc} = y_u\left(\frac{Q_c}{Q_u}\right)^{6/7}\left(\frac{B_u}{B_c}\right)^{6/7\left(\frac{2+a}{3+a}\right)} - y_b \ , \qquad (1)$$

where y_{sc} is depth of contraction scour below the existing bed,
y_u is average depth of flow in the uncontracted (approach) channel,
Q_c is discharge in the part of the contracted channel represented by the specified bottom width,
Q_u is discharge in the part of the uncontracted (approach) channel represented by the specified bottom width,
B_u is bottom width of the uncontracted (approach) section,
B_c is bottom width of the contracted section,
y_b is average depth of flow at the bridge before contraction scour, and
a is a coefficient based on the ratio of the shear velocity to the fall velocity in the uncontracted channel.

a	u_*/ω	Mode of bed-material transport
0.25	<0.5	Mostly contact bed-material discharge
1.00	0.5–2.0	Some suspended bed-material discharge
2.25	>2.0	Mostly suspended bed-material discharge

where u_* is shear velocity, defined as, $\sqrt{gy_uS}$; (g is acceleration of gravity, and S is dimensionless slope of the energy grade line near the bridge), and
ω is fall velocity of the median grain size of the bed material (Richardson and others, 1993, p. 34, fig. 3).

Richardson and others (1993, p. 35) provide a warning on the use of this equation:

> Laursen's equation will overestimate the depth of scour at the bridge if the bridge is located at the upstream end of a natural contraction or if the contraction is the result of the bridge abutments and piers. At this time, however, it is the best equation available.

Clear-Water Scour

The clear-water contraction-scour equation currently recommended by FHWA is based on an equation developed by Laursen (1963). The original equation has been modified to use the effective mean diameter (1.25 x median) of the bed material rather than the median grain size (Richardson and others, 1993, p. 35). With this modification, the clear-water contraction-scour equation used in this study is

$$y_{sc} = \left(\frac{Q_c^2}{120\,(1.25d_{50})^{2/3}B_c^2}\right)^{3/7} - y_b \ , \qquad (2)$$

where d_{50} is median grain size of the bed material.

Note: This equation is not dimensionless; y_{sc}, d_{50}, B_c, y_b are in feet, and Q_c is in cubic feet per second.

Pier-Scour Equations

The recommended pier-scour equation is the HEC-18 equation, which was developed from the Colorado State University (CSU) equation presented originally in Richardson and others (1975).

The HEC-18 equation predicts equilibrium pier-scour depths and is recommended for live-bed and clear-water pier scour (Richardson and others, 1993). The HEC-18 equation has been modified to compute maximum scour, correcting for bed conditions. According to Richardson and others (1993, p. 39),

> For plane-bed conditions, which is typical of most bridge sites for the flood frequencies employed in scour design, the maximum scour may be 10 percent greater than computed with CSU's equation. In the unusual situation where a dune bed configuration with large dunes exists at a site during flood flow, the maximum pier scour may be 30 percent greater than the predicted equation value. This may occur on very large rivers, such as the Mississippi. For smaller streams that have a dune bed configuration at flood flow, the dunes will be smaller and the maximum scour may be only 10 to 20 percent larger than equilibrium scour. For antidune bed configuration the maximum scour depth may be 10 percent greater than the computed equilibrium pier scour depth.

The HEC-18 equation for pier scour is

$$y_{sp} = 2.0 y_o K_1 K_2 K_3 \left(\frac{b}{y_o}\right)^{0.65} \mathbf{F}_o^{0.43} \quad , \qquad (3)$$

where y_{sp} is depth of pier scour below the ambient bed,

y_o is depth of flow just upstream from the pier, excluding local scour,

K_1 is a coefficient based on the shape of the pier nose (1.1 for a square nose; 1.0 for a round nose, a circular cylinder, or a group of cylinders; and 0.9 for a sharp nose),

K_2 is a coefficient based on the attack angle of the approach flow to the pier and the ratio of pier length to pier width,

Angle	L/b=4	L/b=8	L/b=12
0°	1.0	1.0	1.0
15°	1.5	2.0	2.5
30°	2.0	2.5	3.5
45°	2.3	3.3	4.3
90°	2.5	3.9	5.0

K_3 is a coefficient based on the bed condition,

Bed condition	Dune height (H), in feet	K_3
Clear-water scour	--	1.1
Plane bed and antidunes	--	1.1
Small dunes	$2<H<10$	1.1
Medium dunes	$10<H<30$	1.1–1.2
Large dunes	$H>30$	1.3

L is length of pier,

b is width of pier, and

$\mathbf{F}_o$ is the Froude number of the flow just upstream from the pier, defined as:

$$\mathbf{F}_o = \frac{V_o}{\sqrt{g y_o}} \quad ,$$

where V_o is velocity of the approach flow just upstream from the pier, and

g is acceleration due to gravity.

Richardson and others (1993) state that K_1 should be applied for angles of attack up to 5°; but for greater angles, K_1 should be 1.0 because pier shape loses its effect. If the ratio of pier length to pier width is greater than 12, then the values of K_2 for L/b=12 should be used as maximums. In this study a K_3 value of 1.1 was applied for all pier-scour computations with the HEC-18 equation.

The potential scour computations in this report include a correction for the HEC-18 equation for exposed footings (Richardson and others, 1993, p. 41). If a pier footing extended above the streambed or became exposed after subtracting the computed contraction scour from the streambed, the HEC-18 equation was recomputed to account for the exposed footing. This second pier-scour computation used as variables in equation 3 the width of the footing as the pier width and the depth and average velocity in the flow zone obstructed by the footing. The larger of the two HEC-18 computations was used as the potential pier scour. The average velocity of the flow at the exposed footing was determined from the following equation from Richardson and others (1993, p. 41):

$$V_f = \frac{\ln\left(10.93\frac{y_f}{k_s}+1\right)}{\ln\left(10.93\frac{y_o}{k_s}+1\right)} V_o \ , \qquad (4)$$

where V_f is average velocity in the flow zone below the top of the footing,

y_f is distance from the streambed to the top of the footing, and

k_s is grain roughness of the streambed, normally taken as the d_{84} of the bed material.

The values of V_f and y_f are used in equation 3. The value of y_o is the depth of flow to the contraction-scour bed. The velocity of the approach flow, V_o, is the same as that determined for equation 3; a second WSPRO model was not done for the bridge opening to reflect the added depth from contraction scour.

Several published equations were analyzed for how well they reproduced measured historical scour and scour measured during flooding. The selected published equations are the same as those described in Mueller and others (1994), except for the updated version of the HEC-18 (CSU) equation and an equation developed by Southard (1992). The pier-scour equations and references on the development of each equation are listed in table 30. A detailed discussion of the pier-scour equations is not included. The reader is referred to Mueller and others (1994, p. 39-48) for a description of the selected pier-scour equations and information on the development and limitations of each equation.

The above-mentioned equation developed by Southard (1992) is a multiple-linear regression equation based on 22 sets of data from 12 sites on Arkansas streams. Data that were analyzed include measured scour depths, bed-material diameter, pier geometry, flow depth, average velocity, and pier location. Variables determined to be statistically significant (at the 0.05 level) were median grain size of the bed material, average velocity at the pier, and pier-location code. The pier-location code identifies whether a pier is in the main channel or on the overbanks of the bridge opening. Piers on the banks of the main channel were considered to be on the overbanks. The average standard error of estimate of this equation was ±42 percent. Southard (1992) states that the use of this equation should be limited to sites where bed-material diameters are between 0.00036 ft (0.11 mm) and 0.0689 ft (21 mm) and where the average velocity is 1.7 to 12.8 ft/s. Some of the sites in this study fall outside this range of bed-material diameters. The equation, however, was applied at all sites. The equation developed by Southard (1992) is referred to hereafter as the "Arkansas equation." The Arkansas equation for pier scour is

$$y_{sp} = 0.827\,(d_{50})^{-0.117}\,(V_o)^{0.684}\,(e)^{0.476C} \ , \qquad (5)$$

where C is pier-location code (0 for piers in the main channel and 1 for piers on the overbanks), which results in a weighting factor of 1 for piers in the main channel and a weighting factor of 1.61 for piers on the overbanks.

Note: This equation is not dimensionless; y_{sp} and d_{50} are in feet, and V_o is in feet per second.

Table 30. Selected pier-scour equations used in the historical scour analysis of selected bridge sites in Indiana
[From Mueller and others, 1994; variables not defined in this table are defined in the list of symbols on page xi]

Equation name and references	Equation	Variables and units
Ahmad Ahmad (1962)	$y_{sp} = Kq^{2/3} - y_o$	q is discharge per unit width just upstream from the pier, K is a coefficient that is a function of boundary geometry, abutment shape, width of the piers, shape of the piers, and the angle of the approach flow. Ranges from 1.7 to 2.0. For this study, it was assumed to be 1.8. Note: The Ahmad equation is not dimensionless; y_{sp} and y_o are in feet, and q is in cubic feet per second per foot.
Blench-Inglis I Blench (1951, 1962, 1969); and Inglis (1949)	$y_{sp} = 1.8b^{0.25}q^{0.5}\left(\frac{y_o}{V_o^2}\right)^{0.25} - y_o$	
Blench-Inglis II Blench (1951, 1962, 1969); and Inglis (1949)	$y_{sp} = 1.8b^{0.25}\left(\frac{q^2}{1.9d_{50}^{0.5}}\right)^{0.25} - y_o$	Note: The Blench-Inglis II equation is not dimensionless; y_{sp}, b, and y_o are in feet, q is in cubic feet per second per foot, and d_{50} is in millimeters.
Chitale Chitale (1962)	$y_{sp} = y_o\left(-5.49\mathbf{F}_o^2 + 6.65\mathbf{F}_o - 0.51\right)$	
Froehlich Froehlich (1988)	$y_{sp} = 0.32b\phi\left(\frac{b'}{b}\right)^{0.62}\left(\frac{y_o}{b}\right)^{0.46}\mathbf{F}_o^{0.2}\left(\frac{b}{d_{50}}\right)^{0.08}$	b' is width of the bridge pier projected normal to the approach flow $b' = b\cos(\alpha) + L\sin(\alpha)$, ϕ is a coefficient based on the shape of the pier nose (1.3 for a square nose, 1.0 for a round nose, 0.7 for a sharp nose), α is angle of the approach flow referenced to the bridge pier, in degrees.
Inglis-Lacey Inglis (1949); Joglekar (1962); and Lacey (1930)	$y_{sp} = 0.946\left(\frac{Q}{1.76d_{50}^{0.5}}\right)^{1/3} - y_o$	Note: The Inglis-Lacey equation is not dimensionless; y_{sp} and y_o are in feet, Q is in cubic feet per second, and d_{50} is in millimeters.

Table 30. Selected pier-scour equations used in the historical scour analysis of selected bridge sites in Indiana–Continued

Equation name and references	Equation	Variables and units
Inglis-Poona I Inglis (1949) and Joglekar (1962)	$y_{sp} = 1.7b\left(\frac{q^{2/3}}{b}\right)^{0.78} - y_o$	Note: The Inglis-Poona I equation is not dimensionless; y_{sp}, y_o, and b are in feet, and q is in cubic feet per second per foot.
Inglis-Poona II Inglis (1949) and Joglekar (1962)	$y_{sp} = 1.73b\left(\frac{y_o}{b}\right)^{0.78} - y_o$	Note: The Inglis-Poona II equation is not dimensionless; y_{sp}, y_o, and b are in feet, and q is in cubic feet per second per foot.
Larras Larras (1963)	$y_{sp} = 1.42K_{S2}b^{0.75}$	K_{S2} is a coefficient based on the shape of the pier nose (1.0 for cylindrical piers and 1.4 for rectangular piers). Dimensions are in feet.
Laursen Laursen (1962)	$\frac{b}{y_o} = 5.5\left(\frac{y_{sp}}{y_o}\right)\left(\left[\left(\frac{1}{11.5}\right)\left(\frac{y_{sp}}{y_o}\right)+1\right]^{1.70} - 1\right)$ $y_{sp} = K_{S1}y_{sp}$ or $y_{sp} = K_{\alpha L}y_{sp}$	Note: The depth of scour from the Laursen equation has to be corrected for pier shape if the pier is aligned with the flow and for angle of attack if the pier is not aligned with the flow. K_{S1} is a coefficient based on the shape of the pier nose (see table 2 in Mueller and others, 1994). $K_{\alpha L}$ is a coefficient based on the angle of the approach flow referenced to the bridge pier (see fig. 25 in Mueller and others, 1994).
Shen Shen and others (1969)	$y_{sp} = 0.00073\mathbf{R}_p^{0.619}$	$\mathbf{R}_p$ is the pier Reynolds number, defined as $\frac{V_o b}{v}$, where v is the kinematic viscosity of water.
Maza and Sanchez (1964) and Shen and others (1969)	$y_{sp} = 11.0b\mathbf{F}_p^2$ for $\mathbf{F}_p < 0.2$ $y_{sp} = 3.4b\mathbf{F}_p^{0.67}$ for $\mathbf{F}_p > 0.2$	$\mathbf{F}_p$ is is pier Froude number, defined as $\frac{V_o}{\sqrt{gb}}$.

Abutment-Scour Equations

The FHWA currently recommends the use of two abutment-scour equations to compute potential depth of scour at abutments (Richardson and others, 1993). One is a live-bed scour equation developed by Froehlich (1989), and the other is an equation from Richardson and others (1990) that predicts the equilibrium depth of scour, which is referred to in this report as the "HIRE equation." The Froehlich equation was used for all potential abutment-scour computations. The HIRE equation was applied as an alternative method to the sites where the ratio of abutment length to flow depth was greater than 25.

For design purposes, the Froehlich equation adds a factor of safety equal to the depth of flow at the abutment. The Froehlich live-bed equation for abutment scour is

$$y_{sa} = 2.27 K_{sa} K_{\theta} \left(\frac{l}{y_{oa}}\right)^{0.43} \mathbf{F}_a^{0.61} y_{oa} + y_{oa} \;, \qquad (6)$$

where y_{sa} is depth of abutment scour below the ambient bed,

K_{sa} is a coefficient for abutment shape (1.0 for a vertical abutment with square or rounded corners and a vertical embankment; 0.82 for a vertical abutment with wingwalls and a sloped embankment; and 0.55 for a spill-through abutment and a sloped embankment),

K_{θ} is a coefficient based on the angle that an embankment is skewed to the direction of flow, defined as:

$$K_{\theta} = \left(\frac{\theta}{90}\right)^{0.13}$$

where θ is angle an embankment is skewed to the direction of flow, in degrees; if an embankment points downstream, $\theta<90°$; if an embankment points upstream, $\theta>90°$ ($\theta = 90°$ if the embankment skew is 0°);

l is length of an abutment (embankment), defined as A_e/y_{oa};

A_e is cross-sectional area of the flow obstructed by the embankment;

y_{oa} is average depth of flow obstructed by the embankment; and

$\mathbf{F}_a$ is Froude number of the flow at the abutment, defined as:

$$\mathbf{F}_a = \frac{(Q_e/A_e)}{\sqrt{g y_{oa}}} \;,$$

where Q_e is discharge obstructed by the embankment.

The HIRE equation is based on U.S. Army Corps of Engineers data for scour at the end of spur dikes on the Mississippi River. According to Richardson and others (1993, p. 50):

> This field situation closely resembles the laboratory experiments for abutment scour in that the discharge intercepted by the spurs was a function of the spur length.

As stated previously, the HIRE equation is applicable where the ratio of abutment length to flow depth is greater than 25. The abutment length and flow depth used to determine this ratio are those defined for the Froehlich equation in which the flow depth is the average depth of flow being obstructed by the embankment. The depth of flow and velocity used in the HIRE equation are determined from the bridge section. The HIRE equation was developed with spur dikes, which have spill-through shapes. If the equation is applied to abutments with other shapes, it needs to be corrected for abutment shape. The equation also should be corrected for abutments that are skewed to the direction of flow (fig. 22). The HIRE equation for abutment scour is

$$y_{sa} = 4\mathbf{F}_o^{0.33} y_o \left(\frac{K_{sa}}{0.55}\right), \tag{7}$$

Note: Velocity and flow depth at the abutment, which are required to solve for $\mathbf{F}_o$, are determined from the bridge section for this equation and not from the approach section.

Estimation of Hydrologic Conditions

General design procedure outlined in Richardson and others (1993, p. 21-26) suggests that bridges and bridge foundations be designed to withstand the effects of scour resulting from a super flood (exceeding the 100-year flood) with little risk of failing. The design procedure recommends evaluating the floods likely to produce the most severe scour. Richardson and others (1993) indicate that such a flood is likely to be the 100-year flood or the overtopping flood if it is less than the 100-year flood. The initial design is checked by calculating scour for a super flood or check flood equal to the 500-year peak discharge to ensure that all foundations have a minimum factor of safety of 1.0 under ultimate load.

Evaluation of potential scour at existing bridges by use of the recommended equations requires estimates of 100-year and 500-year peak discharges. Wherever possible in this study, published peak discharges were used. Flood insurance studies published by the Federal Emergency Management Agency (FEMA) provided 100-year and 500-year peak discharges for six of the sites. Discharge-frequency curves (discharge plotted against drainage area) published by the Indiana Department of Natural Resources (1993) were used to determine peak discharges for the 10-, 25-, 50-, and 100-year return periods for the other 14 sites.

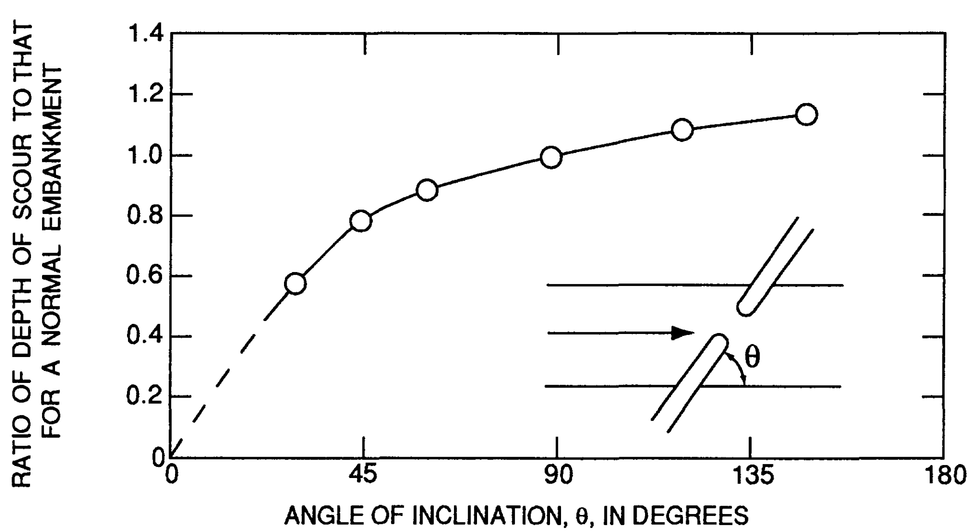


Figure 22. Abutment-scour estimate adjustment in the HIRE equation for skew (modified from Richardson and others, 1993, p. 51).

Discharge-frequency curves were not available for the 500-year return period. The 500-year peak discharges were extrapolated from the 10-, 25-, 50-, and 100-year peak discharges by use of linear regression. The linear regression involved log-transformed discharges and Pearson Type III plotting positions for zero skew listed in "Guidelines for Determining Flood Flow Frequency" (U.S. Geological Survey, 1982). The four peak discharges for each site were plotted against exceedance probability, and a line formed by these four points was analyzed. If the line seemed straight or if no definite curve was delineated, a linear regression on all four points was done to estimate the 500-year peak discharge. If a line through the four points formed a curve, a linear regression on only the 50- and 100-year peak discharges was used to estimate the 500-year peak discharge. The use of only 50- and 100-year peaks for the sets of discharges that did not plot on a straight line resulted in conservative (larger) estimates of the 500-year peak discharge. Estimates of the 500-year peak discharges by use of linear regression are more accurate and reproducible than those derived from graphical methods alone. Peak discharges and the drainage area for each site are listed in table 31.

Historical peak discharge (the maximum discharge during the life of the bridge) was used to evaluate how well selected published equations reproduced measured historical scour by use of the method presented in Mueller and others (1994). At three sites, however, the maximum historical peak discharge occurred during the study, but no scour was detected or it was determined that the maximum peak discharge was not related to the interpreted historical scour. At these sites, the next largest historical peak discharge was used for the analysis. These three exceptions are discussed further in the section, "Comparison of Computed to Historical Scour Around Bridge Piers." Historical peak discharges were estimated from USGS streamflow-gaging stations upstream or downstream from the site or from nearby basins with similar hydrologic conditions. At some sites, a streamflow-gaging station was immediately upstream or downstream, and the historical peak discharge could be obtained directly from the record of peak flows. At other sites, the peak discharge had to be adjusted (by runoff, in cubic feet per square mile) for small differences in drainage area.

Sites where a streamflow-gaging station was not immediately upstream or downstream required identification of at least two gaging stations for which peak-flow records were available for a given flood event. Where available, river profiles provided by the Indiana Department of Natural Resources (IDNR) also were used to identify potential historical peak discharges. The historical peak discharge for each of the identified gaging stations was reviewed for magnitude and timing to ensure that the same flood event was observed. The historical peak discharges were plotted against the runoff (in cubic feet per square mile) with log transformations to identify which gaging stations recorded similar responses for a given flood. Gaging stations where flood records were related were selected for estimating the historical peak discharge at the bridge site by use of linear regression. A linear regression of the peak discharges and drainage areas with log transformations was used to estimate the historical peak discharge. As with the estimates of 500-year peak discharges, estimates of historical peaks by linear regression are more accurate and reproducible than those derived from graphical methods alone. The historical peak discharges for the study sites and their respective dates are listed in table 31.

The durations of the floods were not assessed in this study because duration is not used in any of the selected scour equations. The authors assumed that all the modeled flood discharges were sustained for a sufficient period to allow equilibrium sediment transport through the scour holes.

Table 31. Hydrologic characteristics of selected bridge sites in Indiana

[ft^3/s, cubic feet per second; Q, peak discharge; S.R., State Road; --, no data; U.S., U.S. Route]

				Estimated peak discharge for given recurrence interval (ft^3/s)					Historical peak[1]	
Highway	River	Nearest city	Drainage area (square miles)	Q_{10}	Q_{25}	Q_{50}	Q_{100}	Q_{500}	Discharge (ft^3/s)	Date
S.R. 1	St. Marys	Fort Wayne[2]	780	10,300	--	14,100	15,700	19,400	12,900	March 1982
S.R. 9	Pigeon	Howe	237	1,270	1,520	1,730	1,930	2,410	1,910	March 1982
S.R. 11	Flatrock	Columbus[2]	541	19,500	--	29,000	32,500	43,000	13,500	February 1982
S.R. 14	Tippecanoe	Winamac	941	7,400	8,500	9,600	10,800	13,400	9,280	June 1981
S.R. 15	Little Elkhart	Bristol[2]	118	1,820	--	2,340	2,600	3,120	2,840	February 1985
S.R. 19	Wabash	Peru[2]	2,678	19,500	--	27,000	31,000	68,000	18,000	December 1990
S.R. 25	Wildcat Creek	Lafayette	796	18,000	22,000	25,000	28,000	35,400	25,000	June 1958
S.R. 32	Wabash	Perrysville	8,268	71,000	86,000	97,000	109,000	136,000	94,300	February 1985
U.S. 35	Kankakee	Union Center	313	1,250	1,350	1,440	1,530	1,730	1,660	March 1982
U.S. 41	Kankakee	Schneider	1,642	5,700	6,400	6,900	7,400	8,480	7,840	March 1982
S.R. 54	Busseron Creek	Sullivan	138	4,970	5,990	6,730	7,450	9,250	6,050	July 1979
S.R. 57	East Fork White	Petersburg	5,744	71,000	88,000	102,000	117,000	152,000	48,000	May 1983
S.R. 59	Eel	Clay City	879	23,300	29,000	33,500	38,000	47,100	36,200	June 1957
S.R. 63	Little Vermillion	Newport[2]	237	6,920	--	9,750	11,000	14,100	7,260	February 1985
S.R. 101	St. Joseph	Saint Joe	668	7,700	9,400	10,800	11,900	15,100	9,840	February 1985
S.R. 109	White	Anderson[2]	405	13,800	--	20,500	23,500	31,000	18,700	April 1964
S.R. 110	Tippecanoe	Mentone	434	3,000	3,600	4,000	4,400	5,340	5,300	June 1981
S.R. 135	Muscatatuck	Millport	1,134	35,000	44,000	53,000	60,000	80,500	33,500	January 1959
S.R. 157	White	Worthington	4,392	62,000	75,000	89,500	102,000	132,000	85,500	January 1991
S.R. 163	Wabash	Clinton	11,715	96,000	115,000	132,000	145,000	175,000	114,500	February 1985

[1]Historical peak discharge is based on the life of the bridge, not on the period of record.

[2]Peak discharges are from flood insurance studies published by the Federal Emergency Management Agency.

Estimation of Hydraulic Conditions

All the scour equations require input of hydraulic variables such as velocity and depth. Because measurements of the historical, 100-, and 500-year peak discharges were not available, the hydraulic conditions of these floods at each site were estimated by use of WSPRO, a computer model for water-surface profile computations developed by the USGS for the FHWA (Shearman and others, 1986; Shearman, 1990).

Cross-section data, bridge geometries, and roughness coefficients were obtained from field surveys of each site and input into WSPRO. Starting water-surface elevations were obtained from flood profiles published by FEMA and river profiles provided by IDNR, or they were determined by the slope-conveyance computation of WSPRO. Water-surface slopes for the slope-conveyance computations were estimated from the FEMA or IDNR profiles, where available, or from USGS topographic maps. Where available and applicable, published profiles were used to check water-surface elevations computed by WSPRO to verify the modeling. Measurements of discharge and their associated water-surface elevations also were used to verify the WSPRO models at some of the sites. Because WSPRO is a one-dimensional flow model, cross sections not perpendicular to flow were adjusted for skew.

The bridge routines in WSPRO were used to estimate the hydraulic conditions at the bridges, with the exception of S.R. 25 over Wildcat Creek. Because of a contraction downstream from the bridge, the Wildcat Creek site did not have sufficient contraction through the bridge opening to produce reasonable results with the bridge routines. The bridge geometry at this site was modeled as a composite section by use of the methods similar to those presented in Davidian (1984).

Some of the sites have levees or spoil banks that function as levees on one or both banks. These sites were modeled with the assumption that the levees or spoil banks would confine the discharge, an assumption that results in the worst-case hydraulic conditions for scour computations.

Some sites have complex flow distributions where not all the discharge passes through the bridge opening. At some sites, flow simply overtops the highway embankment, so the discharge through the bridge is reduced accordingly for estimating hydraulic conditions. S.R. 54 near Sullivan has a relief bridge approximately 2,000 ft from the study bridge. The multiple-opening bridge routine in WSPRO was used to identify the separation of flow between the two bridges, and the hydraulic conditions in the study bridge were determined for the portions of the peak flows passing through it. At S.R. 59 north of Clay City, some of the discharge bypasses the bridge and flows south, parallel to the embankment, to a relief bridge. The amount of flow bypassing the bridge was estimated by a model of the flow through the bridge and a model of the flow bypassing the bridge; these estimates were adjusted until a common water-surface elevation was computed for the reach upstream from the bridge. Therefore, the hydraulic conditions modeled in the bridge opening reflect the part of flow determined to pass through the bridge. S.R. 11 at Columbus was modeled similarly because flow overtopping the embankment may not return to Flatrock River but instead may flow to East Fork White River.

WSPRO computes 20 equal-conveyance tubes that describe velocity and discharge distributions along a cross section. These velocity and discharge distributions can be used to determine approach velocities to piers and discharge conveyed through subsections of the bridge and approach cross sections (Richardson and others, 1993, p. 54-61). A computer program for bridge-scour analysis with WSPRO (BSAW) was used to extract hydraulic and geometric data from WSPRO output (Mueller, 1993). BSAW computes the hydraulic variables for any subsection of a cross section and is specifically tailored for bridge-scour computations.

The live-bed contraction-scour equation was applied to the main channel of the bridge opening. This equation requires the following hydraulic characteristics at the bridge and approach sections:

average unconstricted energy slope, average depth of flow, width of flow over which sediment is transported, and discharge conveyed over the specified width. The average unconstricted energy slope was computed as the head loss divided by the distance between the two cross sections (Richardson and others, 1993, p. 57). The bottom width of the main channel (minus the width of piers) was used for the width over which sediment is transported. The discharge conveyed over the bottom width was computed with BSAW, and the average depth of flow was computed as the cross-sectional area of the flow conveyed over the bottom width divided by the bottom width.

The clear-water contraction-scour equation was applied to the overbank areas of the bridge opening. This equation requires the width of flow, average depth of flow, and discharge conveyed over the flow width. The distance from the top of the bank to the toe of the abutment (minus the width of piers) was used for the flow width. The discharge conveyed over the specified width was computed with BSAW, and the average depth of flow was computed as the cross-sectional area divided by the flow width.

The various pier-scour equations require the following hydraulic characteristics: total discharge through the bridge, depth of approach flow, approach velocity, and angle of attack. Depth of approach flow was computed as the difference between the water-surface elevation and the streambed elevation at the center line of the upstream end of the pier. The approach velocity was taken to be the velocity of the flow tube containing the center line of the pier. If the pier was near the boundary of a flow tube with higher velocity, the more conservative higher velocity was used. The angles of attack were determined by means of discharge measurements at several sites and were assumed to be the same for all discharges at those sites. The angles of attack were estimated from bridge plans for sites where discharge measurements were not made.

The two recommended abutment-scour equations are Froehlich's live-bed scour equation (eq. 6) and the HIRE equation (eq. 7). Froehlich's live-bed scour equation requires the following hydraulic characteristics: discharge blocked by the abutment/embankment, average depth of flow blocked by the abutment, the cross-sectional area of the blocked flow, the velocity at the abutment, and the length of the abutment projected normal to flow. These hydraulic characteristics are computed for the approach section. The bridge opening was projected upstream to the approach section and parallel to the direction of flow. The distance from the point corresponding to the toe of the abutment to the edge of water was the length of the abutment. The discharge and cross-sectional area conveyed over this length of the approach section was computed with BSAW. The average depth of flow blocked by the abutment was computed as the cross-sectional area divided by the length. The velocity at the abutment was computed as the discharge divided by the cross-sectional area. The HIRE abutment-scour equation was applied to those abutments where the ratio of the abutment length to flow depth was greater than 25. The HIRE equation requires the average depth of flow at the abutment and the average velocity at the abutment. The average velocity is the velocity computed for the flow tube in the bridge section adjacent to the abutment (flow tube 1 for the left abutment or flow tube 20 for the right abutment). The average depth of flow can be computed as the area of the flow tube adjacent to the abutment divided by the top width of the flow tube (Richardson and others, 1993, p. 59-60).

COMPARISON OF COMPUTED TO MEASURED DEPTHS OF SCOUR

Computed depths of scour were compared to measured depths of historical scour and depths of scour measured during floods. Estimated depths (elevations) for historical scour were measured by use of a combination of the geophysical techniques discussed in the sections "Historical Scour Around Bridge Piers," by probing with a steel rod and by collection of sediment cores. Streambed elevations were determined for flood measurements by measurements of the water-surface elevation and by depth soundings.

Comparison of Computed to Historical Scour Around Bridge Piers

Fourteen pier-scour equations were evaluated for how well they reproduced measured depths of historical scour identified in the subbottom of stream channels. Only piers in the main channel were included in this analysis. This comparison of measured depths of historical scour to computed depths is based on the assumption that the maximum observed scour is associated with the peak historical discharge. This assumption is suspect for field conditions because debris accumulations, ice jams, and other conditions such as backwater can affect the depth of scour at a given discharge. It is possible that the maximum observed scour was associated with a lesser discharge and was affected by debris or ice accumulations. In the sections "Flood Measurements and Soundings," it was mentioned how frequently debris accumulations on piers cause or affect local scour. The scour computations combine the depth of contraction scour and the depth of pier scour; however, the actual contraction-scour conditions at the time of the historical flooding cannot be determined. The measurements made by use of geophysical techniques resulted in an estimated minimum streambed elevation near the piers, but separation of contraction scour from local scour was not possible. This technique of comparing measured depths of historical scour to computed depths also is based on the interpretation that the identified buried interfaces are remnants of old scour holes that have refilled. Given the uncertainties inherent in interpreting buried interfaces and modeling historical discharges, this technique is not as fair an analysis of pier-scour equations as comparisons made with scour holes measured at the time of a known peak discharge.

Historical scour comparisons also produce uncertainty by adding contraction scour. At some sites, computed depths of contraction scour are large, and they cannot be considered reasonable estimates. This problem of excessive contraction-scour estimates was also evident in the potential scour computations. Unreasonably large depths of computed contraction scour are associated with sites where bridge openings are small, flood plains at the approach section are wide, or both. Wide flood plains result in large contraction ratios and small bridges can result in backwater; these situations provide the potential for contraction scour. Unreasonable depths of computed contraction scour are probably a product of the scour equation not being adequate for field situations, inaccurate estimates of the hydraulic conditions, or a combination of both. Although contraction scour could be deep for the discharges modeled in the historical and potential scour analyses, none of the data collected in this study indicates that contraction scour is prevalent at the 20 sites examined.

The clear-water contraction-scour computations for the overbanks seem to be excessive at many sites for the potential as well as the historical scour analyses. At several sites, the computed contraction scour for the main channel is negative (indicating deposition), but on the overbanks, deep contraction scour is computed; this scenario does not seem reasonable. The clear-water contraction-scour equation uses grain size as a variable and computes more scour for small grain sizes than for large sizes. The equation, however, does not consider the increased cohesion of the sediment with small grain sizes. The equation also does not consider vegetation on the overbanks that binds the surface sediments and prevents erosion; however, if peak flows were sustained long enough, this protective cover could fail and predicted values of scour could occur.

In some cases, pier-scour and contraction-scour analyses showed deposition; in these cases, the scour was assumed to be zero. This analysis of historical scour includes 15 observations from Mueller and others (1994). In cases where the pier-scour and contraction-scour computations indicated deposition from that study, the values of pier scour and contraction scour also have been set equal to zero for inclusion in this study.

The 13 pier-scour equations evaluated in Mueller and others (1994) (table 30) and the Arkansas equation (eq. 5) were applied to each bridge for the hydraulic conditions estimated for the historical peak discharge. The historical peak discharges and their dates are listed in table 31 of this report. Long-term scour was assumed to be zero, and a plane bed was assumed at all piers.

Tables 32-51 in the "Supplemental Data" section (at back of report) include the results of the historical scour computations. The hydraulic variables estimated with WSPRO, grain-size data for the bed material, angles of attack, and pier details are shown at the top of the tables. Widths of many bridge piers vary from top to bottom. For consistency, the pier widths used in this report are the widths of the piers at the surveyed bed elevations. Median grain sizes of the streambed material were determined from grain-size analyses of sediment samples collected in the main channels. Median grain sizes for the overbanks were estimated from soil-boring logs included in the bridge plans. Many of the attack angles at the piers were measured during discharge (flood) measurements. At sites where a discharge measurement was not made, the angles of attack were estimated from bridge plans and field surveys.

The contraction scour computed with Laursen's equations (eqs. 1 and 2) and the local pier scour computed from each of the selected pier-scour equations are listed near the center of tables 32-51. The computed bed elevation, listed below the depths of pier scour, was computed by subtracting the contraction scour, pier scour, and approach depth from the water-surface elevation. The estimated historical bed elevation resulting from the field measurements (geophysics, probes, and sediment cores) is listed at the bottom of tables 32-51. Computations of historical scour for piers on the overbanks are included; however, no field measurements of historical bed elevation are available for comparisons. A summary of the differences between computed and historical bed elevation at the nose of the pier—which is where the theory assumes maximum scour will occur (for piers aligned with flow)—is shown in table 52. One of the columns in table 52 is for the Froehlich equation with a factor of safety equal to the pier width added; inclusion of this safety factor is recommended for design purposes (Froehlich, 1988). In all, 23 historical bed elevations are available from 14 of the 20 study sites. A total of 38 comparisons are available with the addition of the data from Mueller and others (1994, table 14, p. 68). Because the contraction-scour computations predict what seems to be excessive scour at some sites, the differences between computed and historical bed elevation were recomputed without contraction scour (table 53). The removal of contraction scour improved the agreement between computed and measured historical bed elevations; however, pier scour was underestimated more frequently without contraction scour.

A site-by-site description of the performance of the equations follows.

S.R. 11 over Flatrock River. The computed contraction scour is minimal and does not affect the computed bed elevation at pier 3. Only the Blench-Inglis II and Inglis-Lacey equations underestimated the depth of scour compared to estimates from the geophysics and probing (tables 34 and 52). These two equations predicted deposition rather than scour, and the results subsequently were set equal to zero. The Inglis-Poona I equation was the only equation (other than the Blench-Inglis II and Inglis-Lacey equations) to predict a bed elevation within 3 ft of the estimated historical bed elevation. The modeled historical peak discharge was a flow of 13,500 ft^3/s in February 1982, not the subsequent, greater peak discharge of 19,400 ft^3/s in December 1990; the probing that confirmed the geophysical interpretation predated the latter peak discharge. Therefore, the estimated historical bed elevation was not associated with the maximum historical peak discharge, and the next largest historical peak discharge was used.

S.R. 14 over Tippecanoe River. The contraction-scour equation predicted 2.5 ft of deposition in the main channel; therefore, contraction scour was not included in the computation of historical scour. All the equations (except the Ahmad, Chitale, and Laursen equations) predicted a bed elevation within 3 ft of the estimated historical bed elevation at pier 4, and many of the equations predicted elevations within 2 ft (tables 35 and 52).

S.R. 15 over Little Elkhart River. The estimated historical peak discharge exceeds the 100-year peak discharge. The contraction scour of 9.9 ft may be excessive. This site is within 2,000 ft of the confluence with St. Joseph River and could be in backwater depending on the timing of peak flows. None of the equations predicted a bed elevation within 5 ft of the estimated historical bed elevation at pier 2 (tables 36 and 52). When contraction scour was removed, several of the equations predicted bed elevations within 2 ft of the estimated historical bed elevation (table 53). The Ahmad and Chitale equations predicted two to three times the scour predicted with most of the other equations.

S.R. 19 over Wabash River. The contraction-scour equation predicted 7.3 ft of deposition; therefore, contraction scour was not included in the computation of historical scour. The hydraulic conditions estimated from WSPRO were similar for piers 2 and 3, as were the computed depths of pier scour. Several of the equations predicted bed elevations within 3 ft of the estimated historical bed elevations (tables 37 and 52). The Ahmad and Chitale equations predicted greater depths of scour than all the other equations. The historical peak discharge of 18,000 ft^3/s occurred in December 1990, during the study period. Discharge and channel depths, however, were not measured to verify scour during the flooding of December 1990. As mentioned previously in the discussion on the field measurements at this site, debris accumulations on piers may have affected the local scour.

S.R. 32 over Wabash River. The predicted contraction scour seems to be excessive. If the predicted contraction scour of 24.3 ft were to occur, the hydraulic conditions in the bridge would change significantly and the pier-scour computations would not be valid. When contraction scour was included, most of the equations overestimated scour by at least 30 ft at piers 4, 5, and 6 (tables 39 and 52). When contraction scour was not included, the Arkansas equation predicted bed elevations within 2 ft of the estimated historical bed elevations at piers 4 and 5 and within 3.2 ft of the estimated historical bed elevation at pier 6 (table 53). Many of the pier-scour equations include approach depth and attack angle as variables, which may explain the large scour depths in table 39. Approach depth and attack angle are not used in the Arkansas equation. The historical bed elevations estimated from the geophysical techniques differ by only about 1 ft at piers 4, 5, and 6. The hydraulic conditions estimated with WSPRO are also similar at all three piers. Throughout the data-collection process at this site, the piers were prone to accumulating debris, an indication that the pier scour at this site is probably affected by debris accumulations.

U.S. Route 41 over Kankakee River. The estimated historical peak discharge exceeds the 100-year peak discharge. None of the equations predicted bed elevations within 3 ft of the estimated historical bed elevations at piers 2 and 3 (tables 41 and 52). At pier 2, the Shen-Maza equation was within 3.1 ft of the estimated historical bed elevation, and the Arkansas equation was within 3.5 ft (table 52). The predicted depth of contraction scour is 4.3 ft, which does not seem excessive relative to many sites. When contraction scour was excluded, however, several of the equations predicted bed elevations within 3 ft at pier 2 (table 53). The predicted bed elevations do not compare as well at pier 3. Because the interface identified as the scour hole at pier 3 is not much deeper than the streambed, the equations probably are biased to overpredict scour. Pier 3 is also in much deeper water than is pier 2.

Table 52. Computed and historical bed elevations at selected bridge sites in Indiana
[F.S., factor of safety; S.R., State Road; U.S., U.S. Route]

Site, magnitude, or category	Difference between the computed bed elevation and the measured historical bed elevation (computed – historic), in feet, for given equation															
	Pier	Ahmad	Arkansas	Blench-Inglis I	Blench-Inglis II	Chitale	Froehlich	Froehlich with F.S.	HEC-18	Inglis-Lacey	Inglis-Poona I	Inglis-Poona II	Larras	Laursen	Shen	Shen-Maza
S.R. 11 over Flatrock River	3	-9.5	-3.1	-5.1	0.1	-5.4	-3.1	-7.9	-7.1	0.1	-1.6	-5.2	-4.5	-9.4	-4.4	-6.7
S.R. 14 over Tippecanoe River	4	-8.2	-1.9	-.7	1.5	-4.0	-.3	-3.2	-3.0	-1.1	.2	-.9	-1.0	-4.3	-1.2	-2.8
S.R. 15 over Little Elkhart River	2	-20.1	-9.1	-5.3	-8.6	-13.8	-5.1	-7.1	-8.0	-6.2	-9.8	-5.4	-5.6	-7.5	-6.9	-8.7
S.R. 19 over	2	-15.9	-1.9	-2.7	1.0	-9.7	-.9	-4.3	-5.6	1.0	-5.4	-2.7	-2.6	-5.9	-3.7	-6.1
Wabash River	3	-17.0	-1.9	-2.5	1.1	-10.4	-.9	-4.3	-5.7	1.1	-5.4	-2.6	-2.5	-6.0	-3.7	-6.2
S.R. 32 over	6	-48.4	-27.5	-35.4	-32.5	-38.1	-30.8	-33.8	-39.8	-28.6	-34.2	-34.9	-31.2	-49.2	-33.2	-40.3
Wabash River	5	-44.6	-25.8	-38.0	-36.2	-35.1	-31.5	-39.4	-42.1	-31.1	-35.9	-36.9	-32.7	-49.8	-34.3	-43.3
	4	-44.1	-25.7	-33.3	-32.9	-34.7	-28.9	-31.9	-37.3	-32.8	-32.0	-32.7	-29.3	-46.1	-31.0	-37.8
U.S. Route 41 over	2	-8.3	-3.5	-7.3	-8.3	-4.8	-4.1	-7.1	-9.6	-8.3	-6.7	-6.6	-7.0	-12.2	-6.3	-3.1
Kankakee River	3	-18.9	-8.2	-12.9	-14.1	-12.7	-9.3	-12.3	-15.6	-3.3	-12.1	-12.3	-10.7	-20.5	-11.3	-16.1
S.R. 54 over	3	-18.1	-7.5	-4.0	-4.4	-12.4	-5.1	-7.1	-7.5	-2.5	-6.0	-4.3	-5.8	-8.4	-5.8	-7.3
Busseron Creek	2	-16.8	-6.2	-2.7	-3.1	-11.1	-3.8	-5.8	-6.2	-1.2	-4.8	-3.0	-4.5	-7.0	-4.5	-6.0
S.R. 57 over East Fork White River	3	-28.3	-13.6	-14.3	-10.7	-20.6	-13.2	-18.7	-18.2	-13.4	-13.7	-14.5	-13.6	-20.2	-14.8	-18.2
S.R. 59 over	2	-27.4	-5.3	-1.4	-4.8	-16.9	-2.1	-5.3	-6.4	-4.3	-7.3	-1.8	-2.1	-6.7	-4.3	-7.2
Eel River	3	-30.7	-4.0	.5	-3.3	-18.5	-.8	-4.1	-5.4	.7	-6.3	0	-.6	-5.9	-3.1	-6.2
S.R. 63 over Little	3	-37.7	-17.1	-22.8	-27.6	-27.7	-18.4	-20.4	-25.0	-10.7	-30.3	-21.8	-20.9	-27.2	-24.5	-33.3
Vermillion River	2	-17.8	-11.0	-8.6	-8.8	-13.7	-8.3	-10.3	-10.7	-12.8	-10.2	-8.7	-9.0	-11.0	-9.6	-10.9

Table 52. Computed and historical bed elevations at selected bridge sites in Indiana–Continued

Site, magnitude, or category	Difference between the computed bed elevation and the measured historical bed elevation (computed – historic), in feet, for given equation															
	Pier	Ahmad	Arkansas	Blench-Inglis I	Blench-Inglis II	Chitale	Froehlich	Froehlich with F.S.	HEC-18	Inglis-Lacey	Inglis-Poona I	Inglis-Poona II	Larras	Laursen	Shen	Shen-Maza
S.R. 101 over	2	-10.7	-.2	-.3	-.5	-5.0	1.3	-.7	-1.6	1.1	-1.9	-.2	.4	-3.6	-.6	-3.4
St. Joseph River	3	-12.9	-1.9	-4.4	-4.2	-7.0	-1.6	-3.6	-5.2	.7	-5.6	-4.1	-3.1	-8.2	-4.0	-7.9
S.R. 109 over White River	6	-18.2	1.3	-7.5	.8	-9.7	-.8	-4.3	-9.0	5.2	-13.3	-6.4	-6.0	-10.1	-8.8	-17.7
S.R. 110 over	3	-12.2	-4.4	-1.7	-1.8	-7.6	-1.6	-3.6	-4.0	-3.3	-3.4	-1.9	-2.2	-4.4	-2.9	-4.2
Tippecanoe River	4	-10.0	-1.8	-.1	1.9	-5.6	.4	-1.6	-2.3	1.1	-1.8	-.2	-.5	-2.6	-1.1	-2.5
S.R. 163 over Wabash River	2	-24.3	-1.0	4.2	4.0	-13.0	1.0	-2.0	-2.9	-6.5	2.7	3.3	1.6	-6.8	-.2	-3.2
Number of occurrences (23 observations)																
Greater than 10 feet		19	6	6	6	14	5	7	7	6	8	6	6	9	6	8
10 to 5 feet		4	5	5	3	7	4	6	11	4	8	5	5	10	5	9
Less than 5 feet		0	12	12	14	2	14	10	5	13	7	12	12	4	12	6
Scour underestimated		0	1	2	7	0	3	0	0	8	2	1	2	0	0	0
Scour overestimated		23	22	21	16	23	20	23	23	15	21	21	21	23	23	23
Number of occurrences including the sites from Mueller and others (1994) (38 observations)																
Greater than 10 feet		29	6	7	6	20	7	8	8	10	11	7	7	10	6	10
10 to 5 feet		7	13	12	11	12	9	16	22	8	15	12	12	18	14	18
Less than 5 feet		2	19	19	21	6	22	14	8	20	12	19	19	10	18	10
Scour underestimated		2	7	10	16	4	12	6	6	15	9	9	10	6	6	6
Scour overestimated		36	31	28	22	34	26	32	32	23	29	28	28	32	32	32

Table 53. Computed and historical bed elevations (excluding contraction scour) at selected bridge sites in Indiana
[F.S., factor of safety; S.R., State Road; U.S., U.S. Route]

Site, magnitude, or category	Pier	Difference between the computed bed elevation and the measured historical bed elevation (computed – historic), in feet, for given equation														
		Ahmad	Arkansas	Blench-Inglis I	Blench-Inglis II	Chitale	Froehlich	Froehlich with F.S.	HEC-18	Inglis-Lacey	Inglis-Poona I	Inglis-Poona II	Larras	Laursen	Shen	Shen-Maza
S.R. 11 over	3	-9.0	-2.6	-4.6	0.6	-4.9	-2.6	-7.4	-6.6	0.6	-1.1	-4.7	-4.0	-8.9	-3.9	-6.2
Flatrock River																
S.R. 14 over	4	-8.2	-1.9	-.7	1.5	-4.0	-.3	-3.2	-3.0	-1.1	.2	-.9	-1.0	-4.3	-1.2	-2.8
Tippecanoe River																
S.R. 15 over Little	2	-10.2	.8	4.6	1.3	-3.9	4.8	2.8	1.9	3.7	.1	4.5	4.3	2.4	3.0	1.2
Elkhart River																
S.R. 19 over	2	-15.9	-1.9	-2.7	1.0	-9.7	-.9	-4.3	-5.6	1.0	-5.4	-2.7	-2.6	-5.9	-3.7	-6.1
Wabash River	3	-17.0	-1.9	-2.5	1.1	-10.4	-.9	-4.3	-5.7	1.1	-5.4	-2.6	-2.5	-6.0	-3.7	-6.2
S.R. 32 over	6	-24.1	-3.2	-11.1	-8.2	-13.8	-6.5	-9.5	-15.5	-4.3	-9.9	-10.6	-6.9	-24.9	-8.9	-16.0
Wabash River	5	-20.3	-1.5	-13.7	-11.9	-10.8	-7.2	-15.1	-17.8	-6.8	-11.6	-12.6	-8.4	-25.5	-10.0	-19.0
	4	-19.8	-1.4	-9.0	-8.6	-10.4	-4.6	-7.6	-13.0	-8.5	-7.7	-8.4	-5.0	-21.8	-6.7	-13.5
U.S. Route 41 over	2	-4.0	.8	-3.0	-4.0	-.5	.2	-2.8	-5.3	-4.0	-2.4	-2.3	-2.7	-7.9	-2.0	1.2
Kankakee River	3	-14.6	-3.9	-8.6	-9.8	-8.4	-5.0	-8.0	-11.3	-1.0	-7.8	-8.0	-6.4	-16.2	-7.0	-11.8
S.R. 54 over	3	-10.8	-.2	3.3	2.9	-5.1	2.2	.2	-.2	4.8	1.3	3.0	1.5	-1.1	1.5	0
Busseron Creek	2	-9.5	1.1	4.6	4.2	-3.8	3.5	1.5	1.1	6.1	2.5	4.3	2.8	.3	2.8	1.3
S.R. 57 over East	3	-13.3	1.4	.7	4.3	-5.6	1.8	-3.7	-3.2	1.6	1.3	.5	1.4	-5.2	.2	-3.2
Fork White River																
S.R. 59 over	2	-21.6	.5	4.4	1.0	-11.1	3.7	.5	-.6	1.5	-1.5	4.0	3.7	-.9	1.5	-1.4
Eel River	3	-24.9	1.8	6.3	2.5	-12.7	5.0	1.7	.4	6.5	-.5	5.8	5.2	-.1	2.7	-.4
S.R. 63 over Little	3	-26.0	-5.4	-11.1	-15.9	-16.0	-6.7	-8.7	-13.3	1.0	-18.6	-10.1	-9.2	-15.5	-12.8	-21.6
Vermillion River	2	-6.1	.7	3.1	2.9	-2.0	3.4	1.4	1.0	-1.1	1.5	3.0	2.7	.7	2.1	.8

Table 53. Computed and historical bed elevations (excluding contraction scour) at selected bridge sites in Indiana–Continued

Site, magnitude, or category	Difference between the computed bed elevation and the measured historical bed elevation (computed – historic), in feet, for given equation															
	Pier	Ahmad	Arkansas	Blench-Inglis I	Blench-Inglis II	Chitale	Froehlich	Froehlich with F.S.	HEC-18	Inglis-Lacey	Inglis-Poona I	Inglis-Poona II	Larras	Laursen	Shen	Shen-Maza
S.R. 101 over St. Joseph River	2	-9.2	1.3	1.2	1.0	-3.5	2.8	.8	-.1	2.6	-.4	1.3	1.9	-2.1	.9	-1.9
	3	-11.4	-.4	-2.9	-2.7	-5.5	-.1	-2.1	-3.7	2.2	-4.1	-2.6	-1.6	-6.7	-2.5	-6.4
S.R. 109 over White River	6	-17.4	2.1	-6.7	1.6	-8.9	0	-3.5	-8.2	6.0	-12.5	-5.6	-5.2	-9.3	-8.0	-16.9
S.R. 110 over Tippecanoe River	3	-9.3	-1.5	1.2	1.1	-4.7	1.3	-.7	-1.1	-.4	-.5	1.0	.7	-1.5	0	-1.3
	4	-7.1	1.1	2.8	4.8	-2.7	3.3	1.3	.6	4.0	1.1	2.7	2.4	.3	1.8	.4
S.R. 163 over Wabash River	2	-23.8	-.5	4.7	4.5	-12.5	1.5	-1.5	-2.4	-6.0	3.2	3.8	2.1	-6.3	.3	-2.7
Number of occurrences (23 observations)																
Greater than 10 feet		15	0	3	2	8	0	1	5	0	3	3	0	5	2	6
10 to 5 feet		7	1	4	3	6	5	5	5	6	5	4	7	8	4	4
Less than 5 feet		1	22	16	18	9	18	17	13	17	15	16	16	10	17	13
Scour underestimated		0	10	11	16	0	12	8	5	14	8	11	11	4	10	5
Scour overestimated		23	13	12	7	23	10	15	18	9	15	12	12	19	12	17
Number of occurrences including the sites from Mueller and others (1994) (38 observations)																
Greater than 10 feet		25	1	3	4	10	2	2	6	1	4	4	1	6	3	8
10 to 5 feet		10	6	12	9	15	9	12	12	14	14	9	13	13	10	10
Less than 5 feet		3	31	23	25	13	27	24	20	23	20	25	24	19	25	20
Scour underestimated		2	20	22	27	5	26	17	13	22	18	23	23	12	20	12
Scour overestimated		36	18	16	11	33	11	21	25	16	20	15	15	26	17	24

S.R. 54 over Busseron Creek. The contraction-scour equation predicted 7.3 ft of scour. When contraction scour was included, the Inglis-Lacey equation was the only equation to predict a bed elevation within 3 ft of the estimated historical bed elevation at bents 2 and 3 (tables 42 and 52); however, the Inglis-Lacey equation predicted deposition at both bents. The Blench-Inglis I and Inglis-Poona II equations predicted bed elevations within 3 ft of the estimated historical bed at bent 2. The hydraulic conditions estimated with WSPRO are similar at bents 2 and 3; therefore, the computed depths of pier scour are almost identical at the two bents. When contraction scour was not included, many of the equations predicted bed elevations within 2 ft of the estimated historical bed elevations at bents 2 and 3 (table 53). The Ahmad and Chitale equations predicted significantly more scour than did the other equations.

S.R. 57 over East Fork White River. The predicted contraction scour of 15.0 ft seems to be excessive, and none of the predicted bed elevations at pier 3 is in reasonable agreement with the estimated historical bed elevation (tables 43 and 52). When contraction scour was not included, many of the equations predicted bed elevations within 2 ft of the estimated historical bed elevation (table 53). The estimated historical peak discharge of 48,000 ft^3/s occurred in May 1983. In January 1991, an estimated peak discharge of 48,900 ft^3/s occurred; however, discharge measurements made during that flood indicated that the site was in backwater from the White River and the streambed was not scouring. Field observations at this site indicated that pier 3 is prone to debris accumulations and that the movement of bed material near pier 3 may be affected more by debris than by discharge.

S.R. 59 over Eel River. Several of the equations predicted bed elevations within 3 ft of the estimated historical bed elevation at pier 2, and many of the equations were within 2 ft of the estimated historical bed elevation at pier 3 (tables 44 and 52). When contraction scour was excluded, many of the equations predicted elevations within 2 ft at each of the piers; however, the equations that predicted closely when contraction scour was included underpredicted when contraction scour was not included (table 53). The Ahmad and Chitale equations predicted significantly more scour in the main channel than did the other equations (table 44).

S.R. 63 over Little Vermillion River. The predicted contraction scour of 11.7 ft seems excessive, and none of the predicted bed elevations at piers 2 and 3 is in reasonable agreement with the estimated historical bed elevations (tables 45 and 52). Many of the equations predicted deep scour at pier 3 because the pier is in deep water and the flow is skewed to the pier. The identified scour hole at pier 3 is shallow, and all the equations except Inglis-Lacey overestimated scour by more than 5 ft when contraction scour was not included (table 53). The Inglis-Lacey equation predicted 1 ft of deposition at pier 3. At pier 2, many of the equations predicted bed elevations within 2 ft of the estimated historical bed elevation. The estimated historical peak discharge of 7,360 ft^3/s occurred in March 1979. A peak discharge of 7,260 ft^3/s was estimated for February 1985, a discharge that probably would produce the same hydraulic conditions. A peak discharge of 8,210 ft^3/s was estimated for the flooding in December 1990. The probe work that confirmed the geophysical interpretation preceded December 1990; thus the identified interfaces could not be a result of the December 1990 flooding.

S.R. 101 over St. Joseph River. The predicted depth of contraction scour was minimal (1.5 ft) for the main channel. Therefore, the computed bed elevations at piers 2 and 3 were similar whether contraction scour was included or not (table 46). Many of the equations predicted bed elevations within 2 ft of the estimated historical bed elevations (tables 52 and 53). The Ahmad equation predicted more scour than did the other equations.

S.R. 109 over White River. The predicted depth of contraction scour was minimal (0.8 ft) for the main channel. The Arkansas, Blench-Inglis II, and Froehlich equations predicted bed elevations within 2 ft of the estimated historical bed elevation at pier 6 (tables 47 and 52). These three equations and the Inglis-Lacey are the only equations in which grain size is a variable; however, the Inglis-Lacey equation predicted 4.2 ft of deposition. Because of the coarse bed material, most of the equations overpredicted the depth of scour.

S.R. 110 over Tippecanoe River. The estimated historical peak discharge approximated the 500-year flood. Several of the equations predicted bed elevations within 3 ft of the estimated historical bed elevation at pier 3 and within 2 ft at pier 4 (tables 48 and 52). When contraction scour was excluded, many of the equations predicted bed elevations within 2 ft of the historical bed at both piers.

S.R. 163 over Wabash River. The predicted depth of contraction scour was minimal (0.5 ft) for the main channel. Many of the equations predicted bed elevations within 3 ft of the estimated historical bed elevation at pier 2 (tables 51 and 52). The Ahmad and Chitale equations predicted substantially more scour at the piers in the main channel than did the other equations.

Summary of the Performance of the Pier-Scour Equations

Summaries of the overall performance of the pier-scour equations are listed at the bottom of tables 52 and 53. The magnitudes of the differences between the computed and measured historical bed elevations are grouped into three categories (differences greater than 10 ft, differences from 10 to 5 ft inclusive, and differences less than 5 ft). The number of times each equation underestimated or overestimated the historical scour also is listed. For bridge design, it is desirable to use an equation that estimates the depth of scour accurately (for cost considerations) but, when in error, tends to overestimate (for safety considerations). The summary counts from the 23 observations in this study were combined with the 15 observations from Mueller and others (1994), and the results are included at the bottom of tables 52 and 53. These same data also are displayed graphically as box plots (fig. 23 and 24). Because this is a small data set and because of the stated assumptions and uncertainties concerning estimation of historical scour, one must be careful when drawing conclusions. Frequent visits to the study sites and analysis of the bed-elevation data collected from depth soundings and discharge measurements have convinced the authors that debris accumulations on piers can greatly affect the movement of sediment in bridge openings.

When contraction scour was included in the analysis, the Froehlich equation provided the most accurate comparison to the measured historical scour (22 differences less than 5 ft) (table 52). The Blench-Inglis II equation was the second most accurate, with 21 differences less than 5 ft; however, the Blench-Inglis II equation predicted deposition rather than scour at 4 piers. For the Inglis-Lacey equation, 20 differences were less than 5 ft, but the equation predicted deposition rather than scour at 7 piers. For the Arkansas, Blench-Inglis I, Inglis-Poona II, and Larras equations, 19 differences (50 percent) were less than 5 ft. Of the seven equations that predicted the estimated historical bed elevation within 5 ft at least 50 percent of the time, the Arkansas equation was the most conservative—it overestimated scour 31 times. The Arkansas, Blench-Inglis II, Froehlich, and Inglis-Lacey equations are the only equations that include median grain size as a variable. When a factor of safety equal to the pier width was added to the Froehlich equation, the accuracy was reduced but only six observations were underestimated. Several of the equations overpredicted scour for 32 of the 38 observations; of these equations, the Shen equation was the most accurate, followed by the Froehlich equation with the factor of safety. The effect of the conservative estimates for contraction scour can be seen in the number of times scour was overestimated (table 52 and fig. 23).

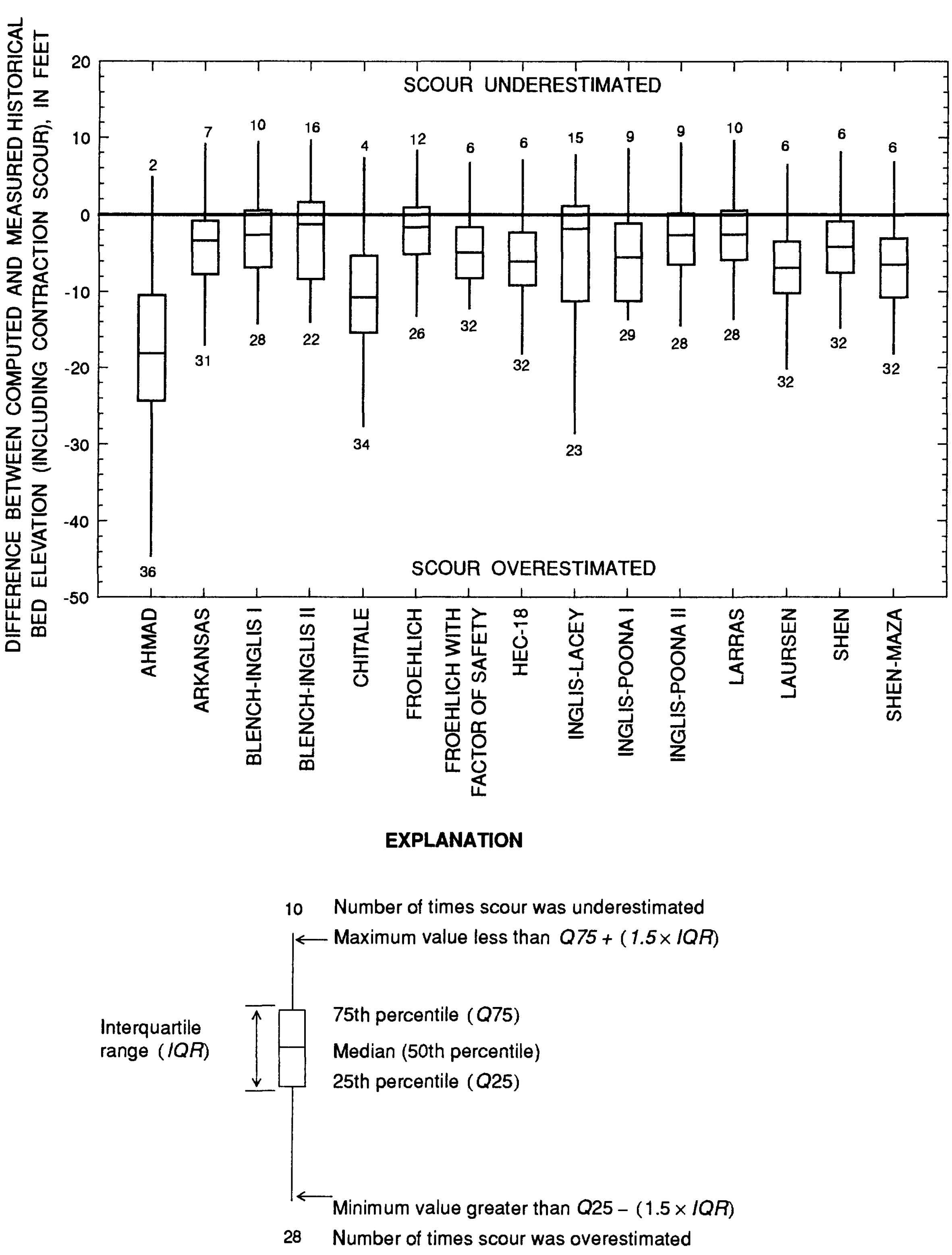


Figure 23. Summary of differences between the computed and measured historical bed elevations for selected pier-scour equations (including contraction scour).

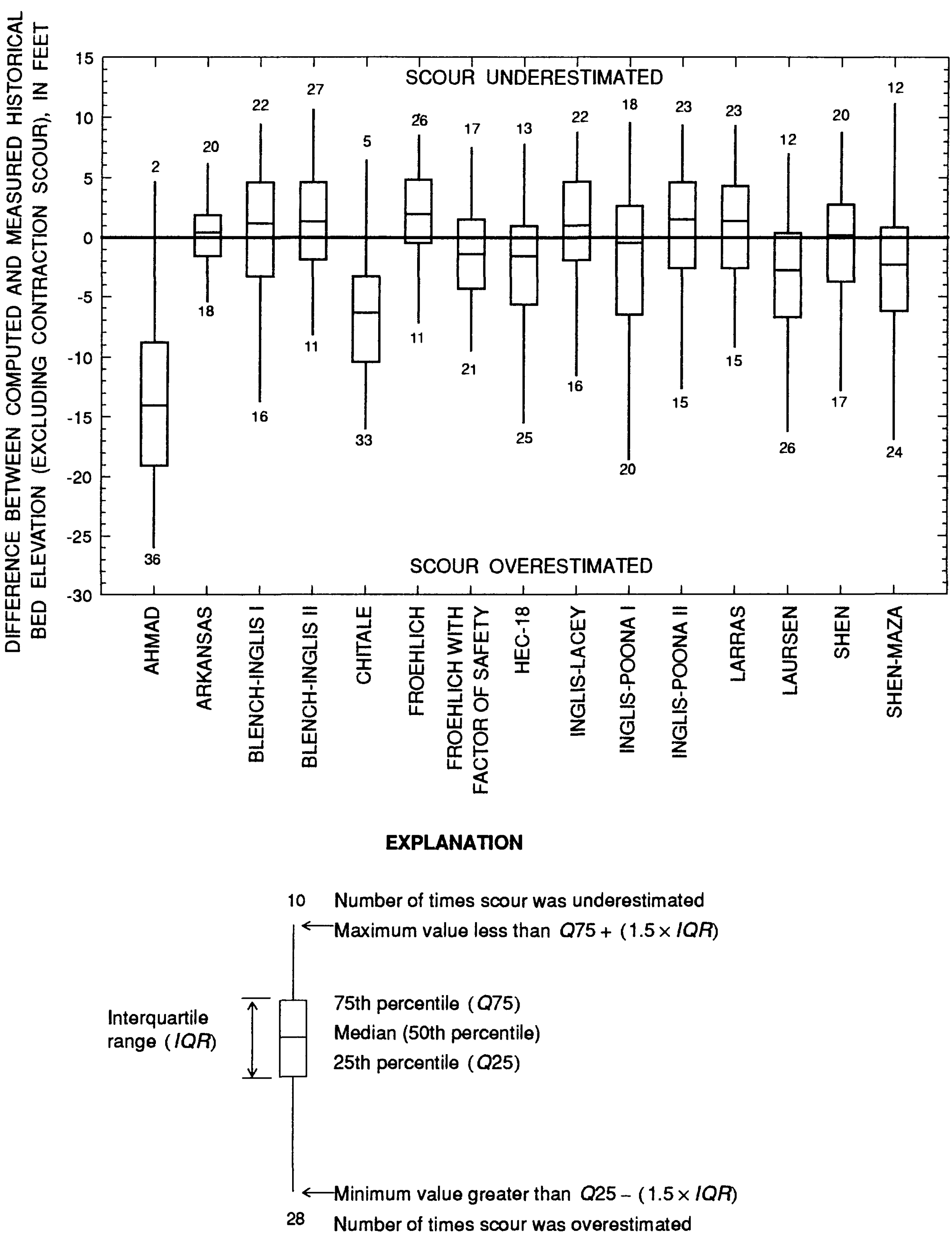


Figure 24. Summary of differences between the computed and measured historical bed elevations for selected pier-scour equations (excluding contraction scour).

When contraction scour was excluded from the analysis, the Arkansas equation was the most accurate in terms of comparison to the measured historical scour (31 differences less than 5 ft) (table 53). The Froehlich equation was the second most accurate (27 differences less than 5 ft) but was less conservative than the Arkansas equation. The Arkansas equation underestimated historical scour 20 times, whereas the Froehlich equation underestimated historical scour 26 times. With the factor of safety applied to the Froehlich equation, it underestimated the historical scour 17 times. Without the effects of contraction scour, all the equations underestimated the historical scour more often (table 53 and fig. 24). This pattern may indicate that contraction scour contributes to maximum historical scour but that the current methodology (either the equation or estimates of variables) results in overestimation of contraction scour. The Ahmad and Chitale equations were the only equations that were so conservative that they were not affected by the contraction scour. Mueller and others (1994) also noted that the Ahmad and Chitale equations tend to predict excessive scour at piers in the main channel. Mueller and others (1994) noted that the Chitale equation is based on model experiments for one bridge and uses only the Froude number and depth of flow as variables. The size and shape of the pier is not considered. The Ahmad equation includes a coefficient that is a function of boundary geometry, abutment shape, pier width, pier shape, and the angle of approach flow. No guidance was provided for the selection of this coefficient, only a range of 1.7 to 2.0, from which 1.8 was applied uniformly to all of the sites. This range of coefficients may not be suitable for the types of bridges, piers, and streambed materials included in this study.

The historical scour analyses summarized in tables 52 and 53 and figures 23 and 24 are based on the comparison of computed bed elevations to measured bed elevations without regard for actual depths of scour. The 14 pier-scour equations also were analyzed for how well they predicted depths of scour relative to the measured depths of scour. The mean and median ratios of the computed depths of scour to the measured depths of historical scour for 38 observations are listed in table 54.

Table 54. Ratio of computed historical scour depths to measured historical scour depths at selected bridge sites in Indiana for selected pier-scour equations

[Ratios greater than 1.0 indicate that scour was overestimated, and ratios less than 1.0 indicate scour was underestimated]

	Ratio of computed scour depth to measured scour depth			
	With contraction scour		Without contraction scour	
Pier-scour equation	Mean	Median	Mean	Median
Ahmad	6.91	4.60	5.47	3.88
Arkansas	2.84	1.71	1.40	.94
Blench-Inglis I	3.24	1.50	1.80	.56
Blench-Inglis II	2.91	1.32	1.46	.54
Chitale	4.84	3.12	3.40	2.44
Froehlich	2.66	1.39	1.22	.58
Froehlich with factor of safety	3.71	1.98	2.27	1.24
HEC-18	4.11	2.16	2.67	1.38
Inglis-Lacey	2.32	1.51	.88	.59
Inglis-Poona I	3.82	2.24	2.37	1.06
Inglis-Poona II	3.21	1.55	1.77	.65
Larras	3.05	1.69	1.60	.73
Laursen	4.68	2.28	3.24	1.46
Shen	3.43	1.84	1.99	.96
Shen-Maza	4.59	2.30	3.15	1.41

A value of 1.0 indicates a perfect match, a value greater than 1.0 indicates that scour was overestimated, and a value less than 1.0 indicates that scour was underestimated. Based on the medians with contraction scour included, the Blench-Inglis II and Froehlich equations best matched the measured depths of scour. Contraction scour excluded, the Shen equation best matched the measured depths of scour, with a median ratio of 0.96. The median ratio for the Arkansas equation was 0.94, and for the Inglis-Poona I equation it was 1.06. The median ratio for the Froehlich equation was only 0.58; but with the factor of safety included, the median ratio was 1.24.

Preferred design equations would provide a combination of accuracy and safety. Based on the results shown in figures 23 and 24 and table 54, no equation accurately predicts the historical scour at all of the study sites. The FHWA procedures (Laursen's contraction-scour equation combined with the HEC-18 pier-scour equation) provided a combination of accuracy and safety comparable to several of the other equations evaluated.

Comparison of Computed to Measured Scour Around Bridge Piers

The 14 pier-scour equations evaluated in the section "Comparison of Computed to Historical Scour Around Bridge Piers" also were evaluated for how well they reproduce measured depths of scour from depth soundings made during discharge measurements. Measurements were made during flooding in an attempt to measure discharge, velocities, local pier scour, and streambed elevations. The evaluation of the pier-scour equations is based on a limited data set from measurements at 14 of the 20 study sites. The magnitude of the measured discharges ranged from less than a 2-year to a 100-year peak discharge.

The discharges from the measurements were modeled with WSPRO to estimate the hydraulic variables, as described in previous sections. The streambed elevations from the last low-flow soundings prior to the flood measurements were used to define the reference bed for the WSPRO models. The streambed elevations determined from the discharge measurements could not be used because they could possibly include new scour. The section on depth soundings indicated that, at most of the study sites, there was continuous movement of the streambed material in the bridge opening and that this movement could not confidently be considered a result of contraction scour. The depth soundings from the flood measurements indicated movement of streambed material, some deposition, and some scouring. Because the fluctuation of the streambed occurred at low flows as well as high flows, however, this movement of the streambed material was not considered to be contraction scour. The contraction-scour equations tend to predict conservative (large) depths of scour, and the limited data set did not verify any contraction scour. Therefore, contraction scour is not included in the comparison of computed to measured depths of pier scour.

Tables 55-68, in the "Supplemental Data" section at the back of this report, include the results of the scour computations and the bed elevations from the discharge measurements. Listed at the top of the tables are the hydraulic variables estimated with WSPRO, grain-size data for the bed material, angles of attack, and pier details. Measured velocities at the piers are included for comparison with velocities estimated with WSPRO. The local pier scour computed from each of the selected pier-scour equations is shown near the center of each table. The computed bed elevation, listed below the depths of pier scour, was computed by subtracting the approach depth and pier scour from the water-surface elevation. The bed elevation at the pier, determined from depth soundings during discharge measurements, is listed at the bottom of each table. Computations of pier scour for piers on the overbanks are included; however, piers on the overbanks were not included in the comparisons because no movement of the overbank material was identified.

A summary of the differences between computed and measured bed elevation at the noses of the piers is given in table 69. In all, 30 comparisons are available from discharge measurements at 14 of the 20 study sites. As in the analysis of historical scour, the magnitudes of the differences between the computed and measured bed elevations are grouped into three categories (differences greater than 10 ft, differences from 10 to 5 ft inclusive, and differences less than 5 ft). The number of times each equation underestimated or overestimated the pier scour also is listed. These same data also are displayed in box plots (fig. 25). As in the analysis of historical scour, negative values of pier scour (deposition) were assumed to be equal to zero.

As is evident from table 69 and figure 25, all the equations overestimated pier scour, and several of them greatly overestimated scour. The recurrence interval for most of the measured discharges was less than 10 years; for several measured discharges, it was approximately 2 years. At these peak discharges, the hydraulic conditions are probably not suitable to induce much scour. A threshold may need to be exceeded before much scour occurs. As noted in the previous section on depth soundings, debris accumulations on piers affect scour. Large debris piles produce contractions in the bridge openings and redirect the flow around piers. Some debris piles present for one set of depth soundings were removed prior to flood measurements, and the flood measurement indicated that more sediment had moved during low flows as a result of the debris than during the higher flows. The debris piles also hindered the depth soundings around some of the piers during flood measurements.

The Arkansas equation was the most accurate in terms of comparison with the measurements (25 of the differences were less than 5 ft), and the Froehlich equation was the next most accurate (19 of the differences were less than 5 ft) (table 69). The Blench-Inglis II, Inglis-Lacey, and Inglis-Poona I equations underpredicted scour the most because these equations predicted deposition instead of scour more often than did the other equations.

Modeling measured discharges with WSPRO provided the opportunity to evaluate how well the WSPRO model estimated velocities in the bridge openings. A comparison of the computed velocities to measured velocities listed in tables 55-68 (at back of report) is shown in figure 26. Of the 47 observations shown in figure 26, 31 are at piers in the main channel and 16 are at piers on the overbank. The measured velocities were selected to represent the undisturbed velocity near piers. Velocities that were affected by piers or debris were not used; instead, the next unaffected velocity measurement closest to the pier was used. The computed velocity was determined from one of the 20 equal-conveyance tubes whose location corresponded to the location of the pier. As figure 26 shows, WSPRO more accurately predicted velocities at piers in the main channel than at piers on the overbanks. Most of the computed velocities for the main channel were within 1 ft/s of the measured velocity. In general, WSPRO overestimated at lower velocities and underestimated at higher velocities, but this trend was more distinct with velocities on the overbanks than for the main channel.

COMPUTED DEPTHS OF POTENTIAL SCOUR AT BRIDGE PIERS AND ABUTMENTS

The potential scour resulting from the 100- and 500-year peak discharges was computed for each of the sites. Procedures outlined in Richardson and others (1993) were used to compute and plot the depths of scour. The results of the WSPRO model and scour computations are listed in tables 70-109 in the "Supplemental Data" section at the back of the report. The surveyed beds and the computed beds resulting from the 100- and 500-year peak discharges are plotted in figures 27-46, which represent the upstream sides of the bridges. Pier and abutment details were obtained from bridge plans provided by the INDOT. The numbering of piers is consistent with the bridge plans. The pier footings and their piles are drawn to depict what was shown on the bridge plans. The horizontal scale, or bridge

Table 69. Differences between computed bed elevations and measured bed elevations (from flood measurements) at selected bridge sites in Indiana
[F.S., factor of safety; S.R., State Road; U.S., U.S. Route]

Site, magnitude, or category	Difference between the computed bed elevation and the measured bed elevation (computed – measured), in feet, for given equation															
	Pier	Ahmad	Arkansas	Blench-Inglis I	Blench-Inglis II	Chitale	Froehlich	Froehlich with F.S.	HEC-18	Inglis-Lacey	Inglis-Poona I	Inglis-Poona II	Larras	Laursen	Shen	Shen-Maza
S.R. 1 over	2	-1.3	-2.4	-2.8	-1.3	-1.3	-2.3	-4.3	-3.9	-1.3	-1.3	-3.1	-3.7	-6.5	-2.8	-1.9
St. Marys River	4	-10.6	-3.7	-2.8	-1.5	-6.9	-2.8	-4.8	-5.4	-1.5	-1.5	-3.2	-3.9	-6.9	-4.1	-5.2
S.R. 9 over	2	-6.7	-3.7	-2.1	-2.2	-4.2	-1.8	-3.8	-3.7	-2.3	-2.8	-2.1	-3.2	-3.9	-2.4	-3.5
Pigeon River	3	-3.7	-3.4	-3.8	-3.6	-2.5	-2.9	-4.9	-4.6	-6.2	-3.6	-3.5	-6.7	-4.7	-3.8	-2.0
S.R. 25 over	5	-9.8	-2.7	-11.1	-10.2	-5.7	-6.6	-9.6	-11.3	-5.0	-12.9	-9.6	-15.9	-12.3	-14.1	-4.6
Wildcat Creek	6	-16.8	-4.7	-13.6	-12.5	-10.7	-8.1	-11.3	-12.7	-2.1	-16.6	-12.2	-14.0	-14.4	-14.8	-9.0
S.R. 32 over	6	-25.4	-5.5	-13.6	-10.3	-15.5	-8.9	-11.9	-17.7	-5.1	-11.9	-13.1	-9.4	-27.2	-11.2	-18.2
Wabash River	5	-18.2	-2.9	-14.5	-12.7	-10.1	-8.0	-15.9	-18.2	-10.5	-12.2	-13.3	-10.1	-24.9	-10.9	-19.4
	4	-17.7	-3.4	-11.1	-9.8	-9.9	-6.4	-9.4	-14.3	-12.4	-8.8	-10.4	-7.5	-22.5	-8.4	-14.7
U.S. Route 35 over	2	-4.2	-3.4	-.3	-.3	-2.3	-1.4	-2.4	-2.3	-.3	-.3	-.5	-1.7	-3.6	-1.6	-2.1
Kankakee River	3	-3.8	-3.3	-3.2	-1.1	-2.2	-2.1	-3.1	-3.6	-3.2	-1.1	-3.1	-3.2	-5.8	-2.6	-3.5
U.S. Route 41 over	2	-7.2	-3.5	-7.2	-7.6	-4.1	-4.0	-7.0	-9.2	-7.5	-6.1	-6.5	-7.1	-12.0	-6.0	-2.6
Kankakee River	3	-15.3	-6.7	-11.6	-11.5	-9.9	-8.0	-11.0	-13.8	-1.6	-9.6	-11.0	-9.5	-19.1	-9.6	-14.0
S.R. 54 over	3	-5.9	-3.7	-2.4	-.5	-3.5	-2.6	-4.6	-4.2	-.5	-.5	-2.6	-3.8	-5.7	-2.7	-3.6
Busseron Creek	2	-6.5	-3.8	-2.2	-.4	-3.8	-2.6	-4.6	-4.2	-.4	-.4	-2.4	-3.7	-5.8	-2.7	-3.6
S.R. 59 over	2	-8.9	-4.4	-3.7	-.6	-5.3	-3.3	-6.5	-5.9	-1.5	-.8	-4.0	-4.0	-8.0	-4.0	-5.5
Eel River	3	-9.4	-3.7	-2.6	.2	-5.1	-2.8	-6.1	-5.5	.2	.2	-3.0	-3.3	-8.0	-3.4	-5.1
S.R. 63 over Little	3	-15.6	-4.6	-11.8	-10.1	-9.7	-6.8	-8.8	-11.6	.2	-12.0	-10.8	-10.0	-16.2	-10.4	-16.7
Vermillion River	2	-.2	-1.3	-1.3	.8	.7	-.5	-2.5	-1.8	-4.1	.8	-1.4	-1.6	-3.4	-.8	.1

Table 69. Differences between computed bed elevations and measured bed elevations (from flood measurements) at selected bridge sites in Indiana–Continued

Site, magnitude, or category	Pier	Ahmad	Arkansas	Blench-Inglis I	Blench-Inglis II	Chitale	Froehlich	Froehlich with F.S.	HEC-18	Inglis-Lacey	Inglis-Poona I	Inglis-Poona II	Larras	Laursen	Shen	Shen-Maza
		Difference between the computed bed elevation and the measured historical bed elevation (computed – measured), in feet, for given equation														
S.R. 101 over	2	-7.8	-3.7	-5.1	-1.5	-4.5	-3.1	-5.1	-5.3	-1.6	-2.5	-5.0	-4.4	-8.3	-4.1	-6.1
St. Joseph River	3	-8.0	-3.8	-7.6	-3.1	-4.6	-4.3	-6.3	-7.0	-.6	-4.0	-7.2	-6.3	-11.1	-5.5	-3.2
S.R. 109 over	5	-14.6	-4.5	-13.5	-6.0	-9.8	-7.2	-10.7	-15.1	-1.4	-15.8	-12.1	-15.5	-16.1	-15.2	-8.5
White River	6	-16.3	-4.7	-12.2	-4.9	-10.9	-6.4	-9.9	-13.0	-1.4	-15.1	-11.2	-12.5	-14.0	-13.1	-20.3
S.R. 135 over	3	-7.8	-2.9	-3.3	-.1	-4.4	-2.3	-5.5	-5.3	-.1	-.4	-3.5	-3.5	-7.2	-3.4	-4.9
Muscatatuck River	4	-6.7	-2.2	-2.6	.6	-3.4	-1.6	-4.8	-4.5	.6	.6	-2.8	-2.8	-6.6	-2.6	-4.1
S.R. 157 over	4	-16.4	-5.6	-6.0	-3.2	-10.6	-4.6	-7.6	-8.3	-10.9	-6.0	-6.1	-5.5	-10.9	-6.3	-8.9
White River	5	-19.5	-3.5	1.5	1.5	-11.6	-.9	-2.9	-3.6	-2.8	.9	1.4	-.9	-5.3	-2.0	-3.6
S.R. 163 over	4	-19.7	-3.3	.1	1.8	-11.1	-1.7	-4.7	-5.2	-11.3	.4	-.6	-1.5	-9.0	-2.7	-5.3
Wabash River	3	-35.2	-14.5	-9.6	-8.5	-24.9	-12.8	-15.8	-16.5	-17.1	-9.8	-10.6	-12.3	-20.7	-13.9	-16.7
	2	-28.0	-8.7	-4.2	-3.1	-18.2	-7.0	-10.0	-10.6	-13.8	-4.2	-5.0	-6.5	-14.6	-8.0	-10.7
		Number of occurrences (30 observations)														
Greater than 10 feet		14	1	9	6	9	1	7	11	6	7	9	7	14	8	8
10 to 5 feet		10	4	5	8	7	10	11	9	6	6	6	8	12	6	7
Less than 5 feet		6	25	16	16	14	19	12	10	18	17	15	15	4	16	15
Scour underestimated		2	0	2	12	3	0	0	0	11	8	1	0	0	0	1
Scour overestimated		28	30	28	18	27	30	30	30	19	22	29	30	30	30	29

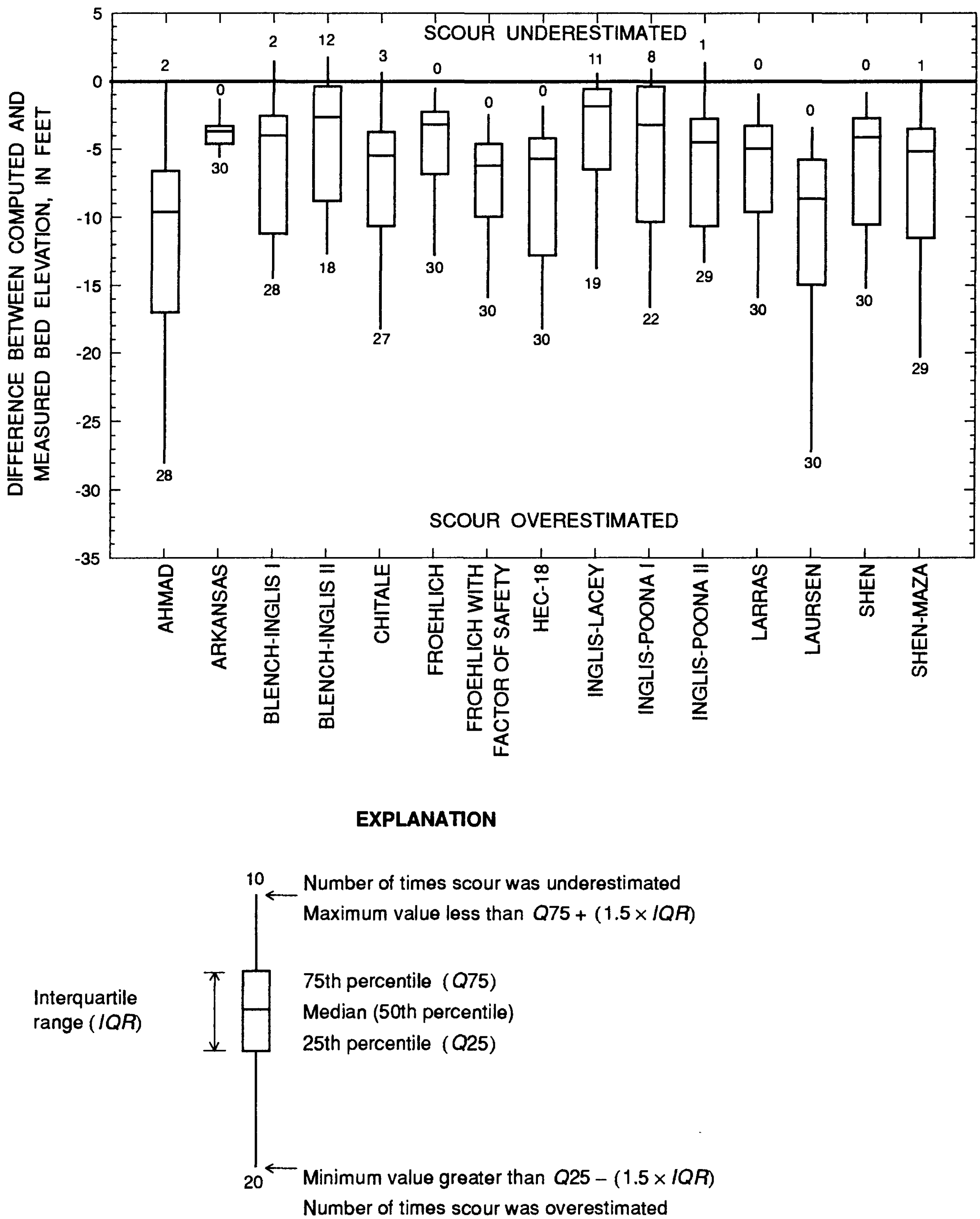


Figure 25. Summary of differences between the computed and measured bed elevations for selected pier-scour equations applied to flood measurements.

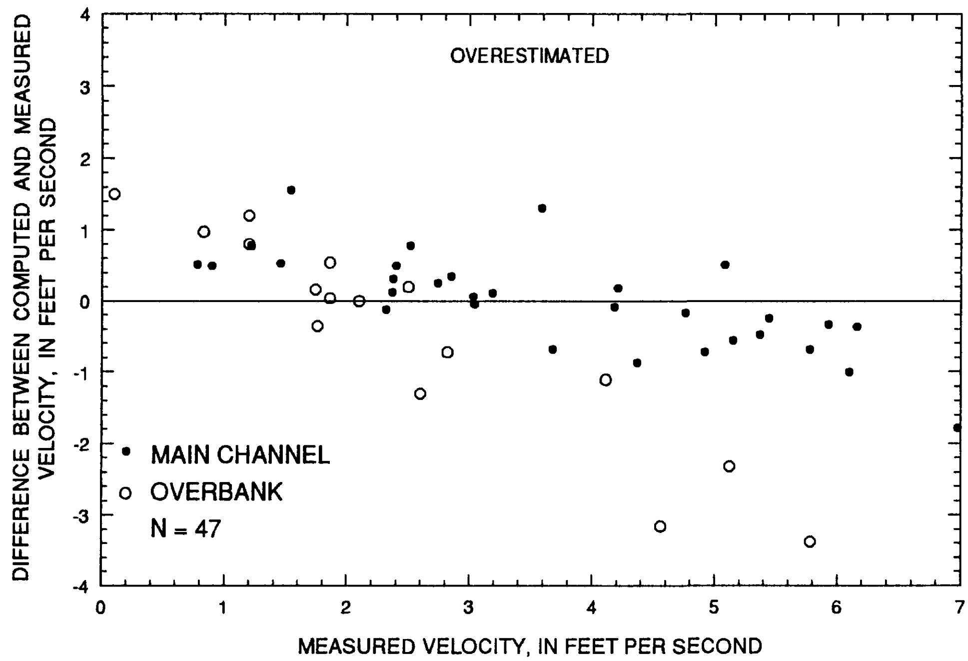


Figure 26. Difference between velocities computed with WSPRO and velocities measured during floods at selected bridge sites in Indiana.

stationing, in figures 27-46 is in feet, referenced to the left-most limit of flow in the bridge opening. The left-most limit of flow is usually the inside edge of the left abutment or end bent.

As a general rule, the local scour holes were plotted with a 30° angle of repose for the bed material and top widths of 1.7 times the depth of scour. Richardson and others (1993, p. 46) provide some guidelines for selecting top widths and side slopes for plotting local scour holes. A top width of 1.7 times the depth of scour resulted in a bottom width equal to the pier width. If the plotted side slope intersected a pier footing, the bottom width was set equal to the footing width and the top width was adjusted. The 30° angle of repose was used wherever possible, but in some instances a steeper angle had to be used to plot abutment scour because of space limitations. For scour holes at piers, the top width of 1.7 times the depth of scour is from each side of the pier. For scour holes at abutments, the top width is applied in the streamward direction from the toe of the abutment. Local scour at piers and abutments was added to the contraction scour. The bottoms of local scour holes are drawn flat, and their elevations are based on elevations at the nose of piers or the toes of abutments minus the depths of scour. Contraction-scour surfaces are drawn to mimic the study bed. At some sites, scour holes for piers and abutments overlap. All components of scour were shown, if possible; at some sites the deeper scour hole obscures the trace of the other scour hole. For example, near pier 4 at S.R. 101 over St. Joseph River (fig. 41), bottom elevations are shown for abutment scour at the right abutment (station 240), for pier scour added to contraction scour at the pier (station 220), and for contraction scour of the right overbank (station 190). Elevations for the base of the scour holes at the right abutment and pier 4 are listed in tables 98 and 99. At S.R. 163 over Wabash River, the scour hole at the left abutment completely overlaps the scour hole at pier 9 (fig. 46). Elevations computed for the scour holes at the left abutment and pier 9 are listed in tables 108 and 109.

At most sites, equation 1 was used to compute live-bed contraction scour in the main channel, and equation 2 was used to compute clear-water contraction scour on the overbanks. Some exceptions were at sites where excessively conservative (greater) depths of scour were computed in the main channel. Equation 2 was used to check contraction scour in the main channel for the sites where unreasonably large values of contraction scour were computed. In theory, the clear-water equation should compute larger depths of scour because sediment is not being transported into the scour zone from upstream. If the clear-water scour equation computed less scour than the live-bed scour equation did, it was assumed that the results of the live-bed scour equation were not as valid as the results of the clear-water equation. This procedure was used at S.R. 54 over Busseron Creek, S.R. 57 over East Fork White River, and S.R. 63 over Little Vermillion River; however, the contraction scour at these sites still seems to be excessive (fig. 37, 38, and 40 at back of report).

Equation 2 was used to compute clear-water contraction scour in the main channel at sites where the critical velocity was determined to be greater than the average velocity at the approach section. Critical velocity can be greater than average velocity at sites where bed material is coarse. Critical velocity was determined by use of equation 14 in Richardson and others (1993, p. 31), and the average velocity was determined with WSPRO.

At some sites, the live-bed scour equation predicts negative values of contraction scour (deposition). This is true for sites where the bridge is not a significant contraction relative to the approach section or where the approach section is contracted. Negative values of contraction scour are shown in the potential scour tables, but they are not used to determine the computed bed elevations. To be conservative when computing potential scour depths, the authors set negative values of contraction scour to zero for subsequent computations of pier and abutment scour. The plotting of negative values of contraction scour would reduce or eliminate some computed scour holes at piers. S.R. 25 over Wildcat Creek is the only site where the live-bed scour equation was used for an overbank. Loose, unvegetated sediment on the left overbank indicated that the live-bed scour equation would be more suitable than the clear-water scour equation.

The HEC-18 equation (eq. 3) was used to compute local pier scour. The computed scour, pier details, and the hydraulic variables estimated with WSPRO are listed in tables 70-109.

At several sites, the computed contraction scour is deep enough to expose pier footings and pile caps. Where footings may become exposed, a second computation for pier scour was made in accordance with guidelines in Richardson and others (1993, p. 41) and the larger of the two scour computations was used to compute bed elevation. Both scour computations are included in tables 70-109, but only the larger value was used to compute the bed elevation. Equation 4 adjusts the average velocity in the flow zone obstructed by the footing. The adjusted velocity and depth of the flow zone obstructed by the footing are used as the velocity and depth variables in equation 3. The width of the exposed footing is used for the pier width, and the pier-nose shape is changed to square. The correction for exposed footings increased the computed pier scour in most situations, so use of the correction is probably a conservative choice. In this computation one assumes that the footing goes as deep as the computed scour, when actually the footing probably has little effect once the streambed has scoured to some point below the base of the footing. The correction for exposed footings also is based on the predicted contraction scour, which may be excessive at several sites.

At five bridge sites, the soil-boring logs from the bridge plans identified bedrock elevations. Because potential scour computations ignore the presence of bedrock, computed bed elevations at some piers may be below bedrock even though scour is assumed to stop at bedrock. The elevation of bedrock is therefore included in the potential scour plots and tables for the following sites:

S.R. 19 over Wabash River (fig. 32, tables 80 and 81), S.R. 32 over Wabash River (fig. 34, tables 84 and 85), S.R. 57 over East Fork White River (fig. 38, tables 92 and 93), S.R. 63 over Little Vermillion River (fig. 40), and S.R. 135 over Muscatatuck River (fig. 44, tables 104 and 105).

Local scour was not computed for pier 2 at S.R. 11 over Flatrock River because the pier was in the riprap protection of the left abutment. Local scour was not computed for pier 8 at S.R. 25 over Wildcat Creek because the pier was in the riprap protection of the right abutment. Some piers near spill-through abutments are protected on the abutment side but not on the streamward side; these include pier 7 at S.R. 11 over Flatrock River, pier 2 at S.R. 25 over Wildcat Creek, piers 2 and 7 at S.R. 109 over White River, and pier 2 at S.R. 135 over Muscatatuck River. Potential scour was computed at these piers, but the potential scour depths may be conservative because of the partial protection provided by the abutment material. Computed depths of potential scour also may be conservative for piers partially armored with chunks of old concrete bridge deck that function as riprap. Concrete debris from previous bridge decks was found at piers 2 and 4 at S.R. 57 over East Fork White River and at pier 2 at S.R. 59 over Eel River. The effectiveness of this concrete debris for preventing scour probably depends on how far the debris extends upstream from the pier nose. If the debris does not extend much beyond the pier nose, local scour could occur at the upstream limit of the debris, possibly undermining the material and the bridge pier.

The bridge opening at S.R. 109 over White River was modified with scour countermeasures in 1995. Riprap was placed along and upstream from piers 3-6, and the left overbank was cleared of brush. The bridge opening was resurveyed so that the potential scour analysis would be based on the current bridge geometry. Although the piers are now protected with riprap, potential scour was computed as if riprap were not present (fig. 42 and tables 100 and 101).

The Froehlich equation (eq. 6) was used to compute local scour at abutments. The computed scour, abutment details, and the hydraulic variables estimated with WSPRO are listed in tables 70-109. Abutment scour also was computed with the HIRE equation (eq. 7) for those sites where ratios of abutment length to flow depth were greater than 25 (length and depth defined for the Froehlich equation). The abutment scour plotted in figures 27-46 was computed with Froehlich's live-bed scour equation. The depths of scour computed with the HIRE equation are listed in the potential scour tables. The depth and velocity of flow also are listed because they are not the same as those determined for the Froehlich equation.

At several abutments, the two equations produced similar results. At three sites with long embankments and significant flow on the overbank (conditions for which the HIRE equation was developed), the HIRE equation predicted less scour than did the Froehlich equation for each abutment at both peak discharges; however, the results still seem to be conservative. These sites are S.R. 57 over East Fork White River (tables 92 and 93), S.R. 135 over Muscatatuck River (tables 104 and 105), and S.R. 157 over White River (tables 106 and 107). The HIRE equation predicted more scour than the Froehlich equation at the two sites with vertical abutments, S.R. 15 over Little Elkhart River (tables 78 and 79) and S.R. 54 over Busseron Creek (tables 90 and 91). This is probably because the HIRE equation's correction for abutment shape increases the scour for abutments that are not the spill-through type.

At some sites, the abutment lengths listed in the potential scour tables are the same for the 100-year and the 500-year peak discharge. This is usually because of engineering judgment applied in the WSPRO modeling, such as fixed limits of flow at the approach section. At S.R. 54 over Busseron Creek, the length of the left abutment is fixed by the stagnation point determined with the multiple-opening bridge routine in WSPRO. At S.R. 59 over Eel River, the length of the left abutment is fixed because some of the discharge would by-pass the bridge and flow parallel to the highway embankment. At S.R. 157 over White River, part of the left embankment approaching the abutment functions as an island of high ground, and the embankment left of that island is inundated by flow over the roadway. Any flow left of this island would bypass the bridge and, therefore, should not be considered as flow obstructed by the abutment.

At several sites, abutment scour was not computed at one or both abutments. At S.R. 1 over St. Marys River, the left abutment is a riprap spill-through abutment, but the toe is in the channel below the overbank; therefore, the flow blocked by the embankment will return to the river above the toe of the abutment. The right abutment is protected with a concrete slopewall and pavement from a road. At S.R. 11 over Flatrock River, the left abutment is protected with riprap and pavement from a park trail. The right abutment does not block flow because the right overbank upstream from the bridge has been filled and developed. At S.R. 19 over Wabash River, both abutments are end bents perched above the river; banks are riprapped and no embankments block flow.

Abutment scour was not computed at S.R. 32 over Wabash River because the spill-through abutments are protected by spur dikes that extend upstream from the bridge. At U.S. Route 35 over Kankakee River, flow is not blocked by the abutments because the abutments are end bents set in line with spoil banks. U.S. Route 41 over Kankakee River is a four-lane highway with dual bridges, and the study site is the downstream bridge (southbound lane). The study bridge does not have embankments that block flow because the overbank flow is obstructed by the embankment of the northbound lane. The left abutment at S.R. 57 over East Fork White River is an end bent perched on the valley wall above the river. Although overbank flow can occur upstream from the bridge, the overbank flow returns to the river before reaching the bridge, and no embankment blocks flow at the bridge.

Abutment scour was not computed for the left abutment at S.R. 63 over Little Vermillion River. The left abutment is a riprap spill-through abutment, but the toe is in the channel below the overbank; therefore, the flow blocked by the embankment will return to the river above the toe of the abutment. At S.R. 109 over White River, the right overbank of the approach section is narrow, and flow is not obstructed by the right abutment. The left abutment at S.R, 135 over Muscatatuck River is an end bent perched on the valley wall above the river. A concrete slopewall extends down to the river, and there is no embankment to block flow at the bridge. At S.R. 157 over White River, the right abutment is an end bent perched on a high riprapped embankment with a spoil bank in line with the abutment. The spoil bank prevents flow blocked by the embankment from returning to the river at the abutment. The right abutment at S.R. 163 over Wabash River also is an end bent perched on a high riprapped bank with no embankment that blocks flow. The abutments in figures 27-46 are drawn to depict the bridge plans. Bridge plans differ considerably in detail; therefore, the abutments in the potential scour plots differ in detail.

Many of the abutment-scour computations seem to be conservative, a finding that is consistent with previous research. Abutment-scour equations are intended for design of new abutments. In this study, these equations are used to evaluate potential scour at existing structures; if they produce excessively conservative depths of scour, their usefulness may be limited for either purpose. According to Richardson and others (1993, p. 26),

> Recognizing that abutment scour equations lack field verification, it is recommended that rock riprap and/or guide banks be considered for abutment protection. Properly designed, these two protective measures make it unnecessary to design abutments to resist the computed abutment scour depths.

On the basis of estimated historical peak discharges, five of the study sites have been subjected to flooding equal to or greater than the 100-year flood. At S.R. 9 over Pigeon River (fig. 28), the estimated historical peak discharge was equal approximately to the 100-year peak discharge. No historical scour interface was identified at this site for comparison with the potential scour computations. At S.R. 15 over Little Elkhart River (fig. 31), the estimated historical peak discharge was between the 100- and 500-year peak discharges. A historical scour bed elevation of 739.5 ft above sea level was identified, but the potential scour bed elevation was 727.7 ft for the 100-year peak discharge. At U.S. Route 35 over Kankakee River (fig. 35) the estimated historical peak discharge was between the 100- and 500-year peak discharges. No historical scour was identified at this site for comparison with the potential scour computations. A flood measurement also was made at U.S. Route 35 that exceeded the 100-year peak discharge. Depth soundings made during the flood measurement did not identify scour. At U.S. Route 41 over Kankakee River (fig. 36), the estimated historical peak discharge was between the 100- and 500-year peak discharges. Historical scour bed elevations of 619.7 and 614.7 ft above sea level were identified at piers 2 and 3, respectively. The potential scour bed elevations for the 100-year flood were 611.0 and 597.9 ft above sea level at piers 2 and 3, respectively. At S.R. 110 over Tippecanoe River (fig. 43), the estimated historical peak discharge was equal approximately to the 500-year peak discharge. Historical scour bed elevations of 751.0 and 750.0 ft above sea level were identified at piers 3 and 4, respectively. The potential scour bed elevations for the 500-year flood were 745.3 and 743.7 ft above sea level at piers 3 and 4, respectively.

On the basis of the five study sites where flooding was equal to or greater than the 100-year flood, the identification and estimates of historical scour bed elevations do not indicate scouring of the extent predicted by the potential scour computations. At S.R. 9 over Pigeon River and U.S. Route 35 over Kankakee River, historical scour interfaces were not identified in the channel subbottom. At S.R. 15 over Little Elkhart River, U.S. Route 41 over Kankakee River, and S.R. 110 over Tippecanoe River, the estimated historical scour interfaces were all above the computed potential scour bed elevations.

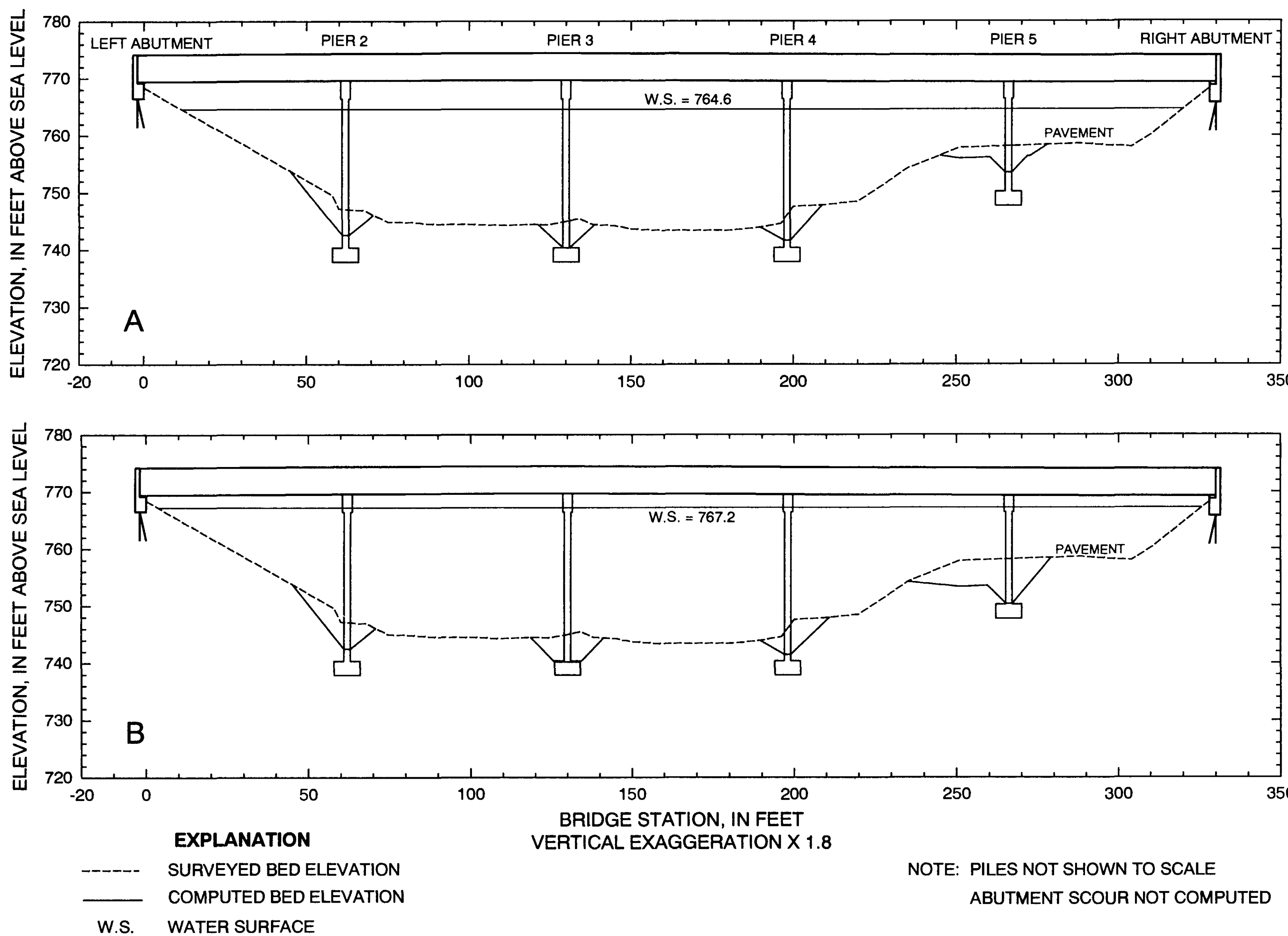


Figure 27. Potential scour at State Road 1 over St. Marys River at Fort Wayne, Indiana: (A) 100-year peak discharge, and (B) 500-year peak discharge.

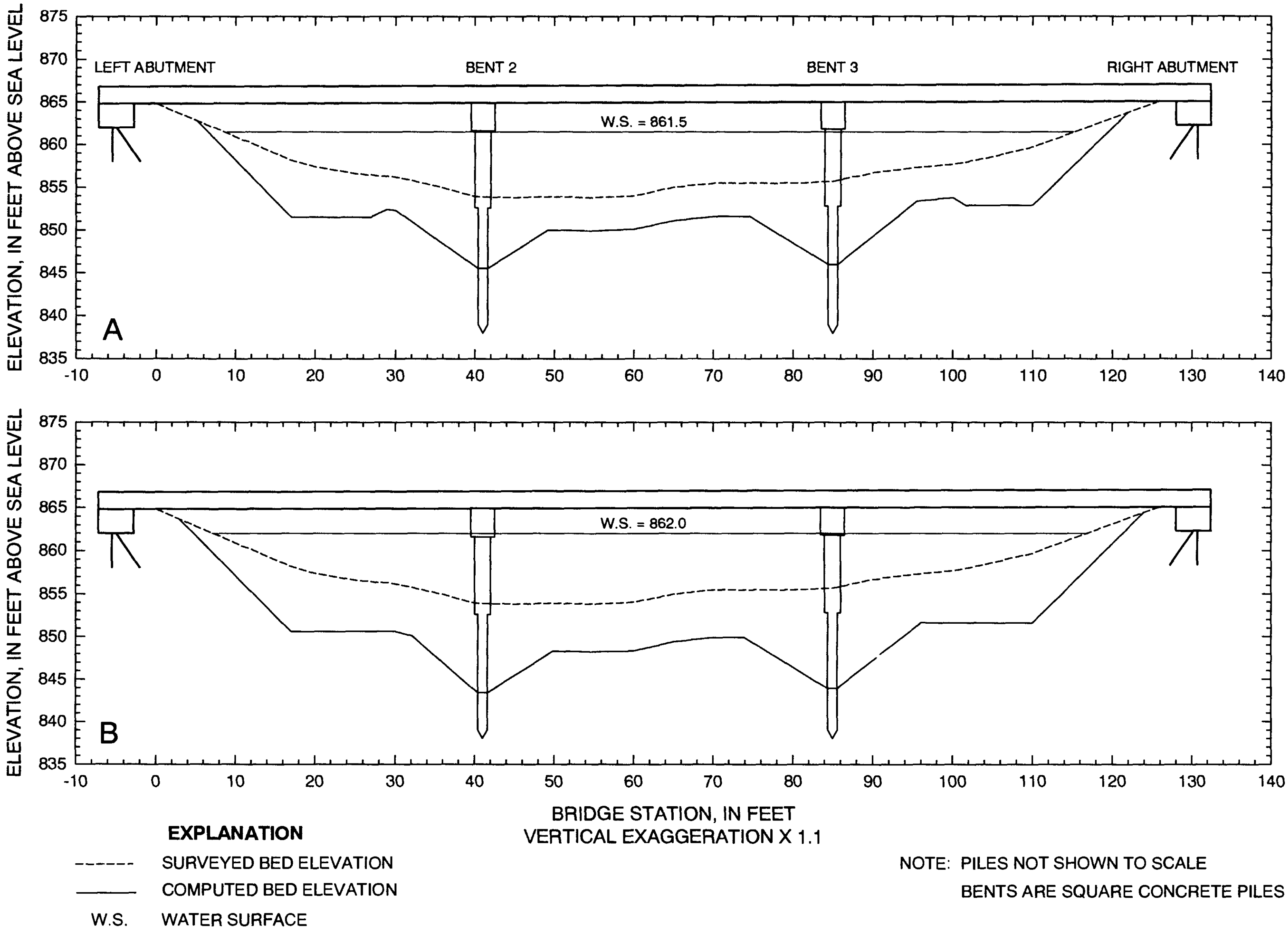


Figure 28. Potential scour at State Road 9 over Pigeon River at Howe, Indiana: (A) 100-year peak discharge, and (B) 500-year peak discharge.

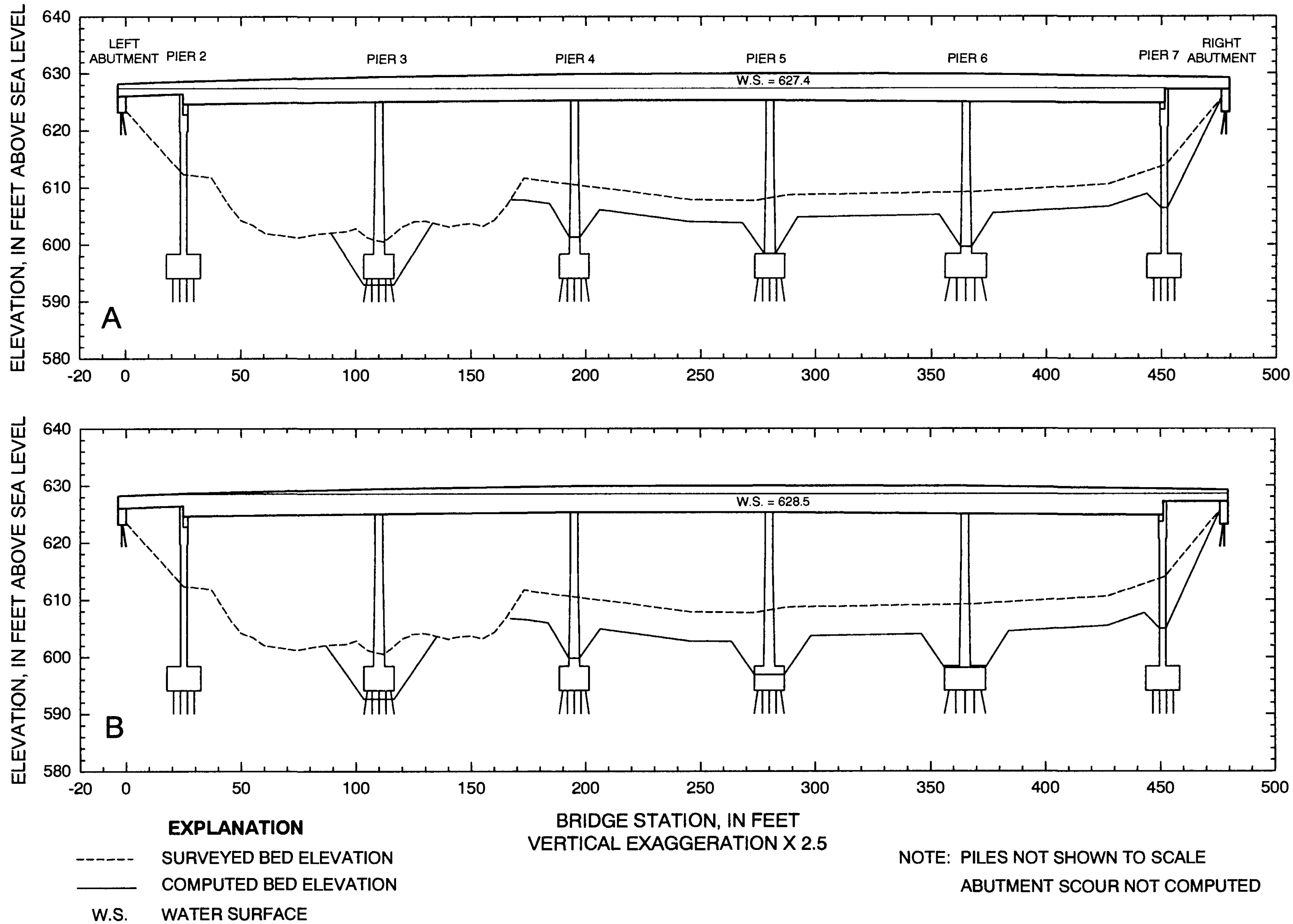


Figure 29. Potential scour at State Road 11 over Flatrock River at Columbus, Indiana: (A) 100-year peak discharge, and (B) 500-year peak discharge.

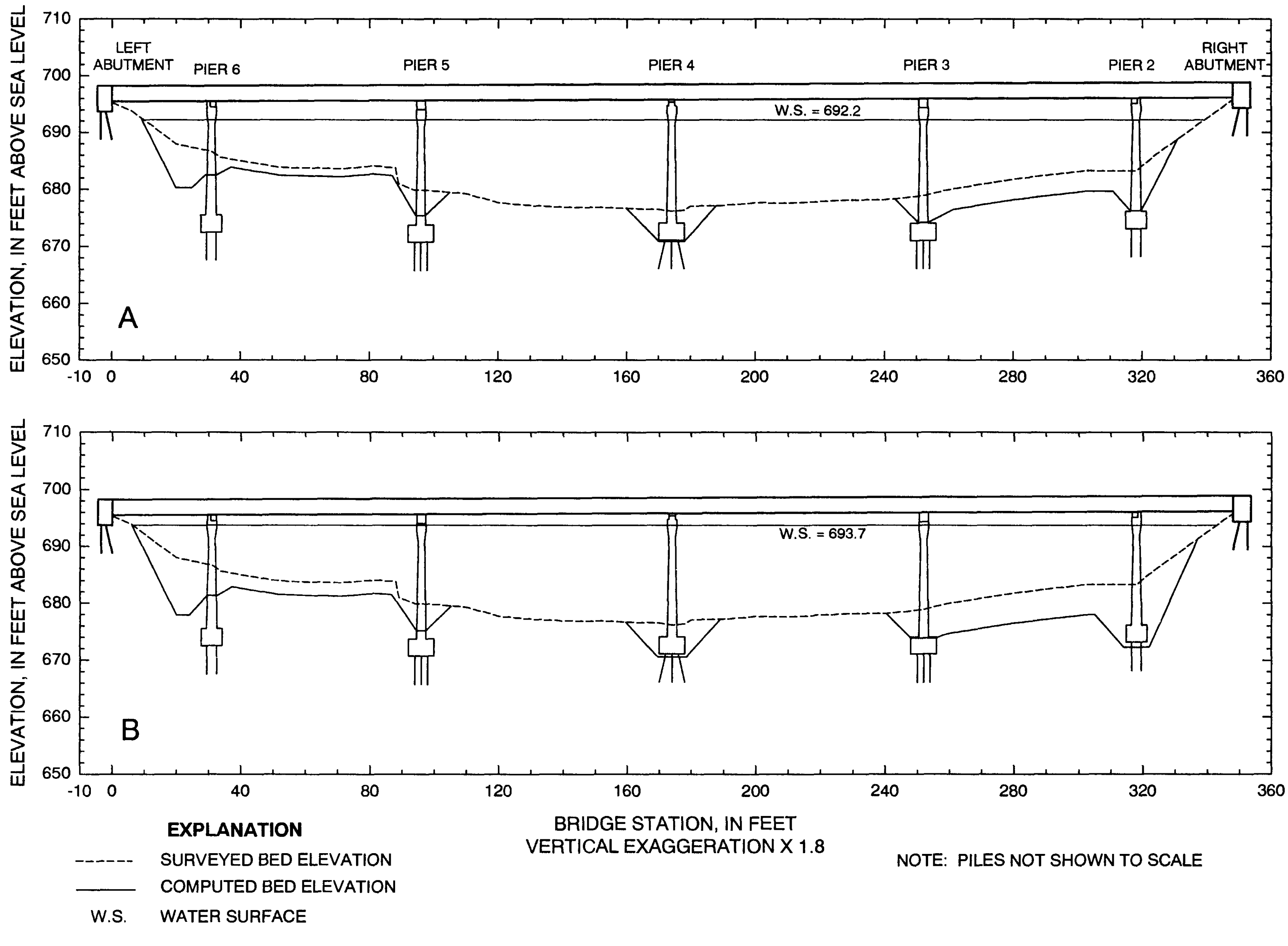
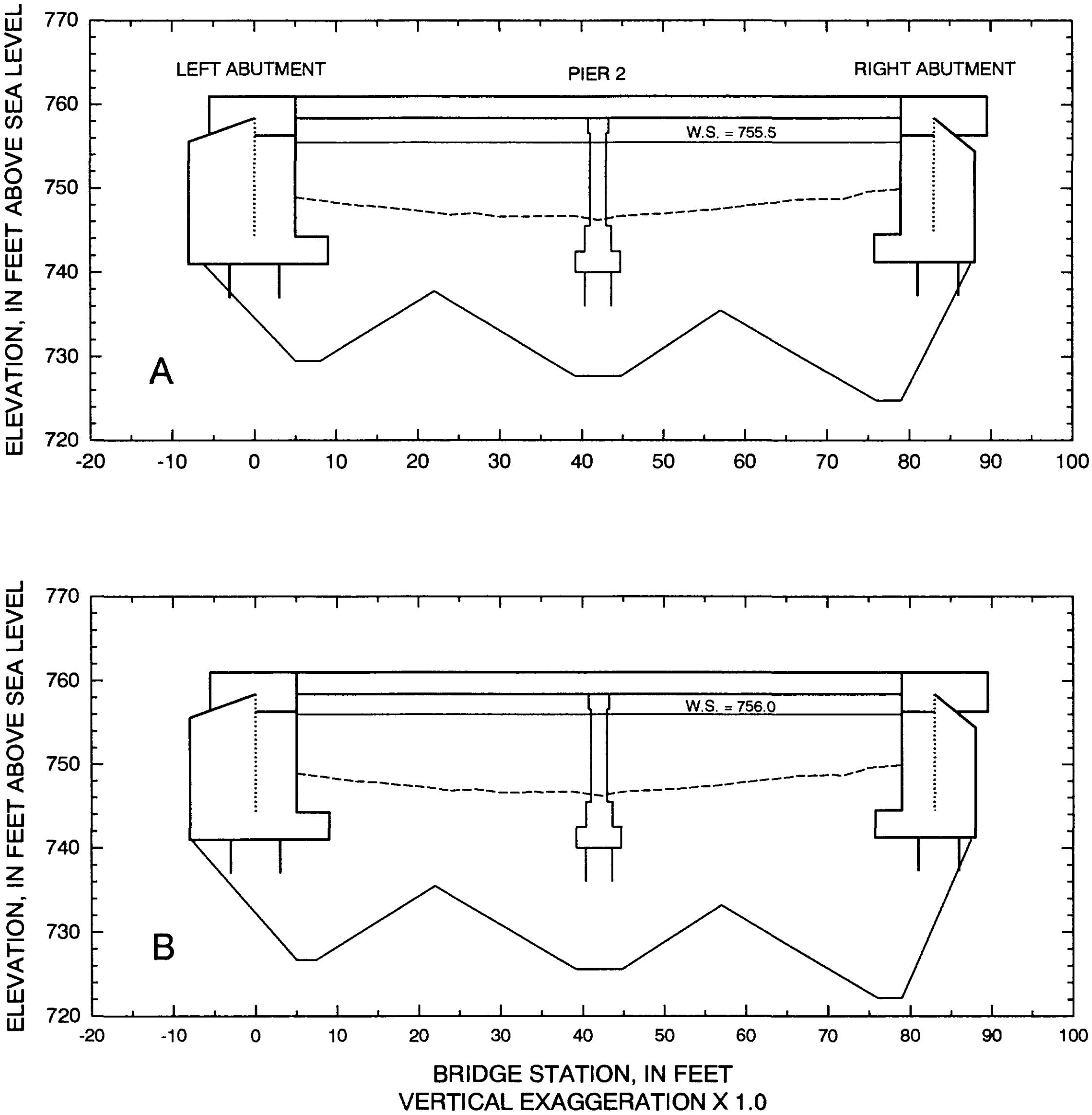


Figure 30. Potential scour at State Road 14 over Tippecanoe River at Winamac, Indiana: (A) 100-year peak discharge, and (B) 500-year peak discharge.



EXPLANATION

------ SURVEYED BED ELEVATION

——— COMPUTED BED ELEVATION

W.S. WATER SURFACE

NOTE: PILES NOT SHOWN TO SCALE

Figure 31. Potential scour at State Road 15 over Little Elkhart River at Bristol, Indiana: (A) 100-year peak discharge, and (B) 500-year peak discharge.

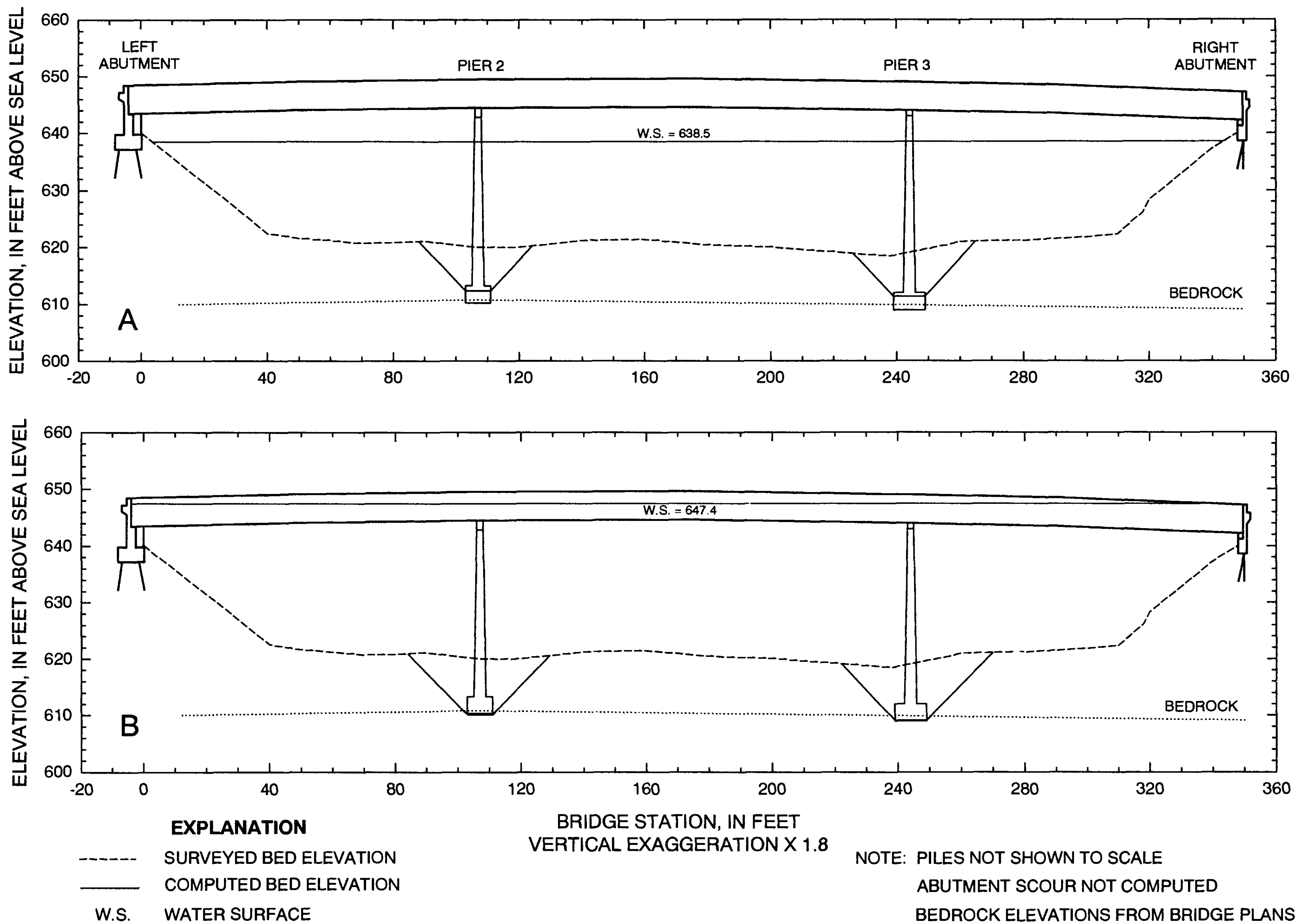


Figure 32. Potential scour at State Road 19 over Wabash River at Peru, Indiana: (A) 100-year peak discharge, and (B) 500-year peak discharge.

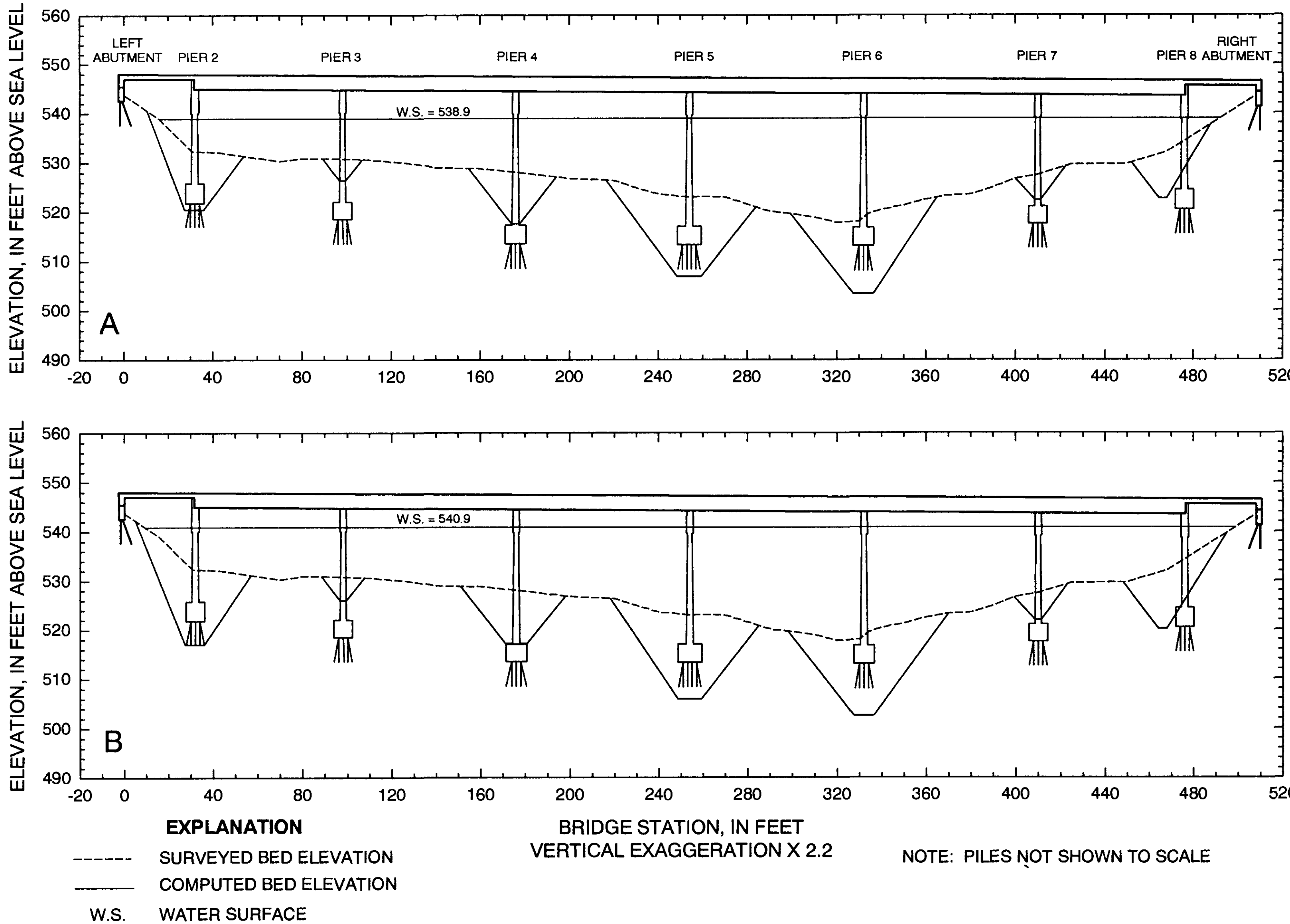


Figure 33. Potential scour at State Road 25 over Wildcat Creek at Lafayette, Indiana: (A) 100-year peak discharge, and (B) 500-year peak discharge.

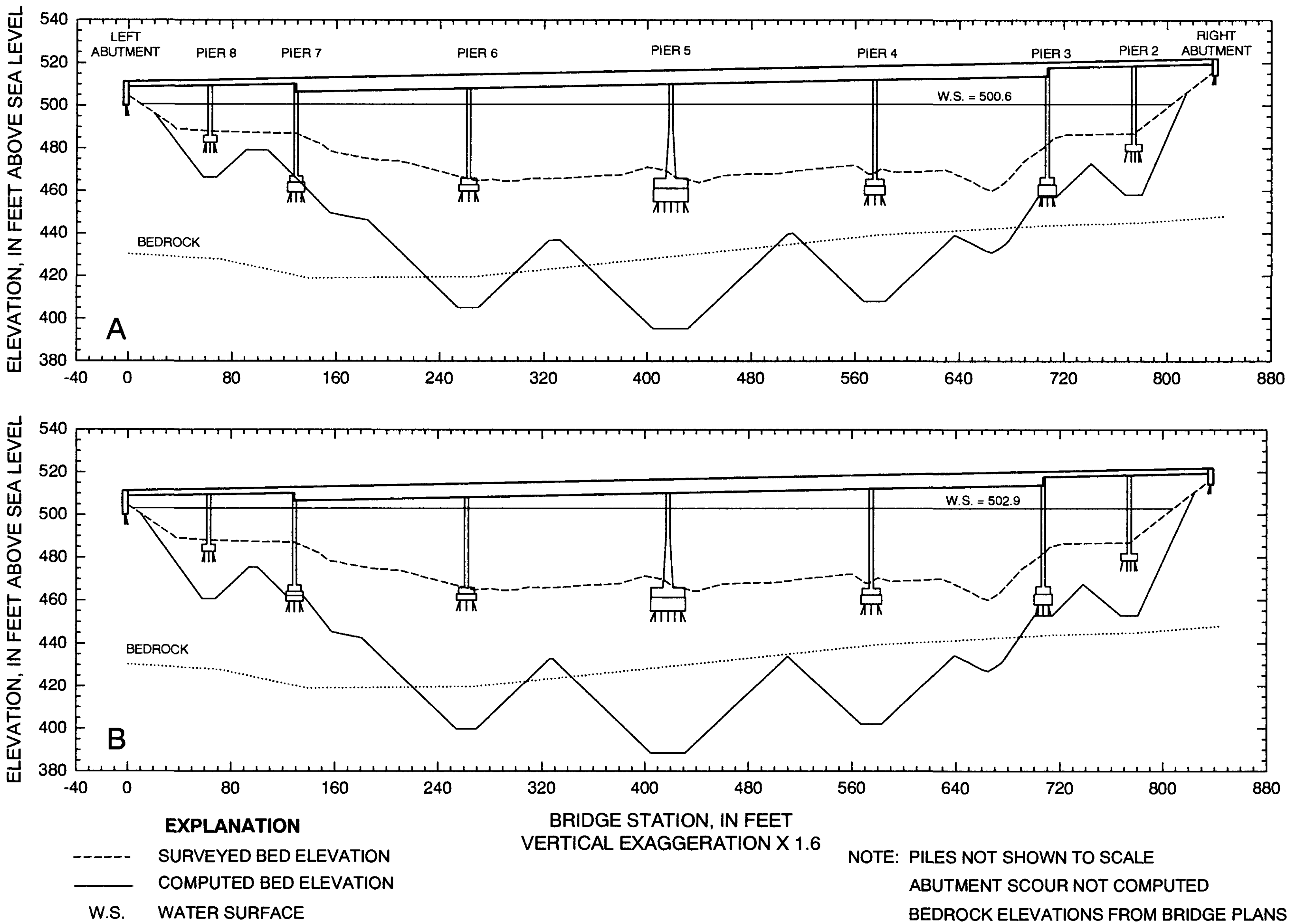


Figure 34. Potential scour at State Road 32 over Wabash River at Perrysville, Indiana: (A) 100-year peak discharge, and (B) 500-year peak discharge.

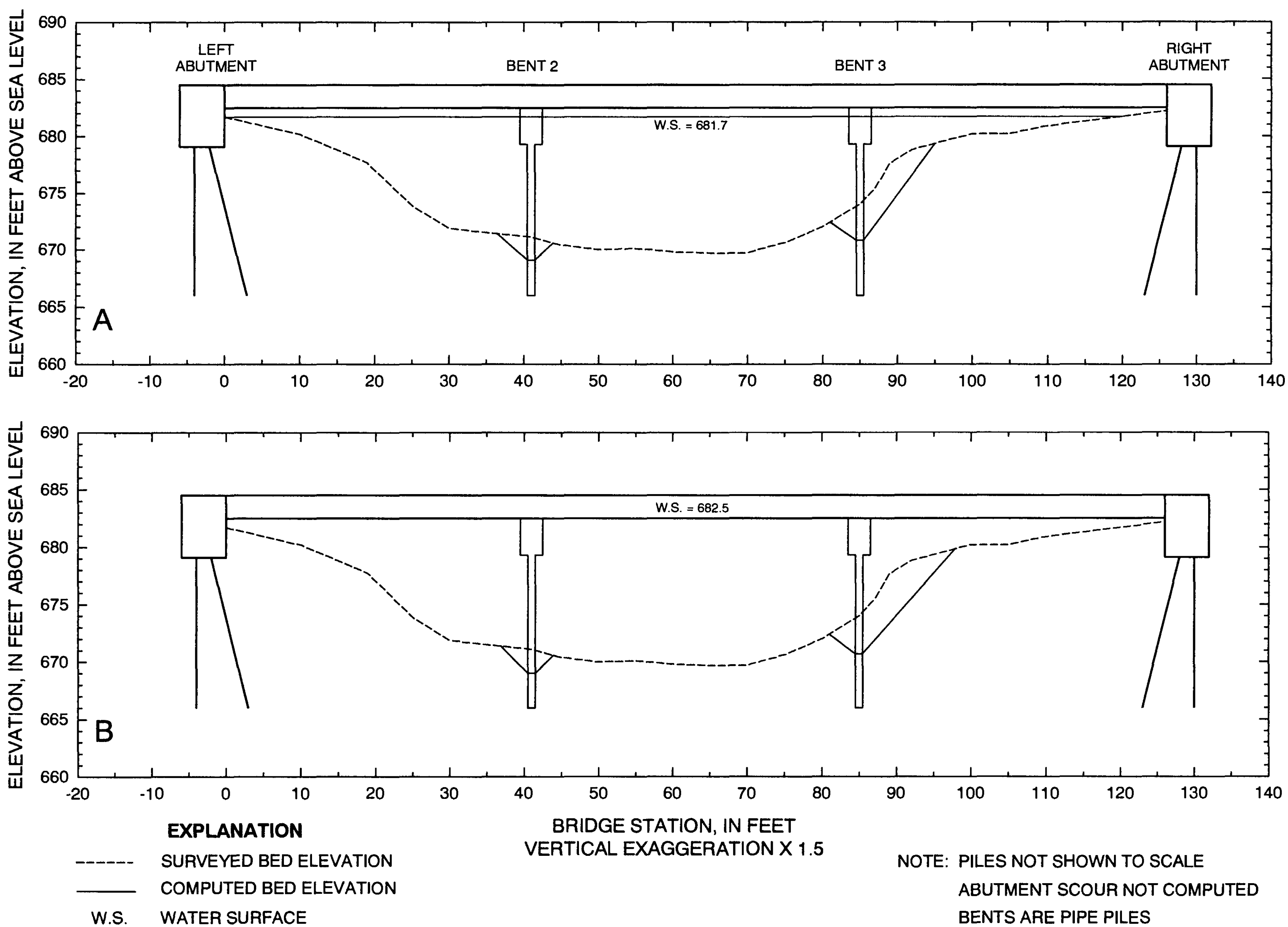


Figure 35. Potential scour at U.S. Route 35 over Kankakee River at Union Center, Indiana: (A) 100-year peak discharge, and (B) 500-year peak discharge.

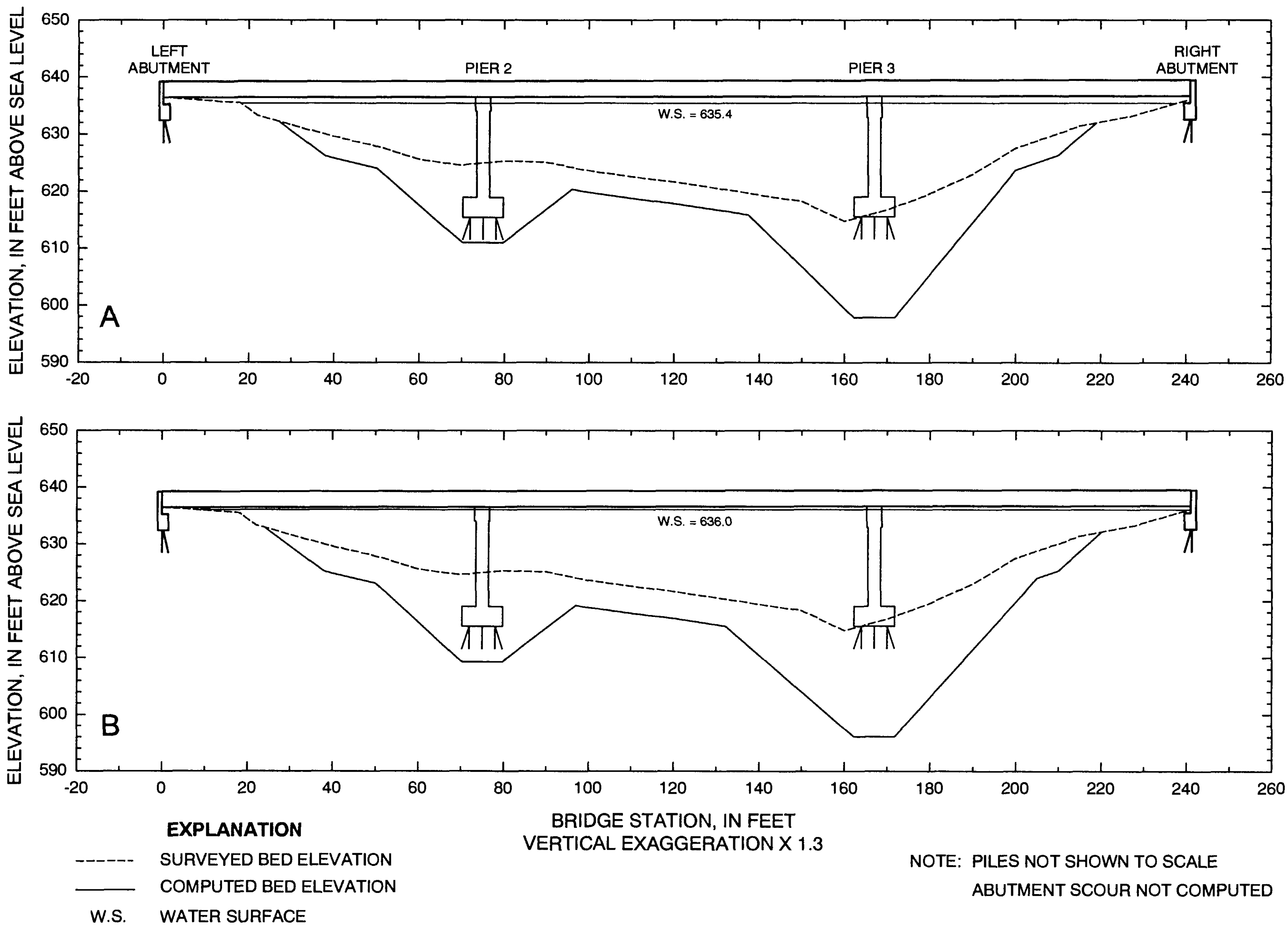
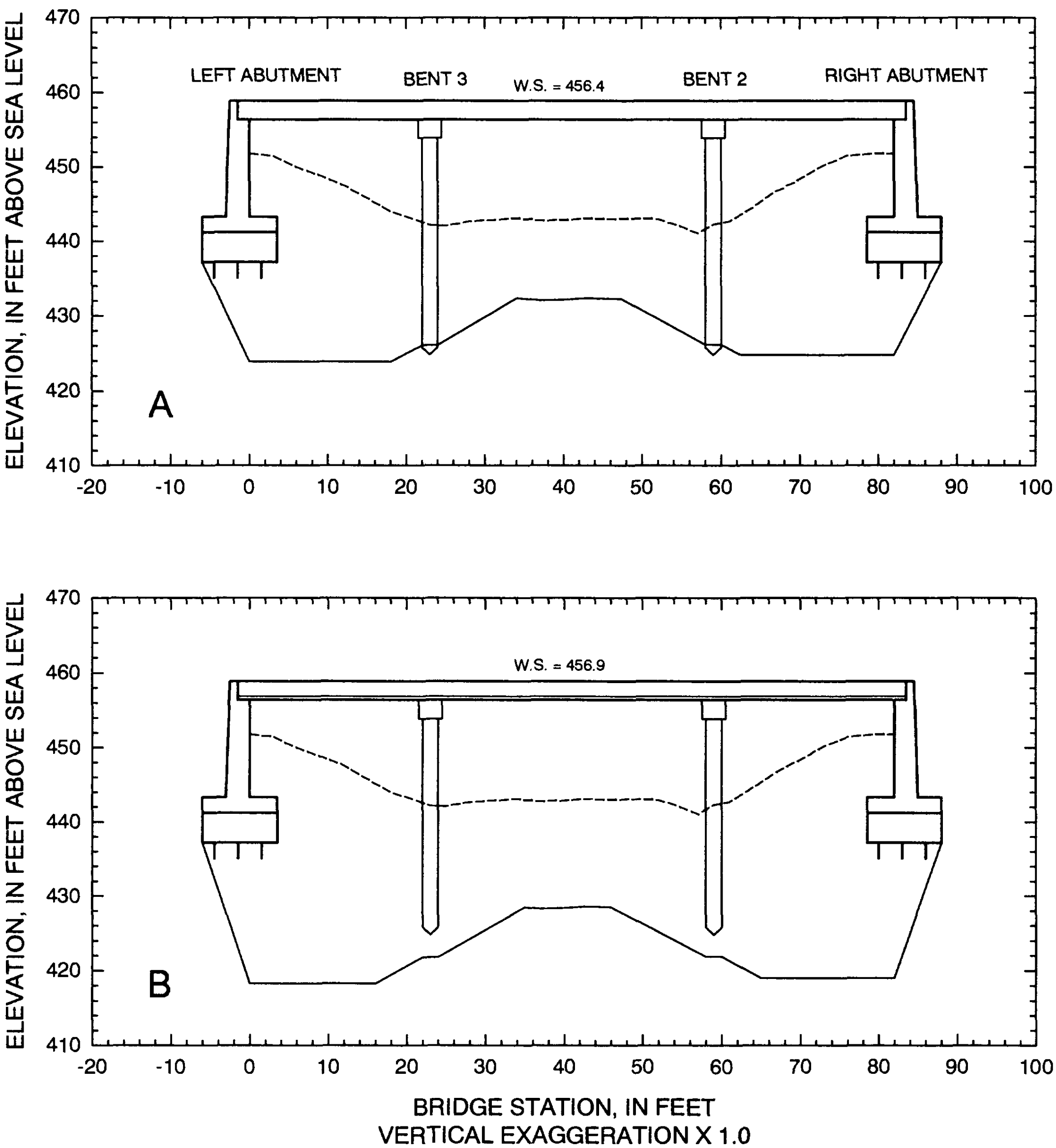


Figure 36. Potential scour at U.S.Route 41 (southbound lane) over Kankakee River at Schneider, Indiana: (A) 100-year peak discharge, and (B) 500-year peak discharge.



EXPLANATION

------ SURVEYED BED ELEVATION

——— COMPUTED BED ELEVATION

W.S. WATER SURFACE

NOTE: PILES NOT SHOWN TO SCALE
BENTS ARE SQUARE CONCRETE PILES

Figure 37. Potential scour at State Road 54 over Busseron Creek near Sullivan, Indiana: (A) 100-year peak discharge, and (B) 500-year peak discharge.

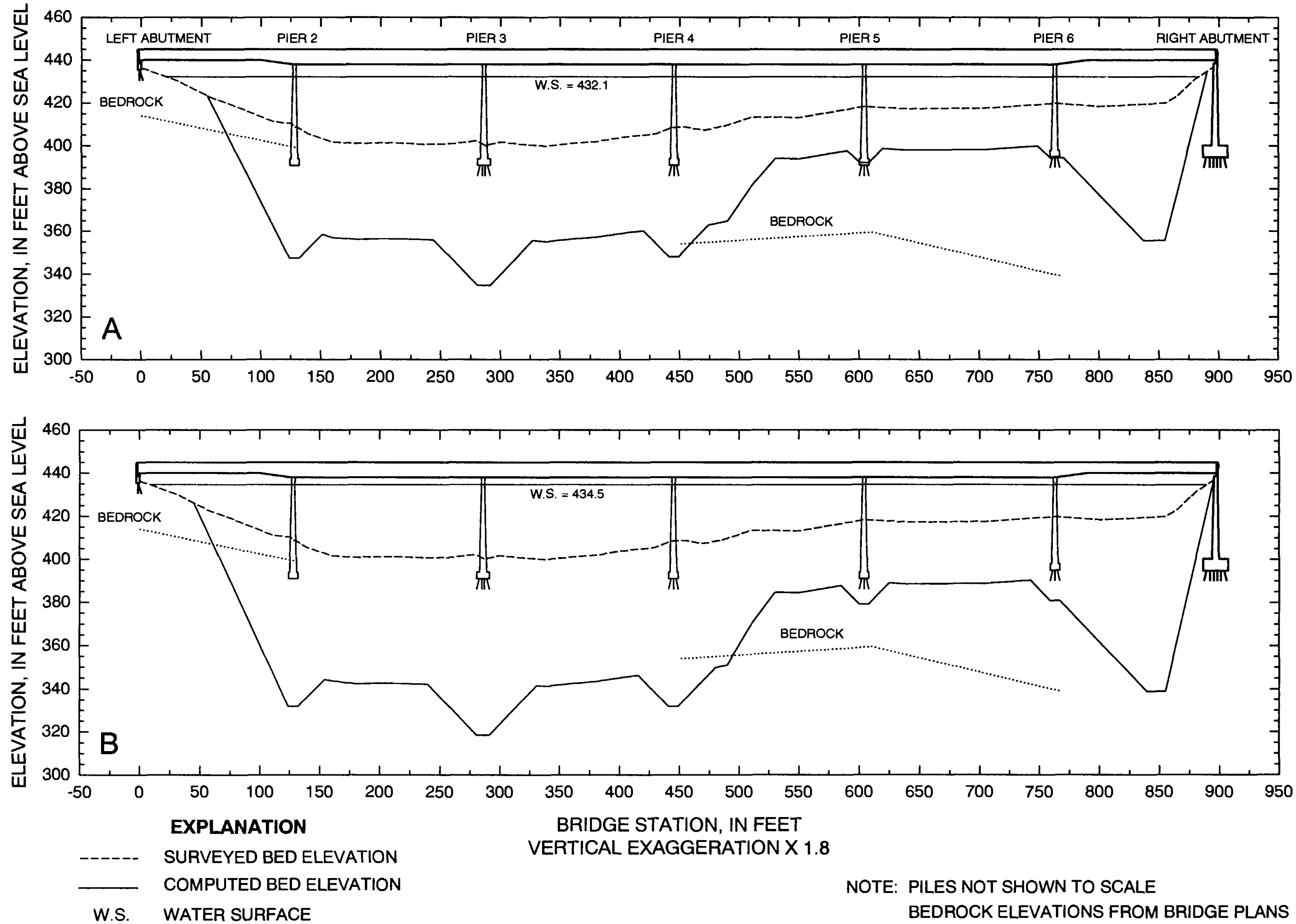


Figure 38. Potential scour at State Road 57 over East Fork White River near Petersburg, Indiana: (A) 100-year peak discharge, and (B) 500-year peak discharge.

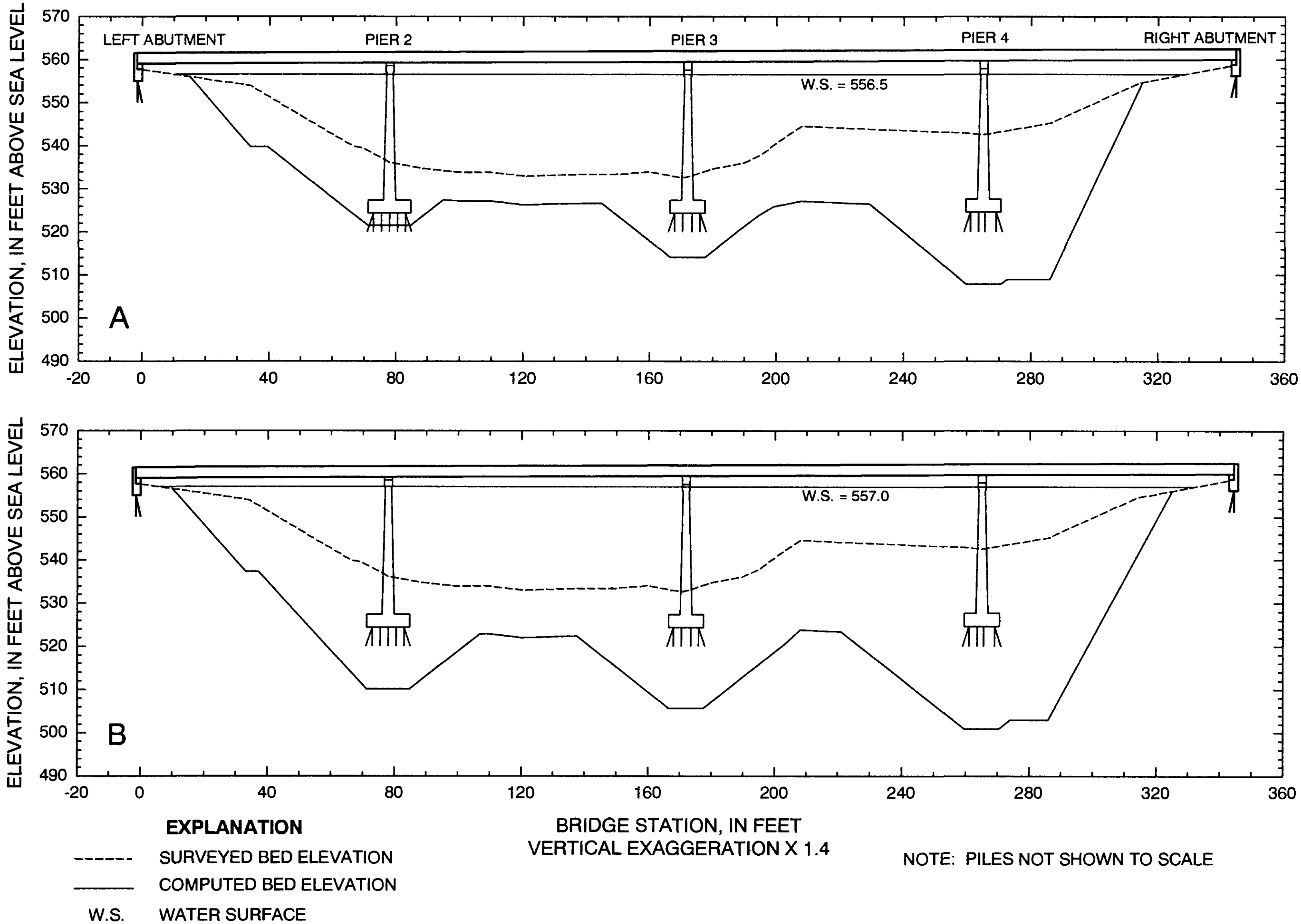


Figure 39. Potential scour at State Road 59 over Eel River north of Clay City, Indiana: (A) 100-year peak discharge, and (B) 500-year peak discharge.

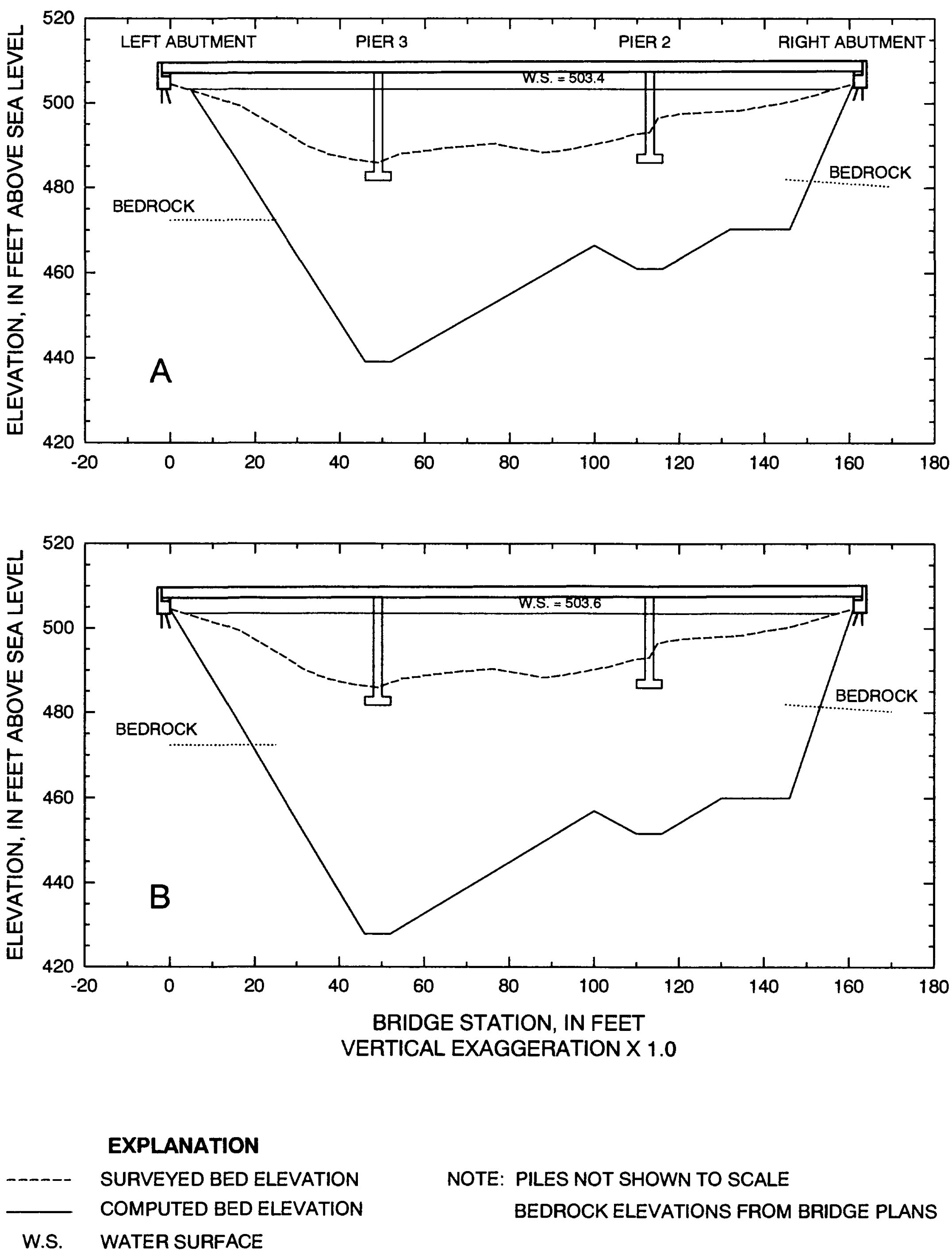


Figure 40. Potential scour at State Road 63 (southbound lane) over Little Vermillion River at Newport, Indiana: (A) 100-year peak discharge, and (B) 500-year peak discharge.

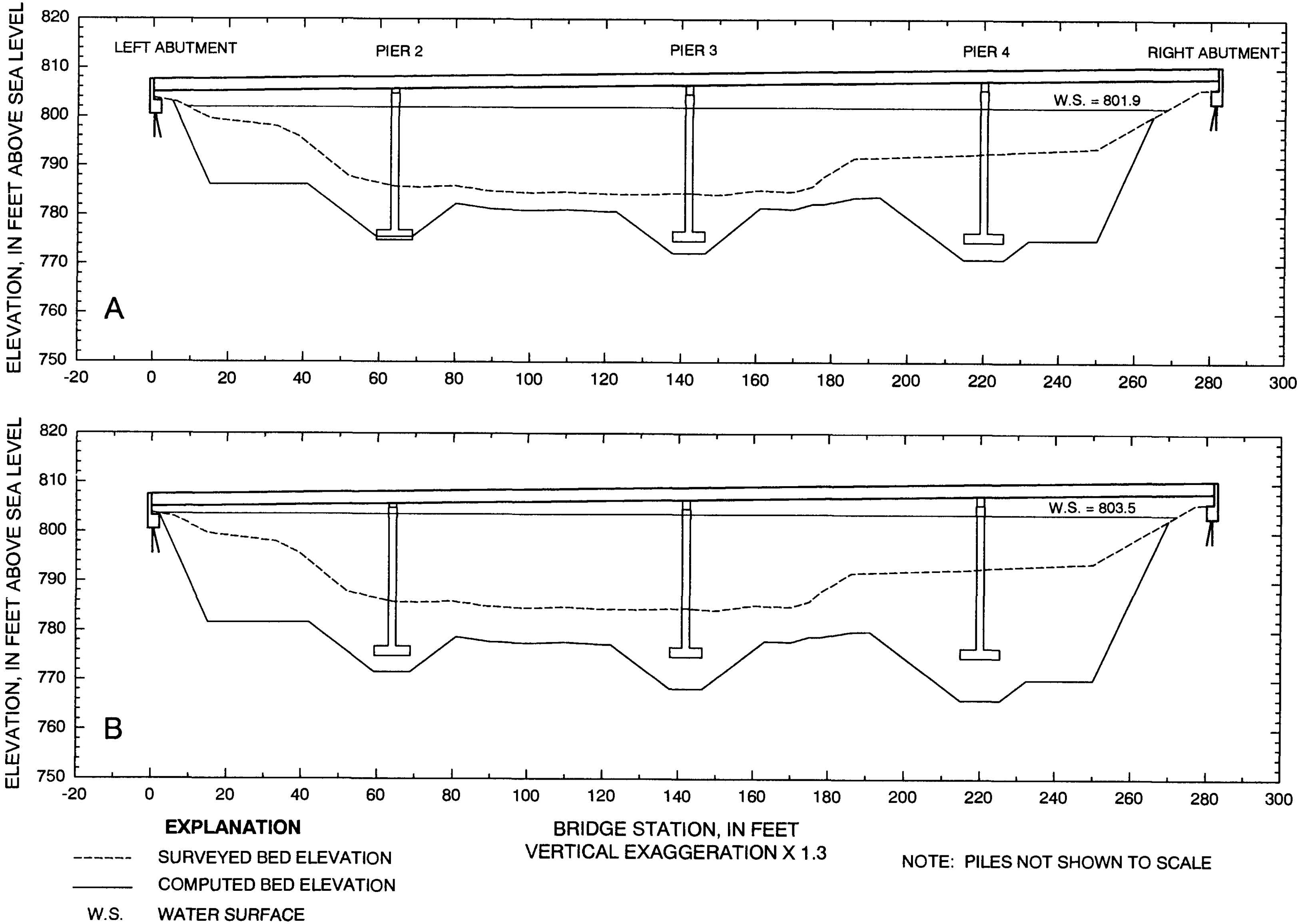


Figure 41. Potential scour at State Road 101 over St. Joseph River at Saint Joe, Indiana: (A) 100-year peak discharge, and (B) 500-year peak discharge.

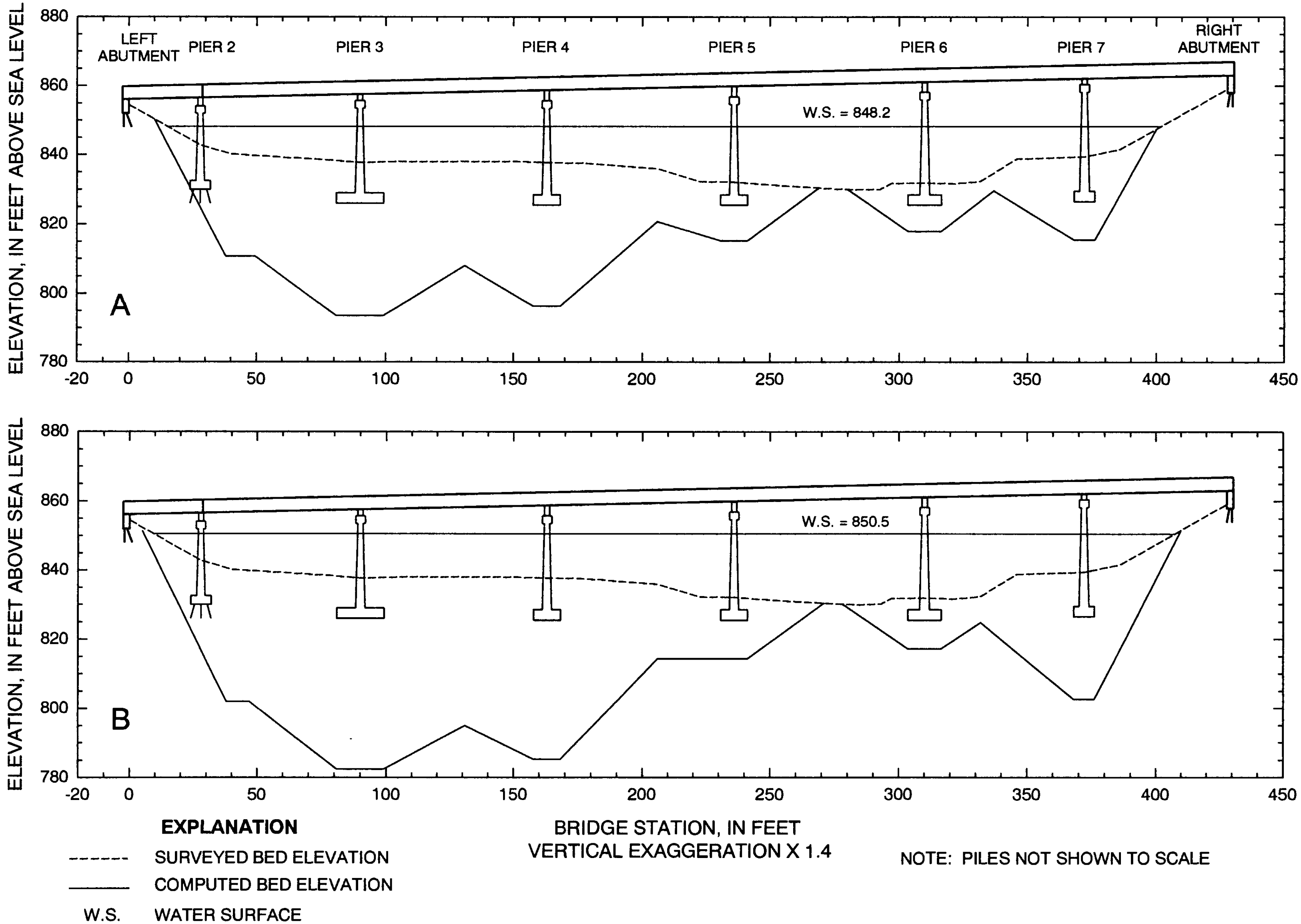


Figure 42. Potential scour at State Road 109 over White River at Anderson, Indiana: (A) 100-year peak discharge, and (B) 500-year peak discharge.

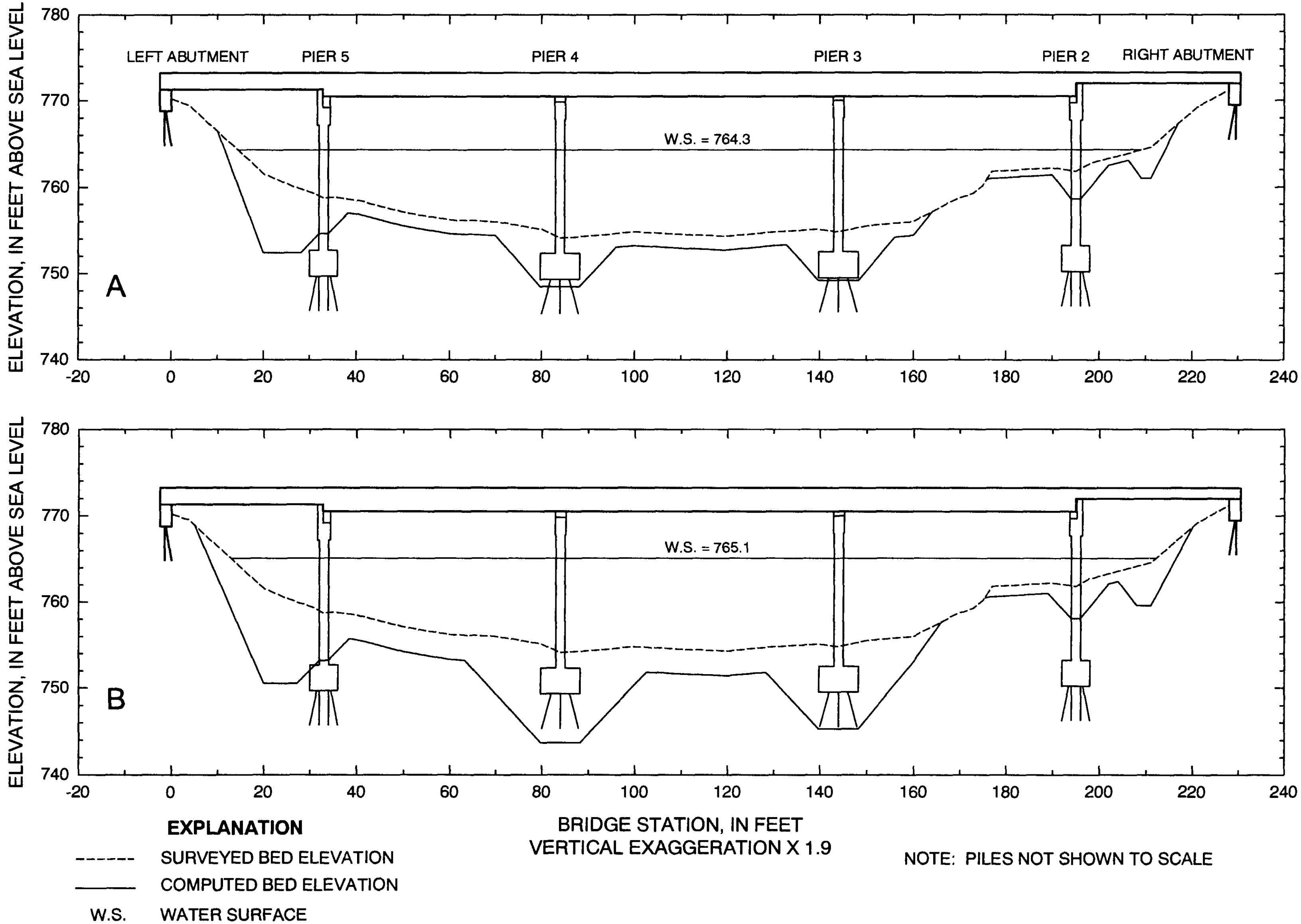


Figure 43. Potential scour at State Road 110 over Tippecanoe River near Mentone, Indiana: (A) 100-year peak discharge, and (B) 500-year peak discharge.

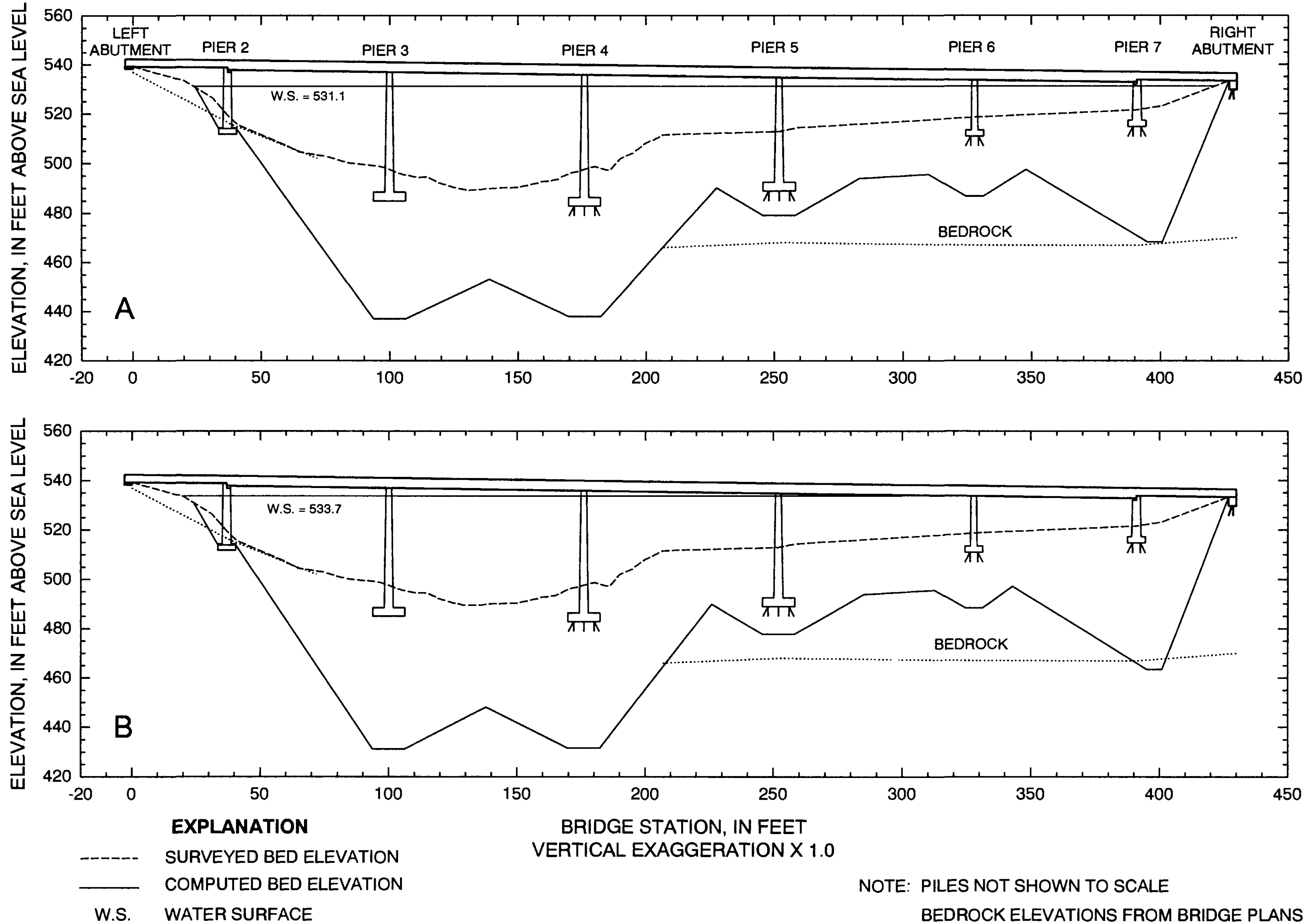


Figure 44. Potential scour at State Road 135 over Muscatatuck River at Millport, Indiana: (A) 100-year peak discharge, and (B) 500-year peak discharge.

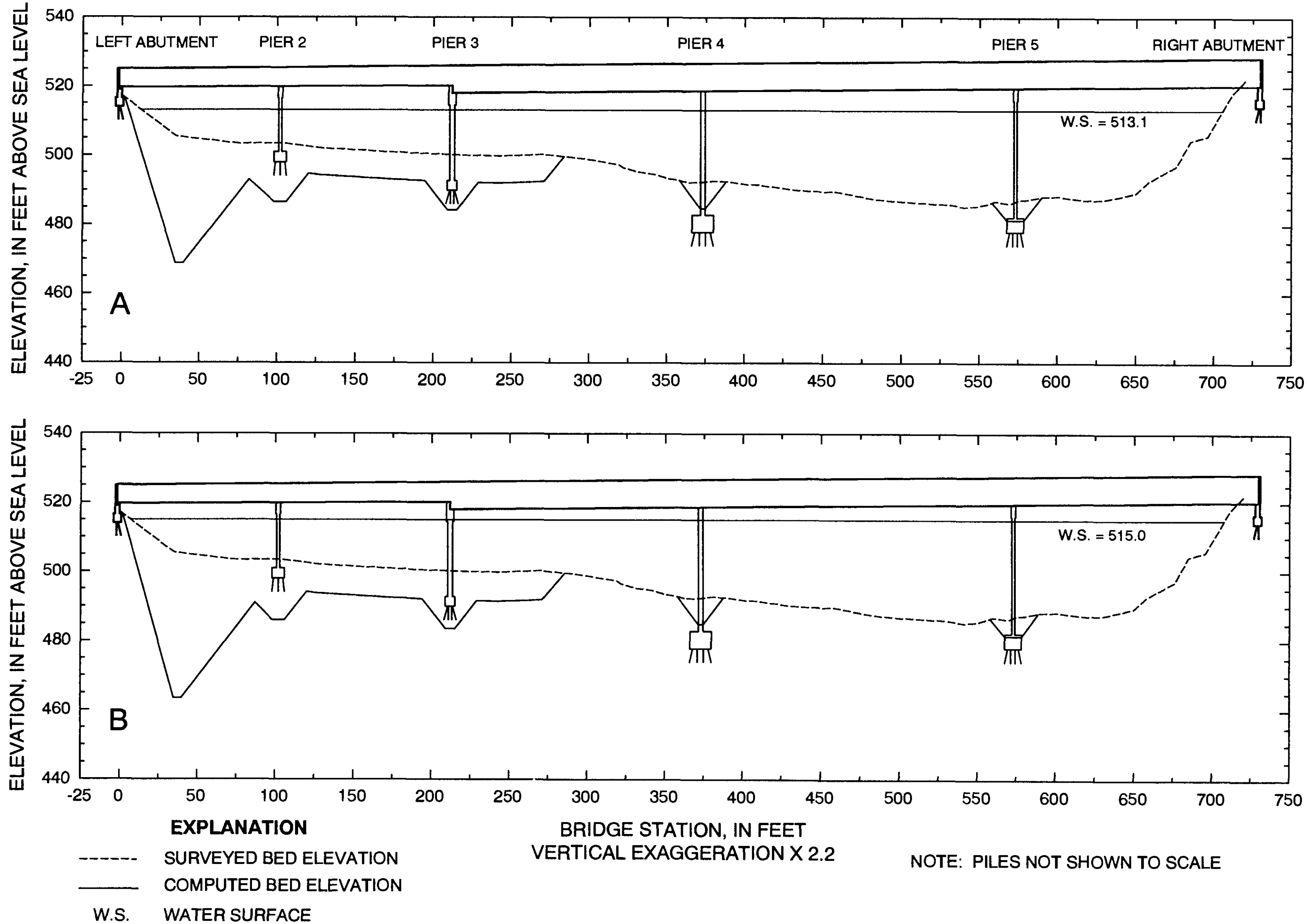


Figure 45. Potential scour at State Road 157 over White River at Worthington, Indiana: (A) 100-year peak discharge, and (B) 500-year peak discharge.

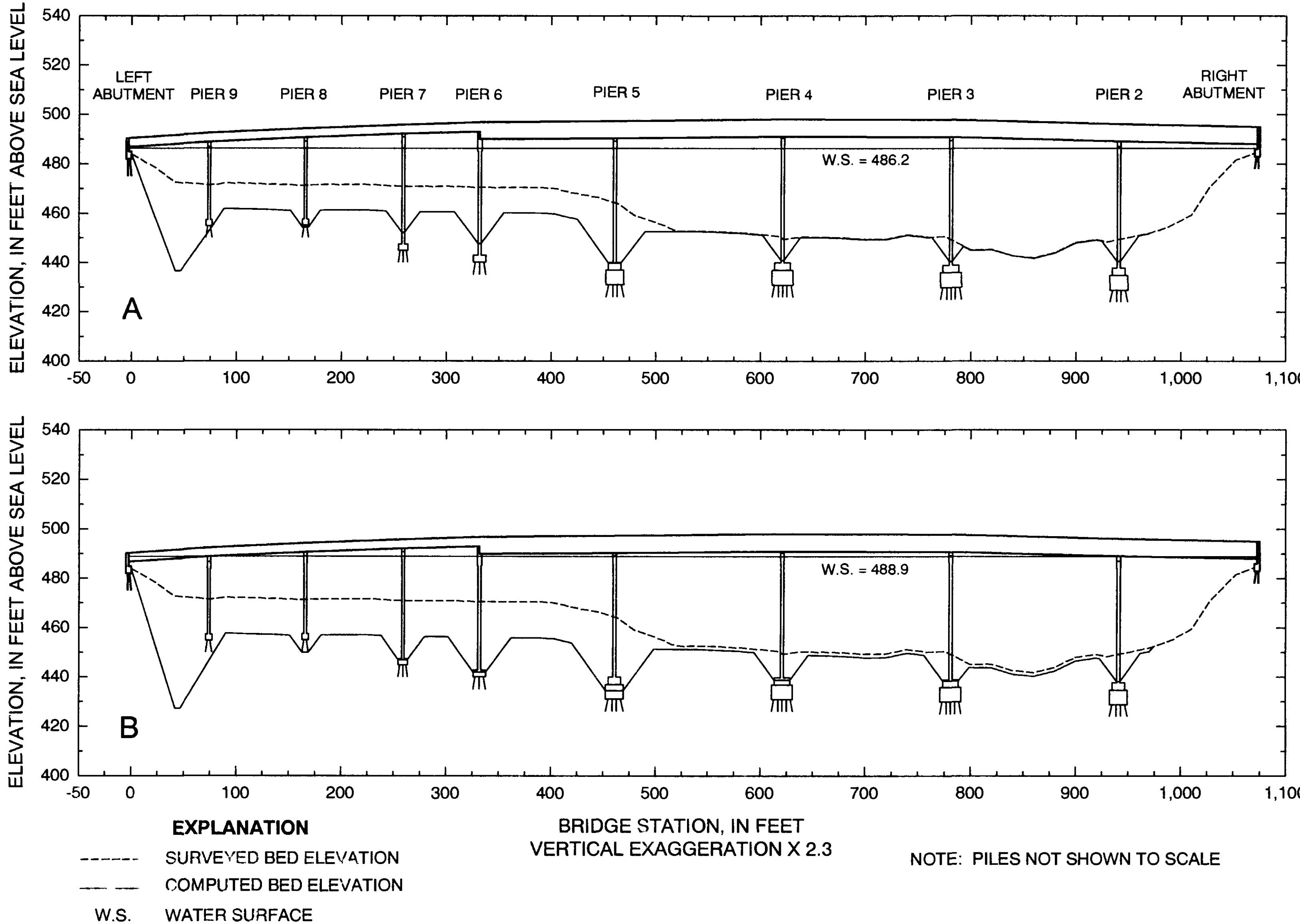


Figure 46. Potential scour at State Road 163 over Wabash River at Clinton, Indiana: (A) 100-year peak discharge, and (B) 500-year peak discharge.

SUMMARY AND CONCLUSIONS

Scour around bridges is a serious problem on many rivers; bridge failure commonly is attributed to undermining of piers or abutments by scour. This study evaluated 20 Indiana bridge sites to determine the scour during measured floods, changes in bed elevations during the study, maximum historical scour, and present estimates of potential scour resulting from the 100- and 500-year floods. The study also assessed the accuracy of 14 scour equations for application in Indiana.

Geophysical techniques consisting of ground-penetrating radar (GPR) and a tuned transducer were used to survey the bridge openings to locate evidence of scour holes that may have refilled. The GPR was used successfully on gravel bars and in water less than 4 ft deep. In water depths greater than 4 ft, the signal was attenuated in the water column because of the high specific conductance of the water. The tuned transducer was used with a 3.5- to 7-kHz and a 14-kHz transducer suspended 6 to 12 in. below the water surface. This equipment was usable in water depths greater than 4 ft. Side echo, debris, point reflections from cobbles and boulders, and multiple reflections obscured some data from the GPR and the tuned transducer. The 20 sites surveyed by use of the geophysical equipment produced record adequate for determination of the approximate location and depth of subsurface interfaces; however, the record was not of sufficient resolution to map the lateral extent of buried scour holes.

Onsite measurements and soundings indicate that scour may not be solely a function of discharge or depth but that it is affected greatly by debris. The flood measurement of 78,700 ft^3/s at S.R. 32 over Wabash River indicates no deepening of the debris-affected hole at pier 6. The maximum discharge during the time span that this hole developed was 29,400 ft^3/s. When the debris was removed, the hole refilled. At S.R. 157 over White River and S.R. 57 over East Fork White River, debris piles were removed from the bridge opening, and the flood measurements indicate that the holes refilled.

The results of the geophysical surveys and the soundings indicate that debris is a major cause of scour within bridge openings. Also, scour can occur anywhere within the bridge opening, an indication that scour holes may not be found during studies relying solely on soundings at the upstream and (or) downstream side of the bridge. The geophysical surveys located buried scour holes at sites where no evidence of scour was available from an inspection of the channel bottom. The GPR and tuned-transducer surveys were effective in locating sites where scour is a problem.

Historical scour data collected by use of geophysical techniques, probing, and sediment cores were used to evaluate the accuracy of 14 pier-scour equations. This evaluation was based on the assumption that the historical scour measured in the channel subbottom was associated with the peak historical discharge. Under laboratory conditions this would be a valid assumption, but it is suspect for field conditions because debris accumulations, ice jams, and other anomalies affect the depth of scour occurring at a given discharge. Measured historical scour possibly was associated with a lesser discharge and was affected by debris or ice accumulations. This was the case at S.R. 11 over the Flatrock River, S.R. 57 over East Fork White River, and S.R. 63 over Little Vermillion River. At these sites, the estimated maximum historical peak discharge occurred during the study; however, the fieldwork that identified the historical scour preceded the flooding, so the historical scour hole was not related to the maximum discharge.

At some sites, the contraction-scour computations predict what appear to be excessive scour. Therefore, the historical scour comparisons also were made without adding contraction scour to the pier scour. When contraction scour was included in the analysis, the Froehlich equation provided the most accurate comparison to the measured historical scour, and the Blench-Inglis II equation was the second most accurate. When contraction scour was not included in the analysis, the Arkansas equation provided the most accurate comparison to the measured historical scour, and the Froehlich equation was the second most accurate. Without the effects of contraction scour, all of the equations underestimated the historical scour more often. This pattern may indicate that contraction scour contributes to maximum historical scour but that the current methodology results in overestimates of contraction scour. The Ahmad and Chitale equations were the only equations that were so conservative that they generally overestimated scour even when contraction scour was not included in the analysis.

Relative to depth of scour, the Blench-Inglis II and Froehlich equations best matched the measured depths of scour when contraction scour was included. When contraction scour was not included, the Shen, Arkansas, and Inglis-Poona I equations best matched the measured depths of scour.

Streambed elevations collected during flood measurements also were used to evaluate the accuracy of the 14 pier-scour equations. Only piers in the main channel were evaluated because no movement of sediment was observed on the overbanks. Contraction scour was not included in the analysis because contraction scour was not positively defined by the flood measurements and periodic soundings. Not much scour was identified during the flood measurements, and all the pier-scour equations tended to overestimate scour. The Arkansas equation was the most accurate in comparison with the measurements, and the Froehlich equation was the next most accurate. Both of these equations overestimated scour for all the observations. The lack of measured scour during the floods may be a result of the high frequency of the floods that were measured. The recurrence interval of most measured discharges was less than 10 years; for several measured discharges it was approximately 2 years. At these high-frequency discharges, either the hydraulic conditions may not be suitable to induce much scour or the streams may naturally be protected to resist scour. The data collected from the discharge measurements and the periodic soundings indicate that debris accumulations may be a significant contributor to scour.

A comparison of velocities computed with WSPRO to velocities measured during floods indicates that WSPRO more accurately predicted velocities at piers in the main channel than at piers on the overbanks. Most of the computed velocities for the main channel were within 1 ft/s of the measured velocity. In general, WSPRO overestimated at lower velocities and underestimated at higher velocities, but this trend was more distinct with velocities for the overbanks than for the main channel.

Potential scour resulting from the 100-year and 500-year peak discharges was computed by use of the procedures recommended by the FHWA. The hydraulic conditions for these floods were estimated by use of WSPRO models. Contraction-scour computations appear to be excessive at many sites, especially in clear-water conditions on the overbanks. The periodic site visits did not indicate any evidence of scour on the overbanks at any of the study sites. The clear-water contraction-scour equation includes grain size as a variable and computes more scour for finer grain sizes. The equation, however, does not consider the increased cohesion of the sediment with finer grain sizes. The equation also does not consider the grassy vegetation on the overbanks that binds the surface sediments and prevents erosion. The estimates of contraction scour in the main channel were excessively conservative at sites where flood plains were wide. This may be a result of the equation not being fully suited to field conditions and (or) poor estimates of hydraulic conditions. Abutment scour was included in the potential scour computations even though the abutment-scour equations generally are recognized as being conservative.

Computed abutment scour at several of the sites seems to be excessive; however, the FHWA states that if rock riprap and (or) guide banks are designed properly to protect abutments, it is unnecessary to design abutments to resist the computed depths of abutment scour.

On the basis of five study sites where flooding has equaled or exceeded the 100-year flood during the life of the bridge, the identification and estimates of historical scour bed elevations do not indicate scouring of the extent predicted by the potential scour computations. At S.R. 9 over Pigeon River and U.S. Route 35 over Kankakee River, historical scour interfaces were not identified in the channel subbottom. At S.R. 15 over Little Elkhart River, U.S. Route 41 over Kankakee River, and S.R. 110 over Tippecanoe River, the estimated historical scour interfaces were all above the computed potential scour bed elevations.

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SUPPLEMENTAL DATA

Soil-Boring and Sediment-Core Logs

Table 2. Soil-boring logs, State Road 1 over St. Marys River at Fort Wayne, Indiana
[From Indiana State Highway Commission, 1968 bridge plans, sheet 2; ft, feet]

Boring No. 3, 7 ft right of pier 3 and 45 ft upstream from centerline of bridge	
Elevation (ft)	**Description**
743.8–743.3	Brown and gray, wet, loose sand and gravel
743.3–722.8	Gray, moist, hard, silty loam or loam with trace of gravel (hardpan)
722.8–718.3	Gray, wet, very dense, fine to coarse sand with some gravel and boulders

Boring No. 4, 5 ft right of pier 4 and 42 ft downstream from centerline of bridge	
Elevation (ft)	**Description**
744.5–742.5	Gray, moist, hard loam with sand seams and little gravel (hardpan)
742.5–737.5	Gray, moist, hard loam or sandy loam with trace of gravel (hardpan)
737.5–735.5	Gray, wet, very dense, fine to medium sand with trace of gravel
735.5–727.7	Gray, moist, hard, silty loam or loam with trace of gravel with few sand lenses or seams
727.7–726.5	Gray, wet, very dense, fine to coarse sand and fine to coarse gravel
726.5–723.0	Gray, moist, hard loam with some gravel (hardpan)
723.0–718.5	Gray, wet, very dense, fine to coarse sand and fine to coarse gravel with boulders and with hardpan seams
718.5–717.0	Brown and gray, very dense, fine sand

Table 3. Sediment-core logs, State Road 9 over Pigeon River at Howe, Indiana
[ft, feet]

Core 9-1, 4 ft upstream from centerline of pier 2; bed elevation, 853.6 ft; top of core elevation, 852.5 ft		
Depth (ft)	**Compacted core elevation**	**Description**
0–1.1	852.5–851.4	Brown, fine to coarse sand with small to medium gravel. Large wood chunk at top; large shell and large piece of gravel at 0.6–0.7 ft
1.1–2.2	851.4–850.3	Light-brown, medium to coarse sand with small to medium gravel, large gravel at 1.35 ft., small gravel mixed in at 1.7 to 2.2 ft
2.2–4.2	850.3–848.3	Light-brown, medium sand with trace of very small gravel

Core 9-2, midway between piers 2 and 3 at upstream face; bed elevation, 855.1 ft; top of core elevation, 853.6 ft		
Depth (ft)	**Compacted core elevation**	**Description**
0–1.4	853.6–852.2	Brown, fine to medium sand with small gravel; trace of medium gravel, organic material at 1.0 ft
1.4–1.7	852.2–851.9	Dark-brown organic material (wood) and fine, brown sand
1.7–2.2	851.9–851.4	Brown, small to medium gravel and coarse sand

Core 9-3, 2 ft upstream from and 0.9 ft right of centerline of pier 2; bed elevation, 857.0 ft; top of core elevation, 856.3 ft		
Depth (ft)	**Compacted core elevation**	**Description**
0–0.8	856.3–855.5	Dark-brown to black organic material (wood) and fine to medium sand; some shell fragments
0.8–1.3	855.5–855.0	Light-brown, fine to medium sand with trace of small gravel, shells
1.3 –1.9	855.0–854.4	Gray silt, sand, and small to large gravel, cemented; large piece of cemented gravel at 1.4 ft

Table 4. Soil-boring logs, State Road 9 over Pigeon River at Howe, Indiana
[From Indiana State Highway Commission, 1959 bridge plans, sheet 5; ft, feet]

Boring No. 1, at left abutment and 40 ft upstream from centerline of bridge	
Elevation (ft)	**Description**
857.5–856.0	Top soil
856.0–853.0	Gravel
853.0–850.5	Probable gravel

Boring No. 3, 6 ft left at pier 3 and 14 ft upstream from centerline of bridge	
Elevation (ft)	**Description**
857.5–853.0	Black muck and top soil
853.0–852.0	Gravel
852.0–847.5	Probable gravel

Table 5. Sediment-core logs, State Road 11 over Flatrock River at Columbus, Indiana
[ft, feet]

Core 11-1, midway between left bank and pier 3; at upstream face, bed elevation, 601.9 ft; top of core elevation, 600.0 ft		
Depth (ft)	**Compacted core elevation**	**Description**
0–2.0	600.0–598.0	Light-brown to gray, small to large gravel with silt and trace of sand, medium-sized gravel throughout but more in upper half
2.0–2.4	598.0–597.6	Small to large gravel similar to upper part of previous section, but has yellowish color. Contains silt and trace of sand
2.4–2.5	597.6–597.5	Brown, fine-grained sand. Bottom .01 to .02 ft of this section is gray sand, fine to medium-grained with some small shell fragments
2.5–2.9	597.5–597.1	Dark-brown, organic material containing light-brown, fine sand. Organic material is coarse textured and contains pieces of wood

Core 11-2, 4 ft upstream from centerline of pier 3; bed elevation, 601.3 ft; top of core elevation, 600.7 ft		
Depth (ft)	**Compacted core elevation**	**Description**
0–1.5	600.7–599.2	Light-brown to gray, small to large gravel with silt and trace of sand. Similar to upper part of core 11–1

Core 11-3, 1.9 ft right of upstream end of pier 3; bed elevation, 600.6 ft; top of core elevation, 600.6 ft		
Depth (ft)	**Compacted core elevation**	**Description**
0–0.7	600.6–599.9	Brown to gray, medium sand with small to large gravel. Some fine to coarse sand
0.7–1.0	599.9–599.6	Stringer of dark-gray clay in medium sand. Small to medium gravel also present. Top surface of clay is sloping
1.0–1.9	599.6–598.7	Gray to light-brown, medium sand with small to medium gravel. Contains more gravel than upper part of this core. Thin (.01 to .02 ft) layer of dark-brown sandy clay at 1.2 ft. Dark-gray clay in half of core at 1.5 to 1.65 ft
1.9–2.0	598.7–598.6	Dark-gray, silty clay with some gravel

Core 11–4, midway between pier 3 and right bank; bed elevation, 603.1 ft; top of core elevation, 602.3 ft		
Depth (ft)	**Compacted core elevation**	**Description**
0–1.5	602.3–600.8	Brown, fine to medium sand with small to large gravel. More gravel in upper part of this section. Trace of shell fragments
1.5–1.9	600.8–600.4	Brown, fine to medium sand. Trace of small gravel and shell fragments
1.9–2.7	600.4–599.6	Brown, medium to coarse sand and small to medium gravel. Trace of fine brown sand and silt

Table 6. Sediment-core logs, State Road 14 over Tippecanoe River at Winamac, Indiana
[ft, feet]

Core 14–1, 1.5 ft upstream from centerline of pier 3; bed elevation, 679.2 ft; top of core elevation, 678.2 ft		
Depth (ft)	**Compacted core elevation**	**Description**
0–0.4	678.2–677.8	Dark-gray, very fine sand with trace of small gravel, some organic material
0.4–0.6	677.8–677.6	Brown, medium to coarse sand, trace of small gravel and shell fragments
0.6–1.0	677.6–677.2	Gray, fine to medium sand with small gravel and shells, organic material at 0.9 ft
1.0–1.3	677.2–676.9	Gray clay, stiff
1.3–2.0	676.9–676.2	Gray to brown, fine to coarse sand with small to medium gravel, some chunks of sandy clay
2.0–2.8	676.2–675.4	Gray to green, very fine sand with silt
2.8–3.1	675.4–675.1	Dark-gray to black, very fine sand with trace of small to medium gravel, shell fragments, and organic material
3.1–3.2	675.1–675.0	Gray, sandy clay, some organic oxidation
3.2–3.8	675.0–674.4	Gray to brown, fine sand with trace of small gravel, shell, organic matter, and intermixed sandy clay
3.8–4.0	674.4–674.2	Gray to brown, medium to coarse sand with small to medium gravel
4.0–4.6	674.2–673.6	Dark-gray to brown, very fine sand with silt and trace of small gravel
4.6–4.9	673.6–673.3	Gray to brown, fine to medium sand and small gravel
4.9–5.8	673.3–672.4	Dark-gray to black, very fine sand with silt and clay, some thin stringers of fine gray sand, large piece of cemented gravel at 5.0 ft
5.8–6.0	672.4–672.2	Gray, medium to coarse sand with small gravel, some silt and clay
6.0–6.2	672.2–672.0	Dark-gray, silty clay with trace of very fine sand
6.2–6.6	672.0–671.6	Dark-gray, very fine sand with organic material
6.6–6.8	671.6–671.4	Gray, medium sand with small gravel, medium gravel at bottom; mostly limestone fragments, some with cementation

Table 6. Sediment-core logs, State Road 14 over Tippecanoe River at Winamac, Indiana—Continued

Core 14–2, upstream face between pier 3 and pier 4; bed elevation, 678.0 ft; top of core elevation, 674.6 ft		
Depth (ft)	**Compacted core elevation**	**Description**
0–1.1	674.6–673.5	Brown, medium to coarse sand with small to medium gravel, small shells and shell fragments
1.1–1.5	673.5–673.1	Gray to brown, medium to coarse sand with small to medium gravel
1.5–2.2	673.1–672.4	Gray, fine to coarse sand with small gravel and some shell fragments, some gray clay intermixed
2.2–2.4	672.4–672.2	Gray, medium sand with clay and silt
2.4–2.8	672.2–671.8	Light gray, fine sand with trace of very small gravel
2.8–4.2	671.8–670.4	Gray, medium to coarse sand with small gravel oxidized 3.6 to 4.2 ft
4.2–4.8	670.4–669.8	Gray to brown, fine sand, alternating gray to brown layers, some small gravel; thin clay at 4.5 ft

Core 14–3, 2.2 ft upstream from and 2.0 ft left of centerline of pier 4; bed elevation, 676.8; top of core elevation, 674.4 ft		
Depth (ft)	**Compacted core elevation**	**Description**
0–3.3	674.4–671.1	Brown, medium to coarse sand with small to large gravel; large gravel at 0.7 and 2.6 ft

Core 14–4, upstream face between pier 4 and pier 5; bed elevation, 677.4 ft; top of core elevation, 676.4 ft		
Depth (ft)	**Compacted core elevation**	**Description**
0–1.8	676.4–674.6	Gray, fine to medium sand, trace of small gravel and some organic material
1.8–3.0	674.6–673.4	Gray clay and very fine sand intermixed and interbedded
3.0–3.2	673.4–673.2	Light-gray, fine sand
3.2–3.6	673.2–672.8	Gray clay, stiff, interbedded with gray, medium sand
3.6–5.6	672.8–670.8	Gray, medium to coarse sand with small gravel

Table 6. Sediment-core logs, State Road 14 over Tippecanoe River at Winamac, Indiana—Continued

Core 14–5, 2.5 ft upstream from centerline of pier 5; bed elevation, 678.8 ft; top of core elevation, 676.4 ft		
Depth (ft)	**Compacted core elevation**	**Description**
0–0.7	676.4–675.7	Dark-gray to black, very fine sand with silt, clay, organic material, and shells
0.7–1.6	675.7–674.8	Gray, medium to coarse sand with small to medium gravel, some organic material
1.6–3.2	674.8–673.2	Gray, fine to coarse sand (coarse at bottom) with small to large gravel and intermixed clay chunks. Large piece of gravel at 2.15 ft, large shell fragment at 2.8 ft
3.2–3.8	673.2–672.6	Gray clay, stiff
3.8–4.6	672.6–671.8	Gray, medium to coarse sand and small to medium gravel
4.6–4.8	671.8–671.6	Gray clay, stiff with trace of coarse sand or small gravel
4.8–5.0	671.6–671.4	Gray, medium to coarse sand and small gravel
5.0–5.3	671.4–671.1	Gray clay, sand and gravel intermixed, thin clay stringer at bottom
5.3–5.8	671.1–670.6	Gray to brown, very fine sand, some shell fragments
5.8–6.9	670.6–669.5	Gray, medium to coarse sand, trace of small, angular gravel; black organic material at 5.9 ft

Table 7. Soil-boring logs, State Road 14 over Tippecanoe River at Winamac, Indiana

[From Indiana State Highway Commission, 1952 bridge plans, sheet 7; ft, feet]

Boring No. 6, at downstream end of pier 3	
Elevation (ft)	**Description**
684.1-682.1	Black clay (peatlike, unstable)
682.1-676.1	Gray clay (clay and fine sand, unstable)
676.1-668.6	Sand (clean)
668.1-641.1	Gravel (pea gravel)

Boring No. 7, at upstream end of pier 5	
Elevation (ft)	**Description**
688.5-681.5	Brown clay and fine sand, unstable
681.5-668.0	Fine sand, stable
668.0-652.5	Coarse sand
652.5-641.5	Gravel (pea gravel)

Table 8. Sediment-core logs, State Road 15 over Little Elkhart River at Bristol, Indiana
[ft, feet]

Core 15–1, upstream face between left abutment and pier 2; bed elevation, 747.3 ft; top of core elevation, 741.8 ft		
Depth (ft)	**Compacted core elevation**	**Description**
0–2.2	741.8–739.6	Brown, medium sand with small gravel, shells, and organic material. Brown clay mixed in at 0.7–0.9 ft, larger gravel at 1.85 ft
2.2–3.0	739.6–738.8	Brown, fine sand, trace of small gravel
3.0–3.4	738.8–738.4	Brown, medium sand
3.4–4.3	738.4–737.5	Brown, small to medium gravel, with fine to coarse sand; large gravel at 3.4 to 3.5 ft
4.3–5.2	737.5–736.6	Brown, medium to coarse sand with small gravel
5.2–5.3	736.6–736.5	Dark-brown to black organic material and medium sand

Core 15–2, 2 ft upstream from and 1 ft right of centerline of pier 2; bed elevation, 747.2 ft; top of core elevation, 743.7 ft		
Depth (ft)	**Compacted core elevation**	**Description**
0–0.9	743.7–742.8	Brown to gray, medium to coarse sand with small gravel, some dark-gray, silty clay mixed in, shells
0.9–1.3	742.8–742.4	Brown, medium to coarse sand with small to medium gravel
1.3–1.6	742.4–742.1	Dark-brown, medium to coarse sand, some small gravel and shells
1.6–1.7	742.1–742.0	Dark-gray to black organic material
1.7–2.3	742.0–741.4	Dark-brown to gray medium sand with small gravel
2.3–3.3	741.4–740.4	Dark-brown to gray to black, medium to coarse sand with small to medium gravel
3.3–4.5	740.4–739.2	Brown, medium to coarse sand with small gravel, gravel at 3.6 ft, organic smear at 3. 95 ft, some dark-brown clay at 4.35 ft
4.5–5.2	739.2–738.5	Dark-brown, fine to medium sand with small gravel
5.2–5.5	738.5–738.2	Brown, small gravel with medium to coarse sand

Table 8. Sediment-core logs, State Road 15 over Little Elkhart River at Bristol, Indiana—Continued

Core 15–3, upstream face between pier 2 and right abutment; bed elevation, 747.4 ft; top of core elevation, 743.9 ft		
Depth (ft)	**Compacted core elevation**	**Description**
0–0.5	743.9-743.4	Dark-gray to brown, fine to medium sand with small gravel
0.5–0.7	743.4–743.2	Dark-gray to black organic material with silt and sand
0.7–1.5	743.2–742.4	Gray, medium sand with small gravel
1.5–2.0	742.4–741.9	Dark-gray to black organic material with trace of sand and small gravel, some fine sand streaks
2.0–2.1	741.9–741.8	Light-gray, medium sand with small gravel
2.1–3.4	741.8–740.5	Dark-gray to black organic material with trace of small gravel
3.4–3.5	740.5–740.4	Light-gray to medium sand with small gravel
3.5–3.9	740.4–740.0	Dark-gray to black organic material with trace of small gravel, large piece of gravel at 3.85 ft
3.9–4.6	740.0–739.3	Brown, medium to coarse sand with small to medium gravel

Table 9. Soil-boring logs, State Road 15 over Little Elkhart River at Bristol, Indiana
[From Indiana State Highway Commission, 1941 bridge plans, sheet 4; ft, feet]

Boring No. 1 at left abutment 34 ft upstream from centerline of bridge	
Compacted core elevation (ft)	**Description**
752.9–748.4	Sandy soil
748.4–742.9	Sand and gravel

Boring No. 2 at right abutment 20 ft downstream from centerline of bridge	
Compacted core elevation (ft)	**Description**
757.8–753.3	Find sand
753.3–747.3	Sand and gravel

Table 10. Soil-boring logs, State Road 19 over Wabash River at Peru, Indiana
[From Indiana State Highway Commission, 1982 bridge plans, sheet 3; ft, feet]

Boring No. 2 at pier 2, 18 ft downstream from centerline of bridge	
Elevation (ft)	**Description**
620.0–617.0	Gray, wet, dense sand and gravel with limestone fragments
617.0–612.0	Gray, moist to dry, hard, silty loam with trace of gravel
612.0–611.0	Gray, brown, very moist, dense, fine sand
611.0–610.8	Gray, moist, stiff, silty clay
610.8–605.8	Brown, gray, hard limestone with some dolomite and chert, little glauconite

Boring No. 3 at pier 3, 18 ft upstream from centerline of bridge	
Elevation (ft)	**Description**
620.1–617.7	Gray, wet, dense, coarse sand
617.7–609.9	Gray, moist to dry, medium, stiff to hard, silty loam with trace of gravel (till)
609.9–604.9	Gray, very hard, fossiliferous limestone with some chert and dolomite, trace of glauconite

Table 11. Soil-boring logs, State Road 25 over Wildcat Creek at Lafayette, Indiana
[From Indiana State Highway Commission, 1982 bridge plans, sheet 3; ft, feet]

Boring No. 5, 32 ft left of pier 5 on centerline of northbound lane	
Elevation (ft)	**Description**
523.5–521.5	Sandy clay
521.5–515.5	Gravel
515.5–510.5	Sand and gravel
510.5–508.5	Fine sand and clay
508.5–506.5	Coarse sand
506.5–502.5	Gravel
502.5–473.5	Sand

Boring No. 6, 25 ft right of pier on centerline of northbound lane	
Elevation (ft)	**Description**
525.7–521.7	Sand and clay
521.7–519.2	Gravel
519.2–508.7	Fine sand
508.7–475.7	Sand

Table 12. Soil-boring logs, State Road 32 over Wabash River at Perrysville, Indiana
[From Indiana State Highway Commission, 1981 bridge plans, sheet 6; ft, feet]

Boring No. 6, at pier 5, 15 ft downstream from centerline of bridge	
Elevation (ft)	**Description**
469.9–466.4	Gray and brown, fine to medium sand, wet, loose
466.4–461.4	Gray, fine, silty sand with silt layers and organic, wet, loose to medium, dense
461.4–453.9	Gray, fine to coarse sand with small gravel, wet, loose to medium, dense
453.9–439.4	Gray, medium to coarse sand and gravel, wet, medium, dense to dense
439.4–438.9	Weathered sandstone, very hard

Boring No. 7, at pier 6, 5 ft upstream from centerline of bridge	
Elevation (ft)	**Description**
472.2–470.2	Brown, fine to medium sand, wet, loose
470.2–452.7	Gray, fine to medium sand and a trace of organic, wet, loose
452.7–429.7	Gray, fine to coarse sand and fine gravel, wet, medium, dense to dense
429.7–428.7	Weathered sandstone, hard
428.7–423.7	Layered, gray sandstone with shale seams

Boring No. 8, at pier 7, 15 ft downstream from centerline of bridge	
Elevation (ft)	**Description**
472.2–459.7	Black and gray sand and gravel with organic, wet, loose
459.7–454.7	Gray clay, sand and gravel with sandy clay seams, wet, loose
454.7–419.7	Brown and gray, fine to coarse sand and fine gravel, wet, dense
419.7–419.2	Weathered sandstone, moist, very hard

Table 13. Sediment-core logs, U.S. Route 35 over Kankakee River at Union Center, Indiana
[ft, feet]

Core 35–1, 1.75 ft upstream from centerline of bent 2; bed elevation, 670.8 ft; top of core elevation, 669.6 ft		
Depth (ft)	**Compacted core elevation**	**Description**
0–0.7	669.6–668.9	Black, organic material; sticks, leaves, and pieces of wood; with trace of fine sand. Grades into more sandy material below
0.7–1.8	668.9–667.8	Dark-brown to black, fine sand containing organic material. Trace of sand and shell fragments
1.8–2.7	667.8–666.9	Dark-gray, fine sand mixed with fine, brown sand in part of section. Some shell fragments and trace of organic material and small gravel
2.7–3.7	666.9–665.9	Gray, fine sand
3.7–4.1	665.9–665.5	Gray, medium sand with small gravel. Trace of shell fragments
4.1–4.4	665.5–665.2	Black, organic material, trace of very fine sand
4.4–5.2	665.2–664.4	Gray, fine sand with some small to medium gravel. Lower 0.1 ft is brown

Core 35–2, midway between bent 2 and bent 3 at the upstream face; bed elevation, 670.3 ft; top of core elevation, 669.1 ft		
Depth (ft)	**Compacted core elevation**	**Description**
0–1.3	669.1–667.8	Dark-brown to black, fine sand with organic material and shell fragments; large piece of gravel at 1.2 ft
1.3–1.9	667.8–667.2	Dark reddish-brown, fine sand with shell fragments, streaks of organic material about 0.03 ft thick at 1.35 and 1.55 ft
1.9–3.1	667.2–666.0	Gray, fine sand with shell fragments and streaks of black organic material. Lower half of this section contains more organic material
3.1–3.6	666.0–665.5	Dark-brown to black organic material with fine sand and shell fragments, contains some red oxidized material
3.6–4.4	665.5–664.7	Gray, fine sand with trace of gravel, streak of dark-brown organic material with shell fragments
4.4–4.9	664.7–664.2	Black organic material, large piece of wood at 4.7 ft, contains shell fragments, and small gravel
4.9–5.1	664.2–664.0	Brown, medium sand with small to medium gravel, trace of organic material, shows some oxidation

Table 13. Sediment-core log, U.S. Route 35 over Kankakee River at Union Center, Indiana—Continued

Core 35–3, 1.25 ft upstream from centerline of bent 3; bed elevation, 673.4 ft; top of core elevation, 672.5 ft		
Depth (ft)	**Compacted core elevation**	**Description**
0–0.3	672.5–672.2	Dark-brown, fine sand with some gravel and shell fragments
0.3–0.9	672.2–671.6	Black, organic material, streaks of fine, gray sand between 0.65 and 0.8 ft
0.9–1.1	671.6–671.4	Gray, medium sand with trace of organic material, shell fragments and small gravel
1.1–1.4	671.4–671.1	Black, organic material, streaks of fine, gray sand between 1.25 and 1.3 ft; contains shell fragments
1.4–1.5	671.1–671.0	Gray, fine sand
1.5–2.8	671.0–669.7	Gray, fine to medium sand with small to medium gravel
2.8–3.6	669.7–668.9	Gray, medium to coarse sand with small gravel
3.6–4.8	668.9–667.7	Gray, fine to very fine sand, trace of small to medium gravel
4.8–5.7	667.7–666.8	Gray, fine to medium sand with trace of small gravel, grades to coarser material in bottom 0.4 ft

Table 14. Soil-boring logs, U.S. Route 35, over Kankakee River at Union Center, Indiana
[From Indiana State Highway Commission, 1968 bridge plans, sheet 5; ft, feet]

Boring No. 1, at left edge of channel on centerline	
Compacted core elevation (ft)	**Description**
678.1–674.1	Soft sand
674.1–670.1	Coarse sand (soft)
670.1-666.1	Probable fine gravel (somewhat firm)

Boring No. 3, at right edge of channel, 21 ft downstream from centerline of bridge	
Compacted core elevation (ft)	**Description**
677.0–673.0	Soft sand
673.0–669.0	Coarse sand (soft)
669.0-665.0	Probable fine gravel (somewhat firm)

Table 15. Soil-boring logs, U.S. Route 41 over Kankakee River at Schneider, Indiana
[From Indiana State Highway Commission, 1954 bridge plans, sheet 7; ft, feet]

Boring No. 1, 20 ft left at right abutment, 4 ft downstream from centerline of southbound bridge	
Elevation (ft)	**Description**
631.7–630.9	Black, sandy clay
630.9–629.4	Yellow sand
629.4–628.7	Yellow sand and clay
628.7–615.9	Coarse, yellow sand

Boring No. 2, 14 ft right of left abutment, 4 ft downstream from centerline of southbound bridge	
Elevation (ft)	**Description**
631.4–630.9	Black sand
630.9–612.2	Coarse, yellow sand

Table 16. Sediment-core logs, at State Road 54 over Busseron Creek near Sullivan, Indiana
[ft, feet]

Core 54-1, midway between bent 2 and bent 3 at upstream face; bed elevation, 441.5 ft; top of core elevation, 440.4 ft		
Depth (ft)	**Compacted core elevation**	**Description**
0–2.5	440.4–437.9	Black, crushed coal (gravel) and organic material (wood, seeds, tree bark)
2.5–4.0	437.9–436.4	Dark-brown to black, small gravel with medium to coarse sand and coal fragments; more coal present at top of section, grading to less coal at bottom, piece of large gravel at 4.0 ft
4.0–4.1	436.4–436.3	Green to gray, clay ball and small gravel
4.1–5.5	436.3–434.9	Gray, fine sand and gray, stiff clay interbedded in 0.1- to 0.2-ft layers
5.5–5.8	434.9–434.6	Medium, dark-gray clay, grades into blue clay below
5.8–8.0	434.6–432.4	Blue to gray clay and very fine sand, more clayey at top of section, organge oxidation along sides and in cracks

Core 54-2, 1.6 ft upstream from centerline of bent 3; bed elevation, 441.4; top of core elevation, 440.2 ft		
Depth (ft)	**Compacted core elevation**	**Description**
0–0.4	440.2–439.8	Gray to brown clay and silt, gelatinous, dark-gray at top, brown in middle, gray at bottom
0.4–1.0	439.8–439.2	Gray clay with silt and small gravel (coal)
1.0–1.2	439.2–439.0	Brown, medium sand with clay and small gravel, less clay at bottom
1.2–3.0	439.0–437.2	Gray, green, yellow to brown clay and silt, some sand, chunk of gray to green clay at 2.2 ft, yellow to brown sand at 2.4 ft, trace of crushed coal
3.0–4.8	437.2–435.4	Gray, fine sand and clay interbedded and intermixed in 0.1- to 0.4-ft layers
4.8–5.2	435.4–435.0	Medium, dark-gray clay with very fine sand
5.2–8.4	435.0–431.8	Blue to gray clay with very fine sand; more clayey at top of section, orange oxidation along sides and in cracks

Table 16. Sediment-core logs, at State Road 54 over Busseron Creek near Sullivan, Indiana—Continued

Core 54-3, 2 ft upstream from centerline of bent 2; bed elevation, 440.8 ft; top of core elevation, 438.7 ft		
Depth (ft)	**Compacted core elevation**	**Description**
0–0.2	438.7–438.5	Wood chunks
0.2–0.5	438.5–438.2	Brown to red, medium sand
0.5–0.6	438.2–438.1	Black, small gravel (coal)
0.6–1.2	438.1–437.5	Gray-black to brown clay, gravel (coal), and sand, disturbed
1.2–2.6	437.5–436.1	Gray to greenish clay with trace of fine sand, more sandy at bottom of section, small gravel (coal) mixed in near bottom of section

Table 17. Soil-boring logs, State Road 57 over East Fork White River near Petersburg, Indiana
[From Indiana State Highway Commission, 1970 bridge plans, sheet 7; ft, feet]

Boring No. 2, at pier 2, 25 ft upstream from centerline of bridge	
Elevation (ft)	**Description**
405.0–399.0	Brown and gray, soft, moist, silty clay with trace of sand
399.0–396.0	Brown and gray, weathered sandstone
396.0–394.5	Gray sandstone
394.5–391.0	Gray, layered shale

Boring No. 4, at pier 4, 25 ft upstream from centerline of bridge	
Elevation (ft)	**Description**
407.0–401.0	Mottled brown and gray, moist, soft, silty clay with organic matter
401.0–394.0	Gray, wet, soft, sandy clay with sand seams and organic matter
394.0–374.0	Gray, wet, loose, fine to medium sand
374.0–354.0	Gray, moist, soft, silty clay with fine sand and silt seams
354.0–353.0	Gray, dry, very hard, weathered shale

Table 18. Sediment-core logs, State Road 59 over Eel River north of Clay City, Indiana
[ft, feet]

Core 59-1, 2.3 ft upstream from centerline of pier 2; bed elevation, 532.7; top of core elevation, 530.6 ft		
Depth (ft)	**Compacted core elevation**	**Description**
0–1.3	530.6–529.3	Gray to brown, fine to medium sand, trace of small gravel
1.3–1.5	529.3–529.1	Gray clay, some sand at bottom
1.5–3.7	529.1–526.9	Light-gray to brown, medium sand with trace of small gravel
3.7–3.8	526.9–526.8	Reddish-brown, medium sand; some small gravel and gray inclusions
3.8–4.0	526.8–526.6	Light-gray, medium sand
4.0–4.1	526.6–526.5	Reddish-brown (oxidized), medium sand
4.1–4.3	526.5–526.3	Light-gray, medium sand with gray clay inclusions
4.3–5.4	526.3–525.2	Brown to reddish-brown, fine to medium sand, trace of small to medium gravel, some gray clay inclusions, streaks of iron staining

Core 59-2, 1.9 ft upstream from and 4.1 ft left of upstream end of pier 2; bed elevation, 532.9; top of core elevation, 530.6 ft		
Depth (ft)	**Compacted core elevation**	**Description**
0–0.9	530.6–529.7	Light-brown, fine to medium sand
0.9–3.2	529.7–527.4	Gray to brown, fine to medium sand with large, gray clay inclusion, trace of small to medium gravel, blotchy iron staining
3.2–5.6	527.4–525.0	Light-gray to brown, fine to medium sand, trace of small gravel; iron staining at 4.7 ft, gray clay inclusion at 5.0 ft
5.6–6.4	525.0–524.2	Light-gray to brown and reddish-brown, fine to medium sand in alternating layers; layers about 0.1 ft thick, some coarse sand and small gravel in reddish-brown layers at 5.85 and at 6.1 ft

Core 59-3, 1/4 point between pier 2 and pier 3; at upstream face of bridge, bed elevation, 533.4; top of core elevation, 531.0 ft		
Depth (ft)	**Compacted core elevation**	**Description**
0–3.5	531.0–527.5	Brown, medium to coarse sand with small gravel, trace of medium gravel, bridge bolt at 2.6 ft, more coarse near bottom
3.5–3.7	527.5–527.3	Reddish-brown, small gravel with medium to coarse sand, iron stained
3.7–4.0	527.3–527.0	Light-brown, very fine to fine sand

Table 18. Sediment-core logs, State Road 59 over Eel River north of Clay City, Indiana—Continued

Core 59-4, midway between pier 2 and pier 3 at upstream face of bridge; bed elevation, 533.8 ft; top of core elevation, 531.6 ft		
Depth (ft)	**Compacted core elevation**	**Description**
0–0.7	531.6–530.9	Brown, small to medium gravel with coarse sand
0.7–1.6	530.9–530.0	Dark-gray to black organic material (mostly wood chips) with silt and very fine sand
1.6–1.8	530.0–529.8	Gray, fine sand
1.8–4.2	529.8–527.4	Brown, medium sand with trace of small gravel, piece of medium gravel at 2.4 ft; brown to green clay inclusions at 3.7 and 3.9 ft
4.2–4.5	527.4–527.1	Brown to green clay with trace of silt and very fine sand
4.5–4.7	527.1–526.9	Light gray, very fine sand, some dark-gray clay; organic material at 4.5 ft
4.7–5.4	526.9–526.2	Gray to green clay, some organic material at 5.1 ft
5.4–6.1	526.2–525.5	Gray, small to medium gravel with silt and sand
6.1–6.2	525.5–525.4	Dark-gray clay
6.2–6.6	525.4–525.0	Gray, small to medium gravel with silt and sand
6.6–9.2	525.0–522.4	Dark-gray clay with streaks of light gray; very fine sand, small gravel at 9.0 ft

Core 59-5, 1.8 ft upstream of centerline pier 3; bed elevation, 532.6 ft; top of core elevation, 531.0 ft		
Depth (ft)	**Compacted core elevation**	**Description**
0–1.4	531.0–529.6	Brown, fine to medium sand with small gravel, trace of medium gravel
1.4–1.7	529.6–529.3	Gray clay and organic material with sand and trace of small gravel
1.7–6.8	529.3–524.2	Gray to brown, fine to medium sand with trace of small gravel; some gray clay inclusions, mostly in upper and lower 1.5 ft; iron staining at 4.6 ft

Table 19. Soil-boring logs, State Road 59 over Eel River north of Clay City, Indiana
[From Indiana State Highway Commission, 1955 bridge plans, sheet 3; ft, feet]

Boring No. B-4, at pier 3, 21 ft upstream from centerline of bridge	
Elevation (ft)	**Description**
546.3–542.3	Fine to coarse sand, some silt, brown, loose
542.3–540.3	Fine to coarse sand, some silt, brown, medium-dense
540.3–537.3	Fine sand, trace of silt, brown, medium-dense
537.3–532.8	Fine to coarse sand, brown, medium-dense
532.8–527.8	Fine to coarse sand, trace of gravel, brown, medium-dense
527.8–521.3	Fine to coarse sand, trace of gravel, gray, medium-dense
521.3–502.8	Fine to medium sand, trace of silt, gray, dense; 3-ft gravel seam at 519.3 ft
502.8–497.8	Fine sand, gray, dense
497.8–492.8	Fine sand, some silt, trace of wood, gray, very dense
492.8–488.8	Fine to medium sand, trace of gravel, brown and gray, very dense
488.8–479.2	Fine sand, trace of silt, gray, very dense

Table 19. Soil-boring logs, State Road 59 over Eel River north of Clay City, Indiana—Continued

Boring No. B-5, 13 ft right of pier 4, and 28 ft upstream from centerline of bridge	
Elevation (ft)	**Description**
547.1–546.4	Sand, silt, gravel, loose
546.4–545.1	Fine sand, some silt, brown, loose
545.1–543.1	Fine sand, brown, loose
543.1–541.1	Fine to coarse sand, trace of gravel, brown, medium-dense
541.1–538.1	Fine sand, trace of silt and gravel, brown, medium-dense
538.1–533.6	Fine to coarse sand, trace of silt, brown, medium-dense
533.6–527.1	Fine to coarse sand, trace of silt and gravel, brown, medium-dense
527.1–513.6	Fine to coarse sand, some fine gravel, trace of silt, gray, medium-dense
513.6–511.6	Organic silt and fine to medium sand, gray, loose
511.6–508.6	Fine to coarse sand, some fine to medium gravel and silt, gray, very dense
508.6–503.6	Fine to coarse sand, trace of silt, gray, dense
503.6–493.6	Fine sand, trace of silt, gray, very dense
493.6–485.1	Fine sand, some silt, gray, very dense

Table 20. Sediment-core logs, State Road 63 over Little Vermillion River at Newport, Indiana
[ft, feet]

Core 63-1, 1.5 ft upstream from centerline of pier 3; bed elevation, 486.8 ft; top of core elevation, 486.0 ft

Depth (ft)	Compacted core elevation	Description
0–1.5	486.0–484.5	Brown, medium sand, slight trace of small gravel, large gravel at bottom, gray clay chunk at 1.25 ft
1.5–2.2	484.5–483.8	Gray clay, hard, somewhat lithified with some small gravel and trace of sand

Core 63-2, midway between piers 2 and 3; at upstream face of bridge, bed elevation, 490.8 ft; top of core elevation, 489.2 ft

Depth (ft)	Compacted core elevation	Description
0–0.8	489.2–488.4	Brown, medium to coarse sand and small gravel
0.8–2.7	488.4–486.5	Brown, medium sand and small gravel, some coarse sand, a few shells and shell fragments, cobble at the bottom

Core 63-3, 1.7 ft upstream from centerline of pier 2; bed elevation, 491.0 ft; top of core elevation, 489.0 ft

Depth (ft)	Compacted core elevation	Description
0–1.2	489.0–487.8	Gray clay with organic material, some fine sand and small gravel in horizontal stripes
1.2–2.0	487.8–487.0	Brown, fine sand with trace of small gravel, coarse sand and cobbles in lower 0.4 ft, organic material throughout

Core 63-4, 3 ft upstream from centerline of pier 2; bed elevation, 491.0 ft; top of core elevation, 490.1 ft

Depth (ft)	Compacted core elevation	Description
0–1.3	490.1–488.8	Gray clay with fine sand in layers, sandy at 0.5 to 0.7 ft, organic material in lower 0.3 ft
1.3–1.7	488.8–488.4	Brown to gray, fine to medium sand, trace of small to medium gravel, some organic material
1.7–1.8	488.4–488.3	Red to brown, coarse sand and small to medium gravel, iron stained
1.8–2.1	488.3–488.0	Gray clay, somewhat lithified

Table 21. Soil-boring logs, State Road 63 over Little Vermillion River at Newport, Indiana
[From Indiana State Highway Commission, 1968 bridge plans, sheet 2; ft, feet]

Boring No. 2, at left edge of channel, 8 ft downstream from centerline of southbound bridge	
Elevation (ft)	**Description**
502.0–500.5	Brown, moist, loose, silty loam
500.5–498.5	Brown, moist, medium stiff, sandy clay loam
498.5–493.5	Brown, moist, very loose sand
493.5–492.2	Brown and gray, wet, loose, fine sand
492.2–488.5	Gray, weathered shale
488.5–483.5	Gray, hard shale

Boring No. 3, at right edge of channel, 4 ft downstream from centerline of southbound bridge	
Elevation (ft)	**Description**
498.1–494.6	Brown, moist, very loose, sandy loam
494.6–491.1	Brown and gray, moist, very soft, silty loam
491.1–489.6	Brown, wet, very loose, fine to coarse sand
489.6–487.6	Gray, wet, very loose, fine sand
487.6–482.6	Gray, wet, loose to medium-dense, fine to coarse sand and fine gravel
482.6–482.0	Gray, hard shale

Table 22. Sediment-core logs, State Road 101 over St. Joseph River at Saint Joe, Indiana
[ft, feet]

Core 101-1, 3.2 ft upstream from centerline of pier 2; bed elevation, 785.6 ft; top of core elevation, 784.0 ft		
Depth (ft)	**Compacted core elevation**	**Description**
0–0.2	784.0–783.8	Gray, fine to medium sand with pieces of wood
0.2–0.7	783.8–783.3	Gray to brown, medium to coarse sand with small gravel, occasional large gravel
0.7–0.9	783.3–783.1	Dark-gray silt, sand and clay, grades from sandy at top to silty at bottom
0.9–1.2	783.1–782.8	Dark-gray, silty clay and black organic material
1.2–1.3	782.8–782.7	Gray, fine to medium sand and silt with some small gravel
1.3–1.7	782.7–782.3	Dark-gray silt, clay and black organic material, numerous wood chips
1.7–2.2	782.3–781.8	Gray, medium to coarse sand with small to medium gravel; clay mixed in near the bottom
2.2–3.4	781.8–780.6	Gray silt and clay with trace of very fine sand; some organic material near top, more sand near bottom
3.4–3.9	780.6–780.1	Gray, fine to medium sand with small gravel; occasional medium to large gravel
3.9–4.0	780.1–780.0	Gray clay with silt and fine gravel
4.0–4.4	780.0–779.6	Gray, fine to coarse sand with small to large gravel, trace of silt; oxidation evident around some gravel
4.4–6.7	779.6–777.3	Light-gray silt and very fine sand streaked with clay in places
6.7–7.0	777.3–777.0	Light-gray, very fine sand

Core 101-2, 3.3 ft upstream from and 0.6 ft left of centerline of pier 2; bed elevation, 785.7 ft; top of core elevation, 783.5 ft		
Depth (ft)	**Compacted core elevation**	**Description**
0–0.3	783.5–783.2	Brown, medium sand with small gravel
0.3–0.8	783.2–782.7	Gray, silt and clay with dark-gray to black organic material
0.8–1.3	782.7–782.2	Gray, fine to medium sand with silt and clay, some organic material
1.3–1.9	782.2–781.6	Brown to gray, fine to medium sand with small to medium gravel; occasional large gravel, large chunk of limestone, and shell fragments
1.9–2.6	781.6–780.9	Dark-gray silt and clay with some very fine sand; organic material at 2.0 ft
2.6–3.1	780.9–780.4	Gray, fine sand and silt, some small gravel
3.1–3.9	780.4–779.6	Gray to brown, medium to coarse sand with small to medium gravel, occasional large gravel
3.9–4.5	779.6–779.0	Light-gray silt and very fine sand

Table 22. Sediment-core logs, State Road 101 over St. Joseph River at Saint Joe, Indiana—Continued

Core 101-3, midway between pier 2 and 3 at upstream face; bed elevation, 784.5 ft; top of core elevation, 783.7 ft		
Depth (ft)	**Compacted core elevation**	**Description**
0–0.3	783.7–783.4	Light-gray, fine to medium sand with small to large gravel
0.3–0.5	783.4–783.2	Light-gray, very fine sand
0.5–2.6	783.2–781.1	Gray silt, sand, and clay streaked with light-gray, very fine sand
2.6–4.1	781.1–779.6	Light-gray, very fine sand and silt, streaked with gray silt and clay
4.1–5.9	779.6–777.8	Gray clay and silt streaked with some very fine sand, very fine gray sand at 5.25 to 5.45 ft
5.9–6.1	777.8–777.6	Light-gray, medium sand with small to large gravel, some very large gravel near bottom
6.1–6.3	777.6–777.4	Gray, silty clay till with small gravel, hard

Core 101-4, 3 ft upstream from centerline of pier 3; bed elevation, 784.1 ft; top of core elevation, 782.5 ft		
Depth (ft)	**Compacted core elevation**	**Description**
0–0.5	782.5–782.0	Gray to brown, medium to coarse sand with some very small gravel and some organic material
0.5–2.3	782.0–780.2	Dark-gray clay with silt and trace of sand and small to medium gravel; organic material at 1.2 to 1.6 ft, iron oxidation at 1.5 ft
2.3–3.8	780.2–778.7	Gray clay, silt and sand, similar to above but with more sand and small to medium gravel
3.8–4.3	778.7–778.2	Gray, silty clay with small to medium gravel, large gravel at 3.8 to 4.0 ft

Table 23. Soil-boring logs, State Road 101 over St. Joseph River at Saint Joe, Indiana
[From Indiana State Highway Commission, 1964 bridge plans, sheet 8; ft, feet; in., inch]

Boring No. 2, at pier 2; 10 ft downstream from centerline of bridge	
Elevation (ft)	**Description**
784.6–784.4	Black, medium-dense, saturated, medium gravel and organic matter
784.4–771.6	Gray, saturated to wet, medium-dense to very dense, silty loam with a trace of gravel and pebbles
771.6–766.6	Gray, moist, very dense, sandy loam with gravel
766.6–756.6	Gray, saturated, very dense, sandy, fine sand with trace of gravel and a 6-in. layer of fine to medium gravel at 764.1 ft
756.6–753.6	Gray, moist, very dense, silty loam with gravel

Boring No. 3, at pier 3; 10 ft upstream from centerline of bridge	
Elevation (ft)	**Description**
784.0–782.0	Brown, saturated, medium-dense, fine to coarse sand
782.0–777.0	Gray, saturated, medium-dense, silty loam
777.0–773.0	Gray, moist, very dense, sandy loam with trace of gravel
773.0–770.6	Brown, saturated, very dense, fine sand
770.6–769.5	Gray, very dense, moist, fine, silty sand
769.5–765.0	Brown, very dense, saturated, fine sand
765.0–763.0	Gray, very dense, moist, fine, silty sand with traces of gravel
763.0–754.0	Gray, moist to saturated, very dense, silty loam with traces of gravel

Table 24. Soil-boring logs, State Road 109 over White River at Anderson, Indiana
[From Indiana State Highway Commission, 1973 bridge plans, sheet 4; ft, feet; in., inch]

Boring No. 4, at pier 5; 5 ft upstream from centerline of bridge	
Elevation (ft)	**Description**
833.1–832.1	Brown, moist, medium, dense sand and gravel
832.1–825.6	Brown, wet, medium, dense sand and gravel with cobbles
825.6–815.6	Gray, moist, hard, silty loam (hardpan)
815.6–810.6	Gray, wet, very dense, fine sand
810.6–805.1	Gray, moist, hard, silty clay
805.1–799.8	Gray, wet, dense, coarse sand with occasional 3-in. layer of stiff, silty clay

Boring No. 5, at pier 6; 35 ft upstream from centerline of bridge	
Elevation (ft)	**Description**
834.3–830.8	Brown, moist, medium, stiff, sandy clay loam
830.8–827.3	Brown, wet, very loose to medium-dense sand and gravel with cobbles
827.3–823.3	Gray, moist, very stiff, silty loam (hardpan)
823.3–822.3	Gray, moist, dense, very fine sand
822.3–818.8	Gray, moist very stiff, silty loam (hardpan)
818.8–811.3	Gray, moist, very dense to medium-dense, fine sand
811.3–806.8	Gray, moist, hard, silty clay
806.8–802.8	Gray, moist, very dense, silty loam

Table 25. Sediment-core logs, State Road 110 over Tippecanoe River near Mentone, Indiana
[ft, feet]

Core 110-1, 1.7 ft upstream from centerline of pier 5; bed elevation, 757.1 ft; top of core elevation, 756.2 ft		
Depth (ft)	**Compacted core elevation**	**Description**
0–0.4	756.2–755.8	Very dark-brown to black, sandy loam with small gravel
0.4–0.6	755.8–755.6	Dark-brown, silty sand
0.6–0.8	755.6–755.4	Dark-brown to gray, fine sand; some small to medium gravel
0.8–1.0	755.4–755.2	Brown to red clay with silt, fine sand, and small gravel
1.0–1.4	755.2–754.8	Gray to brown clay with fine sand and small to medium gravel
1.4–1.8	754.8–754.4	Brown, fine to medium sand with small to medium gravel
1.8–3.4	754.4–752.8	Gray clay with fine to coarse sand and small to medium gravel
3.4–4.4	752.8–751.8	Dark-gray to black, silty clay with trace of fine sand and small gravel
4.4–5.0	751.8–751.2	Light-gray, fine sand layered with black, silty clay

Core 110-2, 2.5 ft upstream from centerline of pier 5; bed elevation, 757.1 ft; top of core elevation, 756.3 ft		
Depth (ft)	**Compacted core elevation**	**Description**
0–0.1	756.3–756.2	Dark-brown, sandy loam with small gravel
0.1–0.2	756.2–756.1	Light-brown, silty sand with small gravel
0.2–0.3	756.1–756.0	Dark-gray, silty clay with some fine sand
0.3–0.4	756.0–755.9	Brown to red silt and sand, oxidized
0.4–1.6	755.9–754.7	Brown, silty clay with some fine to medium sand and small gravel
1.6–1.9	754.7–754.4	Gray to brown, silty clay with some fine to medium sand and small gravel
1.9–2.8	754.4–753.5	Gray, silty clay with small to large gravel

Table 25. Sediment-core logs, State Road 110 over Tippecanoe River near Mentone, Indiana—Continued

Core 110-4, midway between pier 4 and pier 5; at the upstream face of the bridge, bed elevation, 756.1 ft; top of core elevation, 754.9 ft		
Depth (ft)	**Compacted core elevation**	**Description**
0–0.5	754.9–754.4	Light- to dark-gray, fine to medium sand, trace of very small gravel, shells, piece of glass
0.5–0.9	754.4–754.0	Dark-gray to black, silt and organic material, trace of fine sand
0.9–1.1	754.0–753.8	Light-gray, fine sand
1.1–1.2	753.8–753.7	Dark-gray to black silt and organic material
1.2–1.3	753.7–753.6	Light-gray, fine sand with trace of small gravel, shell
1.3–1.8	753.6–753.1	Dark-gray to black silt and organic material, trace of sand
1.8–2.1	753.1–752.8	Gray, silty, medium to coarse sand with small gravel
2.1–2.4	752.8–752.5	Gray, silty clay with small gravel
2.4–2.6	752.5–752.3	Gray, small gravel with silt
2.6–2.9	752.3–752.0	Gray, silty clay with small to medium gravel

Core 110-5, 2.6 ft upstream from centerline of pier 4; bed elevation, 754.8 ft; top of core elevation, 753.1 ft		
Depth (ft)	**Compacted core elevation**	**Description**
0–0.5	753.1–752.6	Dark-brown to black silt and organic material, trace of fine sand
0.5–1.3	752.6–751.8	Dark-gray silt with very fine sand
1.3–1.9	751.8–751.2	Gray, fine to medium sand with small gravel
1.9–3.1	751.2–750.0	Gray, medium to coarse sand with small to large gravel, gravel at 1.9 to 2.2 ft, large gravel at 2.5 and 3.0 ft, a few clay chunks mixed in
3.1–4.1	750.0–749.0	Gray, medium to coarse sand with small gravel, few large gravel and clay balls
4.1–4.9	749.0–748.2	Dark-gray, silty clay with small gravel

Table 25. Sediment-core logs, State Road 110 over Tippecanoe River near Mentone, Indiana—Continued

Core 110-6, midway between pier 3 and pier 4; at the upstream face, bed elevation, 754.3 ft; top of core elevation, 753.7 ft		
Depth (ft)	**Compacted core elevation**	**Description**
0–1.0	753.7–752.7	Light-gray sand, silt, and clay with small to large gravel
1.0–3.5	752.7–750.2	Light-gray, silty clay with small to medium gravel, trace of sand

Core 110-7, 2 ft upstream from pier 3; bed elevation, 755.0 ft; top of core elevation, 753.8 ft		
Depth (ft)	**Compacted core elevation**	**Description**
0–4.1	753.8–749.7	Light-gray, silty clay with small to large gravel, trace of sand and shell, organic layer at 3.7 ft

Table 26. Soil-boring logs, State Road 110 over Tippecanoe River near Mentone, Indiana
[From Indiana State Highway Commission, 1957 bridge plans, sheet 5; ft, feet]

Boring No. 3, 14 ft right of pier 5 and 20 ft downstream from centerline of bridge	
Elevation (ft)	**Description**
761.3–760.3	Sandy loam
760.3–757.8	Sandy-brown clay
757.8–756.2	Sandy-gray clay
756.2–754.7	Fine sand and gravel
754.7–749.8	Probable sand and gravel

Boring No. 5, 17 ft left of pier 3; on centerline of bridge	
Elevation (ft)	**Description**
758.3–749.8	Probable fine sand

Table 27. Soil-boring logs, State Road 135 over Muscatatuck River at Millport, Indiana
[From Indiana State Highway Commission, 1954 bridge plans, sheet 2; ft, feet]

Boring No. 6, 29 ft left of pier 3 and 15 ft downstream from centerline of bridge	
Elevation (ft)	**Description**
502.0–482.0	Blue, medium shale

Boring No. 7, 30 ft right of pier 4 and 15 ft upstream from centerline of bridge	
Elevation (ft)	**Description**
506.0–505.0	Topsoil, moist
505.0–496.0	Brown, sandy, clayey silt
496.0–493.0	Blue, sandy, clayey silt, moist
493.0–486.0	Brown, medium sand, wet
486.0–475.0	Blue, gray, silty clay with some fine sand, wet
475.0–466.0	No sample retained in sampler
466.0–464.0	Blue, medium shale, highly weathered
464.0–461.0	Blue, medium shale

Table 28. Soil-boring logs, State Road 157 over White River at Worthington, Indiana
[From Indiana State Highway Commission, 1982 bridge plans, sheet 2; ft, feet]

Boring No. 3, at pier 5; 22 ft downstream from centerline of bridge	
Elevation (ft)	**Description**
494.9–486.9	Brown, very loose, wet, fine to coarse sand
486.9–451.4	Brown, wet, medium, dense to very dense, sandy gravel to fine sand; loose to very loose, gray, fine sand with a trace of plant organic
451.4–433.4	Brown, wet, medium-dense to dense, coarse sand with trace of gravel

Table 29. Soil-boring logs, State Road 163 over Wabash River at Clinton, Indiana
[From Indiana State Highway Commission, 1964 bridge plans, sheet 7; ft, feet]

Boring No. 2 at pier 2; on centerline	
Elevation (ft)	**Description**
451.6–446.6	Gray, saturated, loose, fine sand with gravel and bits of shell
446.6–442.6	Gray, wet, loose, fine to medium gravel with bits of shell
442.6–437.1	Gray, moist, loose, silty loam with bits of shell
437.1–434.6	Brown, saturated, very loose, fine sand to medium gravel
434.6–417.6	Brown, wet, medium-dense to dense, silty, fine sand to medium gravel
417.6–410.6	Brown, saturated, very dense to medium-dense sand with fine gravel
410.6–406.6	Brown, saturated, medium-dense, fine sand
406.6–401.6	Brown, wet, dense, fine gravel
401.6–398.1	Brown, saturated, dense, fine sand
398.1–396.6	Brown, dense, coarse sand and fine gravel

Boring No. 3 at pier 3; on centerline	
Elevation (ft)	**Description**
444.5–442.5	Gray, wet, very soft, sandy clay
442.5–427.5	Light-brown to brown, saturated, medium-dense to dense, fine to medium sand with pebbles and cobbles
427.5–421.5	Brown, wet, medium-dense, fine to coarse gravel with sand
421.5–409.5	Brown, saturated, medium-dense to dense, fine to coarse sand with cobbles
409.5–405.5	Brown, saturated, medium-dense, fine sand to coarse gravel
405.5–403.0	Brown, moist, dense, silty, fine to coarse gravel

Table 29. Soil-boring logs, State Road 163 over Wabash River at Clinton, Indiana—Continued

Boring No. 4 at pier 4; on centerline	
Elevation (ft)	**Description**
447.0–439.0	Brown, saturated, very loose, fine sand to fine gravel
439.0–424.0	Brown, saturated, loose to coarse gravel with sand lenses
424.0–419.0	Brown, wet, medium-dense, silty, fine to coarse gravel
419.0–414.0	Brown, saturated, loose, fine to coarse gravel with sand lenses
414.0–404.5	Brown, wet, medium-dense to dense, silty, fine to coarse gravel
404.5–402.0	Brown, wet, dense, fine to coarse sand

Boring No. 5 at pier 5; on centerline	
Elevation (ft)	**Description**
454.2–451.2	Brown, saturated, very loose, fine sand
451.2–446.2	Brown, saturated, very loose, silty loam
446.2–436.2	Brown, wet, medium-dense, fine gravel and coarse sand with some cobbles
436.2–413.7	Brown, saturated, medium-dense to very dense, fine to coarse sand

SUPPLEMENTAL DATA

Historical Scour Tables

Table 32. Historical scour at State Road 1 over St. Marys River at Fort Wayne, Indiana

[ft^3/s, cubic feet per second; all elevations refer to feet above sea level; ft/s, feet per second; mm, millimeters; *, pier width at surveyed bed elevation; **, deposition is not included in the computation of bed elevation; --, no data or computation]

Hydraulic characteristic or equation used	Pier number 2	3	4	5
Total discharge, in ft^3/s	12,900	12,900	12,900	12,900
Water-surface elevation	763.5	763.5	763.5	763.5
Approach depth, in feet	16.4	18.5	17.4	5.3
Approach velocity, in ft/s	3.8	3.9	3.5	1.4
Angle of attack, in degrees	0	0	0	0
Estimated grain size, in mm	88.0	88.0	88.0	.25
Pier width*, in feet	2.0	2.0	2.0	2.0
Pier length, in feet	86.5	86.5	86.5	86.5
Pier-nose shape	Round	Round	Round	Round
Computed depth of contraction scour, in feet				
Laursen	-11.8**	-11.8**	-11.8**	.3
Computed depth of pier scour, in feet				
Ahmad	12.0	12.6	10.6	1.6
Arkansas	2.4	2.4	2.2	3.8
Blench-Inglis I	1.0	.6	.8	2.2
Blench-Inglis II	-8.2**	-9.7**	-9.2**	0.6
Chitale	7.3	7.6	6.2	.8
Froehlich	1.4	1.4	1.4	1.2
HEC-18	4.2	4.4	4.1	2.4
Inglis-Lacey	-7.7**	-9.8**	-8.7**	17.9
Inglis-Poona I	.6	-0.2**	-0.6**	.4
Inglis-Poona II	1.5	1.1	1.3	2.1
Larras	2.4	2.4	2.4	2.4
Laursen	5.7	6.0	5.9	3.2
Shen	2.9	2.9	2.7	1.5
Shen-Maza	4.1	4.2	3.9	.7
Computed elevation of bed at nose of pier				
Ahmad	735.1	732.4	735.5	756.3
Arkansas	744.7	742.6	743.9	754.1
Blench-Inglis I	746.1	744.4	745.3	755.7
Blench-Inglis II	747.1	745.0	746.1	757.3
Chitale	739.8	737.4	739.9	757.1
Froehlich	745.7	743.6	744.7	756.7
HEC-18	742.9	740.6	742.0	755.5
Inglis-Lacey	747.1	745.0	746.1	740.0
Inglis-Poona I	746.5	745.0	746.1	757.5
Inglis-Poona II	745.6	743.9	744.8	755.8
Larras	744.7	742.6	743.7	755.5
Laursen	741.4	739.0	740.2	754.7
Shen	744.2	742.1	743.4	756.4
Shen-Maza	743.0	740.8	742.2	757.2
Estimated historical elevation of bed from field measurements				
At nose of pier	--	--	--	--
Maximum depth	--	--	--	--

Table 33. Historical scour at State Road 9 over Pigeon River at Howe, Indiana
[ft^3/s, cubic feet per second; all elevations refer to feet above sea level; ft/s, feet per second; mm, millimeters; *, pier width at surveyed bed elevation; --, no data or computation]

Hydraulic characteristic or equation used	Bent number	
	2	3
Total discharge, in ft^3/s	1,910	1,910
Water-surface elevation	861.5	861.5
Approach depth, in feet	7.6	5.8
Approach velocity, in ft/s	4.5	4.0
Angle of attack, in degrees	0	4
Estimated grain size, in mm	.50	.50
Pier width*, in feet	2.0	2.0
Pier length, in feet	36.0	36.0
Pier-nose shape	Square	Square
Computed depth of contraction scour, in feet		
Laursen	3.9	3.9
Computed depth of pier scour, in feet		
Ahmad	11.4	8.9
Arkansas	4.9	4.5
Blench-Inglis I	2.2	4.0
Blench-Inglis II	4.0	5.9
Chitale	7.2	5.6
Froehlich	2.1	3.1
HEC-18	4.5	5.8
Inglis-Lacey	3.3	5.1
Inglis-Poona I	4.8	6.4
Inglis-Poona II	2.2	3.7
Larras	3.3	6.1
Laursen	4.3	5.2
Shen	3.2	4.9
Shen-Maza	4.6	7.3
Computed elevation of bed at nose of bent		
Ahmad	838.6	842.9
Arkansas	845.1	847.3
Blench-Inglis I	847.8	847.8
Blench-Inglis II	846.0	845.9
Chitale	842.8	846.2
Froehlich	847.9	848.7
HEC-18	845.5	846.0
Inglis-Lacey	846.7	846.7
Inglis-Poona I	845.2	845.4
Inglis-Poona II	847.8	848.1
Larras	846.7	845.7
Laursen	845.7	846.6
Shen	846.8	846.9
Shen-Maza	845.4	844.5
Estimated historical elevation of bed from field measurements		
At nose of pier	--	--
Maximum depth	--	--

Table 34. Historical scour at State Road 11 over Flatrock River at Columbus, Indiana

[ft^3/s, cubic feet per second; all elevations refer to feet above sea level; ft/s, feet per second; mm, millimeters; *, pier width at surveyed bed elevation; --, no data or computation; **, deposition is not included in the computation of bed elevation]

Hydraulic characteristic or equation used	Pier number					
	2	3	4	5	6	7
Total discharge, in ft^3/s	13,500	13,500	13,500	13,500	13,500	13,500
Water-surface elevation	619.8	619.8	619.8	619.8	619.8	619.8
Approach depth, in feet	7.5	19.2	9.3	11.6	10.6	5.9
Approach velocity, in ft/s	1.9	3.3	2.1	2.4	2.3	1.6
Angle of attack, in degrees	0	0	0	0	0	0
Estimated grain size, in mm	Riprap	3.10	.25	.25	.25	.25
Pier width*, in feet	2.8	4.8	3.8	4.1	4.0	2.8
Pier length, in feet	47.0	47.0	47.0	47.0	47.0	47.0
Pier-nose shape	Round	Round	Round	Round	Round	Round
Computed depth of contraction scour, in feet						
Laursen	--	0.5	3.5	3.5	3.5	3.5
Computed depth of pier scour, in feet						
Ahmad	--	9.6	3.8	5.0	4.4	2.1
Arkansas	--	3.2	5.1	5.6	5.4	4.2
Blench-Inglis I	--	5.2	4.1	4.5	4.4	2.9
Blench-Inglis II	--	-3.4**	2.0	2.1	2.1	1.3
Chitale	--	5.5	2.1	2.7	2.4	1.1
Froehlich	--	3.2	2.4	2.8	2.6	1.6
HEC-18	--	7.2	4.6	5.3	5.0	3.2
Inglis-Lacey	--	-3.6**	14.2	11.9	12.9	17.6
Inglis-Poona I	--	1.7	1.4	1.5	1.5	0.9
Inglis-Poona II	--	5.3	3.9	4.4	4.2	2.8
Larras	--	4.6	3.9	4.1	4.0	3.1
Laursen	--	9.5	5.9	6.8	6.4	4.0
Shen	--	4.5	3.0	3.4	3.2	2.0
Shen-Maza	--	6.8	1.5	4.9	4.6	.9
Computed elevation of bed at nose of pier						
Ahmad	--	590.5	603.2	599.7	601.3	608.3
Arkansas	--	596.9	601.9	599.1	600.3	606.2
Blench-Inglis I	--	594.9	602.9	600.2	601.3	607.5
Blench-Inglis II	--	600.1	605.0	602.6	603.6	609.1
Chitale	--	594.6	604.9	602.0	603.3	609.3
Froehlich	--	596.9	604.6	601.9	603.1	608.8
HEC-18	--	592.9	602.4	599.4	600.7	607.2
Inglis-Lacey	--	600.1	592.8	592.8	592.8	592.8
Inglis-Poona I	--	598.4	605.6	603.2	604.2	609.5
Inglis-Poona II	--	594.8	603.1	600.3	601.5	607.6
Larras	--	595.5	603.1	600.6	601.7	607.3
Laursen	--	590.6	601.1	597.9	599.3	606.4
Shen	--	595.6	604.0	601.3	602.5	608.4
Shen-Maza	--	593.3	605.5	599.8	601.1	609.5
Estimated historical elevation of bed from field measurements						
At nose of pier	--	600.0	--	--	--	--
Maximum depth	--	598.4	--	--	--	--

Table 35. Historical scour at State Road 14 over Tippecanoe River at Winamac, Indiana

[ft^3/s, cubic feet per second; all elevations refer to feet above sea level; ft/s, feet per second; mm, millimeters; *, pier width at surveyed bed elevation; **, deposition is not included in the computation of bed elevation; --, no data or computation]

Hydraulic characteristic or equation used	Pier number				
	6	5	4	3	2
Total discharge, in ft^3/s	9,280	9,280	9,280	9,280	9,280
Water-surface elevation	691.1	691.1	691.1	691.1	691.1
Approach depth, in feet	4.4	11.2	14.9	12.2	7.8
Approach velocity, in ft/s	1.6	3.0	3.5	3.2	1.6
Angle of attack, in degrees	0	0	0	0	0
Estimated grain size, in mm	.25	.55	.55	.55	.25
Pier width*, in feet	2.3	2.6	2.9	2.7	2.7
Pier length, in feet	37.0	37.0	37.0	37.0	37.0
Pier-nose shape	Round	Round	Round	Round	Round
Computed depth of contraction scour, in feet					
Laursen	.9	-2.5**	-2.5**	-2.5**	2.7
Computed depth of pier scour, in feet					
Ahmad	2.1	7.8	10.4	8.3	2.0
Arkansas	4.2	3.7	4.1	3.8	4.2
Blench-Inglis I	2.3	2.8	2.9	2.9	3.0
Blench-Inglis II	1.5	1.1	.7	.9	.6
Chitale	1.2	4.7	6.2	5.0	.9
Froehlich	1.2	2.0	2.5	2.1	1.7
HEC-18	2.7	4.3	5.2	4.6	3.2
Inglis-Lacey	16.3	7.0	3.3	6.0	12.9
Inglis-Poona I	1.2	2.0	2.0	1.9	.2
Inglis-Poona II	2.2	2.9	3.1	2.9	2.9
Larras	2.7	2.9	3.2	3.0	3.0
Laursen	3.1	5.3	6.5	5.7	4.5
Shen	1.8	2.9	3.4	3.1	2.0
Shen-Maza	.8	4.2	5.0	4.4	.9
Computed elevation of bed at nose of pier					
Ahmad	683.7	672.1	665.8	670.6	678.6
Arkansas	681.6	676.2	672.1	675.1	676.4
Blench-Inglis I	683.5	677.1	673.3	676.0	677.6
Blench-Inglis II	684.3	678.8	675.5	678.0	680.0
Chitale	684.6	675.2	670.0	673.9	679.7
Froehlich	684.6	677.9	673.7	676.8	678.9
HEC-18	683.1	675.6	671.0	674.3	677.4
Inglis-Lacey	669.5	672.9	672.9	672.9	667.7
Inglis-Poona I	684.6	677.9	674.2	677.0	680.4
Inglis-Poona II	683.6	677.0	673.1	676.0	677.7
Larras	683.1	677.0	673.0	675.9	677.6
Laursen	682.7	674.6	669.7	673.2	676.1
Shen	684.0	677.0	672.8	675.8	678.6
Shen-Maza	685.0	675.7	671.2	674.5	679.7
Estimated historical elevation of bed from field measurements					
At nose of pier	--	--	674.0	--	--
Maximum depth	--	672.1	674.0	679.8	--

Table 36. Historical scour at State Road 15 over Little Elkhart River at Bristol, Indiana

[ft^3/s, cubic feet per second; all elevations refer to feet above sea level; ft/s, feet per second; mm, millimeters; *, pier width at surveyed bed elevation]

Hydraulic characteristic or equation used	Pier number 2
Total discharge, in ft^3/s	2,840
Water-surface elevation	755.7
Approach depth, in feet	9.5
Approach velocity, in ft/s	5.9
Angle of attack, in degrees	0
Estimated grain size, in mm	.50
Pier width*, in feet	2.0
Pier length, in feet	37.0
Pier-nose shape	Round
Computed depth of contraction scour, in feet	
Laursen	9.9
Computed depth of pier scour, in feet	
Ahmad	16.9
Arkansas	5.9
Blench-Inglis I	2.1
Blench-Inglis II	5.4
Chitale	10.6
Froehlich	1.9
HEC-18	4.8
Inglis-Lacey	3.0
Inglis-Poona I	6.6
Inglis-Poona II	2.2
Larras	2.4
Laursen	4.3
Shen	3.7
Shen-Maza	5.5
Computed elevation of bed at nose of pier	
Ahmad	719.4
Arkansas	730.4
Blench-Inglis I	734.2
Blench-Inglis II	730.9
Chitale	725.7
Froehlich	734.4
HEC-18	731.5
Inglis-Lacey	733.3
Inglis-Poona I	729.7
Inglis-Poona II	734.1
Larras	733.9
Laursen	732.0
Shen	732.6
Shen-Maza	730.8
Estimated historical elevation of bed from field measurements	
At nose of pier	739.5
Maximum depth	739.5

Table 37. Historical scour at State Road 19 over Wabash River at Peru, Indiana

[ft^3/s, cubic feet per second; all elevations refer to feet above sea level; ft/s, feet per second; mm, millimeters; *, pier width at surveyed bed elevation; **, deposition is not included in the computation of bed elevation]

Hydraulic characteristic or equation used	Pier number 2	Pier number 3
Total discharge, in ft^3/s	18,000	18,000
Water-surface elevation	634.1	634.1
Approach depth, in feet	14.1	15.0
Approach velocity, in ft/s	5.1	5.3
Angle of attack, in degrees	0	0
Estimated grain size, in mm	90.0	90.0
Pier width*, in feet	3.4	3.4
Pier length, in feet	67.0	67.0
Pier-nose shape	Round	Round
Computed depth of contraction scour, in feet		
Laursen	-7.3**	-7.3**
Computed depth of pier scour, in feet		
Ahmad	16.9	18.1
Arkansas	2.9	3.0
Blench-Inglis I	3.7	3.6
Blench-Inglis II	-4.1**	-4.5**
Chitale	10.7	11.5
Froehlich	1.9	2.0
HEC-18	6.6	6.8
Inglis-Lacey	-4.4**	-5.3**
Inglis-Poona I	6.4	6.5
Inglis-Poona II	3.7	3.7
Larras	3.6	3.6
Laursen	6.9	7.1
Shen	4.7	4.8
Shen-Maza	7.1	7.3
Computed elevation of bed at nose of pier		
Ahmad	603.1	601.0
Arkansas	617.1	616.1
Blench-Inglis I	616.3	615.5
Blench-Inglis II	620.0	619.1
Chitale	609.3	607.6
Froehlich	618.1	617.1
HEC-18	613.4	612.3
Inglis-Lacey	620.0	619.1
Inglis-Poona I	613.6	612.6
Inglis-Poona II	616.3	615.4
Larras	616.4	615.5
Laursen	613.1	612.0
Shen	615.3	614.3
Shen-Maza	612.9	611.8
Estimated historical elevation of bed from field measurements		
At nose of pier	619.0	618.0
Maximum depth	618.0	618.0

Table 38. Historical scour at State Road 25 over Wildcat Creek at Lafayette, Indiana

[ft^3/s, cubic feet per second; all elevations refer to feet above sea level; ft/s, feet per second; mm, millimeters; *, pier width at surveyed bed elevation; **, deposition is not included in the computation of bed elevation; --, no data or computation]

Hydraulic characteristic or equation used	Pier number 2	3	4	5	6	7	8
Total discharge, in ft^3/s	25,000	25,000	25,000	25,000	25,000	25,000	25,000
Water-surface elevation	538.0	538.0	538.0	538.0	538.0	538.0	538.0
Approach depth, in feet	5.7	7.2	9.9	15.0	19.3	10.5	3.7
Approach velocity, in ft/s	2.7	3.5	4.0	6.0	6.7	4.1	3.3
Angle of attack, in degrees	0	0	10	14	10	0	0
Estimated grain size, in mm	.22	.22	3.50	1.50	1.50	.22	Riprap
Pier width*, in feet	2.8	2.5	2.7	3.0	3.2	2.6	2.6
Pier length, in feet	104	104	104	104	104	104	104
Pier-nose shape	Round	Round	Round	Round	Round	Round	Round
Computed depth of contraction scour, in feet							
Laursen	-1.4**	-1.4**	-1.4**	-1.4**	-1.4**	-1.4**	--
Computed depth of pier scour, in feet							
Ahmad	5.4	8.2	10.9	21.0	26.9	11.6	--
Arkansas	6.2	7.3	5.8	5.2	5.7	8.2	--
Blench-Inglis I	2.9	2.7	11.5	16.6	16.3	2.8	--
Blench-Inglis II	3.7	4.4	7.6	16.7	16.3	4.9	--
Chitale	3.4	5.2	6.9	13.3	17.1	7.3	--
Froehlich	1.7	1.9	6.4	10.4	9.8	2.3	--
HEC-18	3.9	4.2	9.8	15.9	15.0	4.9	--
Inglis-Lacey	23.8	22.3	8.7	6.4	2.1	19.0	--
Inglis-Poona I	3.1	3.9	12.4	21.6	22.5	4.3	--
Inglis-Poona II	2.7	2.7	10.2	14.8	14.8	2.9	--
Larras	3.1	2.8	13.8	17.3	14.0	2.9	--
Laursen	3.9	4.2	11.4	17.7	17.3	5.2	--
Shen	2.8	3.1	12.4	19.3	17.5	3.5	--
Shen-Maza	4.1	4.5	5.4	12.1	29.1	5.2	--
Computed elevation of bed at nose of pier							
Ahmad	526.9	522.6	517.2	502.0	491.8	515.9	--
Arkansas	526.1	523.5	522.3	517.8	513.0	519.3	--
Blench-Inglis I	529.4	528.1	516.6	506.4	502.4	524.7	--
Blench-Inglis II	528.6	526.4	520.5	506.3	502.4	522.6	--
Chitale	528.9	525.6	521.2	509.7	501.6	520.2	--
Froehlich	530.6	528.9	521.7	512.6	508.9	525.2	--
HEC-18	528.4	526.6	518.3	507.1	503.7	522.6	--
Inglis-Lacey	508.5	508.5	519.4	516.6	516.6	508.5	--
Inglis-Poona I	529.2	526.9	515.7	501.4	496.2	523.2	--
Inglis-Poona II	529.6	528.1	517.9	508.2	503.9	524.6	--
Larras	529.2	528.0	514.3	505.7	504.7	524.6	--
Laursen	528.4	526.6	516.7	505.3	501.4	522.3	--
Shen	529.5	527.7	515.7	503.7	501.2	524.0	--
Shen-Maza	528.2	526.3	522.7	510.9	489.6	522.3	--
Estimated historical elevation of bed from field measurements							
At nose of pier	--	--	--	--	--	--	--
Maximum depth	--	--	--	--	--	--	--

Table 39. Historical scour at State Road 32 over Wabash River at Perrysville, Indiana

[ft^3/s, cubic feet per second; all elevations refer to feet above sea level; ft/s, feet per second; mm, millimeters; *, pier width at surveyed bed elevation; --, no data or computation]

Hydraulic characteristic or equation used	Pier number						
	8	7	6	5	4	3	2
Total discharge, in ft^3/s	94,300	94,300	94,300	94,300	94,300	94,300	94,300
Water-surface elevation	499.1	499.1	499.1	499.1	499.1	499.1	499.1
Approach depth, in feet	11.1	12.1	33.4	31.0	30.5	17.1	12.2
Approach velocity, in ft/s	2.6	2.6	5.8	5.5	5.5	2.9	2.9
Angle of attack, in degrees	15	15	15	15	15	15	15
Estimated grain size, in mm	.25	.25	.47	.37	.30	.25	.25
Pier width*, in feet	3.0	3.0	3.0	7.9	3.0	3.0	3.0
Pier length, in feet	18.5	38.0	38.0	42.0	38.0	38.0	18.5
Pier-nose shape	Round	Round	Round	Round	Round	Round	Round
Computed depth of contraction scour, in feet							
Laursen	6.2	6.2	24.3	24.3	24.3	8.9	8.9
Computed depth of pier scour, in feet							
Ahmad	5.7	5.7	26.8	24.6	24.4	7.1	7.2
Arkansas	5.9	5.9	5.9	5.8	6.0	6.4	6.4
Blench-Inglis I	7.1	10.0	13.8	18.0	13.6	11.5	7.4
Blench-Inglis II	5.1	7.1	10.9	16.2	13.2	7.1	5.8
Chitale	3.2	3.2	16.5	15.1	15.0	3.9	4.2
Froehlich	4.1	5.7	9.2	11.5	9.2	6.6	4.3
HEC-18	7.8	11.2	18.2	22.1	17.6	12.3	8.3
Inglis-Lacey	33.8	32.8	7.0	11.1	13.1	27.8	32.7
Inglis-Poona I	4.1	5.7	12.6	15.9	12.3	5.5	4.8
Inglis-Poona II	6.6	9.1	13.3	16.9	13.0	10.6	6.9
Larras	6.6	9.6	9.6	12.7	9.6	9.6	6.6
Laursen	11.5	16.6	27.6	29.8	26.4	19.7	12.1
Shen	5.1	7.0	11.6	14.3	11.3	7.6	5.5
Shen-Maza	2.3	2.3	18.7	23.3	18.1	2.9	2.9
Computed elevation of bed at nose of pier							
Ahmad	476.1	475.1	414.6	419.2	419.9	466.0	470.8
Arkansas	475.9	474.9	435.5	438.0	438.3	466.7	471.6
Blench-Inglis I	474.7	470.8	427.6	425.8	430.7	461.6	470.6
Blench-Inglis II	476.7	473.7	430.5	427.6	431.1	466.0	472.2
Chitale	478.6	477.6	424.9	428.7	429.3	469.2	473.8
Froehlich	477.7	475.1	432.2	432.3	435.1	466.5	473.7
HEC-18	474.0	469.6	423.2	421.7	426.7	460.8	469.7
Inglis-Lacey	448.0	448.0	434.4	432.7	431.2	445.3	445.3
Inglis-Poona I	477.7	475.1	428.8	427.9	432.0	467.6	473.2
Inglis-Poona II	475.2	471.7	428.1	426.9	431.3	462.5	471.1
Larras	475.2	471.2	431.8	431.1	434.7	463.5	471.4
Laursen	470.3	464.2	413.8	414.0	417.9	453.4	465.9
Shen	476.7	473.8	429.8	429.5	433.0	465.5	472.5
Shen-Maza	479.5	478.5	422.7	420.5	426.2	470.2	475.1
Estimated historical elevation of bed from field measurements							
At nose of pier	--	--	463.0	463.8	464.0	--	--
Maximum depth	--	--	462.0	460.0	462.6	--	--

Table 40. Historical scour at U.S. Route 35 over Kankakee River at Union Center, Indiana

[ft^3/s, cubic feet per second; all elevations refer to feet above sea level; ft/s, feet per second; mm, millimeters; *, pier width at surveyed bed elevation; **, deposition is not included in the computation of bed elevation; --, no data or computation]

Hydraulic characteristic or equation used	Bent number	
	2	3
Total discharge, in ft^3/s	1,660	1,660
Water-surface elevation	682.2	682.2
Approach depth, in feet	11.1	8.2
Approach velocity, in ft/s	2.3	2.1
Angle of attack, in degrees	0	8
Estimated grain size, in mm	.35	.35
Pier width*, in feet	1.0	1.0
Pier length, in feet	11.0	11.0
Pier-nose shape	Cylinders	Cylinders
Computed depth of contraction scour, in feet		
Laursen	-0.3**	-0.3**
Computed depth of pier scour, in feet		
Ahmad	4.5	3.8
Arkansas	3.2	3.0
Blench-Inglis I	-0.2**	2.8
Blench-Inglis II	-2.3**	.9
Chitale	2.4	2.1
Froehlich	1.1	1.7
HEC-18	2.1	3.3
Inglis-Lacey	0	2.9
Inglis-Poona I	-1.9**	1.0
Inglis-Poona II	.2	2.7
Larras	1.4	2.8
Laursen	3.3	5.5
Shen	1.4	2.3
Shen-Maza	1.9	3.2
Computed elevation of bed at nose of bent		
Ahmad	666.6	670.2
Arkansas	667.9	671.0
Blench-Inglis I	671.1	671.2
Blench-Inglis II	671.1	673.1
Chitale	668.7	671.9
Froehlich	670.0	672.3
HEC-18	669.0	670.7
Inglis-Lacey	671.1	671.1
Inglis-Poona I	671.1	673.0
Inglis-Poona II	670.9	671.3
Larras	669.7	671.2
Laursen	667.8	668.5
Shen	669.7	671.7
Shen-Maza	669.2	670.8
Estimated historical elevation of bed from field measurements		
At nose of pier	--	--
Maximum depth	--	--

Table 41. Historical scour at U.S. Route 41 (southbound lane) over Kankakee River at Schneider, Indiana

[ft^3/s, cubic feet per second; all elevations refer to feet above sea level; ft/s, feet per second; mm, millimeters; *, pier width at surveyed bed elevation]

Hydraulic characteristic or equation used	Pier number	
	2	3
Total discharge, in ft^3/s	7,840	7,840
Water-surface elevation	635.7	635.7
Approach depth, in feet	10.8	19.5
Approach velocity, in ft/s	3.4	4.5
Angle of attack, in degrees	11	11
Estimated grain size, in mm	.22	.22
Pier width*, in feet	3.0	3.0
Pier length, in feet	36.0	36.0
Pier-nose shape	Round	Round
Computed depth of contraction scour, in feet		
Laursen	4.3	4.3
Computed depth of pier scour, in feet		
Ahmad	9.2	16.1
Arkansas	4.4	5.4
Blench-Inglis I	8.2	10.1
Blench-Inglis II	9.2	11.3
Chitale	5.7	9.9
Froehlich	5.0	6.5
HEC-18	10.5	12.8
Inglis-Lacey	9.2	.5
Inglis-Poona I	7.6	9.3
Inglis-Poona II	7.5	9.5
Larras	7.9	7.9
Laursen	13.1	17.7
Shen	7.2	8.5
Shen-Maza	4.0	13.3
Computed elevation of bed at nose of pier		
Ahmad	611.4	595.8
Arkansas	616.2	606.5
Blench-Inglis I	612.4	601.8
Blench-Inglis II	611.4	600.6
Chitale	614.9	602.0
Froehlich	615.6	605.4
HEC-18	610.1	599.1
Inglis-Lacey	611.4	611.4
Inglis-Poona I	613.0	602.6
Inglis-Poona II	613.1	602.4
Larras	612.7	604.0
Laursen	607.5	594.2
Shen	613.4	603.4
Shen-Maza	616.6	598.6
Estimated historical elevation of bed from field measurements		
At nose of pier	619.7	614.7
Maximum depth	615.5	614.7

Table 42. Historical scour at State Road 54 over Busseron Creek near Sullivan, Indiana

[ft^3/s, cubic feet per second; all elevations refer to feet above sea level; ft/s, feet per second; mm, millimeters; *, pier width at surveyed bed elevation; **, deposition is not included in the computation of bed elevation]

Hydraulic characteristic or equation used	Bent number 3	Bent number 2
Total discharge, in ft^3/s	6,050	6,050
Flow through bridge, in ft^3/s	3,350	3,350
Water-surface elevation	456.3	456.3
Approach depth, in feet	14.1	14.0
Approach velocity, in ft/s	4.8	4.8
Angle of attack, in degrees	0	0
Estimated grain size, in mm	.58	.58
Pier width*, in feet	2.0	2.0
Pier length, in feet	40.0	40.0
Pier-nose shape	Square	Square
Computed depth of contraction scour, in feet		
Laursen	7.3	7.3
Computed depth of pier scour, in feet		
Ahmad	15.6	15.6
Arkansas	5.0	5.0
Blench-Inglis I	1.5	1.5
Blench-Inglis II	1.9	1.9
Chitale	9.9	9.9
Froehlich	2.6	2.6
HEC-18	5.0	5.0
Inglis-Lacey	-1.3**	-1.2**
Inglis-Poona I	3.5	3.6
Inglis-Poona II	1.8	1.8
Larras	3.3	3.3
Laursen	5.9	5.8
Shen	3.3	3.3
Shen-Maza	4.8	4.8
Computed elevation of bed at nose of bent		
Ahmad	419.3	419.4
Arkansas	429.9	430.0
Blench-Inglis I	433.4	433.5
Blench-Inglis II	433.0	433.1
Chitale	425.0	425.1
Froehlich	432.3	432.4
HEC-18	429.9	430.0
Inglis-Lacey	434.9	435.0
Inglis-Poona I	431.4	431.4
Inglis-Poona II	433.1	433.2
Larras	431.6	431.7
Laursen	429.0	429.2
Shen	431.6	431.7
Shen-Maza	430.1	430.2
Estimated historical elevation of bed from field measurements		
At nose of pier	437.4	436.2
Maximum depth	437.4	436.2

Table 43. Historical scour at State Road 57 over East Fork White River near Petersburg, Indiana

[ft^3/s, cubic feet per second; all elevations refer to feet above sea level; ft/s, feet per second; mm, millimeters; *, pier width at surveyed bed elevation; --, no data or computation]

Hydraulic characteristic or equation used	Pier number 2	3	4	5	6
Total discharge, in ft^3/s	48,000	48,000	48,000	48,000	48,000
Water-surface elevation	425.8	425.8	425.8	425.8	425.8
Approach depth, in feet	17.2	25.3	17.2	7.5	6.0
Approach velocity, in ft/s	4.7	5.0	4.1	2.3	1.8
Angle of attack, in degrees	0	0	0	0	0
Estimated grain size, in mm	.70	.70	.70	.25	.25
Pier width*, in feet	4.7	5.5	4.7	3.8	3.7
Pier length, in feet	50.0	50.0	50.0	50.0	50.0
Pier-nose shape	Round	Round	Round	Round	Round
Computed depth of contraction scour, in feet					
Laursen	15.0	15.0	15.0	2.8	2.8
Computed depth of pier scour, in feet					
Ahmad	16.3	19.8	13.4	4.4	2.7
Arkansas	4.8	5.1	4.4	5.4	4.6
Blench-Inglis I	5.2	5.8	5.2	3.9	3.6
Blench-Inglis II	3.9	2.2	2.6	3.0	2.2
Chitale	10.2	12.1	8.2	2.6	1.5
Froehlich	3.6	4.7	3.5	2.2	1.9
HEC-18	8.1	9.7	7.7	4.6	4.0
Inglis-Lacey	13.0	4.9	13.0	28.4	29.9
Inglis-Poona I	6.2	5.2	4.6	2.5	1.7
Inglis-Poona II	5.2	6.0	5.2	3.7	3.3
Larras	4.5	5.1	4.5	3.9	3.8
Laursen	8.9	11.7	8.9	5.3	4.6
Shen	5.5	6.3	5.1	3.1	2.6
Shen-Maza	8.3	9.7	7.6	4.5	1.1
Computed elevation of bed at nose of pier					
Ahmad	377.3	365.7	380.2	411.1	414.3
Arkansas	388.8	380.4	389.2	410.1	412.4
Blench-Inglis I	388.4	379.7	388.4	411.6	413.4
Blench-Inglis II	389.7	383.3	391.0	412.5	414.8
Chitale	383.4	373.4	385.4	412.9	415.5
Froehlich	390.0	380.8	390.1	413.3	415.1
HEC-18	385.5	375.8	385.9	410.9	413.0
Inglis-Lacey	380.6	380.6	380.6	387.1	387.1
Inglis-Poona I	387.4	380.3	389.0	413.0	415.3
Inglis-Poona II	388.4	379.5	388.4	411.8	413.7
Larras	389.1	380.4	389.1	411.6	413.2
Laursen	384.7	373.8	384.7	410.2	412.4
Shen	388.1	379.2	388.5	412.4	414.4
Shen-Maza	385.3	375.8	386.0	411.0	415.9
Estimated historical elevation of bed from field measurements					
At nose of pier	--	394.0	--	--	--
Maximum depth	--	389.0	--	--	--

Table 44. Historical scour at State Road 59 over Eel River north of Clay City, Indiana
[ft^3/s, cubic feet per second; all elevations refer to feet above sea level; ft/s, feet per second; mm, millimeters; *, pier width at surveyed bed elevation; --, no data or computation]

Hydraulic characteristic or equation used	Pier number		
	2	3	4
Total discharge, in ft^3/s	36,200	36,200	36,200
Flow through bridge, in ft^3/s	26,600	26,600	26,600
Water-surface elevation	556.3	556.3	556.3
Approach depth, in feet	20.2	23.6	13.7
Approach velocity, in ft/s	7.0	7.6	5.2
Angle of attack, in degrees	0	0	20
Estimated grain size, in mm	.55	.55	.25
Pier width*, in feet	3.2	3.3	2.8
Pier length, in feet	34.0	34.0	34.0
Pier-nose shape	Round	Round	Round
Computed depth of contraction scour, in feet			
Laursen	5.8	5.8	16.7
Computed depth of pier scour, in feet			
Ahmad	28.7	33.6	17.1
Arkansas	6.6	6.9	9.5
Blench-Inglis I	2.7	2.4	11.2
Blench-Inglis II	6.1	6.2	16.1
Chitale	18.2	21.4	10.9
Froehlich	3.4	3.7	7.4
HEC-18	7.7	8.3	16.6
Inglis-Lacey	5.6	2.2	15.8
Inglis-Poona I	8.6	9.2	14.2
Inglis-Poona II	3.1	2.9	10.2
Larras	3.4	3.5	10.4
Laursen	8.0	8.8	19.1
Shen	5.6	6.0	11.6
Shen-Maza	8.5	9.1	18.7
Computed elevation of bed at nose of pier			
Ahmad	501.6	493.3	508.8
Arkansas	523.7	520.0	516.4
Blench-Inglis I	527.6	524.5	514.7
Blench-Inglis II	524.2	520.7	509.8
Chitale	512.1	505.5	515.0
Froehlich	526.9	523.2	518.5
HEC-18	522.6	518.6	509.3
Inglis-Lacey	524.7	524.7	510.1
Inglis-Poona I	521.7	517.7	511.7
Inglis-Poona II	527.2	524.0	515.7
Larras	526.9	523.4	515.5
Laursen	522.3	518.1	506.8
Shen	524.7	520.9	514.3
Shen-Maza	521.8	517.8	507.2
Estimated historical elevation of bed from field measurements			
At nose of pier	529.0	524.0	--
Maximum depth	529.0	524.0	--

Table 45. Historical scour at State Road 63 (southbound lane) over Little Vermillion River at Newport, Indiana

[ft^3/s, cubic feet per second; all elevations refer to feet above sea level; ft/s, feet per second; mm, millimeters; *, pier width at surveyed bed elevation; **, deposition is not included in the computation of bed elevation]

Hydraulic characteristic or equation used	Pier number 3	Pier number 2
Total discharge, in ft^3/s	7,260	7,260
Water-surface elevation	503.0	503.0
Approach depth, in feet	17.1	9.9
Approach velocity, in ft/s	7.1	4.1
Angle of attack, in degrees	16	0
Estimated grain size, in mm	.70	.70
Pier width*, in feet	2.0	2.0
Pier length, in feet	43.0	43.0
Pier-nose shape	Round	Round
Computed depth of contraction scour, in feet		
Laursen	11.7	11.7
Computed depth of pier scour, in feet		
Ahmad	27.0	11.2
Arkansas	6.4	4.4
Blench-Inglis I	12.1	2.0
Blench-Inglis II	16.9	2.2
Chitale	17.0	7.1
Froehlich	7.7	1.7
HEC-18	14.3	4.1
Inglis-Lacey	-1.0**	6.2
Inglis-Poona I	19.6	3.6
Inglis-Poona II	11.1	2.1
Larras	10.2	2.4
Laursen	16.5	4.4
Shen	13.8	3.0
Shen-Maza	22.6	4.3
Computed elevation of bed at nose of pier		
Ahmad	447.2	470.2
Arkansas	467.8	477.0
Blench-Inglis I	462.1	479.4
Blench-Inglis II	457.3	479.2
Chitale	457.2	474.3
Froehlich	466.5	479.7
HEC-18	459.9	477.3
Inglis-Lacey	474.2	475.2
Inglis-Poona I	454.6	477.8
Inglis-Poona II	463.1	479.3
Larras	464.0	479.0
Laursen	457.7	477.0
Shen	460.4	478.4
Shen-Maza	451.6	477.1
Estimated historical elevation of bed from field measurements		
At nose of pier	484.9	488.0
Maximum depth	484.9	488.0

Table 46. Historical scour at State Road 101 over St. Joseph River at Saint Joe, Indiana
[ft^3/s, cubic feet per second; all elevations refer to feet above sea level; ft/s, feet per second; mm, millimeters; *, pier width at surveyed bed elevation; --, no data or computation]

Hydraulic characteristic or equation used	Pier number		
	2	3	4
Total discharge, in ft^3/s	9,840	9,840	9,840
Water-surface elevation	800.6	800.6	800.6
Approach depth, in feet	14.8	16.1	8.0
Approach velocity, in ft/s	4.7	4.7	3.0
Angle of attack, in degrees	4	8	31
Estimated grain size, in mm	.55	.55	.25
Pier width*, in feet	2.0	2.0	2.0
Pier length, in feet	37.0	37.0	37.0
Pier-nose shape	Round	Round	Round
Computed depth of contraction scour, in feet			
Laursen	1.5	1.5	5.7
Computed depth of pier scour, in feet			
Ahmad	15.5	16.0	7.1
Arkansas	5.0	5.0	6.5
Blench-Inglis I	5.1	7.5	10.3
Blench-Inglis II	5.3	7.3	11.2
Chitale	9.8	10.1	4.4
Froehlich	3.5	4.7	6.9
HEC-18	6.4	8.3	12.4
Inglis-Lacey	3.7	2.4	13.2
Inglis-Poona I	6.7	8.7	9.4
Inglis-Poona II	5.0	7.2	9.1
Larras	4.4	6.2	13.8
Laursen	8.4	11.3	15.2
Shen	5.4	7.1	10.5
Shen-Maza	8.2	11.0	3.1
Computed elevation of bed at nose of pier			
Ahmad	768.8	767.0	779.8
Arkansas	779.3	778.0	780.4
Blench-Inglis I	779.2	775.5	776.6
Blench-Inglis II	779.0	775.7	775.7
Chitale	774.5	772.9	782.5
Froehlich	780.8	778.3	780.0
HEC-18	777.9	774.7	774.5
Inglis-Lacey	780.6	780.6	773.7
Inglis-Poona I	777.6	774.3	777.5
Inglis-Poona II	779.3	775.8	777.8
Larras	779.9	776.8	773.1
Laursen	775.9	771.7	771.7
Shen	778.9	775.9	776.4
Shen-Maza	776.1	772.0	783.8
Estimated historical elevation of bed from field measurements			
At nose of pier	779.5	779.9	--
Maximum depth	779.5	779.9	--

Table 47. Historical scour at State Road 109 over White River at Anderson, Indiana

[ft^3/s, cubic feet per second; all elevations refer to feet above sea level; ft/s, feet per second; mm, millimeters; *, pier width at surveyed bed elevation; **, deposition is not included in the computation of bed elevation; --, no data or computation]

Hydraulic characteristic or equation used	Pier number					
	2	3	4	5	6	7
Total discharge, in ft^3/s	18,700	18,700	18,700	18,700	18,700	18,700
Water-surface elevation	846.2	846.2	846.2	846.2	846.2	846.2
Approach depth, in feet	3.0	8.5	9.5	15.5	16.2	7.7
Approach velocity, in ft/s	2.8	4.0	4.3	5.9	6.4	3.0
Angle of attack, in degrees	20	20	12	12	8	20
Estimated grain size, in mm	.25	.25	.25	26.5	26.5	.25
Pier width*, in feet	2.5	3.0	3.0	3.5	3.5	3.2
Pier length, in feet	86.0	86.0	86.0	86.0	86.0	86.0
Pier-nose shape	Round	Round	Round	Round	Round	Round
Computed depth of contraction scour, in feet						
Laursen	--	11.7	11.7	.8	.8	6.5
Computed depth of pier scour, in feet						
Ahmad	4.4	10.4	11.9	21.2	23.4	6.8
Arkansas	6.2	7.9	8.3	3.7	3.9	6.5
Blench-Inglis I	6.7	12.9	11.3	14.7	12.7	12.2
Blench-Inglis II	9.5	16.8	15.5	5.5	4.4	13.1
Chitale	2.8	6.6	7.6	13.5	14.9	4.2
Froehlich	6.2	9.8	7.9	7.0	6.0	8.9
HEC-18	9.6	14.6	11.9	16.1	14.2	13.2
Inglis-Lacey	23.2	17.7	16.7	-3.5**	-4.2**	18.5
Inglis-Poona I	7.9	14.3	13.4	19.5	18.5	10.9
Inglis-Poona II	5.7	11.2	10.0	13.3	11.6	10.6
Larras	19.0	19.2	13.8	14.1	11.2	19.3
Laursen	8.4	15.5	12.9	17.8	15.3	15.3
Shen	12.9	16.4	13.2	16.3	14.0	13.7
Shen-Maza	2.6	5.5	6.4	26.8	22.9	3.0
Computed elevation of bed at nose of pier						
Ahmad	838.8	815.6	813.1	808.7	805.8	825.2
Arkansas	837.0	818.1	816.7	826.2	825.3	825.5
Blench-Inglis I	836.5	813.1	813.7	815.2	816.5	819.8
Blench-Inglis II	833.7	809.2	809.5	824.4	824.8	818.9
Chitale	840.4	819.4	817.4	816.4	814.3	827.8
Froehlich	837.0	816.2	817.1	822.9	823.2	823.1
HEC-18	833.6	811.4	813.1	813.8	815.0	818.8
Inglis-Lacey	820.0	808.3	808.3	829.9	829.2	813.5
Inglis-Poona I	835.3	811.7	811.6	810.4	810.7	821.1
Inglis-Poona II	837.5	814.8	815.0	816.6	817.6	821.4
Larras	824.2	806.8	811.2	815.8	818.0	812.7
Laursen	834.8	810.5	812.1	812.1	813.9	816.7
Shen	830.3	809.6	811.8	813.6	815.2	818.3
Shen-Maza	840.6	820.5	818.6	803.1	806.3	829.0
Estimated historical elevation of bed from field measurements						
At nose of pier	--	--	--	--	824.0	--
Maximum depth	--	--	--	--	824.0	--

Table 48. Historical scour at State Road 110 over Tippecanoe River near Mentone, Indiana
[ft^3/s, cubic feet per second; all elevations refer to feet above sea level; ft/s, feet per second; mm, millimeters; *, pier width at surveyed bed elevation; **, deposition is not included in the computation of bed elevation; --, no data or computation]

Hydraulic characteristic or equation used	Pier number			
	5	4	3	2
Total discharge, in ft^3/s	5,300	5,300	5,300	5,300
Water-surface elevation	765.1	765.1	765.1	765.1
Approach depth, in feet	6.4	11.0	10.3	3.3
Approach velocity, in ft/s	1.6	4.3	4.2	1.9
Angle of attack, in degrees	0	0	0	0
Estimated grain size, in mm	.25	.70	3.60	.25
Pier width*, in feet	2.0	2.0	2.0	2.0
Pier length, in feet	31.5	30.5	30.5	31.5
Pier-nose shape	Round	Round	Round	Round
Computed depth of contraction scour, in feet				
Laursen	2.9	2.9	2.9	1.2
Computed depth of pier scour, in feet				
Ahmad	2.2	12.4	11.9	2.8
Arkansas	2.6	4.6	3.7	4.8
Blench-Inglis I	2.2	1.9	2.0	1.9
Blench-Inglis II	.6	2.0	-0.1**	2.1
Chitale	1.1	7.8	7.5	1.7
Froehlich	1.3	1.8	1.5	1.1
HEC-18	2.6	4.2	4.2	2.5
Inglis-Lacey	10.9	3.5	.8	14.0
Inglis-Poona I	.3	3.6	3.7	1.8
Inglis-Poona II	2.2	2.1	2.1	1.8
Larras	2.4	2.4	2.4	2.4
Laursen	3.5	4.6	4.5	2.5
Shen	1.7	3.1	3.0	1.8
Shen-Maza	2.3	4.4	4.4	2.6
Computed elevation of bed at nose of pier				
Ahmad	753.6	738.8	740.0	757.8
Arkansas	753.2	746.6	748.2	755.8
Blench-Inglis I	753.6	749.3	749.9	758.7
Blench-Inglis II	755.2	749.2	751.9	758.5
Chitale	754.7	743.4	744.4	758.9
Froehlich	754.5	749.4	750.4	759.5
HEC-18	753.2	747.0	747.7	758.1
Inglis-Lacey	744.9	747.7	751.1	746.6
Inglis-Poona I	755.5	747.6	748.2	758.8
Inglis-Poona II	753.6	749.1	749.8	758.8
Larras	753.4	748.8	749.5	758.2
Laursen	752.3	746.6	747.4	758.1
Shen	754.1	748.1	748.9	758.8
Shen-Maza	753.5	746.8	747.5	758.0
Estimated historical elevation of bed from field measurements				
At nose of pier	--	751.0	750.0	--
Maximum depth	--	749.0	750.0	--

Table 49. Historical scour at State Road 135 over Muscatatuck River at Millport, Indiana

[ft^3/s, cubic feet per second; all elevations refer to feet above sea level; ft/s, feet per second; mm, millimeters; *, pier width at surveyed bed elevation; --, no data or computation; **, deposition is not included in the computation of bed elevation]

Hydraulic characteristic or equation used	Pier number					
	2	3	4	5	6	7
Total discharge, in ft^3/s	33,500	33,500	33,500	33,500	33,500	33,500
Water-surface elevation	526.0	526.0	526.0	526.0	526.0	526.0
Approach depth, in feet	6.5	28.5	28.4	13.1	7.4	4.5
Approach velocity, in ft/s	2.4	6.7	6.7	3.6	2.0	2.0
Angle of attack, in degrees	0	0	0	0	0	0
Estimated grain size, in mm	4.80	4.80	4.80	.25	.25	.25
Pier width*, in feet	3.5	3.2	3.2	2.8	2.5	3.4
Pier length, in feet	36.0	31.0	31.0	31.0	31.0	36.0
Pier-nose shape	Round	Round	Round	Round	Round	Round
Computed depth of contraction scour, in feet						
Laursen	--	17.8	17.8	7.1	7.1	7.1
Computed depth of pier scour, in feet						
Ahmad	4.8	31.1	31.4	10.3	3.6	3.4
Arkansas	2.4	4.9	4.9	7.3	4.9	4.9
Blench-Inglis I	3.5	1.2	1.2	2.9	2.8	3.1
Blench-Inglis II	.3	-5.2**	-5.1**	3.1	1.5	3.0
Chitale	2.9	19.7	19.9	6.3	2.0	2.0
Froehlich	1.6	3.2	3.2	2.5	1.7	1.7
HEC-18	4.4	7.9	7.9	5.0	3.4	3.8
Inglis-Lacey	12.9	-9.1**	-9.0**	18.7	24.4	27.3
Inglis-Poona I	2.9	5.2	5.3	2.7	1.1	2.5
Inglis-Poona II	3.3	2.0	2.0	3.0	2.7	2.8
Larras	3.6	3.4	3.4	3.1	2.8	3.6
Laursen	4.7	9.5	9.5	6.0	4.3	3.8
Shen	3.0	5.4	5.4	3.4	2.2	2.7
Shen-Maza	4.4	8.2	8.3	5.0	3.1	1.4
Computed elevation of bed at nose of pier						
Ahmad	514.7	448.6	448.4	495.5	507.9	511.0
Arkansas	517.1	474.8	474.9	498.5	506.6	509.5
Blench-Inglis I	516.0	478.5	478.6	502.9	508.7	511.3
Blench-Inglis II	519.2	479.7	479.8	502.7	510.0	511.4
Chitale	516.6	460.0	459.9	499.5	509.5	512.4
Froehlich	517.9	476.5	476.6	503.3	509.8	512.7
HEC-18	515.1	471.8	471.9	500.8	508.1	510.6
Inglis-Lacey	506.6	479.7	479.8	487.1	487.1	487.1
Inglis-Poona I	516.6	474.5	474.5	503.1	510.4	511.9
Inglis-Poona II	516.2	477.7	477.8	502.8	508.8	511.6
Larras	515.9	476.3	476.4	502.7	508.7	510.8
Laursen	514.8	470.2	470.3	499.8	507.2	510.6
Shen	516.5	474.3	474.4	502.4	509.3	511.7
Shen-Maza	515.1	471.5	471.5	500.8	508.4	513.0
Estimated historical elevation of bed from field measurements						
At nose of pier	--	--	--	--	--	--
Maximum depth	--	--	--	--	--	--

Table 50. Historical scour at State Road 157 over White River at Worthington, Indiana
[ft^3/s, cubic feet per second; all elevations refer to feet above sea level; ft/s, feet per second; mm, millimeters; *, pier width at surveyed bed elevation; **, deposition is not included in the computation of bed elevation; --, no data or computation]

Hydraulic characteristic or equation used	Pier number			
	2	3	4	5
Total discharge, in ft^3/s	85,500	85,500	85,500	85,500
Flow through bridge, in ft^3/s	55,100	55,100	55,100	55,100
Water-surface elevation	511.8	511.8	511.8	511.8
Approach depth, in feet	8.3	11.6	19.4	24.9
Approach velocity, in ft/s	2.6	3.5	5.3	6.2
Angle of attack, in degrees	6	6	2	0
Estimated grain size, in mm	.25	.25	.90	.90
Pier width*, in feet	2.0	3.0	3.0	2.0
Pier length, in feet	46.0	47.5	43.0	42.0
Pier-nose shape	Round	Round	Round	Round
Computed depth of contraction scour, in feet				
Laursen	7.7	7.7	-1.9**	-1.9**
Computed depth of pier scour, in feet				
Ahmad	5.7	9.5	20.4	27.0
Arkansas	5.9	7.2	5.1	5.7
Blench-Inglis I	5.9	7.4	4.8	-1.0**
Blench-Inglis II	5.4	7.8	3.6	-1.9**
Chitale	3.4	5.9	12.8	17.1
Froehlich	3.4	4.5	3.7	2.5
HEC-18	5.3	8.1	7.8	5.5
Inglis-Lacey	29.3	26.0	10.9	5.4
Inglis-Poona I	4.6	6.7	7.1	2.4
Inglis-Poona II	5.4	6.9	4.9	-0.2**
Larras	6.0	6.7	4.4	2.4
Laursen	7.2	10.4	10.1	7.0
Shen	4.8	6.3	5.8	3.9
Shen-Maza	2.3	9.7	8.9	5.7
Computed elevation of bed at nose of pier				
Ahmad	490.1	483.0	472.0	459.9
Arkansas	489.9	485.3	487.3	481.2
Blench-Inglis I	489.9	485.1	487.6	486.9
Blench-Inglis II	490.4	484.7	488.8	486.9
Chitale	492.4	486.6	479.6	469.8
Froehlich	492.4	488.0	488.7	484.4
HEC-18	490.5	484.4	484.6	481.4
Inglis-Lacey	466.5	466.5	481.5	481.5
Inglis-Poona I	491.2	485.8	485.3	484.5
Inglis-Poona II	490.4	485.6	487.5	486.9
Larras	489.8	485.8	488.0	484.5
Laursen	488.6	482.1	482.3	479.9
Shen	491.0	486.2	486.6	483.0
Shen-Maza	493.5	482.8	483.5	481.2
Estimated historical elevation of bed from field measurements				
At nose of pier	--	--	--	--
Maximum depth	--	--	--	477.0

Table 51. Historical scour at State Road 163 over Wabash River at Clinton, Indiana

[ft^3/s, cubic feet per second; all elevations refer to feet above sea level; ft/s, feet per second; mm, millimeters; *, pier width at surveyed bed elevation; --, no data or computation]

Hydraulic characteristic or equation used	Pier number							
	9	8	7	6	5	4	3	2
Total discharge, in ft^3/s	114,500	114,500	114,500	114,500	114,500	114,500	114,500	114,500
Water-surface elevation	482.8	482.8	482.8	482.8	482.8	482.8	482.8	482.8
Approach depth, in feet	11.4	11.6	11.9	12.3	18.5	33.2	33.5	33.6
Approach velocity, in ft/s	2.2	2.2	2.2	2.5	4.2	5.9	6.1	6.2
Angle of attack, in degrees	6	6	9	15	15	1	1	1
Estimated grain size, in mm	.25	.25	.25	.25	.34	.39	.39	.34
Pier width*, in feet	2.5	2.5	2.5	3.0	3.0	3.0	3.0	3.0
Pier length, in feet	35.5	35.5	35.5	38.0	38.0	38.0	38.0	38.0
Pier-nose shape	Round	Round	Round	Round	Round	Round	Round	Round
Computed depth of contraction scour, in feet								
Laursen	5.2	5.2	5.2	5.2	5.2	.5	.5	.5
Computed depth of pier scour, in feet								
Ahmad	4.0	4.0	4.0	5.4	14.3	27.5	28.9	29.7
Arkansas	5.3	5.3	5.3	5.7	7.9	6.1	6.2	6.4
Blench-Inglis I	6.2	6.3	7.5	10.0	11.8	1.2	1.2	1.2
Blench-Inglis II	3.0	2.9	3.8	6.8	10.7	.2	.6	1.4
Chitale	2.1	2.0	2.0	2.9	8.7	17.0	17.9	18.4
Froehlich	3.5	3.5	4.1	5.7	7.2	4.3	4.4	4.4
HEC-18	5.9	5.9	7.0	11.1	14.6	8.1	8.2	8.3
Inglis-Lacey	36.5	36.3	36.0	35.6	27.0	11.3	11.0	11.9
Inglis-Poona I	2.2	2.1	2.8	5.4	10.1	2.0	2.5	2.7
Inglis-Poona II	5.8	5.9	7.0	9.1	11.0	2.2	2.1	2.1
Larras	5.6	5.6	6.8	9.6	9.6	3.8	3.8	3.8
Laursen	9.4	9.5	11.4	16.7	20.5	12.1	12.2	12.2
Shen	4.1	4.1	4.8	6.9	9.5	5.4	5.6	5.6
Shen-Maza	1.7	1.7	1.7	2.1	15.1	8.3	8.5	8.6
Computed elevation of bed at nose of pier								
Ahmad	462.2	462.0	461.7	459.9	444.8	421.6	419.9	419.0
Arkansas	460.9	460.7	460.4	459.6	451.2	443.0	442.6	442.3
Blench-Inglis I	460.0	459.7	458.2	455.3	447.3	447.9	447.6	447.5
Blench-Inglis II	463.2	463.1	461.9	458.5	448.4	448.9	448.2	447.3
Chitale	464.1	464.0	463.7	462.4	450.4	432.1	430.9	430.3
Froehlich	462.7	462.5	461.6	459.6	451.9	444.8	444.4	444.3
HEC-18	460.3	460.1	458.7	454.2	444.5	441.0	440.6	440.4
Inglis-Lacey	429.7	429.7	429.7	429.7	432.1	437.8	437.8	436.8
Inglis-Poona I	464.0	463.9	462.9	459.9	449.0	447.1	446.3	446.0
Inglis-Poona II	460.4	460.1	458.7	456.2	448.1	446.9	446.7	446.6
Larras	460.6	460.4	458.9	455.7	449.5	445.3	445.0	444.9
Laursen	456.8	456.5	454.3	448.6	438.6	437.0	436.6	436.5
Shen	462.1	461.9	460.9	458.4	449.6	443.7	443.2	443.1
Shen-Maza	464.5	464.3	464.0	463.2	444.0	440.8	440.3	440.1
Estimated historical elevation of bed from field measurements								
At nose of pier	--	--	--	--	--	--	--	443.3
Maximum depth	--	--	--	--	--	--	--	443.3

SUPPLEMENTAL DATA

Computed and Measured Pier Scour Tables

Table 55. Computed and measured pier scour for the flood of January 2, 1991, at State Road 1 over St. Marys River at Fort Wayne, Indiana

[ft^3/s, cubic feet per second; all elevations refer to feet above sea level; ft/s, feet per second; mm, millimeters; *, pier width at surveyed bed elevation; **, deposition is not included in the computation of bed elevation; --, no data or computation]

Hydraulic characteristic or equation used	Pier number			
	2	3	4	5
Total discharge, in ft^3/s	9,580	9,580	9,580	9,580
Water-surface elevation	760.7	760.7	760.7	760.7
Approach depth, in feet	13.9	16.3	14.9	2.5
Approach velocity, in ft/s	1.3	3.5	3.3	1.3
Measured velocity, in ft/s	.78	4.37	3.19	2.60
Angle of attack, in degrees	0	0	0	0
Estimated grain size, in mm	88.0	88.0	88.0	.25
Pier width*, in feet	2.0	2.0	2.0	2.0
Pier length, in feet	86.5	86.5	86.5	86.5
Pier-nose shape	Round	Round	Round	Round
Computed depth of pier scour, in feet				
Ahmad	-1.6**	10.4	9.1	1.5
Arkansas	1.1	2.2	2.2	3.6
Blench-Inglis I	1.5	1.1	1.3	1.8
Blench-Inglis II	-9.5**	-8.4**	-7.6**	1.5
Chitale	-1.8**	6.2	5.4	.9
Froehlich	1.0	1.3	1.3	.9
HEC-18	2.6	4.1	3.9	2.1
Inglis-Lacey	-6.0**	-8.4**	-7.0**	18.5
Inglis-Poona I	-5.1**	-.1**	0	1.2
Inglis-Poona II	1.8	1.5	1.7	1.6
Larras	2.4	2.4	2.4	2.4
Laursen	5.2	5.7	5.4	2.2
Shen	1.5	2.7	2.6	1.5
Shen-Maza	.6	3.9	3.7	.6
Computed elevation of bed at nose of pier				
Ahmad	746.8	734.0	736.7	756.7
Arkansas	745.7	742.2	743.6	754.6
Blench-Inglis I	745.3	743.3	744.5	756.4
Blench-Inglis II	746.8	744.4	745.8	756.7
Chitale	746.8	738.2	740.4	757.3
Froehlich	745.8	743.1	744.5	757.3
HEC-18	744.2	740.3	741.9	756.1
Inglis-Lacey	746.8	744.4	745.8	739.7
Inglis-Poona I	746.8	744.4	745.8	757.0
Inglis-Poona II	745.0	742.9	744.1	756.6
Larras	744.4	742.0	743.4	755.8
Laursen	741.6	738.7	740.4	756.0
Shen	745.3	741.7	743.2	756.7
Shen-Maza	746.2	740.5	742.1	757.6
Elevation of bed from flood measurement				
At nose of pier	748.1	--	747.3	757.4

Table 56. Computed and measured pier scour for the flood of January 1, 1991, at State Road 9 over Pigeon River at Howe, Indiana

[ft^3/s, cubic feet per second; all elevations refer to feet above sea level; ft/s, feet per second; mm, millimeters; *, pier width at surveyed bed elevation]

Hydraulic characteristic or equation used	Bent number	
	2	3
Total discharge, in ft^3/s	1,100	1,100
Water-surface elevation	860.5	860.5
Approach depth, in feet	6.7	3.5
Approach velocity, in ft/s	3.1	2.0
Measured velocity, in ft/s	3.03	1.22
Angle of attack, in degrees	0	4
Estimated grain size, in mm	.50	.50
Pier width*, in feet	2.0	2.0
Pier length, in feet	36.0	36.0
Pier-nose shape	Square	Square
Computed depth of pier scour, in feet		
Ahmad	6.8	3.1
Arkansas	3.8	2.8
Blench-Inglis I	2.2	3.2
Blench-Inglis II	2.3	3.0
Chitale	4.3	1.9
Froehlich	1.9	2.3
HEC-18	3.8	4.0
Inglis-Lacey	2.4	5.6
Inglis-Poona I	2.9	3.0
Inglis-Poona II	2.2	2.9
Larras	3.3	6.1
Laursen	4.0	4.1
Shen	2.5	3.2
Shen-Maza	3.6	1.4
Computed elevation of bed at nose of bent		
Ahmad	847.0	853.9
Arkansas	850.0	854.2
Blench-Inglis I	851.6	853.8
Blench-Inglis II	851.5	854.0
Chitale	849.5	855.1
Froehlich	851.9	854.7
HEC-18	850.0	853.0
Inglis-Lacey	851.4	851.4
Inglis-Poona I	850.9	854.0
Inglis-Poona II	851.6	854.1
Larras	850.5	850.9
Laursen	849.8	852.9
Shen	851.3	853.8
Shen-Maza	850.2	855.6
Elevation of bed from flood measurement		
At nose of pier	853.7	857.6

Table 57. Computed and measured pier scour for the flood of July 14, 1992, at State Road 25 over Wildcat Creek at Lafayette, Indiana

[ft^3/s, cubic feet per second; all elevations refer to feet above sea level; ft/s, feet per second; --, no data or computation; mm, millimeters; *, pier width at surveyed bed elevation]

Hydraulic characteristic or equation used	Pier number						
	2	3	4	5	6	7	8
Total discharge, in ft^3/s	9,270	9,270	9,270	9,270	9,270	9,270	9,270
Water-surface elevation	532.1	532.1	532.1	532.1	532.1	532.1	532.1
Approach depth, in feet	--	1.3	4.0	9.0	13.3	4.6	--
Approach velocity, in ft/s	--	1.4	1.4	4.2	5.1	1.6	--
Measured velocity, in ft/s	--	--	4.56	4.92	6.10	.10	--
Angle of attack, in degrees	--	0	10	14	10	0	--
Estimated grain size, in mm	.22	.22	3.50	1.50	1.50	.22	Riprap
Pier width*, in feet	2.8	2.5	2.7	3.0	3.2	2.6	2.6
Pier length, in feet	104	104	104	104	104	104	104
Pier-nose shape	Round	Round	Round	Round	Round	Round	Round
Computed depth of pier scour, in feet							
Ahmad	--	1.3	1.6	11.2	16.8	2.2	--
Arkansas	--	3.9	2.8	4.1	4.7	4.3	--
Blench-Inglis I	--	1.5	6.9	12.5	13.6	2.6	--
Blench-Inglis II	--	1.8	2.5	11.6	12.5	1.8	--
Chitale	--	.8	.9	7.1	10.7	1.2	--
Froehlich	--	.8	3.7	8.0	8.1	1.4	--
HEC-18	--	2.2	5.5	12.7	12.7	2.9	--
Inglis-Lacey	--	19.9	9.4	6.4	2.1	16.6	--
Inglis-Poona I	--	1.5	4.0	14.3	16.6	1.3	--
Inglis-Poona II	--	1.3	5.9	11.0	12.2	2.4	--
Larras	--	2.8	13.8	17.3	14.0	2.9	--
Laursen	--	1.8	7.2	13.7	14.4	3.4	--
Shen	--	1.7	6.4	15.5	14.8	2.0	--
Shen-Maza	--	.6	.6	6.0	9.0	.9	--
Computed elevation of bed at nose of pier							
Ahmad	--	529.5	526.5	511.9	502.0	525.3	--
Arkansas	--	526.9	525.3	519.0	514.1	523.2	--
Blench-Inglis I	--	529.3	521.2	510.6	505.2	524.9	--
Blench-Inglis II	--	529.0	525.6	511.5	506.3	525.7	--
Chitale	--	530.0	527.2	516.0	508.1	526.3	--
Froehlich	--	530.0	524.4	515.1	510.7	526.1	--
HEC-18	--	528.6	522.6	510.4	506.1	524.6	--
Inglis-Lacey	--	510.9	518.7	516.7	516.7	510.9	--
Inglis-Poona I	--	529.3	524.1	508.8	502.2	526.2	--
Inglis-Poona II	--	529.5	522.2	512.1	506.6	525.1	--
Larras	--	528.0	514.3	505.8	504.8	524.6	--
Laursen	--	529.0	520.9	509.4	504.4	524.1	--
Shen	--	529.1	521.7	507.6	504.0	525.5	--
Shen-Maza	--	530.2	527.5	517.1	509.8	526.6	--
Elevation of bed from flood measurement							
At nose of pier	--	529.4	528.1	521.7	518.8	527.5	--

Table 58. Computed and measured pier scour for the flood of January 1, 1991, at State Road 32 over Wabash River at Perrysville, Indiana

[ft^3/s, cubic feet per second; all elevations refer to feet above sea level; ft/s, feet per second; --, no data or computation; mm, millimeters; *, pier width at surveyed bed elevation]

Hydraulic characteristic or equation used	Pier number						
	8	7	6	5	4	3	2
Total discharge, in ft^3/s	78,700	78,700	78,700	78,700	78,700	78,700	78,700
Water-surface elevation	498.5	498.5	498.5	498.5	498.5	498.5	498.5
Approach depth, in feet	10.5	11.5	32.8	26.5	26.5	16.5	11.6
Approach velocity, in ft/s	2.4	2.4	5.6	5.1	4.9	2.8	2.8
Measured velocity, in ft/s	--	5.78	5.93	5.78	3.59	5.12	--
Angle of attack, in degrees	15	15	15	15	15	15	15
Estimated grain size, in mm	.25	.25	.47	.37	.30	.25	.25
Pier width*, in feet	3.0	3.0	3.0	7.9	3.0	3.0	3.0
Pier length, in feet	18.5	38.0	38.0	42.0	38.0	38.0	18.5
Pier-nose shape	Round	Round	Round	Round	Round	Round	Round
Computed depth of pier scour, in feet							
Ahmad	5.1	5.1	25.6	20.8	19.8	6.5	6.6
Arkansas	5.6	5.6	5.7	5.5	5.5	6.2	6.2
Blench-Inglis I	7.0	9.7	13.8	17.1	13.2	11.3	7.2
Blench-Inglis II	4.8	6.7	10.5	15.3	11.9	6.8	5.6
Chitale	2.9	2.8	15.7	12.7	12.0	3.5	3.8
Froehlich	3.9	5.6	9.1	10.6	8.5	6.5	4.2
HEC-18	7.6	10.8	17.9	20.8	16.4	12.0	8.1
Inglis-Lacey	31.8	30.8	5.3	13.1	14.5	25.8	30.7
Inglis-Poona I	3.8	5.3	12.1	14.8	10.9	5.2	4.6
Inglis-Poona II	6.5	8.8	13.3	15.9	12.5	10.5	6.7
Larras	6.6	9.6	9.6	12.7	9.6	9.6	6.6
Laursen	11.2	16.1	27.4	27.5	24.6	19.4	11.8
Shen	5.0	6.8	11.4	13.5	10.5	7.4	5.4
Shen-Maza	2.0	2.0	18.4	22.0	16.8	2.6	2.6
Computed elevation of bed at nose of pier							
Ahmad	482.9	481.9	440.1	451.2	452.2	475.5	480.3
Arkansas	482.4	481.4	460.0	466.5	466.5	475.8	480.7
Blench-Inglis I	481.0	477.3	451.9	454.9	458.8	470.7	479.7
Blench-Inglis II	483.2	480.3	455.2	456.7	460.1	475.2	481.3
Chitale	485.1	484.2	450.0	459.3	460.0	478.5	483.1
Froehlich	484.1	481.4	456.6	461.4	463.5	475.5	482.7
HEC-18	480.4	476.2	447.8	451.2	455.6	470.0	478.8
Inglis-Lacey	456.2	456.2	460.4	458.9	457.5	456.2	456.2
Inglis-Poona I	484.2	481.7	453.6	457.2	461.1	476.8	482.3
Inglis-Poona II	481.5	478.2	452.4	456.1	459.5	471.5	480.2
Larras	481.4	477.4	456.1	459.3	462.4	472.4	480.3
Laursen	476.8	470.9	438.3	444.5	447.4	462.6	475.1
Shen	483.0	480.2	454.3	458.5	461.5	474.6	481.5
Shen-Maza	486.0	485.0	447.3	450.0	455.2	479.4	484.3
Elevation of bed from flood measurement							
At nose of pier	488.1	486.3	465.5	469.4	469.9	480.6	487.5

Table 59. Computed and measured pier scour for the flood of January 1, 1991, at U.S. Route 35 over Kankakee River at Union Center, Indiana

[ft^3/s, cubic feet per second; all elevations refer to feet above sea level; ft/s, feet per second; mm, millimeters; *, pier width at surveyed bed elevation; **, deposition is not included in the computation of bed elevation]

Hydraulic characteristic or equation used	Bent number	
	2	3
Total discharge, in ft^3/s	1,600	1,600
Water-surface elevation	682.0	682.0
Approach depth, in feet	11.3	8.1
Approach velocity, in ft/s	2.2	2.0
Measured velocity, in ft/s	2.32	1.46
Angle of attack, in degrees	0	8
Estimated grain size, in mm	.35	.35
Pier width*, in feet	1.0	1.0
Pier length, in feet	11.0	11.0
Pier-nose shape	Cylinders	Cylinders
Computed depth of pier scour, in feet		
Ahmad	3.9	3.4
Arkansas	3.1	2.9
Blench-Inglis I	-.2**	2.8
Blench-Inglis II	-2.6**	.7
Chitale	2.0	1.8
Froehlich	1.1	1.7
HEC-18	2.0	3.2
Inglis-Lacey	-.4**	2.8
Inglis-Poona I	-2.3**	.7
Inglis-Poona II	.2	2.7
Larras	1.4	2.8
Laursen	3.3	5.4
Shen	1.3	2.2
Shen-Maza	1.8	3.1
Computed elevation of bed at nose of bent		
Ahmad	666.8	670.5
Arkansas	667.6	671.0
Blench-Inglis I	670.7	671.1
Blench-Inglis II	670.7	673.2
Chitale	668.7	672.1
Froehlich	669.6	672.2
HEC-18	668.7	670.7
Inglis-Lacey	670.7	671.1
Inglis-Poona I	670.7	673.2
Inglis-Poona II	670.5	671.2
Larras	669.3	671.1
Laursen	667.4	668.5
Shen	669.4	671.7
Shen-Maza	668.9	670.8
Elevation of bed from flood measurement		
At nose of pier	671.0	674.3

Table 60. Computed and measured pier scour for the flood of January 1, 1991, at U.S. Route 41 (southbound lane) over Kankakee River at Schneider, Indiana

[ft^3/s, cubic feet per second; all elevations refer to feet above sea level; ft/s, feet per second; mm, millimeters; *, pier width at surveyed bed elevation; **, deposition is not included in the computation of bed elevation]

Hydraulic characteristic or equation used	Pier number	
	2	3
Total discharge, in ft^3/s	6,160	6,160
Water-surface elevation	634.8	634.8
Approach depth, in feet	10.2	19.0
Approach velocity, in ft/s	3.2	4.1
Measured velocity, in ft/s	2.85	4.18
Angle of attack, in degrees	11	11
Estimated grain size, in mm	.22	.22
Pier width*, in feet	3.0	3.0
Pier length, in feet	36.0	36.0
Pier-nose shape	Round	Round
Computed depth of pier scour, in feet		
Ahmad	8.0	13.7
Arkansas	4.3	5.1
Blench-Inglis I	8.0	10.0
Blench-Inglis II	8.4	9.9
Chitale	4.9	8.3
Froehlich	4.8	6.4
HEC-18	10.0	12.2
Inglis-Lacey	8.3	-.5**
Inglis-Poona I	6.9	8.0
Inglis-Poona II	7.3	9.4
Larras	7.9	7.9
Laursen	12.8	17.5
Shen	6.8	8.0
Shen-Maza	3.4	12.4
Computed elevation of bed at nose of pier		
Ahmad	616.6	602.1
Arkansas	620.3	610.7
Blench-Inglis I	616.6	605.8
Blench-Inglis II	616.2	605.9
Chitale	619.7	607.5
Froehlich	619.8	609.4
HEC-18	614.6	603.6
Inglis-Lacey	616.3	615.8
Inglis-Poona I	617.7	607.8
Inglis-Poona II	617.3	606.4
Larras	616.7	607.9
Laursen	611.8	598.3
Shen	617.8	607.8
Shen-Maza	621.2	603.4
Elevation of bed from flood measurement		
At nose of pier	623.8	617.4

Table 61. Computed and measured pier scour for the flood of January 5, 1993, at State Road 54 over Busseron Creek near Sullivan, Indiana

[ft^3/s, cubic feet per second; all elevations refer to feet above sea level; ft/s, feet per second; mm, millimeters; *, pier width at surveyed bed elevation; **, deposition is not included in the computation of bed elevation]

Hydraulic characteristic or equation used	Bent number 3	Bent number 2
Total discharge, in ft^3/s	1,270	1,270
Water-surface elevation	453.3	453.3
Approach depth, in feet	11.2	12.0
Approach velocity, in ft/s	2.5	2.7
Measured velocity, in ft/s	2.37	2.38
Angle of attack, in degrees	0	0
Estimated grain size, in mm	.58	.58
Pier width*, in feet	2.0	2.0
Pier length, in feet	40.0	40.0
Pier-nose shape	Square	Square
Computed depth of pier scour, in feet		
Ahmad	5.4	6.1
Arkansas	3.2	3.4
Blench-Inglis I	1.9	1.8
Blench-Inglis II	-.9**	-1.0**
Chitale	3.0	3.4
Froehlich	2.1	2.2
HEC-18	3.7	3.8
Inglis-Lacey	-1.9**	-2.7**
Inglis-Poona I	0	0
Inglis-Poona II	2.1	2.0
Larras	3.3	3.3
Laursen	5.2	5.4
Shen	2.2	2.3
Shen-Maza	3.1	3.2
Computed elevation of bed at nose of bent		
Ahmad	436.7	435.2
Arkansas	438.9	437.9
Blench-Inglis I	440.2	439.5
Blench-Inglis II	442.1	441.3
Chitale	439.1	437.9
Froehlich	440.0	439.1
HEC-18	438.4	437.5
Inglis-Lacey	442.1	441.3
Inglis-Poona I	442.1	441.3
Inglis-Poona II	440.0	439.3
Larras	438.8	438.0
Laursen	436.9	435.9
Shen	439.9	439.0
Shen-Maza	439.0	438.1
Elevation of bed from flood measurement		
At nose of pier	442.6	441.7

Table 62. Computed and measured pier scour for the flood of November 13, 1992, at State Road 59 over Eel River north of Clay City, Indiana

[ft^3/s, cubic feet per second; all elevations refer to feet above sea level; ft/s, feet per second; mm, millimeters; *, pier width at surveyed bed elevation; **, deposition is not included in the computation of bed elevation]

Hydraulic characteristic or equation used	Pier number		
	2	3	4
Total discharge, in ft^3/s	9,100	9,100	9,100
Water-surface elevation	553.3	553.3	553.3
Approach depth, in feet	17.2	20.8	10.7
Approach velocity, in ft/s	3.1	3.3	1.4
Measured velocity, in ft/s	1.54	2.52	1.76
Angle of attack, in degrees	0	0	20
Estimated grain size, in mm	.55	.55	.25
Pier width*, in feet	3.2	3.3	2.8
Pier length, in feet	34.0	34.0	34.0
Pier-nose shape	Round	Round	Round
Computed depth of pier scour, in feet			
Ahmad	8.3	9.6	.3
Arkansas	3.8	3.9	3.8
Blench-Inglis I	3.1	2.8	10.0
Blench-Inglis II	-1.1**	-2.3**	3.1
Chitale	4.7	5.3	-.4**
Froehlich	2.7	3.0	5.2
HEC-18	5.3	5.7	9.2
Inglis-Lacey	.9	-2.7**	9.9
Inglis-Poona I	.2	-.8**	1.8
Inglis-Poona II	3.4	3.2	9.0
Larras	3.4	3.5	10.4
Laursen	7.4	8.2	16.9
Shen	3.4	3.6	5.2
Shen-Maza	4.9	5.3	.7
Computed elevation of bed at nose of pier			
Ahmad	527.8	522.9	542.3
Arkansas	532.3	528.6	538.8
Blench-Inglis I	533.0	529.7	532.6
Blench-Inglis II	536.1	532.5	539.5
Chitale	531.4	527.2	542.6
Froehlich	533.4	529.5	537.4
HEC-18	530.8	526.8	533.4
Inglis-Lacey	535.2	532.5	532.7
Inglis-Poona I	535.9	532.5	540.8
Inglis-Poona II	532.7	529.3	533.6
Larras	532.7	529.0	532.2
Laursen	528.7	524.3	525.7
Shen	532.7	528.9	537.4
Shen-Maza	531.2	527.2	541.9
Elevation of bed from flood measurement			
At nose of pier	536.7	532.3	542.7

Table 63. Computed and measured pier scour for the flood of November 12, 1992, at State Road 63 (southbound lane) over Little Vermillion River at Newport, Indiana

[ft³/s, cubic feet per second; all elevations refer to feet above sea level; ft/s, feet per second; mm, millimeters; *, pier width at surveyed bed elevation; **, deposition is not included in the computation of bed elevation]

Hydraulic characteristic or equation used	Pier number	
	3	2
Total discharge, in ft³/s	4,550	4,550
Water-surface elevation	502.0	502.0
Approach depth, in feet	16.8	8.9
Approach velocity, in ft/s	4.6	1.4
Measured velocity, in ft/s	4.76	.90
Angle of attack, in degrees	16	0
Estimated grain size, in mm	.70	.70
Pier width*, in feet	2.0	2.0
Pier length, in feet	43.0	43.0
Pier-nose shape	Round	Round
Computed depth of pier scour, in feet		
Ahmad	15.8	1.0
Arkansas	4.8	2.1
Blench-Inglis I	12.0	2.1
Blench-Inglis II	10.3	-2.1**
Chitale	9.9	.1
Froehlich	7.0	1.3
HEC-18	11.8	2.6
Inglis-Lacey	-3.0**	4.9
Inglis-Poona I	12.2	-1.4**
Inglis-Poona II	11.0	2.2
Larras	10.2	2.4
Laursen	16.4	4.2
Shen	10.6	1.6
Shen-Maza	16.9	.7
Computed elevation of bed at nose of pier		
Ahmad	469.4	492.1
Arkansas	480.4	491.0
Blench-Inglis I	473.2	491.0
Blench-Inglis II	474.9	493.1
Chitale	475.3	493.0
Froehlich	478.2	491.8
HEC-18	473.4	490.5
Inglis-Lacey	485.2	488.2
Inglis-Poona I	473.0	493.1
Inglis-Poona II	474.2	490.9
Larras	475.0	490.7
Laursen	468.8	488.9
Shen	474.6	491.5
Shen-Maza	468.3	492.4
Elevation of bed from flood measurement		
At nose of pier	485.0	492.3

Table 64. Computed and measured pier scour for the flood of January 2, 1991, at State Road 101 over St. Joseph River at Saint Joe, Indiana

[ft^3/s, cubic feet per second; all elevations refer to feet above sea level; ft/s, feet per second; mm, millimeters; *, pier width at surveyed bed elevation]

Hydraulic characteristic or equation used	Pier number		
	2	3	4
Total discharge, in ft^3/s	6,220	6,220	6,220
Water-surface elevation	800.1	800.1	800.1
Approach depth, in feet	14.3	15.4	7.5
Approach velocity, in ft/s	3.0	3.0	2.0
Measured velocity, in ft/s	2.74	3.04	1.20
Angle of attack, in degrees	4	8	31
Estimated grain size, in mm	.55	.55	.25
Pier width*, in feet	2.0	2.0	2.0
Pier length, in feet	37.0	37.0	37.0
Pier-nose shape	Round	Round	Round
Computed depth of pier scour, in feet			
Ahmad	7.8	7.9	3.4
Arkansas	3.7	3.7	4.9
Blench-Inglis I	5.1	7.5	9.9
Blench-Inglis II	1.5	3.0	7.5
Chitale	4.5	4.5	1.9
Froehlich	3.1	4.2	6.2
HEC-18	5.3	6.9	10.2
Inglis-Lacey	1.6	.5	10.7
Inglis-Poona I	2.5	3.9	6.0
Inglis-Poona II	5.0	7.1	8.7
Larras	4.4	6.2	13.8
Laursen	8.3	11.0	14.7
Shen	4.1	5.4	8.1
Shen-Maza	6.1	3.1	1.3
Computed elevation of bed at nose of pier			
Ahmad	778.0	776.8	789.2
Arkansas	782.1	781.0	787.7
Blench-Inglis I	780.7	777.2	782.7
Blench-Inglis II	784.3	781.7	785.1
Chitale	781.3	780.2	790.7
Froehlich	782.7	780.5	786.4
HEC-18	780.5	777.8	782.4
Inglis-Lacey	784.2	784.2	781.9
Inglis-Poona I	783.3	780.8	786.6
Inglis-Poona II	780.8	777.6	783.9
Larras	781.4	778.5	778.8
Laursen	777.5	773.7	777.9
Shen	781.7	779.3	784.5
Shen-Maza	779.7	781.6	791.3
Elevation of bed from flood measurement			
At nose of pier	785.8	784.8	792.0

Table 65. Computed and measured pier scour for the flood of January 1, 1991, at State Road 109 over White River at Anderson, Indiana

[ft^3/s, cubic feet per second; --, no data or computation; all elevations refer to feet above sea level; ft/s, feet per second; mm, millimeters; *, pier width at surveyed bed elevation; **, deposition is not included in the computation of bed elevation]

Hydraulic characteristic or equation used	Pier number					
	2	3	4	5	6	7
Total discharge, in ft^3/s	--	7,700	7,700	7,700	7,700	7,700
Water-surface elevation	--	841.4	841.4	841.4	841.4	841.4
Approach depth, in feet	--	3.7	4.6	10.5	11.6	2.9
Approach velocity, in ft/s	--	1.8	2.7	4.6	4.9	2.1
Measured velocity, in ft/s	--	.83	2.50	5.15	5.37	2.1
Angle of attack, in degrees	--	20	12	12	8	20
Estimated grain size, in mm	0.25	.25	.25	26.5	26.5	.25
Pier width*, in feet	2.5	3.0	3.0	3.5	3.5	3.2
Pier length, in feet	86.0	86.0	86.0	86.0	86.0	86.0
Pier-nose shape	Round	Round	Round	Round	Round	Round
Computed depth of pier scour, in feet						
Ahmad	--	2.7	4.9	13.2	14.9	3.1
Arkansas	--	4.6	6.0	3.1	3.3	5.1
Blench-Inglis I	--	7.7	7.5	12.1	10.8	6.6
Blench-Inglis II	--	7.5	9.0	4.6	3.5	7.8
Chitale	--	1.6	3.1	8.4	9.5	1.9
Froehlich	--	6.2	5.5	5.8	5.0	5.9
HEC-18	--	9.3	8.8	13.7	11.6	10.0
Inglis-Lacey	--	15.8	14.9	-1.5**	-2.6**	16.6
Inglis-Poona I	--	6.1	7.6	14.4	13.7	6.4
Inglis-Poona II	--	6.6	6.5	10.7	9.8	5.6
Larras	--	19.2	13.8	14.1	11.1	19.3
Laursen	--	10.2	8.9	14.7	12.6	9.3
Shen	--	10.1	9.7	13.8	11.7	11.0
Shen-Maza	--	1.1	2.4	7.1	18.9	1.5
Computed elevation of bed at nose of pier						
Ahmad	--	835.0	831.9	817.7	814.9	835.4
Arkansas	--	833.1	830.8	827.8	826.5	833.4
Blench-Inglis I	--	830.0	829.3	818.8	819.0	831.9
Blench-Inglis II	--	830.2	827.8	826.3	826.3	830.7
Chitale	--	836.1	833.7	822.5	820.3	836.6
Froehlich	--	831.5	831.3	825.1	824.8	832.6
HEC-18	--	828.4	828.0	817.2	818.2	828.5
Inglis-Lacey	--	821.9	821.9	830.9	829.8	821.9
Inglis-Poona I	--	831.6	829.2	816.5	816.1	832.1
Inglis-Poona II	--	831.1	830.3	820.2	820.0	832.9
Larras	--	818.5	823.0	816.8	818.7	819.2
Laursen	--	827.5	827.9	816.2	817.2	829.2
Shen	--	827.6	827.1	817.1	818.1	827.5
Shen-Maza	--	836.6	834.4	823.8	810.9	837.0
Elevation of bed from flood measurement						
At nose of pier	--	838.2	836.8	832.3	831.2	838.1

Table 66. Computed and measured pier scour for the flood of August 9, 1992, at State Road 135 over Muscatatuck River at Millport, Indiana

[ft^3/s, cubic feet per second; --, no data or computation; all elevations refer to feet above sea level; ft/s, feet per second; mm, millimeters; *, pier width at surveyed bed elevation; **, deposition is not included in the computation of bed elevation]

Hydraulic characteristic or equation used	Pier number					
	2	3	4	5	6	7
Total discharge, in ft^3/s	--	7,160	7,160	7,160	--	--
Water-surface elevation	--	514.0	514.0	514.0	--	--
Approach depth, in feet	--	16.1	16.5	1.1	--	--
Approach velocity, in ft/s	--	3.0	2.9	1.1	--	--
Measured velocity, in ft/s	--	3.68	2.40	--	--	--
Angle of attack, in degrees	--	0	0	0	--	--
Estimated grain size, in mm	4.80	4.80	4.80	.25	0.25	0.25
Pier width*, in feet	3.5	3.2	3.2	2.8	2.5	3.4
Pier length, in feet	36.0	31.0	31.0	31.0	31.0	36.0
Pier-nose shape	Round	Round	Round	Round	Round	Round
Computed depth of pier scour, in feet						
Ahmad	--	7.7	7.3	1.0	--	--
Arkansas	--	2.8	2.8	3.5	--	--
Blench-Inglis I	--	3.2	3.2	1.4	--	--
Blench-Inglis II	--	-4.4**	-4.8**	1.8	--	--
Chitale	--	4.3	4.0	.6	--	--
Froehlich	--	2.2	2.2	.9	--	--
HEC-18	--	5.2	5.1	2.2	--	--
Inglis-Lacey	--	-4.5**	-4.9**	20.3	--	--
Inglis-Poona I	--	.3	-.1**	1.3	--	--
Inglis-Poona II	--	3.4	3.4	1.2	--	--
Larras	--	3.4	3.4	3.1	--	--
Laursen	--	7.1	7.2	1.7	--	--
Shen	--	3.3	3.2	1.7	--	--
Shen-Maza	--	4.8	4.7	.5	--	--
Computed elevation of bed at nose of pier						
Ahmad	--	490.2	490.2	511.9	--	--
Arkansas	--	495.1	494.7	509.4	--	--
Blench-Inglis I	--	494.7	494.3	511.5	--	--
Blench-Inglis II	--	497.9	497.5	511.1	--	--
Chitale	--	493.6	493.5	512.3	--	--
Froehlich	--	495.7	495.3	512.0	--	--
HEC-18	--	492.7	492.4	510.7	--	--
Inglis-Lacey	--	497.9	497.5	492.6	--	--
Inglis-Poona I	--	497.6	497.5	511.6	--	--
Inglis-Poona II	--	494.5	494.1	511.7	--	--
Larras	--	494.5	494.1	509.8	--	--
Laursen	--	490.8	490.3	511.2	--	--
Shen	--	494.6	494.3	511.2	--	--
Shen-Maza	--	493.1	492.8	512.4	--	--
Elevation of bed from flood measurement						
At nose of pier	--	498.0	496.9	512.9	--	--

Table 67. Computed and measured pier scour for the flood of January 3, 1991, at State Road 157 over White River at Worthington, Indiana

[ft^3/s, cubic feet per second; all elevations refer to feet above sea level; ft/s, feet per second; mm, millimeters; *, pier width at surveyed bed elevation; **, deposition is not included in the computation of bed elevation]

Hydraulic characteristic or equation used	Pier number			
	2	3	4	5
Total discharge, in ft^3/s	43,400	43,400	43,400	43,400
Water-surface elevation	510.6	510.6	510.6	510.6
Approach depth, in feet	7.1	10.4	18.2	23.7
Approach velocity, in ft/s	2.1	3.0	4.4	5.2
Measured velocity, in ft/s	2.82	4.11	4.21	5.44
Angle of attack, in degrees	6	6	2	0
Estimated grain size, in mm	.25	.25	.90	.90
Pier width*, in feet	2.0	3.0	3.0	2.0
Pier length, in feet	46.0	47.5	43.0	42.0
Pier-nose shape	Round	Round	Round	Round
Computed depth of pier scour, in feet				
Ahmad	3.9	7.3	15.3	21.0
Arkansas	5.1	6.5	4.5	5.0
Blench-Inglis I	5.5	7.1	4.9	-.7**
Blench-Inglis II	4.4	6.6	2.1	-3.1**
Chitale	2.3	4.4	9.5	13.1
Froehlich	3.1	4.2	3.5	2.4
HEC-18	4.7	7.5	7.2	5.1
Inglis-Lacey	27.6	24.3	9.8	4.3
Inglis-Poona I	3.6	5.5	4.9	.6
Inglis-Poona II	5.1	6.6	5.0	.1
Larras	6.0	6.7	4.4	2.4
Laursen	6.6	9.8	9.8	6.8
Shen	4.3	5.7	5.2	3.5
Shen-Maza	1.6	3.0	7.8	5.1
Computed elevation of bed at nose of pier				
Ahmad	499.6	492.9	477.1	465.9
Arkansas	498.4	493.7	487.9	481.9
Blench-Inglis I	498.0	493.1	487.5	486.9
Blench-Inglis II	499.1	493.6	490.3	486.9
Chitale	501.2	495.8	482.9	473.8
Froehlich	500.4	496.0	488.9	484.5
HEC-18	498.8	492.7	485.2	481.8
Inglis-Lacey	475.9	475.9	482.6	482.6
Inglis-Poona I	499.9	494.7	487.5	486.3
Inglis-Poona II	498.4	493.6	487.4	486.8
Larras	497.5	493.5	488.0	484.5
Laursen	496.9	490.4	482.6	480.1
Shen	499.2	494.5	487.2	483.4
Shen-Maza	501.9	497.2	484.6	481.8
Elevation of bed from flood measurement				
At nose of pier	503.3	498.0	493.5	485.4

Table 68. Computed and measured pier scour for flood of January 3, 1991, at State Road 163 over Wabash River at Clinton, Indiana

[ft^3/s, cubic feet per second; all elevations refer to feet above sea level; ft/s, feet per second; --, no data or computation; mm, millimeters; *, pier width at surveyed bed elevation; **, deposition is not included in the computation of bed elevation]

Hydraulic characteristic or equation used	Pier number							
	9	8	7	6	5	4	3	2
Total discharge, in ft^3/s	98,200	98,200	98,200	98,200	98,200	98,200	98,200	98,200
Water-surface elevation	481.2	481.2	481.2	481.2	481.2	481.2	481.2	481.2
Approach depth, in feet	9.8	10.0	10.3	10.7	16.9	28.7	33.7	32.2
Approach velocity, in ft/s	1.9	1.9	1.9	2.4	2.4	5.2	5.8	5.6
Measured velocity, in ft/s	--	1.86	1.74	1.86	1.20	6.98	6.16	5.08
Angle of attack, in degrees	6	6	9	15	15	1	1	1
Estimated grain size, in mm	.25	.25	.25	.25	.34	.39	.39	.34
Pier width*, in feet	2.5	2.5	2.5	3.0	3.0	3.0	3.0	3.0
Pier length, in feet	35.5	35.5	35.5	38.0	38.0	38.0	38.0	38.0
Pier-nose shape	Round	Round	Round	Round	Round	Round	Round	Round
Computed depth of pier scour, in feet								
Ahmad	2.8	2.8	2.7	5.1	4.5	22.0	26.7	25.3
Arkansas	4.7	4.7	4.7	5.6	5.4	5.6	6.0	6.0
Blench-Inglis I	5.9	6.0	7.1	9.4	11.4	2.2	1.1	1.5
Blench-Inglis II	2.6	2.5	3.2	6.8	4.3	.5	-.4**	.4
Chitale	1.3	1.3	1.2	2.8	2.0	13.4	16.4	15.5
Froehlich	3.2	3.2	3.8	5.4	6.2	4.0	4.3	4.3
HEC-18	5.4	5.4	6.5	10.7	11.4	7.5	8.0	7.9
Inglis-Lacey	35.7	35.5	35.2	34.8	26.4	13.6	8.6	11.1
Inglis-Poona I	1.8	1.7	2.3	5.5	3.6	1.9	1.3	1.5
Inglis-Poona II	5.5	5.6	6.6	8.5	10.6	2.9	2.1	2.3
Larras	5.6	5.6	6.8	9.6	9.6	3.8	3.8	3.8
Laursen	8.7	8.8	10.6	15.6	19.6	11.3	12.2	11.9
Shen	3.7	3.7	4.4	6.8	6.8	5.0	5.4	5.3
Shen-Maza	1.2	1.2	1.2	2.0	2.0	7.6	8.2	8.0
Computed elevation of bed at nose of pier								
Ahmad	468.6	468.4	468.2	465.4	459.8	430.5	420.8	423.7
Arkansas	466.7	466.5	466.2	464.9	458.9	446.9	441.5	443.0
Blench-Inglis I	465.5	465.2	463.8	461.1	452.9	450.3	446.4	447.5
Blench-Inglis II	468.8	468.7	467.7	463.7	460.0	452.0	447.5	448.6
Chitale	470.1	469.9	469.7	467.7	462.3	439.1	431.1	433.5
Froehlich	468.2	468.0	467.1	465.1	458.1	448.5	443.2	444.7
HEC-18	466.0	465.8	464.4	459.8	452.9	445.0	439.5	441.1
Inglis-Lacey	435.7	435.7	435.7	435.7	437.9	438.9	438.9	437.9
Inglis-Poona I	469.6	469.5	468.6	465.0	460.7	450.6	446.2	447.5
Inglis-Poona II	465.9	465.6	464.3	462.0	453.7	449.6	445.4	446.7
Larras	465.8	465.6	464.1	460.9	454.7	448.7	443.7	445.2
Laursen	462.7	462.4	460.3	454.9	444.7	441.2	435.3	437.1
Shen	467.7	467.5	466.5	463.7	457.5	447.5	442.1	443.7
Shen-Maza	470.2	470.0	469.7	468.5	462.3	444.9	439.3	441.0
Elevation of bed from flood measurement								
At nose of pier	--	--	--	471.3	464.4	450.2	456.0	451.7

SUPPLEMENTAL DATA

Potential Scour Tables

Table 70. Potential scour resulting from the 100-year peak discharge at State Road 1 over St. Marys River at Fort Wayne, Indiana

[ft^3/s, cubic feet per second; all elevations refer to feet above sea level; ft/s, feet per second; mm, millimeters; *, pier width at surveyed bed elevation; **, deposition is not included in computation of bed elevation; --, no data or computation]

Pier-scour characteristic	Pier number			
	2	3	4	5
Total discharge, in ft^3/s	15,700	15,700	15,700	15,700
Water-surface elevation	764.6	764.6	764.6	764.6
Approach depth, in feet	17.5	19.6	18.5	6.4
Approach velocity, in ft/s	4.3	4.4	4.0	1.9
Angle of attack, in degrees	0	0	0	0
Estimated grain size, in mm	88.0	88.0	88.0	.25
Pier width*, in feet	2.0	2.0	2.0	2.0
Pier length, in feet	86.5	86.5	86.5	86.5
Pier-nose shape	Round	Round	Round	Round
Computed depth of scour or elevation (HEC-18)				
Contraction scour, in feet	-11.7**	-11.7**	-11.7**	1.9
Pier scour, in feet	4.5	4.6	4.4	2.8
Computed elevation	742.6	740.4	741.7	753.5

Abutment-scour characteristic	Abutment	
	Left	Right
Total discharge, in ft^3/s	15,700	15,700
Water-surface elevation	764.6	764.6
Abutment location	Edge of channel	Set back
Overbank flow	Yes	Yes
Bedload condition	--	Clear water
Abutment type	Spill through	Spill through
Discharge blocked, in ft^3/s	--	--
Length, in feet	--	--
Approach depth, in feet	--	--
Approach velocity, in ft/s	--	--
Angle of abutment, in degrees	--	--
Estimated grain size, in mm	Riprap	Concrete protection
Abutment toe elevation	747.2	758.0
Computed depth of scour or elevation (Froehlich)		
Contraction scour, in feet	--	--
Abutment scour, in feet	--	--
Computed elevation	--	--

Table 71. Potential scour resulting from the 500-year peak discharge at State Road 1 over St. Marys River at Fort Wayne, Indiana

[ft^3/s, cubic feet per second; all elevations refer to feet above sea level; ft/s, feet per second; mm, millimeters; *, pier width at surveyed bed elevation; **, deposition is not included in computation of bed elevation; --, no data or computation]

Pier-scour characteristic	Pier number			
	2	3	4	5
Total discharge, in ft^3/s	19,400	19,400	19,400	19,400
Water-surface elevation	767.2	767.2	767.2	767.2
Approach depth, in feet	20.1	22.2	21.1	9.0
Approach velocity, in ft/s	4.4	4.7	4.3	2.5
Angle of attack, in degrees	0	0	0	0
Estimated grain size, in mm	88.0	88.0	88.0	.25
Pier width*, in feet	2.0	2.0	2.0	2.0
Pier length, in feet	86.5	86.5	86.5	86.5
Pier-nose shape	Round	Round	Round	Round
Computed depth of scour or elevation (HEC-18)				
Contraction scour, in feet	-13.1**	-13.1**	-13.1**	4.6
Pier scour, in feet	4.6	4.8	4.6	3.3
Computed elevation	742.5	740.2	741.5	750.3

Abutment-scour characteristic	Abutment	
	Left	Right
Total discharge, in ft^3/s	19,400	19,400
Water-surface elevation	767.2	767.2
Abutment location	Edge of channel	Set back
Overbank flow	Yes	Yes
Bedload condition	--	Clear water
Abutment type	Spill through	Spill through
Discharge blocked, in ft^3/s	--	--
Length, in feet	--	--
Approach depth, in feet	--	--
Approach velocity, in ft/s	--	--
Angle of abutment, in degrees	--	--
Estimated grain size, in mm	Riprap	Concrete protection
Abutment toe elevation	747.2	758.0
Computed depth of scour or elevation (Froehlich)		
Contraction scour, in feet	--	--
Abutment scour, in feet	--	--
Computed elevation	--	--

Table 72. Potential scour resulting from the 100-year peak discharge at State Road 9 over Pigeon River at Howe, Indiana

[ft^3/s, cubic feet per second; all elevations refer to feet above sea level; ft/s, feet per second; mm, millimeters; *, pier width at surveyed bed elevation; data in parentheses are for the HIRE equation, which can be applied where the ratio of abutment length to flow depth is greater than 25; --, no data or computation]

Pier-scour characteristic	Bent number 2	Bent number 3
Total discharge, in ft^3/s	1,930	1,930
Water-surface elevation	861.5	861.5
Approach depth, in feet	7.6	5.8
Approach velocity, in ft/s	4.5	4.0
Angle of attack, in degrees	0	4
Estimated grain size, in mm	.50	.50
Pier width*, in feet	2.0	2.0
Pier length, in feet	36.0	36.0
Pier-nose shape	Square	Square
Computed depth of scour or elevation (HEC-18)		
Contraction scour, in feet	3.9	3.9
Pier scour, in feet	4.5	5.8
Computed elevation	845.5	846.0

Abutment-scour characteristic	Abutment Left	Abutment Right
Total discharge, in ft^3/s	1,930	1,930
Water-surface elevation	861.5	861.5
Abutment location	Edge of channel	Edge of channel
Overbank flow	Yes	Yes
Bedload condition	Live bed	Live bed
Abutment type	Spill through	Spill through
Discharge blocked, in ft^3/s	362	473
Length, in feet	347	501
Approach depth, in feet	2.7 (3.0)	2.5 (2.8)
Approach velocity, in ft/s	.4 (1.8)	.4 (1.5)
Angle of abutment, in degrees	15	-15
Estimated grain size, in mm	.50	.50
Abutment toe elevation	858.2	859.7
Computed depth of scour or elevation (Froehlich)		
Contraction scour, in feet	--	--
Abutment scour, in feet	6.7 (7.0)	6.8 (5.7)
Computed elevation	851.5	852.9

Table 73. Potential scour resulting from the 500-year peak discharge at State Road 9 over Pigeon River at Howe, Indiana

[ft^3/s, cubic feet per second; all elevations refer to feet above sea level; ft/s, feet per second; mm, millimeters; *, pier width at surveyed bed elevation; data in parentheses are for the HIRE equation, which can be applied where the ratio of abutment length to flow depth is greater than 25; --, no data or computation]

Pier-scour characteristic	Bent number 2	Bent number 3
Total discharge, in ft^3/s	2,410	2,410
Water-surface elevation	862.0	862.0
Approach depth, in feet	8.1	6.3
Approach velocity, in ft/s	5.3	4.6
Angle of attack, in degrees	0	4
Estimated grain size, in mm	.50	.50
Pier width*, in feet	2.0	2.0
Pier length, in feet	36.0	36.0
Pier-nose shape	Square	Square
Computed depth of scour or elevation (HEC-18)		
Contraction scour, in feet	5.6	5.6
Pier scour, in feet	4.9	6.2
Computed elevation	843.4	843.9

Abutment-scour characteristic	Abutment Left	Abutment Right
Total discharge, in ft^3/s	2,410	2,410
Water-surface elevation	862.0	862.0
Abutment location	Edge of channel	Edge of channel
Overbank flow	Yes	Yes
Bedload condition	Live bed	Live bed
Abutment type	Spill through	Spill through
Discharge blocked, in ft^3/s	478	680
Length, in feet	351	503
Approach depth, in feet	3.2 (3.2)	3.1 (3.0)
Approach velocity, in ft/s	.4 (2.0)	.4 (1.7)
Angle of abutment, in degrees	15	-15
Estimated grain size, in mm	.50	.50
Abutment toe elevation	858.2	859.7
Computed depth of scour or elevation (Froehlich)		
Contraction scour, in feet	--	--
Abutment scour, in feet	7.6 (7.6)	8.1 (6.2)
Computed elevation	850.6	851.6

Table 74. Potential scour resulting from the 100-year peak discharge at State Road 11 over Flatrock River at Columbus, Indiana

[ft^3/s, cubic feet per second; all elevations refer to feet above sea level; ft/s, feet per second; mm, millimeters; *, pier width at surveyed bed elevation; --, no data or computation; **, deposition is not included in computation of bed elevation]

Pier-scour characteristic	Pier number					
	2	3	4	5	6	7
Total discharge, in ft^3/s	32,500	32,500	32,500	32,500	32,500	32,500
Flow through bridge, in ft^3/s	20,500	20,500	20,500	20,500	20,500	20,500
Water-surface elevation	627.4	627.4	627.4	627.4	627.4	627.4
Approach depth, in feet	15.1	26.8	16.9	19.2	18.2	13.5
Approach velocity, in ft/s	1.9	3.4	2.4	2.6	2.5	1.7
Angle of attack, in degrees	0	0	0	0	0	0
Estimated grain size, in mm	Riprap	3.10	.25	.25	.25	.25
Pier width*, in feet	2.8	4.8	3.8	4.1	4.0	2.8
Pier length, in feet	47.0	47.0	47.0	47.0	47.0	47.0
Pier-nose shape	Round	Round	Round	Round	Round	Round
Computed depth of scour or elevation (HEC-18)						
Contraction scour, in feet	--	-4.6**	3.9	3.9	3.9	3.9
Pier scour, in feet	--	7.6	5.3	5.9	5.7	3.6
Computed elevation	--	593.0	601.3	598.4	599.6	606.4

Abutment-scour characteristic	Abutment	
	Left	Right
Total discharge, in ft^3/s	32,500	32,500
Water-surface elevation	627.4	627.4
Abutment location	Set back	Set back
Overbank flow	Yes	No
Bedload condition	Clear water	Clear water
Abutment type	Spill through	Spill through
Discharge blocked, in ft^3/s	--	0
Length, in feet	--	--
Approach depth, in feet	--	--
Approach velocity, in ft/s	--	--
Angle of abutment, in degrees	--	--
Estimated grain size, in mm	Riprap/pavement	--
Abutment toe elevation	612.3	613.9
Computed depth of scour or elevation (Froehlich)		
Contraction scour, in feet	--	--
Abutment scour, in feet	--	--
Computed elevation	--	--

Table 75. Potential scour resulting from the 500-year peak discharge at State Road 11 over Flatrock River at Columbus, Indiana

[ft^3/s, cubic feet per second; all elevations refer to feet above sea level; ft/s, feet per second; mm, millimeters; *, pier width at surveyed bed elevation; --, no data or computation; **, deposition is not included in computation of bed elevation]

Pier-scour characteristic	Pier number 2	3	4	5	6	7
Total discharge, in ft^3/s	43,000	43,000	43,000	43,000	43,000	43,000
Flow through bridge, in ft^3/s	22,800	22,800	22,800	22,800	22,800	22,800
Water-surface elevation	628.5	628.5	628.5	628.5	628.5	628.5
Approach depth, in feet	16.2	27.9	18.0	20.3	19.3	14.6
Approach velocity, in ft/s	2.1	3.8	2.7	2.9	2.8	1.9
Angle of attack, in degrees	0	0	0	0	0	0
Estimated grain size, in mm	Riprap	3.10	.25	.25	.25	.25
Pier width*, in feet	2.8	4.8	3.8	4.1	4.0	2.8
Pier length, in feet	47.0	47.0	47.0	47.0	47.0	47.0
Pier-nose shape	Round	Round	Round	Round	Round	Round
Computed depth of scour or elevation (HEC-18)						
Contraction scour, in feet	--	-6.6**	5.1	5.1	5.1	5.1
Pier scour, in feet	--	8.0	5.6	6.2	6.0	3.8
Computed elevation	--	592.6	599.8	596.9	598.1	605.0

Abutment-scour characteristic	Abutment Left	Right
Total discharge, in ft^3/s	43,000	43,000
Water-surface elevation	628.5	628.5
Abutment location	Set back	Set back
Overbank flow	Yes	No
Bedload condition	Clear Water	Clear water
Abutment type	Spill through	Spill through
Discharge blocked, in ft^3/s	--	0
Length, in feet	--	--
Approach depth, in feet	--	--
Approach velocity, in ft/s	--	--
Angle of abutment, in degrees	--	--
Estimated grain size, in mm	Riprap/pavement	--
Abutment toe elevation	612.3	613.9
Computed depth of scour or elevation (Froehlich)		
Contraction scour, in feet	--	--
Abutment scour, in feet	--	--
Computed elevation	--	--

Table 76. Potential scour resulting from the 100-year peak discharge at State Road 14 over Tippecanoe River at Winamac, Indiana

[ft^3/s, cubic feet per second; all elevations refer to feet above sea level; ft/s, feet per second; mm, millimeters; *, pier width at surveyed bed elevation; **, deposition is not included in computation of bed elevation; --, no data or computation; data in parentheses are for the HIRE equation, which can be applied where the ratio of abutment length to flow depth is greater than 25]

Pier-scour characteristic	Pier number 6	5	4	3	2
Total discharge, in ft^3/s	10,800	10,800	10,800	10,800	10,800
Water-surface elevation	692.2	692.2	692.2	692.2	692.2
Approach depth, in feet	5.5	12.3	16.0	13.3	8.9
Approach velocity, in ft/s	1.7	3.2	3.7	3.3	1.7
Angle of attack, in degrees	0	0	0	0	0
Estimated grain size, in mm	.25	.55	.55	.55	.25
Pier width*, in feet	2.3	2.6	2.9	2.7	2.7
Pier length, in feet	37.0	37.0	37.0	37.0	37.0
Pier-nose shape	Round	Round	Round	Round	Round
Computed depth of scour or elevation (HEC-18)					
Contraction scour, in feet	1.4	-2.8**	-2.8**	-2.8**	3.6
Pier scour, in feet	2.8	4.5	5.3	4.7	3.4
Computed elevation	682.5	675.4	670.9	674.2	676.3

Abutment-scour characteristic	Abutment Left	Right
Total discharge, in ft^3/s	10,800	10,800
Water-surface elevation	692.2	692.2
Abutment location	Set back	Set back
Overbank flow	Yes	No
Bedload condition	Clear water	Clear water
Abutment type	Spill through	Spill through
Discharge blocked, in ft^3/s	284	0
Length, in feet	218	--
Approach depth, in feet	2.5 (6.0)	--
Approach velocity, in ft/s	.5 (1.7)	--
Angle of abutment, in degrees	0	--
Estimated grain size, in mm	.25	--
Abutment toe elevation	688.0	683.3
Computed depth of scour or elevation (Froehlich)		
Contraction scour, in feet	1.4	3.6
Abutment scour, in feet	6.3 (12.0)	0
Computed elevation	680.3	679.7

Table 77. Potential scour resulting from the 500-year peak discharge at State Road 14 over Tippecanoe River at Winamac, Indiana

[ft^3/s, cubic feet per second; all elevations refer to feet above sea level; ft/s, feet per second; mm, millimeters; *, pier width at surveyed bed elevation; **, deposition is not included in computation of bed elevation; data in parentheses are for the HIRE equation, which can be applied where the ratio of abutment length to flow depth is greater than 25]

Pier-scour characteristic	Pier number				
	6	5	4	3	2
Total discharge, in ft^3/s	13,400	13,400	13,400	13,400	13,400
Water-surface elevation	693.7	693.7	693.7	693.7	693.7
Approach depth, in feet	7.0	13.8	17.5	14.8	10.4
Approach velocity, in ft/s	1.8	3.4	4.0	3.7	1.9
Angle of attack, in degrees	0	0	0	0	0
Estimated grain size, in mm	.25	.55	.55	.55	.25
Pier width*, in feet	2.3	2.6	2.9	2.7	2.7
Pier length, in feet	37.0	37.0	37.0	37.0	37.0
Pier-nose shape	Round	Round	Round	Round	Round
Computed depth of scour or elevation (HEC-18)					
Contraction scour, in feet	2.4	-2.7**	-2.7**	-2.7**	5.3
Pier scour, in feet	3.0	4.7	5.6	5.0	3.6
Computed elevation	681.3	675.2	670.6	673.9	674.4

Abutment-scour characteristic	Abutment	
	Left	Right
Total discharge, in ft^3/s	13,400	13,400
Water-surface elevation	693.7	693.7
Abutment location	Set back	Set back
Overbank flow	Yes	Yes
Bedload condition	Clear water	Clear water
Abutment type	Spill through	Spill through
Discharge blocked, in ft^3/s	525	244
Length, in feet	338	220
Approach depth, in feet	3.0 (6.8)	1.0 (7.6)
Approach velocity, in ft/s	.5 (1.8)	1.1 (1.9)
Angle of abutment, in degrees	0	0
Estimated grain size, in mm	.25	.25
Abutment toe elevation	688.0	683.3
Computed depth of scour or elevation (Froehlich)		
Contraction scour, in feet	2.4	5.3
Abutment scour, in feet	7.7 (13.6)	5.7 (15.2)
Computed elevation	677.9	672.3

Table 78. Potential scour resulting from the 100-year peak discharge at State Road 15 over Little Elkhart River at Bristol, Indiana

[ft^3/s, cubic feet per second; all elevations refer to feet above sea level; ft/s, feet per second; mm, millimeters; *, pier width at surveyed bed elevation; data in parentheses are for the HIRE equation, which can be applied where the ratio of abutment length to flow depth is greater than 25]

Pier-scour characteristic	Pier number 2
Total discharge, in ft^3/s	2,600
Water-surface elevation	755.5
Approach depth, in feet	9.3
Approach velocity, in ft/s	5.5
Angle of attack, in degrees	0
Estimated grain size, in mm	.50
Pier width*, in feet	2.0
Pier length, in feet	37.0
Pier-nose shape	Round
Computed depth of scour or elevation (HEC-18)	
Contraction scour, in feet	9.2
Pier scour, in feet	4.6
Pier scour for exposed footing	9.3
Computed elevation	727.7

Abutment-scour characteristic	Abutment: Left	Abutment: Right
Total discharge, in ft^3/s	2,600	2,600
Water-surface elevation	755.5	755.5
Abutment location	Edge of channel	Edge of channel
Overbank flow	Yes	Yes
Bedload condition	Live bed	Live bed
Abutment type	Wing wall	Wing wall
Discharge blocked, in ft^3/s	407	1,300
Length, in feet	148	259
Approach depth, in feet	3.2	6.0 (6.0)
Approach velocity, in ft/s	.9	.8 (2.2)
Angle of abutment, in degrees	15	-15
Estimated grain size, in mm	.50	.50
Abutment toe elevation	748.9	749.9
Computed depth of scour or elevation (Froehlich)		
Contraction scour, in feet	9.2	9.2
Abutment scour, in feet	10.2	15.9 (18.1)
Computed elevation	729.5	724.8

Table 79. Potential scour resulting from the 500-year peak discharge at State Road 15 over Little Elkhart River at Bristol, Indiana

[ft^3/s, cubic feet per second; all elevations refer to feet above sea level; ft/s, feet per second; mm, millimeters; *, pier width at surveyed bed elevation; data in parentheses are for the HIRE equation, which can be applied where the ratio of abutment length to flow depth is greater than 25]

Pier-scour characteristic	Pier number 2
Total discharge, in ft^3/s	3,120
Water-surface elevation	756.0
Approach depth, in feet	9.8
Approach velocity, in ft/s	6.3
Angle of attack, in degrees	0
Estimated grain size, in mm	.50
Pier width*, in feet	2.0
Pier length, in feet	37.0
Pier-nose shape	Round
Computed depth of scour or elevation (HEC-18)	
Contraction scour, in feet	10.5
Pier scour, in feet	4.9
Pier scour for exposed footing	10.1
Computed elevation	725.6

Abutment-scour characteristic	Abutment Left	Abutment Right
Total discharge, in ft^3/s	3,120	3,120
Water-surface elevation	756.0	756.0
Abutment location	Edge of channel	Edge of channel
Overbank flow	Yes	Yes
Bedload condition	Live bed	Live bed
Abutment type	Wing wall	Wing wall
Discharge blocked, in ft^3/s	550	1,530
Length, in feet	151	259
Approach depth, in feet	3.7	6.6 (6.5)
Approach velocity, in ft/s	1.0	.9 (2.4)
Angle of abutment, in degrees	15	-15
Estimated grain size, in mm	.50	.50
Abutment toe elevation	748.9	749.9
Computed depth of scour or elevation (Froehlich)		
Contraction scour, in feet	10.5	10.5
Abutment scour, in feet	11.7	17.2 (19.9)
Computed elevation	726.7	722.2

Table 80. Potential scour resulting from the 100-year peak discharge at State Road 19 over Wabash River at Peru, Indiana

[ft^3/s, cubic feet per second; all elevations refer to feet above sea level; ft/s, feet per second; mm, millimeters; *, pier width at surveyed bed elevation; **, deposition is not included in computation of bed elevation; --, no data or computation]

Pier-scour characteristic	Pier number 2	Pier number 3
Total discharge, in ft^3/s	31,000	31,000
Water-surface elevation	638.5	638.5
Approach depth, in feet	18.5	19.4
Approach velocity, in ft/s	6.4	6.6
Angle of attack, in degrees	0	0
Estimated grain size, in mm	90.0	90.0
Pier width*, in feet	3.4	3.4
Pier length, in feet	67.0	67.0
Pier-nose shape	Round	Round
Computed depth of scour or elevation (HEC-18)		
Contraction scour, in feet	-8.2**	-8.2**
Pier scour, in feet	7.6	7.7
Computed elevation	612.4	611.4
Bedrock elevation	610.8	609.9

Abutment-scour characteristic	Abutment Left	Abutment Right
Total discharge, in ft^3/s	31,000	31,000
Water-surface elevation	638.5	638.5
Abutment location	Edge of channel	Edge of channel
Overbank flow	No	No
Bedload condition	--	--
Abutment type	End bent	End bent
Discharge blocked, in ft^3/s	0	0
Length, in feet	0	0
Approach depth, in feet	--	--
Approach velocity, in ft/s	--	--
Angle of abutment, in degrees	--	--
Estimated grain size, in mm	--	--
Abutment toe elevation	--	--
Computed depth of scour or elevation (Froehlich)		
Contraction scour, in feet	-8.2	-8.2
Abutment scour, in feet	--	--
Computed elevation	--	--

Table 81. Potential scour resulting from the 500-year peak discharge at State Road 19 over Wabash River at Peru, Indiana

[ft^3/s, cubic feet per second; all elevations refer to feet above sea level; ft/s, feet per second; mm, millimeters; *, pier width at surveyed bed elevation; **, deposition is not included in computation of bed elevation; --, no data or computation]

Pier-scour characteristic	Pier number 2	Pier number 3
Total discharge, in ft^3/s	68,000	68,000
Water-surface elevation	647.4	647.4
Approach depth, in feet	27.4	28.3
Approach velocity, in ft/s	10.4	10.6
Angle of attack, in degrees	0	0
Estimated grain size, in mm	90.0	90.0
Pier width*, in feet	3.4	3.4
Pier length, in feet	67.0	67.0
Pier-nose shape	Round	Round
Computed depth of scour or elevation (HEC-18)		
Contraction scour, in feet	-4.9**	-4.9**
Pier scour, in feet	9.9	10.0
Computed elevation	610.1	609.1
Bedrock elevation	610.8	609.9

Abutment-scour characteristic	Abutment Left	Abutment Right
Total discharge, in ft^3/s	68,000	68,000
Water-surface elevation	647.4	647.4
Abutment location	Edge of channel	Edge of channel
Overbank flow	No	No
Bedload condition	--	--
Abutment type	End bent	End bent
Discharge blocked, in ft^3/s	0	0
Length, in feet	0	0
Approach depth, in feet	--	--
Approach velocity, in ft/s	--	--
Angle of abutment, in degrees	--	--
Estimated grain size, in mm	--	--
Abutment toe elevation	--	--
Computed depth of scour or elevation (Froehlich)		
Contraction scour, in feet	-4.9	-4.9
Abutment scour, in feet	--	--
Computed elevation	--	--

Table 82. Potential scour resulting from the 100-year peak discharge at State Road 25 over Wildcat Creek at Lafayette, Indiana

[ft^3/s, cubic feet per second; all elevations refer to feet above sea level; ft/s, feet per second; mm, millimeters; *, pier width at surveyed bed elevation; **, deposition is not included in computation of bed elevation; --, no data or computation; data in parentheses are for the HIRE equation, which can be applied where the ratio of abutment length to flow depth is greater than 25]

Pier-scour characteristic	Pier number 2	3	4	5	6	7	8
Total discharge, in ft^3/s	28,000	28,000	28,000	28,000	28,000	28,000	28,000
Water-surface elevation	538.9	538.9	538.9	538.9	538.9	538.9	538.9
Approach depth, in feet	6.6	8.1	10.8	15.9	20.2	11.4	4.6
Approach velocity, in ft/s	2.9	3.6	4.5	6.1	6.9	4.3	3.4
Angle of attack, in degrees	0	0	10	14	10	0	0
Estimated grain size, in mm	.22	.22	3.50	1.50	1.50	.22	Riprap
Pier width*, in feet	2.8	2.5	2.7	3.0	3.2	2.6	2.6
Pier length, in feet	104	104	104	104	104	104	104
Pier-nose shape	Round	Round	Round	Round	Round	Round	Round
Computed depth of scour or elevation (HEC-18)							
Contraction scour, in feet	-1.4**	-1.4**	-1.4**	-1.4**	-1.4**	-1.4**	--
Pier scour, in feet	4.1	4.4	10.5	16.1	15.3	5.1	--
Computed elevation	528.2	526.4	517.6	506.9	503.4	522.4	--

Abutment-scour characteristic	Abutment Left	Right
Total discharge, in ft^3/s	28,000	28,000
Water-surface elevation	538.9	538.9
Abutment location	Set back	Set back
Overbank flow	Yes	Yes
Bedload condition	Clear water	Clear water
Abutment type	Spill through	Spill through
Discharge blocked, in ft^3/s	1,040	621
Length, in feet	97	142
Approach depth, in feet	4.2	1.8 (6.4)
Approach velocity, in ft/s	2.5	2.4 (3.4)
Angle of abutment, in degrees	-30	30
Estimated grain size, in mm	.22	.22
	532.3	532.1
Computed depth of scour or elevation (Froehlich)		
Contraction scour, in feet	-1.4**	-1.4**
Abutment scour, in feet	11.8	9.4 (16.9)
Computed elevation	520.5	522.7

Table 83. Potential scour resulting from the 500-year peak discharge at State Road 25 over Wildcat Creek at Lafayette, Indiana

[ft^3/s, cubic feet per second; all elevations refer to feet above sea level; ft/s, feet per second; mm, millimeters; *, pier width at surveyed bed elevation; **, deposition is not included in computation of bed elevation; --, no data or computation; data in parentheses are for the HIRE equation, which can be applied where the ratio of abutment length to flow depth is greater than 25]

Pier-scour characteristic	Pier number 2	3	4	5	6	7	8
Total discharge, in ft^3/s	35,400	35,400	35,400	35,400	35,400	35,400	35,400
Water-surface elevation	540.9	540.9	540.9	540.9	540.9	540.9	540.9
Approach depth, in feet	8.6	10.1	12.8	17.9	22.2	13.4	6.6
Approach velocity, in ft/s	3.2	4.2	4.8	6.6	7.5	4.9	3.7
Angle of attack, in degrees	0	0	10	14	10	0	0
Estimated grain size, in mm	.22	.22	3.50	1.50	1.50	.22	Riprap
Pier width*, in feet	2.8	2.5	2.7	3.0	3.2	2.6	2.6
Pier length, in feet	104	104	104	104	104	104	104
Pier-nose shape	Round	Round	Round	Round	Round	Round	Round
Computed depth of scour or elevation (HEC-18)							
Contraction scour, in feet	-1.2**	-1.2**	-1.2**	-1.2**	-1.2**	-1.2**	--
Pier scour, in feet	4.5	4.8	11.0	17.0	16.1	5.5	--
Computed elevation	527.8	526.0	517.1	506.0	502.6	522.0	--

Abutment-scour characteristic	Abutment Left	Right
Total discharge, in ft^3/s	35,400	35,400
Water-surface elevation	540.9	540.9
Abutment location	Set back	Set back
Overbank flow	Yes	Yes
Bedload condition	Clear water	Clear water
Abutment type	Spill through	Spill through
Discharge blocked, in ft^3/s	1,800	1,060
Length, in feet	101	142
Approach depth, in feet	5.9	3.7 (7.4)
Approach velocity, in ft/s	3.0	2.0 (3.7)
Angle of abutment, in degrees	-30	30
Estimated grain size, in mm	.22	.22
Abutment toe elevation	532.3	532.1
Computed depth of scour or elevation (Froehlich)		
Contraction scour, in feet	-1.2**	-1.2**
Abutment scour, in feet	15.3	11.9 (19.6)
Computed elevation	517.0	520.2

Table 84. Potential scour resulting from the 100-year peak discharge at State Road 32 over Wabash River at Perrysville, Indiana

[ft^3/s, cubic feet per second; all elevations refer to feet above sea level; ft/s, feet per second; mm, millimeters; *, pier width at surveyed bed elevation; --, no data or computation]

Pier-scour characteristic	Pier number						
	8	7	6	5	4	3	2
Total discharge, in ft^3/s	109,000	109,000	109,000	109,000	109,000	109,000	109,000
Water-surface elevation	500.6	500.6	500.6	500.6	500.6	500.6	500.6
Approach depth, in feet	12.6	13.6	34.9	32.5	32.0	18.6	13.7
Approach velocity, in ft/s	2.8	2.8	6.4	6.0	6.0	3.2	3.2
Angle of attack, in degrees	15	15	15	15	15	15	15
Estimated grain size, in mm	.25	.25	.47	.37	.30	.25	.25
Pier width*, in feet	3.0	3.0	3.0	7.9	3.0	3.0	3.0
Pier length, in feet	18.5	38.0	38.0	42.0	38.0	38.0	18.5
Pier-nose shape	Round	Round	Round	Round	Round	Round	Round
Computed depth of scour or elevation (HEC-18)							
Contraction scour, in feet	8.2	8.2	29.1	29.1	29.1	11.7	11.7
Pier scour, in feet	8.3	11.8	19.1	23.0	18.4	13.0	8.9
Pier scour for exposed footing	13.3	--	31.4	43.7	31.3	--	16.9
Computed elevation	466.5	467.0	405.2	395.3	408.2	457.3	458.3
Bedrock elevation	427.9	419.0	419.7	429.7	439.4	443.9	445.0

Abutment-scour characteristic	Abutment	
	Left	Right
Total discharge, in ft^3/s	109,000	109,000
Water-surface elevation	500.6	500.6
Abutment location	Set back	Set back
Overbank flow	Yes	Yes
Bedload condition	Clear water	Clear water
Abutment type	Spur dike	Spur dike
Discharge blocked, in ft^3/s	--	--
Length, in feet	--	--
Approach depth, in feet	--	--
Approach velocity, in ft/s	--	--
Angle of abutment, in degrees	--	--
Estimated grain size, in mm	--	--
Abutment toe elevation	489.1	486.9
Computed depth of scour or elevation (Froehlich)		
Contraction scour, in feet	8.2	11.7
Abutment scour, in feet	--	--
Computed elevation	--	--

Table 85. Potential scour resulting from the 500-year peak discharge at State Road 32 over Wabash River at Perrysville, Indiana

[ft^3/s, cubic feet per second; all elevations refer to feet above sea level; ft/s, feet per second; mm, millimeters; *, pier width at surveyed bed elevation; --, no data or computation]

Pier-scour characteristic	Pier number						
	8	7	6	5	4	3	2
Total discharge, in ft^3/s	136,000	136,000	136,000	136,000	136,000	136,000	136,000
Flow through bridge, in ft^3/s	131,000	131,000	131,000	131,000	131,000	131,000	131,000
Water-surface elevation	502.9	502.9	502.9	502.9	502.9	502.9	502.9
Approach depth, in feet	14.9	15.9	37.2	34.8	34.3	20.9	16.0
Approach velocity, in ft/s	3.2	3.2	6.8	6.6	6.6	3.5	3.5
Angle of attack, in degrees	15	15	15	15	15	15	15
Estimated grain size, in mm	.25	.25	.47	.37	.30	.25	.25
Pier width*, in feet	3.0	3.0	3.0	7.9	3.0	3.0	3.0
Pier length, in feet	18.5	38.0	38.0	42.0	38.0	38.0	18.5
Pier-nose shape	Round	Round	Round	Round	Round	Round	Round
Computed depth of scour or elevation (HEC-18)							
Contraction scour, in feet	12.1	12.1	33.1	33.1	33.1	15.3	15.3
Pier scour, in feet	9.0	12.8	19.8	24.2	19.3	13.8	9.4
Pier scour for exposed footing	15.2	--	32.8	46.4	33.3	--	18.7
Computed elevation	460.7	462.1	399.8	388.6	402.2	452.9	452.9
Bedrock elevation	427.9	419.0	419.7	429.7	439.4	443.9	445.0

Abutment-scour characteristic	Abutment	
	Left	Right
Total discharge, in ft^3/s	136,000	136,000
Water-surface elevation	502.9	502.9
Abutment location	Set back	Set back/spur dike
Overbank flow	Yes	Yes
Bedload condition	Clear water	Clear water
Abutment type	Spur dike	Spur dike
Discharge blocked, in ft^3/s	--	--
Length, in feet	--	--
Approach depth, in feet	--	--
Approach velocity, in ft/s	--	--
Angle of abutment, in degrees	--	--
Estimated grain size, in mm	--	--
Abutment toe elevation	489.1	486.9
Computed depth of scour or elevation (Froehlich)		
Contraction scour, in feet	12.1	15.3
Abutment scour, in feet	--	--
Computed elevation	--	--

Table 86. Potential scour resulting from the 100-year peak discharge at U.S. Route 35 over Kankakee River at Union Center, Indiana

[ft^3/s, cubic feet per second; all elevations refer to feet above sea level; ft/s, feet per second; mm, millimeters; *, pier width at surveyed bed elevation; **, deposition is not included in computation of bed elevation; --, no data or computation]

Pier-scour characteristic	Bent number 2	Bent number 3
Total discharge, in ft^3/s	1,530	1,530
Water-surface elevation	681.7	681.7
Approach depth, in feet	10.6	7.7
Approach velocity, in ft/s	2.3	2.0
Angle of attack, in degrees	0	8
Estimated grain size, in mm	.35	.35
Pier width*, in feet	1.0	1.0
Pier length, in feet	11.0	11.0
Pier-nose shape	Cylinders	Cylinders
Computed depth of scour or elevation (HEC-18)		
Contraction scour, in feet	-0.2**	-0.2**
Pier scour, in feet	2.0	3.2
Computed elevation	669.1	670.8

Abutment-scour characteristic	Abutment Left	Abutment Right
Total discharge, in ft^3/s	1,530	1,530
Water-surface elevation	681.7	681.7
Abutment location	Edge of channel	Edge of channel
Overbank flow	No	No
Bedload condition	--	--
Abutment type	End bent	End bent
Discharge blocked, in ft^3/s	0	0
Length, in feet	0	0
Approach depth, in feet	--	--
Approach velocity, in ft/s	--	--
Angle of abutment, in degrees	--	--
Estimated grain size, in mm	--	--
Abutment toe elevation	--	--
Computed depth of scour or elevation (Froehlich)		
Contraction scour, in feet	--	--
Abutment scour, in feet	--	--
Computed elevation	--	--

Table 87. Potential scour resulting from the 500-year peak discharge at U.S. Route 35 over Kankakee River at Union Center, Indiana

[ft^3/s, cubic feet per second; all elevations refer to feet above sea level; ft/s, feet per second; mm, millimeters; *, pier width at surveyed bed elevation; **, deposition is not included in computation of bed elevation; --, no data or computation]

Pier-scour characteristic	Bent number 2	Bent number 3
Total discharge, in ft^3/s	1,730	1,730
Water-surface elevation	682.5	682.5
Approach depth, in feet	11.4	8.5
Approach velocity, in ft/s	2.3	2.1
Angle of attack, in degrees	0	8
Estimated grain size, in mm	.35	.35
Pier width*, in feet	1.0	1.0
Pier length, in feet	11.0	11.0
Pier-nose shape	Cylinders	Cylinders
Computed depth of scour or elevation (HEC-18)		
Contraction scour, in feet	-0.4**	-0.4**
Pier scour, in feet	2.1	3.3
Computed elevation	669.0	670.7

Abutment-scour characteristic	Abutment Left	Abutment Right
Total discharge, in ft^3/s	1,730	1,730
Water-surface elevation	682.5	682.5
Abutment location	Edge of channel	Edge of channel
Overbank flow	No	No
Bedload condition	--	--
Abutment type	End bent	End bent
Discharge blocked, in ft^3/s	0	0
Length, in feet	0	0
Approach depth, in feet	--	--
Approach velocity, in ft/s	--	--
Angle of abutment, in degrees	--	--
Estimated grain size, in mm	--	--
Abutment toe elevation	--	--
Computed depth of scour or elevation (Froehlich)		
Contraction scour, in feet	--	--
Abutment scour, in feet	--	--
Computed elevation	--	--

Table 88. Potential scour resulting from the 100-year peak discharge at U.S. Route 41 (southbound lane) over Kankakee River at Schneider, Indiana

[ft^3/s, cubic feet per second; all elevations refer to feet above sea level; ft/s, feet per second; mm, millimeters; *, pier width at surveyed bed elevation; --, no data or computation]

Pier-scour characteristic	Pier number 2	Pier number 3
Total discharge, in ft^3/s	7,400	7,400
Water-surface elevation	635.4	635.4
Approach depth, in feet	10.5	19.2
Approach velocity, in ft/s	3.2	4.5
Angle of attack, in degrees	11	11
Estimated grain size, in mm	.22	.22
Pier width*, in feet	3.0	3.0
Pier length, in feet	36.0	36.0
Pier-nose shape	Round	Round
Computed depth of scour or elevation (HEC-18)		
Contraction scour, in feet	3.8	3.8
Pier scour, in feet	10.1	12.7
Pier scour for exposed footing	--	14.5
Computed elevation	611.0	597.9

Abutment-scour characteristic	Abutment Left	Abutment Right
Total discharge, in ft^3/s	7,400	7,400
Water-surface elevation	635.4	635.4
Abutment location	Edge of channel	Edge of channel
Overbank flow	No	No
Bedload condition	--	--
Abutment type	End bent	End bent
Discharge blocked, in ft^3/s	0	0
Length, in feet	0	0
Approach depth, in feet	--	--
Approach velocity, in ft/s	--	--
Angle of abutment, in degrees	--	--
Estimated grain size, in mm	--	--
Abutment toe elevation	--	--
Computed depth of scour or elevation (Froehlich)		
Contraction scour, in feet	--	--
Abutment scour, in feet	--	--
Computed elevation	--	--

Table 89. Potential scour resulting from the 500-year peak discharge at U.S. Route 41 (southbound lane) over Kankakee River at Schneider, Indiana

[ft^3/s, cubic feet per second; all elevations refer to feet above sea level; ft/s, feet per second; mm, millimeters; *, pier width at surveyed bed elevation; --, no data or computation]

Pier-scour characteristic	Pier number 2	Pier number 3
Total discharge, in ft^3/s	8,480	8,480
Water-surface elevation	636.0	636.0
Approach depth, in feet	11.1	19.8
Approach velocity, in ft/s	3.7	4.9
Angle of attack, in degrees	11	11
Estimated grain size, in mm	.22	.22
Pier width*, in feet	3.0	3.0
Pier length, in feet	36.0	36.0
Pier-nose shape	Round	Round
Computed depth of scour or elevation (HEC-18)		
Contraction scour, in feet	4.8	4.8
Pier scour, in feet	10.8	13.2
Pier scour for exposed footing	--	15.3
Computed elevation	609.3	596.1

Abutment-scour characteristic	Abutment Left	Abutment Right
Total discharge, in ft^3/s	8,480	8,480
Water-surface elevation	636.0	636.0
Abutment location	Edge of channel	Edge of channel
Overbank flow	No	No
Bedload condition	--	--
Abutment type	End bent	End bent
Discharge blocked, in ft^3/s	0	0
Length, in feet	0	0
Approach depth, in feet	--	--
Approach velocity, in ft/s	--	--
Angle of abutment, in degrees	--	--
Estimated grain size, in mm	--	--
Abutment toe elevation	--	--
Computed depth of scour or elevation (Froehlich)		
Contraction scour, in feet	--	--
Abutment scour, in feet	--	--
Computed elevation	--	--

Table 90. Potential scour resulting from the 100-year peak discharge at State Road 54 over Busseron Creek near Sullivan, Indiana

[ft^3/s, cubic feet per second; all elevations refer to feet above sea level; ft/s, feet per second; mm, millimeters; *, pier width at surveyed bed elevation; data in parentheses are for the HIRE equation, which can be applied where the ratio of abutment length to flow depth is greater than 25]

Pier-scour characteristic	Bent number 3	Bent number 2
Total discharge, in ft^3/s	7,450	7,450
Flow through bridge, in ft^3/s	4,120	4,120
Water-surface elevation	456.4	456.4
Approach depth, in feet	14.2	14.1
Approach velocity, in ft/s	5.5	5.5
Angle of attack, in degrees	0	0
Estimated grain size, in mm	.58	.58
Pier width*, in feet	2.0	2.0
Pier length, in feet	40.0	40.0
Pier-nose shape	Square	Square
Computed depth of scour or elevation (HEC-18)		
Contraction scour, in feet	10.7	10.7
Pier scour, in feet	5.4	5.4
Computed elevation	426.1	426.2

Abutment-scour characteristic	Abutment Left	Abutment Right
Total discharge, in ft^3/s	7,450	7,450
Water-surface elevation	456.4	456.4
Abutment location	Edge of channel	Edge of channel
Overbank flow	Yes	Yes
Bedload condition	Clear water	Clear water
Abutment type	Vertical	Vertical
Discharge blocked, in ft^3/s	1,800	1,280
Length, in feet	1,210	542
Approach depth, in feet	5.2 (6.8)	3.8 (6.6)
Approach velocity, in ft/s	.3 (2.1)	.6 (1.9)
Angle of abutment, in degrees	0	0
Estimated grain size, in mm	.25	.25
Abutment toe elevation	451.8	451.8
Computed depth of scour or elevation (Froehlich)		
Contraction scour, in feet	10.7	10.7
Abutment scour, in feet	17.2 (26.3)	16.3 (24.5)
Computed elevation	423.9	424.8

Table 91. Potential scour resulting from the 500-year peak discharge at State Road 54 over Busseron Creek near Sullivan, Indiana

[ft^3/s, cubic feet per second; all elevations refer to feet above sea level; ft/s, feet per second; mm, millimeters; *, pier width at surveyed bed elevation; data in parentheses are for the HIRE equation, which can be applied where the ratio of abutment length to flow depth is greater than 25]

Pier-scour characteristic	Bent number 3	Bent number 2
Total discharge, in ft^3/s	9,250	9,250
Flow through bridge, in ft^3/s	5,080	5,080
Water-surface elevation	456.9	456.9
Approach depth, in feet	14.7	14.6
Approach velocity, in ft/s	6.8	6.8
Angle of attack, in degrees	0	0
Estimated grain size, in mm	.58	.58
Pier width*, in feet	2.0	2.0
Pier length, in feet	40.0	40.0
Pier-nose shape	Square	Square
Computed depth of scour or elevation (HEC-18)		
Contraction scour, in feet	14.5	14.5
Pier scour, in feet	5.9	5.9
Computed elevation	421.8	421.9

Abutment-scour characteristic	Abutment Left	Abutment Right
Total discharge, in ft^3/s	9,250	9,250
Water-surface elevation	456.9	456.9
Abutment location	Edge of channel	Edge of channel
Overbank flow	Yes	Yes
Bedload condition	Clear water	Clear water
Abutment type	Vertical	Vertical
Discharge blocked, in ft^3/s	2,240	1,640
Length, in feet	1,210	562
Approach depth, in feet	5.7 (7.2)	4.2 (7.1)
Approach velocity, in ft/s	.3 (2.6)	.7 (2.3)
Angle of abutment, in degrees	0	0
Estimated grain size, in mm	.25	.25
Abutment toe elevation	451.8	451.8
Computed depth of scour or elevation (Froehlich)		
Contraction scour, in feet	14.5	14.5
Abutment scour, in feet	19.0 (29.9)	18.3 (27.8)
Computed elevation	418.3	419.0

Table 92. Potential scour resulting from the 100-year peak discharge at State Road 57 over East Fork White River near Petersburg, Indiana

[ft^3/s, cubic feet per second; all elevations refer to feet above sea level; ft/s, feet per second; mm, millimeters; *, pier width at surveyed bed elevation; --, no data or computation; data in parentheses are for the HIRE equation, which can be applied where the ratio of abutment length to flow depth is greater than 25]

Pier-scour characteristic	Pier number				
	2	3	4	5	6
Total discharge, in ft^3/s	117,000	117,000	117,000	117,000	117,000
Water-surface elevation	432.1	432.1	432.1	432.1	432.1
Approach depth, in feet	23.5	31.6	23.5	13.8	12.3
Approach velocity, in ft/s	7.6	8.3	7.0	4.5	3.7
Angle of attack, in degrees	0	0	0	0	0
Estimated grain size, in mm	.70	.70	.70	.25	.25
Pier width*, in feet	4.7	5.5	4.7	3.8	3.7
Pier length, in feet	50.0	50.0	50.0	50.0	50.0
Pier-nose shape	Round	Round	Round	Round	Round
Computed depth of scour or elevation (HEC-18)					
Contraction scour, in feet	44.9	44.9	44.9	19.2	19.2
Pier scour, in feet	10.4	12.5	10.1	6.8	6.0
Pier scour for exposed footing	16.3	21.0	15.7	--	--
Computed elevation	347.4	334.6	348.0	392.3	394.6
Bedrock elevation	399.0	--	354.0	359.5	339.0

Abutment-scour characteristic	Abutment	
	Left	Right
Total discharge, in ft^3/s	117,000	117,000
Water-surface elevation	432.1	432.1
Abutment location	Edge of channel	Set back
Overbank flow	No	Yes
Bedload condition	--	Clear water
Abutment type	End bent	Spill through
Discharge blocked, in ft^3/s	0	73,600
Length, in feet	0	9,320
Approach depth, in feet	--	11.7 (11.6)
Approach velocity, in ft/s	--	.7 (3.7)
Angle of abutment, in degrees	--	0
Estimated grain size, in mm	--	.25
Abutment toe elevation	--	419.9
Computed depth of scour or elevation (Froehlich)		
Contraction scour, in feet	--	19.2
Abutment scour, in feet	--	45.0 (26.9)
Computed elevation	--	355.7

Table 93. Potential scour resulting from the 500-year peak discharge at State Road 57 over East Fork White River near Petersburg, Indiana

[ft^3/s, cubic feet per second; all elevations refer to feet above sea level; ft/s, feet per second; mm, millimeters; *, pier width at surveyed bed elevation; --, no data or computation; data in parentheses are for the HIRE equation, which can be applied where the ratio of abutment length to flow depth is greater than 25]

Pier-scour characteristic	Pier number				
	2	3	4	5	6
Total discharge, in ft^3/s	152,000	152,000	152,000	152,000	152,000
Water-surface elevation	434.5	434.5	434.5	434.5	434.5
Approach depth, in feet	25.9	34.0	25.9	16.2	14.7
Approach velocity, in ft/s	8.6	9.6	8.6	5.6	4.5
Angle of attack, in degrees	0	0	0	0	0
Estimated grain size, in mm	.70	.70	.70	.25	.25
Pier width*, in feet	4.7	5.5	4.7	3.8	3.7
Pier length, in feet	50.0	50.0	50.0	50.0	50.0
Pier-nose shape	Round	Round	Round	Round	Round
Computed depth of scour or elevation (HEC-18)					
Contraction scour, in feet	58.6	58.6	58.6	28.7	28.7
Pier scour, in feet	11.2	13.4	11.2	7.6	6.7
Pier scour for exposed footing	18.2	23.4	18.2	10.4	10.3
Computed elevation	331.8	318.5	331.8	379.2	380.8
Bedrock elevation	399.0	--	354.0	359.5	339.0

Abutment-scour characteristic	Abutment	
	Left	Right
Total discharge, in ft^3/s	152,000	152,000
Water-surface elevation	434.5	434.5
Abutment location	Edge of channel	Set back
Overbank flow	No	Yes
Bedload condition	--	Clear water
Abutment type	End bent	Spill through
Discharge blocked, in ft^3/s	0	102,650
Length, in feet	0	9,370
Approach depth, in feet	--	14.5 (13.2)
Approach velocity, in ft/s	--	.8 (4.5)
Angle of abutment, in degrees	--	0
Estimated grain size, in mm	--	.25
Abutment toe elevation	--	419.9
Computed depth of scour or elevation (Froehlich)		
Contraction scour, in feet	--	28.7
Abutment scour, in feet	--	52.3 (31.9)
Computed elevation	--	338.9

Table 94. Potential scour resulting from the 100-year peak discharge at State Road 59 over Eel River north of Clay City, Indiana

[ft^3/s, cubic feet per second; all elevations refer to feet above sea level; ft/s, feet per second; mm, millimeters; *, pier width at surveyed bed elevation; --, no data or computation; data in parentheses are for the HIRE equation, which can be applied where the ratio of abutment length to flow depth is greater than 25]

Pier-scour characteristic	Pier number 2	Pier number 3	Pier number 4
Total discharge, in ft^3/s	38,000	38,000	38,000
Flow through bridge, in ft^3/s	27,600	27,600	27,600
Water-surface elevation	556.5	556.5	556.5
Approach depth, in feet	20.4	23.8	13.9
Approach velocity, in ft/s	7.4	7.8	5.3
Angle of attack, in degrees	0	0	20
Estimated grain size, in mm	.55	.55	.25
Pier width*, in feet	3.2	3.3	2.8
Pier length, in feet	34.0	34.0	34.0
Pier-nose shape	Round	Round	Round
Computed depth of scour or elevation (HEC-18)			
Contraction scour, in feet	6.7	6.7	17.4
Pier scour, in feet	7.9	8.4	16.8
Pier scour for exposed footing	--	11.9	17.3
Computed elevation	521.5	514.1	507.9

Abutment-scour characteristic	Abutment Left	Abutment Right
Total discharge, in ft^3/s	38,000	38,000
Water-surface elevation	556.5	556.5
Abutment location	Edge of channel	Set back
Overbank flow	Yes	Yes
Bedload condition	Clear water	Clear water
Abutment type	Spill through	Spill through
Discharge blocked, in ft^3/s	2,780	6,670
Length, in feet	863	2,250
Approach depth, in feet	2.8 (7.5)	3.1 (7.2)
Approach velocity, in ft/s	1.2 (2.8)	1.0 (3.0)
Angle of abutment, in degrees	0	0
Estimated grain size, in mm	.25	.25
Abutment toe elevation	553.9	545.2
Computed depth of scour or elevation (Froehlich)		
Contraction scour, in feet	--	17.4
Abutment scour, in feet	14.1 (17.0)	18.8 (16.8)
Computed elevation	539.8	509.0

Table 95. Potential scour resulting from the 500-year peak discharge at State Road 59 over Eel River north of Clay City, Indiana

[ft^3/s, cubic feet per second; all elevations refer to feet above sea level; ft/s, feet per second; mm, millimeters; *, pier width at surveyed bed elevation; data in parentheses are for the HIRE equation, which can be applied where the ratio of abutment length to flow depth is greater than 25; --, no data or computation]

Pier-scour characteristic	Pier number 2	Pier number 3	Pier number 4
Total discharge, in ft^3/s	47,100	47,100	47,100
Flow through bridge, in ft^3/s	31,200	31,200	31,200
Water-surface elevation	557.0	557.0	557.0
Approach depth, in feet	20.9	24.3	14.4
Approach velocity, in ft/s	7.9	8.5	5.7
Angle of attack, in degrees	0	0	20
Estimated grain size, in mm	.55	.55	.25
Pier width*, in feet	3.2	3.3	2.8
Pier length, in feet	34.0	34.0	34.0
Pier-nose shape	Round	Round	Round
Computed depth of scour or elevation (HEC-18)			
Contraction scour, in feet	11.0	11.0	20.8
Pier scour, in feet	8.1	8.8	17.5
Pier scour for exposed footing	15.0	16.0	20.8
Computed elevation	510.1	505.7	501.0

Abutment-scour characteristic	Abutment Left	Abutment Right
Total discharge, in ft^3/s	47,100	47,100
Water-surface elevation	557.0	557.0
Abutment location	Edge of channel	Set back
Overbank flow	Yes	Yes
Bedload condition	Clear water	Clear water
Abutment type	Spill through	Spill through
Discharge blocked, in ft^3/s	4,040	9,200
Length, in feet	863	2,250
Approach depth, in feet	3.8 (7.3)	4.1 (7.3)
Approach velocity, in ft/s	1.2 (3.1)	1.0 (3.2)
Angle of abutment, in degrees	0	0
Estimated grain size, in mm	.25	.25
Abutment toe elevation	553.9	545.2
Computed depth of scour or elevation (Froehlich)		
Contraction scour, in feet	--	20.8
Abutment scour, in feet	16.6 (17.2)	21.4 (17.4)
Computed elevation	537.3	503.0

Table 96. Potential scour resulting from the 100-year peak discharge at State Road 63 (southbound lane) over Little Vermillion River at Newport, Indiana

[ft^3/s, cubic feet per second; all elevations refer to feet above sea level; ft/s, feet per second; mm, millimeters; *, pier width at surveyed bed elevation; --, no data or computation; data in parentheses are for the HIRE equation, which can be applied where the ratio of abutment length to flow depth is greater than 25]

Pier-scour characteristic	Pier number 3	Pier number 2
Total discharge, in ft^3/s	11,000	11,000
Water-surface elevation	503.3	503.3
Approach depth, in feet	17.4	10.2
Approach velocity, in ft/s	10.4	5.7
Angle of attack, in degrees	16	0
Estimated grain size, in mm	.70	.70
Pier width*, in feet	2.0	2.0
Pier length, in feet	43.0	43.0
Pier-nose shape	Round	Round
Computed depth of scour or elevation (HEC-18)		
Contraction scour, in feet	21.1	21.1
Pier scour, in feet	16.9	4.7
Pier scour for exposed footing	25.7	11.0
Computed elevation	439.1	461.0

Abutment-scour characteristic	Abutment Left	Abutment Right
Total discharge, in ft^3/s	11,000	11,000
Water-surface elevation	503.3	503.3
Abutment location	Edge of channel	Set back
Overbank flow	Yes	Yes
Bedload condition	--	Clear water
Abutment type	Spill through	Spill through
Discharge blocked, in ft^3/s	--	1,000
Length, in feet	--	722
Approach depth, in feet	--	2.4 (3.8)
Approach velocity, in ft/s	--	.6 (3.7)
Angle of abutment, in degrees	--	0
Estimated grain size, in mm	--	.70
Abutment toe elevation	--	500.4
Computed depth of scour or elevation (Froehlich)		
Contraction scour, in feet	--	21.1
Abutment scour, in feet	--	9.0 (10.6)
Computed elevation	--	470.3

Table 97. Potential scour resulting from the 500-year peak discharge at State Road 63 (southbound lane) over Little Vermillion River at Newport, Indiana

[ft^3/s, cubic feet per second; all elevations refer to feet above sea level; ft/s, feet per second; mm, millimeters; *, pier width at surveyed bed elevation; --, no data or computation; data in parentheses are for the HIRE equation, which can be applied where the ratio of abutment length to flow depth is greater than 25]

Pier-scour characteristic	Pier number 3	Pier number 2
Total discharge, in ft^3/s	14,100	14,100
Water-surface elevation	503.5	503.5
Approach depth, in feet	17.6	10.4
Approach velocity, in ft/s	12.8	7.3
Angle of attack, in degrees	16	0
Estimated grain size, in mm	.70	.70
Pier width*, in feet	2.0	2.0
Pier length, in feet	43.0	43.0
Pier-nose shape	Round	Round
Computed depth of scour or elevation (HEC-18)		
Contraction scour, in feet	28.5	28.5
Pier scour, in feet	18.5	5.3
Pier scour for exposed footing	29.5	12.9
Computed elevation	427.9	451.7

Abutment-scour characteristic	Abutment Left	Abutment Right
Total discharge, in ft^3/s	14,100	14,100
Water-surface elevation	503.5	503.5
Abutment location	Edge of channel	Set back
Overbank flow	Yes	Yes
Bedload condition	--	Clear water
Abutment type	Spill through	Spill through
Discharge blocked, in ft^3/s	--	1,820
Length, in feet	--	722
Approach depth, in feet	--	3.4 (3.9)
Approach velocity, in ft/s	--	.7 (4.5)
Angle of abutment, in degrees	--	0
Estimated grain size, in mm	--	.70
Abutment toe elevation	--	500.4
Computed depth of scour or elevation (Froehlich)		
Contraction scour, in feet	--	28.5
Abutment scour, in feet	--	11.9 (11.5)
Computed elevation	--	460.0

Table 98. Potential scour resulting from the 100-year peak discharge at State Road 101 over St. Joseph River at Saint Joe, Indiana

[ft^3/s, cubic feet per second; all elevations refer to feet above sea level; ft/s, feet per second; mm, millimeters; *, pier width at surveyed bed elevation; data in parentheses are for the HIRE equation, which can be applied where the ratio of abutment length to flow depth is greater than 25]

Pier-scour characteristic	Pier number 2	3	4
Total discharge, in ft^3/s	11,900	11,900	11,900
Water-surface elevation	801.9	801.9	801.9
Approach depth, in feet	16.1	17.4	9.3
Approach velocity, in ft/s	5.0	5.0	3.5
Angle of attack, in degrees	4	8	31
Estimated grain size, in mm	.55	.55	.25
Pier width*, in feet	2.0	2.0	2.0
Pier length, in feet	37.0	37.0	37.0
Pier-nose shape	Round	Round	Round
Computed depth of scour or elevation (HEC-18)			
Contraction scour, in feet	3.6	3.6	8.1
Pier scour, in feet	6.7	8.7	13.5
Computed elevation	775.5	772.2	771.0

Abutment-scour characteristic	Abutment Left	Right
Total discharge, in ft^3/s	11,900	11,900
Water-surface elevation	801.9	801.9
Abutment location	Set back	Set back
Overbank flow	Yes	Yes
Bedload condition	Clear water	Clear water
Abutment type	Spill through	Spill through
Discharge blocked, in ft^3/s	2,130	835
Length, in feet	658	160
Approach depth, in feet	3.2 (7.2)	4.8 (6.1)
Approach velocity, in ft/s	1.0 (1.4)	1.1 (2.4)
Angle of abutment, in degrees	26	-26
Estimated grain size, in mm	.25	.25
Abutment toe elevation	799.6	793.7
Computed depth of scour or elevation (Froehlich)		
Contraction scour, in feet	0.2	8.1
Abutment scour, in feet	13.2 (13.8)	10.7 (12.3)
Computed elevation	786.2	774.9

Table 99. Potential scour resulting from the 500-year peak discharge at State Road 101 over St. Joseph River at Saint Joe, Indiana

[ft^3/s, cubic feet per second; all elevations refer to feet above sea level; ft/s, feet per second; mm, millimeters; *, pier width at surveyed bed elevation; data in parentheses are for the HIRE equation, which can be applied where the ratio of abutment length to flow depth is greater than 25]

Pier-scour characteristic	Pier number 2	3	4
Total discharge, in ft^3/s	15,100	15,100	15,100
Water-surface elevation	803.5	803.5	803.5
Approach depth, in feet	17.7	19.0	10.9
Approach velocity, in ft/s	5.6	5.6	4.1
Angle of attack, in degrees	4	8	31
Estimated grain size, in mm	.55	.55	.25
Pier width*, in feet	2.0	2.0	2.0
Pier length, in feet	37.0	37.0	37.0
Pier-nose shape	Round	Round	Round
Computed depth of scour or elevation (HEC-18)			
Contraction scour, in feet	7.1	7.1	11.9
Pier scour, in feet	7.1	9.2	14.7
Computed elevation	771.6	768.2	766.0

Abutment-scour characteristic	Abutment Left	Right
Total discharge, in ft^3/s	15,100	15,100
Water-surface elevation	803.5	803.5
Abutment location	Set back	Set back
Overbank flow	Yes	Yes
Bedload condition	Clear water	Clear water
Abutment type	Spill through	Spill through
Discharge blocked, in ft^3/s	4,100	1,110
Length, in feet	675	210
Approach depth, in feet	4.9 (7.7)	5.2 (6.8)
Approach velocity, in ft/s	1.2 (1.6)	1.0 (2.7)
Angle of abutment, in degrees	26	-26
Estimated grain size, in mm	.25	.25
Abutment toe elevation	799.6	793.7
Computed depth of scour or elevation (Froehlich)		
Contraction scour, in feet	0.3	11.9
Abutment scour, in feet	17.7 (15.2)	11.7 (14.0)
Computed elevation	781.6	770.1

Table 100. Potential scour resulting from the 100-year peak discharge at State Road 109 over White River at Anderson, Indiana

[ft^3/s, cubic feet per second; all elevations refer to feet above sea level; ft/s, feet per second; mm, millimeters; *, pier width at surveyed bed elevation; --, no data or computation; **, deposition is not included in computation of bed elevation]

Pier-scour characteristic	Pier number					
	2	3	4	5	6	7
Total discharge, in ft^3/s	23,500	23,500	23,500	23,500	23,500	23,500
Water-surface elevation	848.2	848.2	848.2	848.2	848.2	848.2
Approach depth, in feet	5.4	10.5	10.5	16.1	16.4	8.8
Approach velocity, in ft/s	3.2	4.7	4.8	6.5	6.6	3.3
Angle of attack, in degrees	20	20	12	12	8	20
Estimated grain size, in mm	.25	.25	.25	26.5	26.5	.25
Pier width*, in feet	2.5	3.0	3.0	3.5	3.5	3.2
Pier length, in feet	86.0	86.0	86.0	86.0	86.0	86.0
Pier-nose shape	Round	Round	Round	Round	Round	Round
Computed depth of scour or elevation (HEC-18)						
Contraction scour, in feet	--	15.2	15.2	-2.7**	-2.7**	9.9
Pier scour, in feet	11.0	16.1	12.7	16.9	13.9	14.1
Pier scour for exposed footing	--	28.9	26.1	--	--	--
Computed elevation	831.8	793.6	796.4	815.2	817.9	815.4

Abutment-scour characteristic	Abutment	
	Left	Right
Total discharge, in ft^3/s	23,500	23,500
Water-surface elevation	848.2	848.2
Abutment location	Set back	Set back
Overbank flow	Yes	No
Bedload condition	Clear water	--
Abutment type	Spill through	Spill through
Discharge blocked, in ft^3/s	1,470	0
Length, in feet	104	--
Approach depth, in feet	5.9	--
Approach velocity, in ft/s	2.4	--
Angle of abutment, in degrees	-20	--
Estimated grain size, in mm	.25	--
Abutment toe elevation	840.2	841.6
Computed depth of scour or elevation (Froehlich)		
Contraction scour, in feet	15.2	9.9
Abutment scour, in feet	14.3	--
Computed elevation	810.7	--

Table 101. Potential scour resulting from the 500-year peak discharge at State Road 109 over White River at Anderson, Indiana

[ft^3/s, cubic feet per second; all elevations refer to feet above sea level; ft/s, feet per second; mm, millimeters; *, pier width at surveyed bed elevation; --, no data or computation; **, deposition is not included in computation of bed elevation]

Pier-scour characteristic	Pier number 2	3	4	5	6	7
Total discharge, in ft^3/s	31,000	31,000	31,000	31,000	31,000	31,000
Water-surface elevation	850.5	850.5	850.5	850.5	850.5	850.5
Approach depth, in feet	7.7	12.8	12.8	18.4	18.7	11.1
Approach velocity, in ft/s	3.5	5.2	5.5	7.0	7.1	3.7
Angle of attack, in degrees	20	20	12	12	8	20
Estimated grain size, in mm	.25	.25	.25	26.5	26.5	.25
Pier width*, in feet	2.5	3.0	3.0	3.5	3.5	3.2
Pier length, in feet	86.0	86.0	86.0	86.0	86.0	86.0
Pier-nose shape	Round	Round	Round	Round	Round	Round
Computed depth of scour or elevation (HEC-18)						
Contraction scour, in feet	--	21.5	21.5	-3.3**	-3.3**	14.9
Pier scour, in feet	12.1	17.3	13.8	17.7	14.6	15.2
Pier scour for exposed footing	--	33.8	30.9	--	--	21.8
Computed elevation	830.7	782.4	785.3	814.4	817.2	802.7

Abutment-scour characteristic	Abutment Left	Right
Total discharge, in ft^3/s	31,000	31,000
Water-surface elevation	850.5	850.5
Abutment location	Set back	Set back
Overbank flow	Yes	No
Bedload condition	Clear water	--
Abutment type	Spill through	Spill through
Discharge blocked, in ft^3/s	2,260	0
Length, in feet	131	--
Approach depth, in feet	6.7	--
Approach velocity, in ft/s	2.6	--
Angle of abutment, in degrees	-20	--
Estimated grain size, in mm	.25	--
Abutment toe elevation	840.2	841.6
Computed depth of scour or elevation (Froehlich)		
Contraction scour, in feet	21.5	14.9
Abutment scour, in feet	16.7	--
Computed elevation	802.0	--

Table 102. Potential scour resulting from the 100-year peak discharge at State Road 110 over Tippecanoe River near Mentone, Indiana

[ft^3/s, cubic feet per second; all elevations refer to feet above sea level; ft/s, feet per second; mm, millimeters; *, pier width at surveyed bed elevation; data in parentheses are for the HIRE equation, which can be applied where the ratio of abutment length to flow depth is greater than 25; --, no data or computation]

Pier-scour characteristic	Pier number			
	5	4	3	2
Total discharge, in ft^3/s	4,400	4,400	4,400	4,400
Water-surface elevation	764.3	764.3	764.3	764.3
Approach depth, in feet	5.6	10.2	9.5	2.5
Approach velocity, in ft/s	1.5	4.0	3.8	1.8
Angle of attack, in degrees	0	0	0	0
Estimated grain size, in mm	.25	.70	3.60	.25
Pier width*, in feet	2.0	2.0	2.0	2.0
Pier length, in feet	31.5	30.5	30.5	31.5
Pier-nose shape	Round	Round	Round	Round
Computed depth of scour or elevation (HEC-18)				
Contraction scour, in feet	1.6	1.6	1.6	0.8
Pier scour, in feet	2.5	4.0	4.0	2.4
Computed elevation	754.6	748.5	749.2	758.6

Abutment-scour characteristic	Abutment	
	Left	Right
Total discharge, in ft^3/s	4,400	4,400
Water-surface elevation	764.3	764.3
Abutment location	Edge of channel	Set back
Overbank flow	Yes	Yes
Bedload condition	Live bed	Clear water
Abutment type	Spill through	Spill through
Discharge blocked, in ft^3/s	1,190	26
Length, in feet	1,120	20
Approach depth, in feet	2.7 (4.5)	1.0
Approach velocity, in ft/s	.4 (1.5)	1.2
Angle of abutment, in degrees	0	0
Estimated grain size, in mm	.25	.25
Abutment toe elevation	761.6	764.6
Computed depth of scour or elevation (Froehlich)		
Contraction scour, in feet	--	0.8
Abutment scour, in feet	9.2 (9.4)	2.8
Computed elevation	752.4	761.0

Table 103. Potential scour resulting from the 500-year peak discharge at State Road 110 over Tippecanoe River near Mentone, Indiana

[ft^3/s, cubic feet per second; all elevations refer to feet above sea level; ft/s, feet per second; mm, millimeters; *, pier width at surveyed bed elevation; --, no data or computation; data in parentheses are for the HIRE equation, which can be applied where the ratio of abutment length to flow depth is greater than 25]

Pier-scour characteristic	Pier number			
	5	4	3	2
Total discharge, in ft^3/s	5,340	5,340	5,340	5,340
Water-surface elevation	765.1	765.1	765.1	765.1
Approach depth, in feet	6.4	11.0	10.3	3.3
Approach velocity, in ft/s	1.6	4.3	4.2	1.9
Angle of attack, in degrees	0	0	0	0
Estimated grain size, in mm	.25	.70	3.60	.25
Pier width*, in feet	2.0	2.0	2.0	2.0
Pier length, in feet	31.5	30.5	30.5	31.5
Pier-nose shape	Round	Round	Round	Round
Computed depth of scour or elevation (HEC-18)				
Contraction scour, in feet	2.9	2.9	2.9	1.2
Pier scour, in feet	2.6	4.2	4.2	2.5
Pier scour for exposed footing	--	7.5	6.6	--
Computed elevation	753.2	743.7	745.3	758.1

Abutment-scour characteristic	Abutment	
	Left	Right
Total discharge, in ft^3/s	5,340	5,340
Water-surface elevation	765.1	765.1
Abutment location	Edge of channel	Set back
Overbank flow	Yes	Yes
Bedload condition	Live bed	Clear water
Abutment type	Spill through	Spill through
Discharge blocked, in ft^3/s	1,750	53
Length, in feet	1,120	28
Approach depth, in feet	3.6 (4.9)	1.5
Approach velocity, in ft/s	.4 (1.6)	1.2
Angle of abutment, in degrees	0	0
Estimated grain size, in mm	.25	.25
Abutment toe elevation	761.6	764.6
Computed depth of scour or elevation (Froehlich)		
Contraction scour, in feet	--	1.2
Abutment scour, in feet	11.1 (10.3)	3.8
Computed elevation	750.5	759.6

Table 104. Potential scour resulting from the 100-year peak discharge at State Road 135 over Muscatatuck River at Millport, Indiana

[ft^3/s, cubic feet per second; all elevations refer to feet above sea level; ft/s, feet per second; mm, millimeters; *, pier width at surveyed bed elevation; --, no data or computation; data in parentheses are for the HIRE equation, which can be applied where the ratio of abutment length to flow depth is greater than 25]

Pier-scour characteristic	Pier number					
	2	3	4	5	6	7
Total discharge, in ft^3/s	60,000	60,000	60,000	60,000	60,000	60,000
Water-surface elevation	531.1	531.1	531.1	531.1	531.1	531.1
Approach depth, in feet	11.6	33.6	33.5	18.2	12.5	9.6
Approach velocity, in ft/s	3.3	9.7	9.2	5.5	3.3	3.3
Angle of attack, in degrees	0	0	0	0	0	0
Estimated grain size, in mm	4.80	4.80	4.80	.25	.25	.25
Pier width*, in feet	3.5	3.2	3.2	2.8	2.5	3.4
Pier length, in feet	36.0	31.0	31.0	31.0	31.0	36.0
Pier-nose shape	Round	Round	Round	Round	Round	Round
Computed depth of scour or elevation (HEC-18)						
Contraction scour, in feet	--	36.7	36.7	22.0	22.0	22.0
Pier scour, in feet	5.4	9.5	9.3	6.3	4.4	5.2
Pier scour for exposed footing	--	23.7	22.8	11.7	9.7	9.8
Computed elevation	514.1	437.1	438.1	479.2	486.9	489.7
Bedrock elevation	516.0	--	--	468.0	467.0	467.0

Abutment-scour characteristic	Abutment	
	Left	Right
Total discharge, in ft^3/s	60,000	60,000
Water-surface elevation	531.1	531.1
Abutment location	Edge of channel	Set back
Overbank flow	No	Yes
Bedload condition	--	Clear water
Abutment type	End bent	Spill through
Discharge blocked, in ft^3/s	0	22,900
Length, in feet	0	1,890
Approach depth, in feet	--	8.6 (9.4)
Approach velocity, in ft/s	--	1.4 (3.3)
Angle of abutment, in degrees	--	0
Estimated grain size, in mm	Concrete protection	.25
Abutment toe elevation	--	523.2
Computed depth of scour or elevation (Froehlich)		
Contraction scour, in feet	--	22.0
Abutment scour, in feet	--	32.8 (21.7)
Computed elevation	--	468.4

Table 105. Potential scour resulting from the 500-year peak discharge at State Road 135 over Muscatatuck River at Millport, Indiana

[ft^3/s, cubic feet per second; all elevations refer to feet above sea level; ft/s, feet per second; mm, millimeters; *, pier width at surveyed bed elevation; --, no data or computation; data in parentheses are for the HIRE equation, which can be applied where the ratio of abutment length to flow depth is greater than 25]

Pier-scour characteristic	Pier number					
	2	3	4	5	6	7
Total discharge, in ft^3/s	80,500	80,500	80,500	80,500	80,500	80,500
Flow through bridge, in ft^3/s	69,300	69,300	69,300	69,300	69,300	69,300
Water-surface elevation	533.7	533.7	533.7	533.7	533.7	533.7
Approach depth, in feet	14.2	36.2	36.1	20.8	15.1	12.2
Approach velocity, in ft/s	3.3	10.0	10.0	6.7	2.1	2.1
Angle of attack, in degrees	0	0	0	0	0	0
Estimated grain size, in mm	4.80	4.80	4.80	.25	.25	.25
Pier width*, in feet	3.5	3.2	3.2	2.8	2.5	3.4
Pier length, in feet	36.0	31.0	31.0	31.0	31.0	36.0
Pier-nose shape	Round	Round	Round	Round	Round	Round
Computed depth of scour or elevation (HEC-18)						
Contraction scour, in feet	--	41.7	41.7	22.2	22.2	22.2
Pier scour, in feet	5.6	9.7	9.7	7.0	3.7	4.4
Pier scour for exposed footing	--	24.6	24.3	12.9	7.9	8.0
Computed elevation	513.9	431.2	431.6	477.8	488.5	491.3
Bedrock elevation	516.0	--	--	468.0	467.0	467.0

Abutment-scour characteristic	Abutment	
	Left	Right
Total discharge, in ft^3/s	80,500	80,500
Water-surface elevation	533.7	533.7
Abutment location	Edge of channel	Set back
Overbank flow	No	Yes
Bedload condition	--	Clear water
Abutment type	End bent	Spill through
Discharge blocked, in ft^3/s	0	25,500
Length, in feet	0	1,940
Approach depth, in feet	--	11.2 (12.4)
Approach velocity, in ft/s	--	2.2 (2.1)
Angle of abutment, in degrees	--	0
Estimated grain size, in mm	Concrete protection	.25
Abutment toe elevation	--	523.2
Computed depth of scour or elevation (Froehlich)		
Contraction scour, in feet	--	22.2
Abutment scour, in feet	--	37.5 (23.6)
Computed elevation	--	463.5

Table 106. Potential scour resulting from the 100-year peak discharge at State Road 157 over White River at Worthington, Indiana

[ft^3/s, cubic feet per second; all elevations refer to feet above sea level; ft/s, feet per second; mm, millimeters; *, pier width at surveyed bed elevation; **, deposition is not included in computation of bed elevation; --, no data or computation; data in parentheses are for the HIRE equation, which can be applied where the ratio of abutment length to flow depth is greater than 25]

Pier-scour characteristic	Pier number 2	3	4	5
Total discharge, in ft^3/s	102,000	102,000	102,000	102,000
Flow through bridge, in ft^3/s	54,800	54,800	54,800	54,800
Water-surface elevation	513.1	513.1	513.1	513.1
Approach depth, in feet	9.6	12.9	20.7	26.2
Approach velocity, in ft/s	2.4	3.4	4.9	5.8
Angle of attack, in degrees	6	6	2	0
Estimated grain size, in mm	.25	.25	.90	.90
Pier width*, in feet	2.0	3.0	3.0	2.0
Pier length, in feet	46.0	47.5	43.0	42.0
Pier-nose shape	Round	Round	Round	Round
Computed depth of scour or elevation (HEC-18)				
Contraction scour, in feet	7.8	7.8	-3.7**	-3.7**
Pier scour, in feet	5.2	8.1	7.6	5.4
Pier scour for exposed footing	9.1	6.0	--	--
Computed elevation	486.6	484.3	484.8	481.5

Abutment-scour characteristic	Abutment Left	Right
Total discharge, in ft^3/s	102,000	102,000
Water-surface elevation	513.1	513.1
Abutment location	Set back	Edge of channel
Overbank flow	Yes	No
Bedload condition	Clear water	--
Abutment type	Spill through	End bent
Discharge blocked, in ft^3/s	12,780	0
Length, in feet	626	--
Approach depth, in feet	8.5 (8.5)	--
Approach velocity, in ft/s	2.4 (2.4)	--
Angle of abutment, in degrees	-10	--
Estimated grain size, in mm	.25	--
Abutment toe elevation	505.5	--
Computed depth of scour or elevation (Froehlich)		
Contraction scour, in feet	7.8	--
Abutment scour, in feet	28.9 (17.1)	--
Computed elevation	468.8	--

Table 107. Potential scour resulting from the 500-year peak discharge at State Road 157 over White River at Worthington, Indiana

[ft^3/s, cubic feet per second; all elevations refer to feet above sea level; ft/s, feet per second; mm, millimeters; *, pier width at surveyed bed elevation; **, deposition is not included in computation of bed elevation; --, no data or computation; data in parentheses are for the HIRE equation, which can be applied where the ratio of abutment length to flow depth is greater than 25]

Pier-scour characteristic	Pier number 2	3	4	5
Total discharge, in ft^3/s	132,000	132,000	132,000	132,000
Flow through bridge, in ft^3/s	57,400	57,400	57,400	57,400
Water-surface elevation	515.0	515.0	515.0	515.0
Approach depth, in feet	11.5	14.8	22.6	28.1
Approach velocity, in ft/s	2.4	3.3	4.6	5.4
Angle of attack, in degrees	6	6	2	0
Estimated grain size, in mm	.25	.25	.90	.90
Pier width*, in feet	2.0	3.0	3.0	2.0
Pier length, in feet	46.0	47.5	43.0	42.0
Pier-nose shape	Round	Round	Round	Round
Computed depth of scour or elevation (HEC-18)				
Contraction scour, in feet	8.4	8.4	-6.1**	-6.1**
Pier scour, in feet	5.3	8.2	7.5	5.3
Pier scour for exposed footing	9.1	7.0	--	--
Computed elevation	486.0	483.6	484.9	481.6

Abutment-scour characteristic	Abutment Left	Right
Total discharge, in ft^3/s	132,000	132,000
Water-surface elevation	515.0	515.0
Abutment location	Set back	Edge of channel
Overbank flow	Yes	No
Bedload condition	Clear water	--
Abutment type	Spill through	End bent
Discharge blocked, in ft^3/s	17,770	0
Length, in feet	626	--
Approach depth, in feet	10.3 (9.7)	--
Approach velocity, in ft/s	2.8 (2.4)	--
Angle of abutment, in degrees	-10	--
Estimated grain size, in mm	.25	--
Abutment toe elevation	505.5	--
Computed depth of scour or elevation (Froehlich)		
Contraction scour, in feet	8.4	--
Abutment scour, in feet	33.7 (19.1)	--
Computed elevation	463.4	--

Table 108. Potential scour resulting from the 100-year peak discharge at State Road 163 over Wabash River at Clinton, Indiana

[ft^3/s, cubic feet per second; all elevations refer to feet above sea level; ft/s, feet per second; mm, millimeters; *, pier width at surveyed bed elevation; --, no data or computation; data in parentheses are for the HIRE equation, which can be applied where the ratio of abutment length to flow depth is greater than 25]

Pier-scour characteristic	Pier number							
	9	8	7	6	5	4	3	2
Total discharge, in ft^3/s	145,000	145,000	145,000	145,000	145,000	145,000	145,000	145,000
Water-surface elevation	486.2	486.2	486.2	486.2	486.2	486.2	486.2	486.2
Approach depth, in feet	14.8	15.0	15.3	15.7	21.9	36.6	36.9	37.0
Approach velocity, in ft/s	2.6	2.6	3.1	3.1	3.7	6.6	6.6	6.7
Angle of attack, in degrees	6	6	9	15	15	1	1	1
Estimated grain size, in mm	.25	.25	.25	.25	.34	.39	.39	.34
Pier width*, in feet	2.5	2.5	2.5	3.0	3.0	3.0	3.0	3.0
Pier length, in feet	35.5	35.5	35.5	38.0	38.0	38.0	38.0	38.0
Pier-nose shape	Round	Round	Round	Round	Round	Round	Round	Round
Computed depth of scour or elevation (HEC-18)								
Contraction scour, in feet	10.3	10.3	10.3	10.3	10.3	0.2	0.2	0.2
Pier scour, in feet	6.6	6.6	8.5	12.6	14.2	8.6	8.6	8.6
Computed elevation	454.4	454.3	452.1	447.6	439.8	440.8	440.5	440.4

Abutment-scour characteristic	Abutment	
	Left	Right
Total discharge, in ft^3/s	145,000	145,000
Water-surface elevation	486.2	486.2
Abutment location	Set back	Edge of channel
Overbank flow	Yes	No
Bedload condition	Clear water	--
Abutment type	Spill through	End bent
Discharge blocked, in ft^3/s	6,850	0
Length, in feet	397	0
Approach depth, in feet	13.3 (12.6)	--
Approach velocity, in ft/s	1.3 (2.6)	--
Angle of abutment, in degrees	-35	--
Estimated grain size, in mm	.25	--
Abutment toe elevation	472.6	--
Computed depth of scour or elevation (Froehlich)		
Contraction scour, in feet	10.3	--
Abutment scour, in feet	25.7 (21.8)	--
Computed elevation	436.6	--

Table 109. Potential scour resulting from the 500-year peak discharge at State Road 163 over Wabash River at Clinton, Indiana

[ft^3/s, cubic feet per second; all elevations refer to feet above sea level; ft/s, feet per second; mm, millimeters; *, pier width at surveyed bed elevation; --, no data or computation]

Pier-scour characteristic	Pier number 9	8	7	6	5	4	3	2
Total discharge, in ft^3/s	175,000	175,000	175,000	175,000	175,000	175,000	175,000	175,000
Water-surface elevation	488.9	488.9	488.9	488.9	488.9	488.9	488.9	488.9
Approach depth, in feet	17.5	17.7	18.0	18.4	24.6	39.3	39.6	39.7
Approach velocity, in ft/s	2.6	2.6	3.8	3.8	4.2	7.8	7.8	8.1
Angle of attack, in degrees	6	6	9	15	15	1	1	1
Estimated grain size, in mm	.25	.25	.25	.25	.34	.39	.39	.34
Pier width*, in feet	2.5	2.5	2.5	3.0	3.0	3.0	3.0	3.0
Pier length, in feet	35.5	35.5	35.5	38.0	38.0	38.0	38.0	38.0
Pier-nose shape	Round	Round	Round	Round	Round	Round	Round	Round
Computed depth of scour or elevation (HEC-18)								
Contraction scour, in feet	14.5	14.5	14.5	14.5	14.5	1.5	1.5	1.5
Pier scour, in feet	6.7	6.7	9.4	14.0	15.2	9.3	9.3	9.5
Pier scour for exposed footing	5.0	5.6	--	--	--	--	--	--
Computed elevation	450.2	450.0	447.0	442.0	434.6	438.8	438.5	438.2

Abutment-scour characteristic	Abutment Left	Right
Total discharge, in ft^3/s	175,000	175,000
Water-surface elevation	488.9	488.9
Abutment location	Set back	Edge of channel
Overbank flow	Yes	No
Bedload condition	Clear water	--
Abutment type	Spill through	End bent
Discharge blocked, in ft^3/s	10,150	0
Length, in feet	397	0
Approach depth, in feet	16.0	--
Approach velocity, in ft/s	1.6	--
Angle of abutment, in degrees	-35	--
Estimated grain size, in mm	.25	--
Abutment toe elevation	472.6	--
Computed depth of scour or elevation (Froehlich)		
Contraction scour, in feet	14.5	--
Abutment scour, in feet	30.8	--
Computed elevation	427.3	--