Scour Measurements at Bridge Sites During 1993 Upper Mississippi River Basin Flood

DAVID S. MUELLER, MARK N. LANDERS, AND EDWARD E. FISCHER

The record flood on the upper Mississippi River basin during the summer of 1993 provided a rare opportunity for collection of data on streambed scour at bridges and for testing of scour data collection equipment under extreme hydraulic conditions. Real-time scour measurements at bridges are categorized into one of three classes according to their objective: inspection measurements, limited-detail measurements, and detailed measurements. All three types of measurements were made during the 1993 flood. Recent advances in technology and improved application of existing technology allow hydraulic and channel bathymetry data to be collected more accurately, in greater detail, and more efficiently than previously possible. Two limited-detail and two detailed data sets are presented. The observed depths of scour are consistently less than the depths of pier scour estimated by use of recommended procedures. Additional data processing, analysis, and visualization are required to characterize and understand complex processes measured by use of state-of-the-art instrumentation.

The severe flooding in the upper Mississippi River Basin during the summer of 1993 resulted in record peak discharges at 41 streamflow-gaging stations and peak discharges with recurrence intervals of greater than 100 years at 45 stations (*1*). Many bridges spanning streams in this region were subjected to hydraulic conditions equal to or more severe than design conditions. These severe conditions provided a rare opportunity for collection of data on streambed scour at bridges and for testing of newly developed instruments.

Real-time bridge scour data can be categorized into three classes according to the measurement objective: inspection measurements are made to determine bridge safety and are made during routine inspections and during floods, limited-detail measurements are made to evaluate published scour equations or to put practical limits on equations developed solely from laboratory and theoretical research, and detailed measurements are made to help understand the processes causing scour and to evaluate and develop numerical models of these processes. All three types of measurements were made during the 1993 flood in the upper Mississippi River Basin.

INSPECTION MEASUREMENTS

Most bridge inspection data are collected during low flows. Although low flow data are adequate for many aspects of bridge inspections, they are not adequate for identifying scour and stream stability problems that develop during floods. The severity of the hydraulic conditions associated with the 1993 flood in the upper Mississippi River Basin, combined with the uncertainty of the design procedures, caused concern for public safety at the affected bridges. Therefore, the respective state departments of transportation (SDOT) made measurements of streambed elevation at the affected bridges to assess bridge foundation stability.

Inspection measurements during the flood ranged from a small set of streambed elevation measurements in the vicinity of the bridge piers to a complete bathymetric map of the bridge opening. Likewise, the instrumentation ranged from simple sounding weights and low cost echo sounders to expensive scanning sonar (*2*). At the time of the flood, the U.S. Geological Survey (USGS), in cooperation with FHWA, was developing instrumentation for SDOTs to measure scour at bridges (*3*). The flood, therefore, was an opportunity to test and demonstrate the instrumentation being developed.

Instrumentation and Techniques

Inspection data are typically collected from the bridge deck by measurement of streambed elevation along the upstream and downstream edges of the bridge or by measurement of spot streambed elevations near the piers and abutments. At bridges where decks are high above the water surface or where traffic is heavy and shoulders are narrow, a boat may be used to collect the data. Echo sounders—consisting of a processing unit, cable, and transducer—have been found to be superior to sounding weights for measuring streambed elevations in most conditions (*3*). An echo sounder produces a continuous record of the cross section, and the transducer can be floated beneath the bridge to collect data in locations not accessible with a sounding weight. Various types of floats have been tried, including a spherical power line warning marker, rubber balls, a raft made from PVC pipe, and water skis. Spherical floats did not work well because of substantial drag on the sphere when partly submerged and the resulting instability, which caused the transducer to be raised and tilted out of the vertical position. The raft made of polyvinyl chloride pipe worked reasonably well. The SDOTs in Texas and Arkansas have had success using a water ski to deploy a transducer. The primary problems associated with the use of a water ski are air entrainment beneath the transducer and instability during high flows (*3*).

A recreational knee board was modified to deploy a transducer (Figure 1). The knee board is wider and more stable than a water ski. Several echo sounders were used with the transducers mounted on the board, and the transducer cables for each extended to 30.5 m (100 ft). The board was deployed over the side of the bridge and maneuvered around the bridge piers, beneath the bridge, and across

D. S. Mueller, U.S. Geological Survey, 2301 Bradley Avenue, Louisville, Ky. 40217. M. N. Landers, U.S. Geographical Survey, 12201 Sunrise Valley Drive, Reston, Va. 22092. E. E. Fischer, U.S. Geological Survey, P. O. Box 1230, Iowa City, Iowa. 52242.

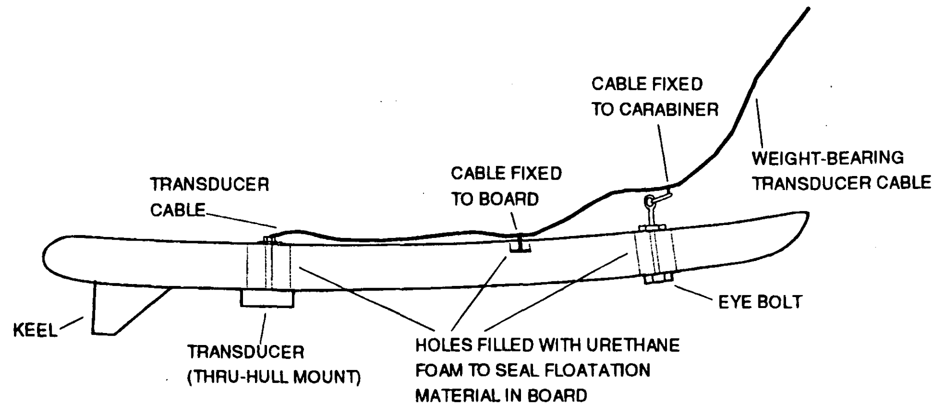

FIGURE 1 Design of knee board for deploying transducer to measure channel bathymetry near bridge.

the stream with a nylon rope. Investigators recorded data in a field notebook from numerical display echo sounders and directly on the strip chart of analog recording echo sounders. The horizontal position of the transducer was estimated visually.

Results of Instrumentation Evaluation

The knee board worked well for collecting inspection data during the 1993 flood. The knee board was deployable by hand and created only a small amount of drag. The board was stable except in the most turbulent water, and it enabled the investigators to collect data along the edges of the bridge and along the sides of the piers. Air entrainment was a problem only in very turbulent water (*3*). Some echo sounders are sensitive to the length of cable and need to be recalibrated for a long cable. The analog recording echo sounder was the preferred instrument. It did not require recalibration when used with a long cable, and it produced a permanent graphic record of the streambed; moreover the site information and horizontal position of the transducer could be recorded directly on the chart. Overall, this knee board deployment system is a valuable tool for making quick measurements of the streambed from the bridge deck.

LIMITED-DETAIL MEASUREMENTS

Limited-detail measurements are valuable for assessing the accuracy of published scour equations and for developing empirical relationships for maximum scour. The limited-detail data set should contain sufficient channel bathymetry to allow local scour to be separated from contraction, general, and long-term scour. Contraction, general, and long-term scour cannot typically be delineated from one another by use of limited-detail measurements only; however, a reasonable estimate of contraction scour can be obtained from some limited-detail data sets. A limited-detail data set should include water discharge, water surface elevation, streambed elevations along the upstream and downstream edges of the bridge, velocity measurements representative of the velocity upstream from each pier (approach velocity), and water temperature. Bed material samples may be collected during the flood or during low flow, if necessary. Notes on debris present, surface velocity directions, channel and overbank roughness, and vegetation cover also should be recorded. Bridge and pier geometry and subsurface bed material classifications are commonly available from bridge plans, although field verification is recommended.

Instrumentation and Techniques

Streambed elevation was measured by use of instrumentation similar to that used for inspection measurements. An analog chart recording echo sounder was used to measure channel cross sections so that a permanent record of the measured data was obtained. The location of the transducer was recorded in reference to various features of the bridge. The horizontal scale for the cross sections was obtained from the horizontal position of the various features as shown on the bridge plans. Standard discharge measurements (*4*) were used to estimate the approach velocity at each pier. Skew of the pier to the approach flow was estimated visually. Bed material samples could not be collected during the flood because of the high velocities and deep water.

Local scour cannot be measured directly; instead, it is determined by interpretation of the streambed elevation data. The depth of local scour is the vertical distance between the measured channel geometry and a surface, line, or point that represents the channel geometry that would exist in the absence of the obstruction. The concurrent ambient bed is the preferred reference surface for local scour because it separates local scour from contraction and long-term scour. The concurrent ambient bed is typically estimated from high flow channel bathymetry by drawing a trend line from the ambient streambed on one side of the scour hole to the ambient streambed on the other side of the scour hole (*5*). Local scour depth is the maximum vertical distance between this trend line and the bottom of the scour hole. Determining the concurrent ambient bed can be difficult and requires engineering judgement, especially for complex cross-section geometries.

Discussion of Data Collected

Limited-detail data were collected at the Martin Luther King Bridge over the Mississippi River at St. Louis, Missouri, and at the State

Highway 99 bridge over the Iowa River at Wapello, Iowa. Scour resulting from various processes was measured at the two bridges.

Martin Luther King Bridge over Mississippi River at St. Louis, Missouri

Channel cross sections were measured at the Martin Luther King Bridge on July 15, 1993 (Figure 2). The cross section along the upstream edge of the bridge clearly indicates a scour hole at Pier 10 that is 4.1 m (13.5 ft) deep. The width of Pier 10 varies with depth; the weighted average pier width, which does not include the width of the caisson below the ambient bed, is 5.5 m (17.9 ft). The pier was sharp nosed (but with a flat internal angle) for the main part of the pier, and the caisson was round nosed; therefore, the shape of the pier was classified as round. The flow was aligned with the pier, the approach depth was 20.0 m (65.7 ft), and the bed material was sand. Approach velocities were estimated from a discharge measurement on the Mississippi River made the same day at the Poplar Street Bridge on I-70, which is about 1.2 km (0.75 mi) downstream from the Martin Luther King Bridge. A nearly straight channel alignment and similarity of the measured cross-sectional areas and channel shape at the two bridges allowed the discharge measurement made at Poplar Street Bridge to be transferred with little error to the Martin Luther King Bridge. The discharge measured on July 15, 1993, was 22,500 m^3/sec (804,000 ft^3/sec), and the mean velocity of the subsection of the river containing Pier 10 was 2.6 m/sec (8.6 ft/sec). For comparison with observed scour the HEC-18 equation (*6*) was used to compute an estimated scour based on the measured velocity and depth, the weighted pier width, small dune bedforms, and a round-nosed pier to represent the pier shape. The resulting estimated depth of scour was 9.2 m (30.2 ft), significantly greater than the 4.1-m (13.5-ft) observed scour depth (Table 1). If a sharp-nosed pier shape is assumed, the computed depth of scour is reduced about 10 percent.

State Highway 99 over Iowa River at Wapello, Iowa

The State Highway 99 bridge over the Iowa River at Wapello, built in 1946, is a 371-m (1,217-ft) multiple span structure with five spans over 194.8 m (639 ft) of the main channel and 11 spans over 176.2 m (578 ft) of the left flood plain (*7*). The concrete piers and footings are supported on wood pilings. The streambed in the main channel is sand and gravel to an elevation of about 154 m (505.3 ft) and is underlain by glacial clay (all elevations are in reference to the National Geodetic Vertical Datum of 1929.) The flood plain in the vicinity of the bridge between the levee and the main channel is covered by dense tree growth. The right abutment and Pier 1 of the bridge were protected with riprap in 1988. The right bank upstream from the bridge was protected with mats in 1992 (*8*).

The Iowa River at Wapello, Iowa, was above flood stage from June 8 through September 22, 1993. A levee on the left overbank

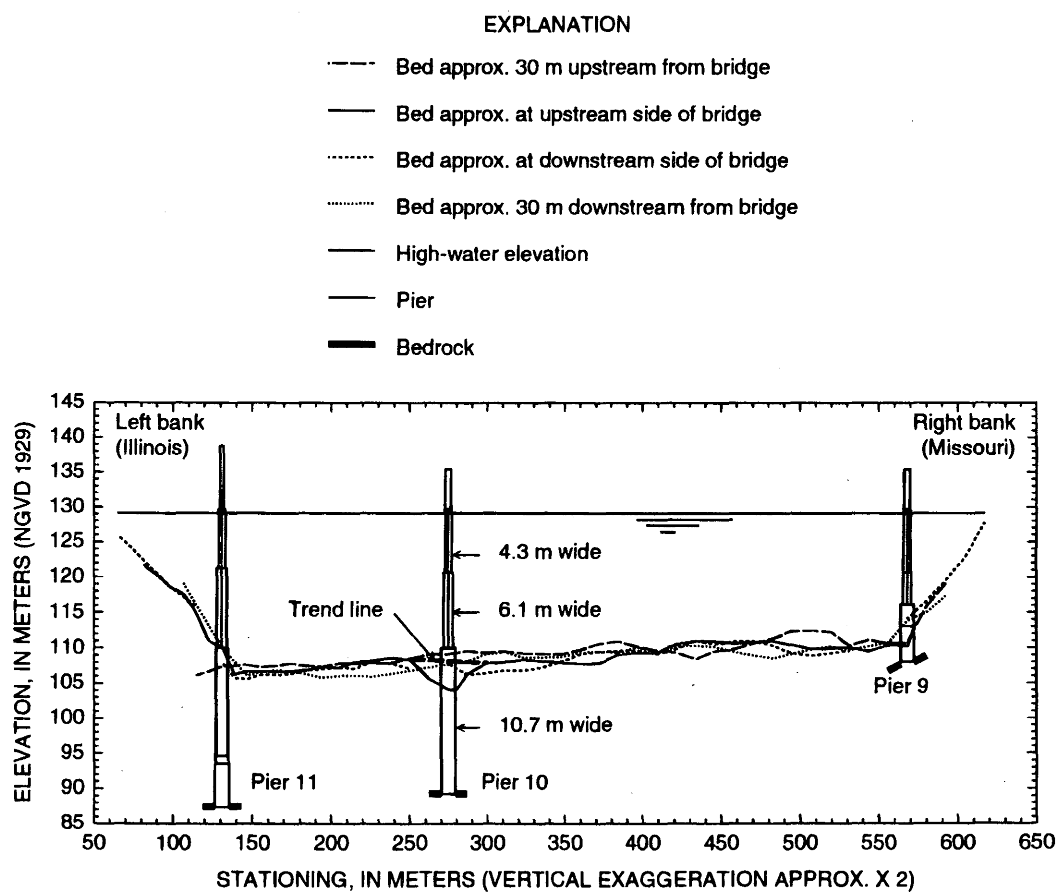

FIGURE 2 Measured cross sections collected at Martin Luther King Bridge over Mississippi River at St. Louis, July 15, 1993 (1 m = 3.28 ft).

TABLE 1 Basic Local Pier Scour Data Collected During 1993 Mississippi River Flood (1 m = 3.28 ft)

Measurement Number	Bridge	Date	Pier Number
1	Martin Luther King Bridge over Mississippi River near St. Louis, MO	July 15, 1993	10
2	I-255 over Mississippi River near St. Louis, MO	July 17, 1993	8
3	(same as above)	July 19, 1993	9
4	State Route 51/150 over Mississippi River at Chester, IL	August 3, 1993	11
5	(same as above)	August 12, 1993	11
6	(same as above)	September 13, 1992	11

Measurement Number	Average Pier Width (m)	Approach Depth (m)	Approach Velocity (m/s)	Skew (deg)	Observed Depth of Scour (m)	Computed Depth of Scour (m)
1	5.5	20.0	2.6	0	4.1	9.2
2	2.8	14.0	1.9	0	4.0	5.5
3	2.9	15.4	2.0	0	3.6	5.8
4	4.0	22.5	2.4	11	7.1	10.4
5	4.1	22.4	2.0	4	6.2	8.9
6	4.7	16.7	1.8	4	6.5	9.1

failed on July 7, 1993, approximately 0.5 km (0.3 mi) downstream from the bridge (Figure 3). A peak water surface elevation of 173.03 m (567.71 ft) was recorded before failure of the levee. The peak discharge of 3,140 m^3/sec (111,000 ft^3/sec) occurred on July 8, 1993, at a water surface elevation of 172.59 m (566.27 ft).

The streambed elevation on May 19, 1993, was at the footing of Pier 2 (Figure 4). Data collected at the bridge on July 9, 1993, just after the peak discharge, showed that the streambed had degraded and exposed the piles at Pier 2 (Figure 4). At least 3.3 m (10.8 ft) of the piling at Pier 2 was exposed during the flood. The channel makes a nearly 90 degree bend just upstream from the bridge, and the flood plain is contracted by the levee from a width of about 2 km (1.25 mi) to about 0.4 km (0.25 mi) near the bridge (Figure 3). Additional contraction at the bridge by the bridge piers is minor, and no local scour is apparent. Thus, general scour resulting from the channel bend and contraction scour resulting from the levee and the dense tree growth on the left bank are the likely causes of scour at the bridge. Data collected at the bridge after the flood indicated that the scoured area did not refill, so a postflood survey was made to determine the extent of the scoured area. The results of the survey (Figure 5) show that scour began upstream from the bridge and extended through the bridge opening to just downstream from the bridge. The spatial distribution of the scour indicates that the scour was caused by general and contraction scour associated with channel configuration and levee alignment, not by the bridge.

DETAILED MEASUREMENTS

Detailed measurements are used to study and model the processes associated with scour at bridges. A complete data set should include three-dimensional velocities, channel bathymetry, bed material load, bed material samples, water surface elevations, water surface slope, water temperature, and streamflow. Ideally, these data should be collected during the rise, at the peak, and during the recession of the flood in the reaches upstream from, at, and downstream from the bridge, with increased detail around bridge piers and abutments. Collection of these data requires state-of-the-art instrumentation.

Instrumentation and Techniques

The spatial coverage necessary for detailed measurements requires a boat to deploy the instruments. The development of a remote-controlled boat (*9*) was not completed at the time of the flood, so a manned boat was used. The need for adequate clearance under the bridge for the manned boat restricted site selection to the Mississippi River because the clearance under bridges on small streams was often less than 1.5 m (5 ft) during the flood.

A digital echo sounder with peak detection, a paper chart recorder, digital output, and a transducer with a 3-degree beam-width was used to measure streambed elevations. The accuracy of the streambed elevation measurements is a function of the dynamic motion of the boat and the slope of the water surface. No corrections for boat motion (heave, pitch, and roll) were used during scour data collection. The water surface elevation was recorded and was assumed to be constant near the bridge. In the approach and exit reaches, the water surface elevation was adjusted to the average water surface slope in the area. Side echoes off the side of the piers were frequently digitized as the bottom by the echo sounder. If digital data had been the only data used, the depth and extent of the

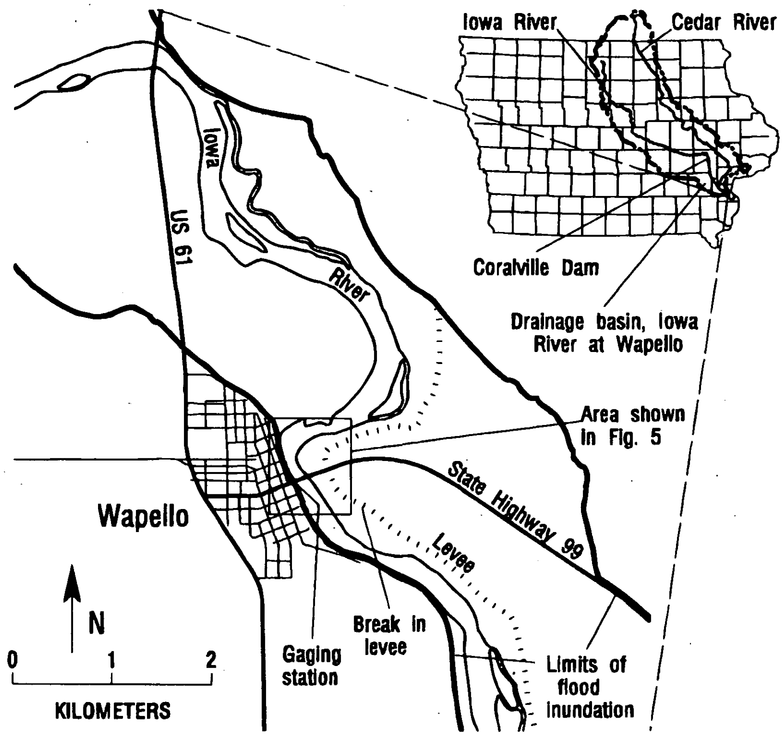

FIGURE 3 Site Map of State Highway 99 over Iowa River at Wapello, Iowa (1 km = 0.6 mi).

scour hole would have been misinterpreted; however, the depth and extent of the scour hole was clearly indicated on the paper chart, so the digital data were manually corrected. The estimated accuracy of the streambed elevation data is about 0.3 m (1 ft) (*10*).

The broadband acoustic Doppler current profiler (BB-ADCP) can collect three-dimensional velocity profiles from a moving survey vessel. The BB-ADCP measures velocity magnitude and direction by means of the Doppler shift associated with the reflection of acoustic waves off moving objects. The instrument sends an encoded pair of acoustic pulses through the water column and records the reflected acoustic signals. The reflected signal is then discretized by time difference into individual segments representing specific depth cells within the water column. Further acoustic signal analysis yields the velocity of the acoustic reflectors along each of these beams, which is then used to compute the three-dimensional velocity vectors for each depth cell. The geometric arrangement of the four transducers allows the horizontal and vertical components of the velocity to be computed. Theoretically, only three beams are needed, but the fourth beam allows a quality check of the measurement (*11*). If the BB-ADCP is deployed from a moving boat, then the measured water velocity (relative to the instrument on the boat) must be corrected for the speed and direction of the boat. Under most conditions, the BB-ADCP compensates for the boat speed and direction by tracking the speed and direction of the streambed relative to the instrument. If the bed material has not become mobilized at the streambed, the velocity of the boat can be measured accurately on the basis of this principle. If the stream is actively transporting material along the streambed, however, this technique may not adequately measure the speed and direction of the boat. During the 1993 flood on the Mississippi River, a 1,200-kHz instrument failed to provide adequate bottom tracking under conditions of water depth greater than 19 m (60 ft), high suspended sediment concentration, and bed load characterized by 2-m (6-ft) dunes. A 300-kHz instrument was able to penetrate the mobile bed layer and provide an acceptable bottom track.

The BB-ADCP allows very detailed velocity data to be collected in the approach and exit sections and in the vicinity of the bridge. However, extreme care must be taken when using the BB-ADCP to collect velocity information in the vortices at the bridge piers. The computational routines in the BB-ADCP are based on the assumption that the water velocity is uniform along a horizontal plane passing through the four beams. The size of the vortices is often smaller than the area bounded by the four beams, so flow measured by one beam may not be continuous with flow measured by another beam. Therefore, although the BB-ADCP can measure three-dimensional velocity profiles under most conditions, it may not accurately measure the velocity profile in the vortices around bridge piers.

Streambed elevation data and three-dimensional velocities are useful only if their horizontal positions are known. A range-azimuth tracking system was used to determine the horizontal position of the data collected at and near the bridges. Although the system specifications of the range-azimuth tracking system indicate an accuracy of 0.2 m (0.6 ft), in practice it is very difficult to keep the instrument pointed directly at a moving target. During data collection on the Mississippi River, an accuracy of approximately 0.7 m (2.3 ft) was achieved when the range-azimuth tracking system was used to track

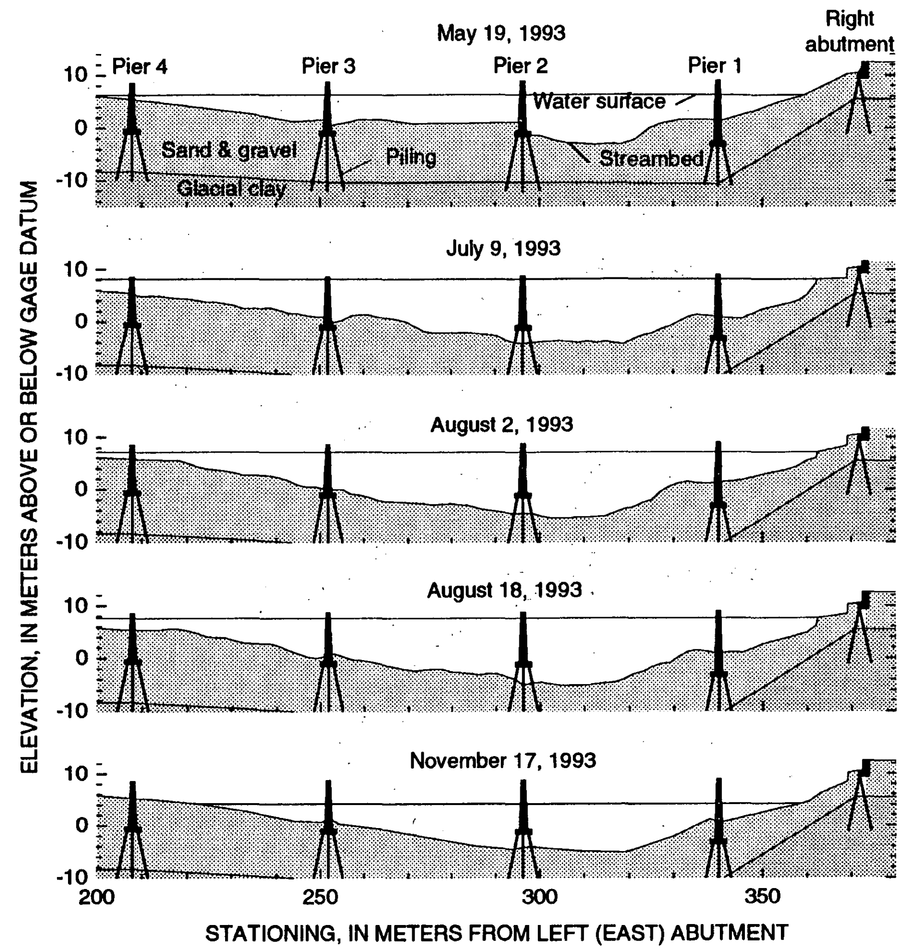

FIGURE 4 Streambed elevations at State Highway 99 over Iowa River at Wapello, Iowa (all cross sections shown were measured along upstream side of bridge except May 19, 1993, section, which was measured along downstream side of bridge; 1 m = 3.28 ft).

the target mounted on the moving survey vessel. The power of the laser used in this system allowed setup points to be referenced to the bridge in about 15 min, often without the need of a prism, by pointing the instrument at the centerline of each pier and reflecting the laser directly off the concrete pier. Plots of pier and setup locations showed an accuracy of about 0.3 m (1 ft) with this technique.

Tracking the boat in the approach and exit reaches with the range-azimuth tracking system was complicated by vegetation on the riverbank, which limited the view upstream and downstream from the bridge. A low cost global positioning system (GPS) receiver was initially used to obtain the approximate location of the beginning and ending points of BB-ADCP transects in the approach and exit reaches. During the recession of the flood, positions were measured by real-time kinematic differential GPS (DGPS). Differential corrections transmitted by the U.S. Army Corps of Engineers, St. Louis District, were used. Because DGPS required no setups on shore and no personnel to track the boat, data were collected in less time and over a much longer reach than would have been feasible with the range-azimuth tracking system. However, tree lines and bridges blocked the sky, resulting in loss of adequate satellite coverage and thus hampering the use of GPS in these areas. Therefore, the range-azimuth tracking system was used as a supplement to DGPS to measure horizontal positions for detailed data collection in the vicinity of the bridge. The accuracy of the horizontal positions collected by use of DGPS is believed to be about 1 m (3.3 ft).

Data were recorded digitally on a field computer. Data radios were used to transmit the data from the boat to the shore, allowing the data and horizontal positions to be recorded simultaneously. Initial processing of the data into contour maps and three-dimensional meshes clearly illustrates the depth and shape of local scour holes. However, the spatial and temporal range of bathymetric and three-dimensional velocities require significant additional processing and visualization to interpret the basic observations.

Discussion of Data Collected

The collection of detailed data sets to study contraction and abutment scour was given highest priority. Equipment limitations and river conditions did not permit data collection at sites where contraction and abutment scour processes were dominant. However, detailed data were collected at two sites during the 1993 upper Mississippi River flood. Hydraulic and bathymetric data were collected in the approach and exit reaches extending approximately 3.2 km (2 mi) upstream and downstream from the bridge at both sites. Only a partial analysis of local scour at piers has been

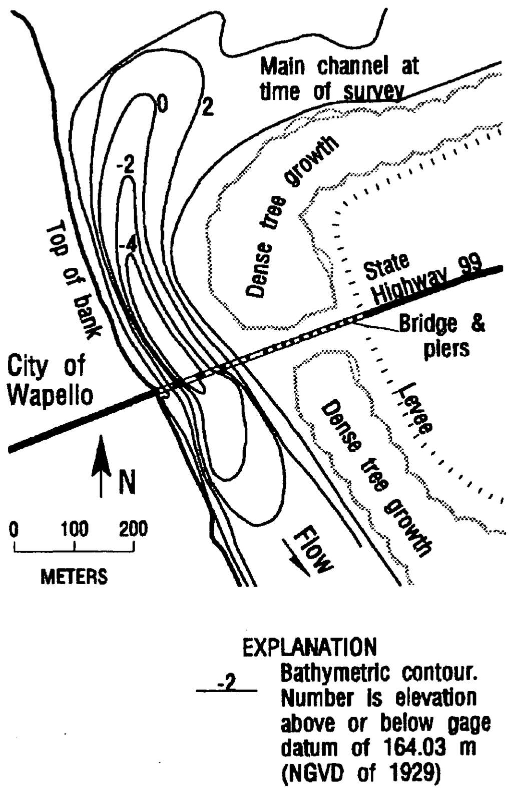

FIGURE 5 Channel Bathymetry near State Highway 99 over Iowa River at Wapello, Iowa, November 17, 1993 (location of area is shown in Figure 3; 1 m = 3.28 ft).

completed and is presented. Examples of three-dimensional bathymetric data are presented to help depict the shape of the scour hole.

I-255 over Mississippi River near St. Louis, Missouri

The I-255 bridge over the Mississippi River south of St. Louis, Missouri, is 1220 m (4,003 ft) long and is supported by 14 piers. The navigation channel is along the right (Missouri) bank. Piers 12 and 13 support the navigation span of 277.4 m (910 ft). Piers 8 through 10 are set on a large sand bar along the left (Illinois) bank, which is exposed during very low flow. Dikes have been installed by the U.S. Army Corps of Engineers along the left bank upstream and downstream from the bridge to maintain sufficient depth in the navigation channel during low flow. All of the piers were surveyed during the flood, but scour holes were found only at Piers 8 and 9. Piers 8 and 9 have identical configurations: a seal 2.7 m (9 ft) thick by 11.0 m (36 ft) wide set on H-piles. The top of the seal and bottom of the footing is at elevation 110.3 m (362.0 ft). The square-nosed footing is 8.5 m (28 ft) wide and 12.0 m (40 ft) long, and its top is at elevation 112.3 m (368.5 ft). A square-nosed pedestal 4.6 m (15 ft) wide and 9.6 m (31.5 ft) long extends from the top of the footing to elevation 114.4 m (375.5 ft). The pier consists of two square caissons 2.7 m (9 ft) wide connected by a web to elevation 126.8 m (416 ft). The piers are tapered slightly in the direction of flow and are 9.0 m (30 ft) long at the base and 10.4 m (34 ft) long at the bridge deck.

An initial check survey of the bridge on July 14, 1993, resulted in the establishment of this site as a detailed study site. Detailed bathymetric data were collected on July 17 and 19, 1993; however, only average approach velocities were measured on these dates because of the failure of the 1,200-kHz BB-ADCP to measure velocities accurately under the extreme conditions. Detailed bathymetric and three-dimensional velocities were measured at this site on August 17 and September 16, 1993. The water surface elevations were measured by use of a staff gage about 300 m (1,000 ft) downstream from the bridge. The water surface elevations initially peaked at an elevation of 128.2 m (420.7 ft) on July 19, but additional rain resulted in a slightly higher peak in the following weeks. No scour data were collected during this second peak.

The sediment transport upstream from Pier 9 was characterized by 1.8- to 2.4-m (6- to 8-ft) dunes; upstream from Pier 8 dunes were somewhat smaller (Figure 6). The basic variables associated with local pier scour were summarized from the detailed data and are listed in Table 1. The HEC-18 equation overestimates the observed local scour at Piers 8 and 9 by 38 and 61 percent, respectively. The passage of dunes could cause the difference between observed and predicted values; however, soundings collected in the scour hole at various times over a period of several days were consistent, indicating little or no influence from the dunes. The minimum streambed elevation was near the top of the seal, an indication that the seal may have provided some scour protection. Additional analysis and modeling of these data will be required to determine the extent to which the pier shape may have reduced the local depth of scour.

SR 51/150 over Mississippi River at Chester, Illinois

The SR 51/150 bridge over the Mississippi River at Chester, Illinois, was built in 1940 and is 861.3 m (2,826 ft) long. The supporting structure consists of nine pile bents and four piers. Piers 10, 11, and 12 are in the main channel, but data for only Pier 11 are presented. Pier 11 has a rectangular caisson footing 16.0 m (52.5 ft) long by 7.3 m (24 ft) wide and extends from elevation 78.0 m (256.0 ft) to elevation 99.1 m (325.0 ft). A solid, round-nosed section 14.8 m (48.5 ft) long by 5.5 m (18 ft) wide rises from the top of the caisson to elevation 109.7 m (360.0 ft). Two tapered columns 4.6 m (15 ft) wide at the base extend from elevation 109.7 m (360.0 ft) to the bridge deck [elevation 134 m (440.1 ft)]. The columns are connected by a continuous web 1.1 m (3.5 ft) wide from elevation 109.7 to 116.6 m (360.0 to 382.5 ft) and are 3.4 m (11 ft) wide at elevation 122.8 m (403.0 ft). The columns have a stepped, square face that was classified as square.

A USGS streamflow-gaging station is at the bridge and has been in operation since 1942. Stage records at this station are available back to 1891. Periodic bed material samples and daily suspended sediment samples were obtained at the station during the flood. The peak discharge of 20,000 m^3/sec (708,600 ft^3/sec) occurred on August 6, 1993, at a water-surface elevation of 119.06 m (390.64 ft).

Detailed data sets were collected during August 3 to 4, August 12 to 15, and September 13 to 15, 1993. The basic variables normally associated with local pier scour were summarized from the detailed data and are listed in Table 1. The location of maximum scour depth was consistently at the upstream left (northeast) corner of the pier, as a result of the slight skew of the pier to flow. The depth of scour remained fairly constant over the period measured, even though velocities decreased by 24 percent, and depth dropped by about

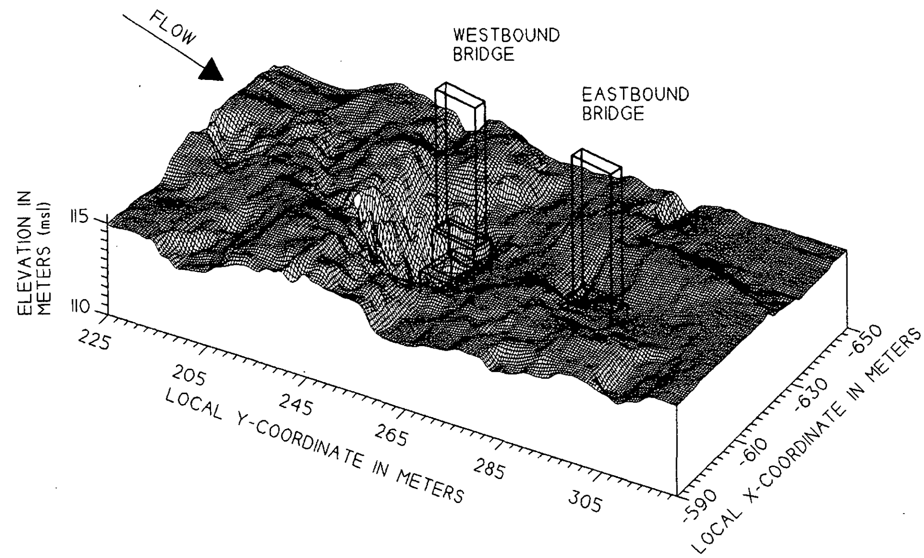

FIGURE 6 Three-dimensional mesh of Channel Bathymetry near Pier 8 on I-255 over Mississippi River near St. Louis, July 17, 1993 (1 m = 3.28 ft).

5.8 m (19 ft) (Figure 7). Between August 3 and September 13, the ambient bed elevation rose 1.0 m (3.3 ft), and the minimum elevation in the scour hole rose 1.6 m (5.2 ft). The depth of the scour did not change significantly for the period of measurements, although theory suggests that the holes should refill during the flood recession. The detailed bathymetric data allowed the shape and volume change of the scour hole to be analyzed in addition to the depth of the hole. The volume of the scour hole below the ambient bed was computed for each date. No change in the volume of the scour hole beyond the possible measurement error could be identified. Comparison of the observed data with depths of scour computed by use of the HEC-18 equation showed that the HEC-18 equation significantly overestimated local scour by about 40 percent for the three measurements.

SUMMARY AND CONCLUSIONS

Real-time measurements of scour at bridges during the 1993 upper Mississippi River Basin flood are classified according to the measurement objective: inspection measurements, limited-detail measurements, and detailed measurements. Inspection measurements were made to ensure bridge safety. A knee board used to deploy an

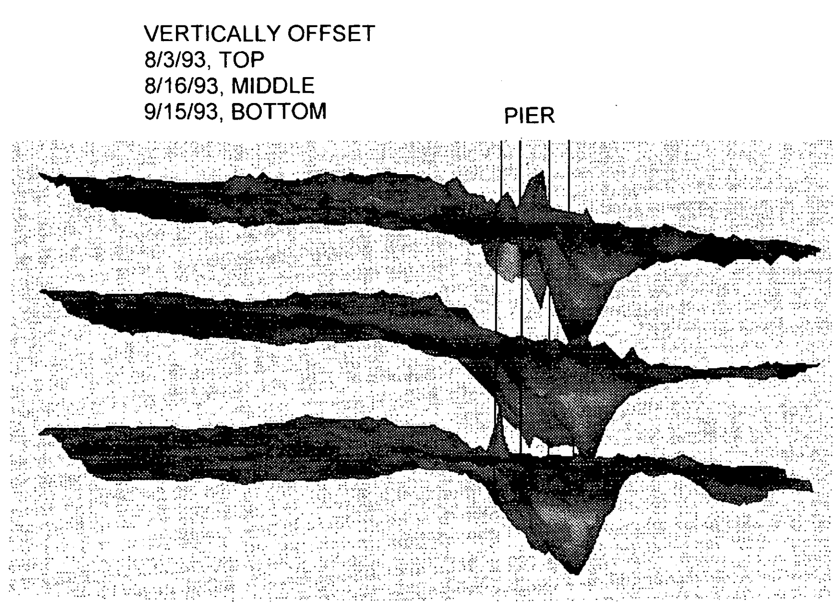

FIGURE 7 Visualization of scour hole at Pier 11 on State Route 51/150 over Mississippi River at Chester, Illinois.

echo sounder transducer around the bridge piers proved to be a valuable low cost tool for making quick measurements of the streambed from the bridge deck. Limited-detail measurements were made to provide data for evaluating recommended methods of scour prediction. At two limited-detail study sites, significant scour resulted from different processes. By use of state-of-the-art instrumentation, detailed measurements of velocity and channel bathymetry, which were previously not possible, can now be made. However, limitations of the deployment systems prevented collection of data on small streams where abutment and contraction scour are often the primary concern. Future developments in deployment systems should remove these limitations and allow much needed data to be collected on small streams. A brief summary of the two detailed study sites indicates the detail at which local scour can now be measured. Comparison with observed data shows that recommended scour prediction procedures consistently overestimated the depth of pier scour. This overestimation could result from a number of factors, including complex pier geometry, unsteady flow conditions, and limitations of the HEC-18 equation. The spatial and temporal extent of detailed data sets requires computer analysis and visualization techniques to identify and characterize the complex scour processes measured. Through the use of these techniques, the study of scour processes is no longer restricted to the laboratory but also can be studied in the field. New technology is sure to provide instruments that will allow more accurate and more detailed field data on scour processes to be collected in the future.

ACKNOWLEDGMENT

The development of instrumentation and collection and analysis of real-time scour data presented in this paper were completed under two projects sponsored by FHWA.

REFERENCES

1. Parrett, C., N. B. Melcher, and R. W. James. *Flood Discharges in the Upper Mississippi River Basin.* 1993. Circular 1120-A. U.S. Geological Survey, 1993.
2. Barksdale, G. G. Bridge Scour During the 1993 Floods in the Upper Mississippi River Basin. In *Hydraulic Engineering '94.* American Society of Civil Engineers, New York, 1994, pp. 21–25.
3. Mueller, D. S., and M. N. Landers. Development of Bridge-Scour Instrumentation for Inspection and Maintenance Personnel. In *Hydraulic Engineering '93.* American Society of Civil Engineers, New York, 1993, pp. 2045–2050.
4. Rantz, S. E., et al. *Measurement and Computation of Streamflow.* Water-Supply Paper 2175. U.S. Geological Survey, 1982.
5. Landers, M. N., and D. S. Mueller. Reference Surface for Bridge Scour Depths. In *Hydraulic Engineering '93.* American Society of Civil Engineers, New York, 1993, pp. 2075–2080.
6. Richardson, E. V., L. J. Harrison, J. R. Richardson, and S. R. Davis. *Evaluating Scour at Bridges—Second Edition.* Hydraulic Engineering Circular 18. Publication FHWA-IP-90-017, FHWA, U.S. Department of Transportation, 1993.
7. *Design of 1217-Foot Multiple Span Bridge, 639-Foot Five Span Continuous Deck Girder, 578-Foot Eleven Span Continuous I-Beam, Louisa County.* Iowa State Highway Commission. File 11861, Design 145. Iowa Department of Transportation, Ames, 1945.
8. Fischer, E. E. Contraction Scour at a Bridge over the Iowa River. In *Hydraulic Engineering '94.* American Society of Civil Engineers, New York, 1994, pp. 31–35.
9. Landers, M. N., D. S. Mueller, and R. E. Trent. Instrumentation for Detailed Bridge-Scour Measurements. In *Hydraulic Engineering '93.* American Society of Civil Engineers, New York, 1993, pp. 2063–2068.
10. Mueller, D. S., and M. N. Landers. Real-Time Data Collection of Scour at Bridges. In *Fundamentals and Advancements in Hydraulic Measurements and Experimentation.* American Society of Civil Engineers, New York, 1994, pp. 104–113.
11. *Direct-Reading Broadband Acoustic Doppler Current Profiler—Technical Manual.* RD Instruments, San Diego, Cali., 1993.