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Analysis of Contraction and Abutment Scour at Two Sites in Minnesota

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Abstract

The U.S. Geological Survey (USGS) deployed the USGS bridge-scour data collection team to collect real-time scour (contraction and local) measurements at two contracted bridge openings over the Pomme de Terre River in western Minnesota during record flooding in the Minnesota River Basin in April 1997. The compiled field data were used to calibrate a step-backwater model (HEC-RAS) at each site. The total computed scour depths compared very well with total scour depths measured in the field. A much poorer agreement was found when comparing the computed abutment and contraction scour depths with the depths measured in the field. The overall comparison provided insight to the capabilities and limitations of using one-dimensional models and the available abutment and contraction scour equations to predict scour at contracted bridge openings. New methodologies must balance the desire to fully explain complex processes with the need to provide procedures that are time and cost effective to apply.

Introduction

During record flooding in the Minnesota River Basin in April 1997, the U.S. Geological Survey (USGS), in cooperation with the Federal Highway Administration (FHWA), deployed the USGS bridge-scour, data-collection team to collect real-time scour (contraction and local) measurements at contracted bridge openings. An analysis of two surveyed sites during the April 1997 flooding is presented. Both contracted bridges span the Pomme de Terre River, where an estimated 200-year discharge was calculated at the USGS Appleton streamflow-gaging station (05294000) located approximately 19 km downstream of the U.S. Route 12 bridge. The compiled field data (channel and floodplain bathymetry, water discharge, water-surface elevations, roughness, and bridge geometry) were used to calibrate a step-backwater model at each site. Abutment and contraction scour were calculated in HEC-RAS (U.S. Army Corps of Engineers, 1998) using the equations and methods outlined in HEC-18 (Richardson and Davis, 2001). The hydraulics and predicted depth of scour based on the calibrated model were compared with the field measurements.

U.S. Route 12 over the Pomme de Terre River

Site Description

U.S. Route 12 crosses the Pomme de Terre River about 20 km west of Danvers, Minn. The single-span steel-truss structure was constructed in 1933 with a maximum span length of 26.9 meters. The bridge has vertical-wall abutments with wing walls; each abutment and wing wall rests on concrete footings supported on timber piling. Neither abutment was riprapped nor was there any other scour protection measures. A field investigation conducted by BRW, Inc. (1995) prior to the flood revealed no evidence of significant scour at the abutment face.

During the April 1997, flood both contraction and abutment scour resulted at the bridge. A large scour hole developed at the right abutment, scouring below the abutment cutoff wall resulting in failure of the fill material behind the abutment. Slumping of the embankment slope and some deformation of the approach highway were observed. Although scour measurements showed a scour hole 2 m below the footing of the left abutment, no deformation was observed near the left abutment. These conditions resulted in closure of the bridge. Because of the age and scheduled replacement of the bridge, the bridge was not repaired but was replaced with a new structure after the flood.

Discussion of Field Data

Data were collected during the flood (on 4/5/97 and 4/9/97) at U.S. Route 12 over the Pomme de Terre River. A manned boat was deployed during the initial visit on 4/5/97. The use of the manned boat and an acoustic Doppler current profiler (ADCP) allowed bathymetry and three-dimensional velocities to be measured at the bridge, and in the approach and exit sections extending about 100 m upstream and 70 m downstream. Heavy vegetation and submerged obstructions in the floodplains limited data collection to the main channel. Measurements on 4/9/97 were limited to data collected from the bridge deck. Channel bathymetry was measured along the upstream and downstream faces of the bridge, and at selected locations beneath the bridge using an echo sounder deployed on a knee-board. Velocity magnitudes and water discharge were measured using a vertical axis current meter. Water-surface elevations were measured by taping down from the top-of-curb on the bridge both upstream and downstream, near the left abutment. On 4/5/97, the water-surface elevation was 310.70 m above North American Geodetic Vertical Datum (NGVD) of 1929 at the upstream edge of the bridge, and the total discharge was 141.6 cubic meters per second (m^3/s). By 4/9/97, the water-surface had risen to an elevation of 311.5 m, and the discharge had increased to 162.8 m^3/s.

The direction of flow through the bridge was controlled by the configuration of the upstream floodplains. The channel upstream of the bridge was straight but the left floodplain was much wider and carried considerably more flow than the right floodplain. A sketch of spot streambed elevations and the flow direction on 4/9/97, which shows the severe skew of the flow to the bridge opening is shown in Figure 1.

An elevation of 307.9 m was used as the contraction scour reference surface from analysis of pre-flood cross-sections throughout the study reach. A summary of the contraction-scour data is shown in table 1. The profile of the contracted section on 4/5/97 was measured under the bridge from data collected by an ADCP. The maximum erosion of the streambed was 2.3 m from the defined reference surface; however, when the entire streambed below the bridge was averaged the depth of contraction scour was only 0.9 m. The hydraulic data presented for 4/5/97, also were collected with the ADCP. Measurements made with a sounding weight on 4/9/97, were collected during the discharge measurement along the upstream face of the bridge, and no approach data are available. An echo sounder mounted on a knee-board also was used to make measurements on 4/9/97. The board was floated from upstream to downstream under the bridge; the measurements reflect the depths at the upstream or downstream face of the bridge.

The reference surface used to determine the depth of abutment scour was the concurrent ambient bed; therefore, the depth of abutment scour reported is additional local scour below the depth of contraction scour (table 2). An ADCP was used for data collection on 4/5/97, using a weighted-average of all four beams as the measured depth. Because a weighted-average was used, it is possible that the local abutment scour was not accurately measured, and no values are reported.

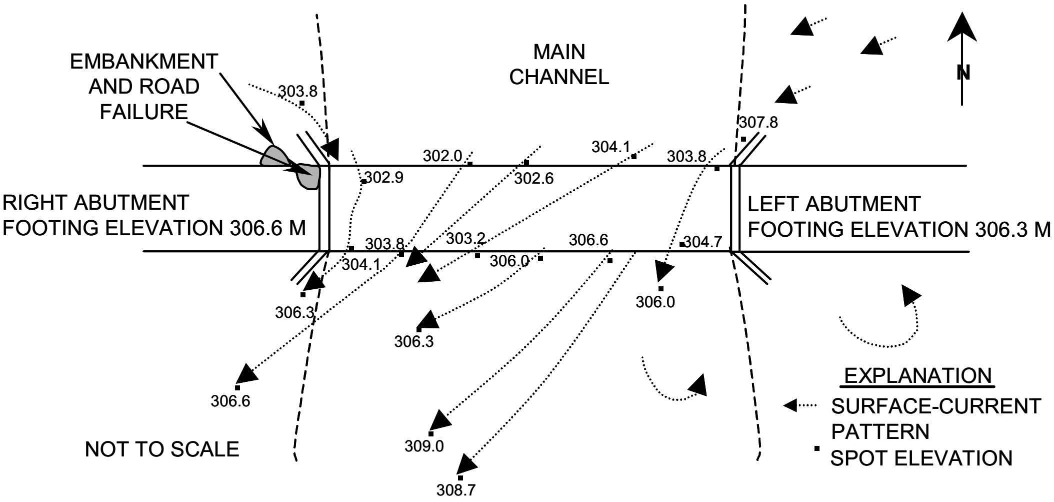

Figure 1. Sketch of U.S. Route 12 over Pomme de Terre River, Minnesota showing spot elevations and surface current patterns on April 9, 1997. (Elevations are in meters referenced to NGVD of 1929.)

Table 1. Summary of contraction scour measurements at U.S. Route 12 over the Pomme de Terre River in Minnesota.

Measurement Number	Date	Location	Equipment	Scour Depth (m)	Accuracy (m)
1	4/5/97	Centerline	ADCP	0.9	0.6
2	4/9/97	Upstream	Sounding weight	3.2	0.6
3	4/9/97	Upstream	Echo sounder	3.8	0.6
4	4/9/97	Downstream	Echo sounder	1.4	0.6

	Contracted Section				Uncontracted Section			
	Width (m)	Depth (m)	Discharge (m^3/s)	Average Velocity (m/s)	Width (m)	Depth (m)	Discharge (m^3/s)	Average Velocity (m/s)
1	26.8	3.7	142	1.5	21.3	2.4	51.0	1.0
2	26.8	7.3	163	0.8	--	--	--	--
3	26.8	7.2	163	0.9	--	--	--	--
4	26.8	5.3	163	1.2	--	--	--	--

The cross sections measured on 4/9/97 all showed a similar pattern with abutment scour holes on each side and a sharp mound in between the scour holes but skewed toward the left abutment (figure 2). It appears that the abutment scour holes may have overlapped. The highest elevation in the center of the cross section was subtracted from the reference surface to obtain the depth of contraction scour. The abutment scour was reported as the depth below the highest elevation in the center of the cross section. All velocities presented in table 2 were from the discharge measurement made along the upstream side of the bridge. Although no abutment scour was observed on 4/5/97, the velocities at the abutments were much higher (left – 1.6 m/s, and right – 1.8 m/s).

Model Calibration

The HEC-RAS model (Hydraulic Engineering Center, 1998), a one-dimensional step-backwater model, was calibrated to represent the field hydraulics as accurately as possible. The bathymetry from the April 1997 flood was used to build the calibration models for the two sets of data (4/5/97 and 4/9/97). Because bathymetry data collected on 4/9/97, was limited to the upstream and downstream edges of the bridge, the cross sections collected on 4/5/97 were used to build the HEC-RAS model for 4/9/97. The majority of the floodplain bathymetry utilized in developing the models was taken from a full valley section found in the original bridge plans and adjusted to be consistent with topographic maps. The water-surface elevation observed at the upstream bridge face rose 0.76 m between 4/5/97 and 4/9/97. The model only showed a 0.3 m change and was unable to accurately reproduce the observed change without unreasonable changes to the model input. This large hydraulic variation may be attributed to the U.S. Route 12 bridge reach being under a backwater condition because of some unidentified downstream condition.

Table 2. Summary of abutment scour data for
U.S. Route 12 over the Pomme de Terre River in Minnesota.

Date	Abutment	Location	Equipment	Scour Depth (m)	Accuracy (m)	Embankment Length (m)	Velocity At Abutment (m/s)	Depth At Abutment (m)
4/9/97	Right	Upstream	Sounding weight	2.4	0.6	307	1.3	9.1
4/9/97	Right	Upstream	Echo sounder	2.1	0.6	307	1.3	9.4
4/9/97	Right	Downstream	Echo sounder	3.4	0.6	307	1.3	8.2
4/9/97	Left	Upstream	Sounding weight	0.9	0.6	121	1.2	7.6
4/9/97	Left	Upstream	Echo sounder	0.5	0.6	121	1.2	7.6
4/9/97	Left	Downstream	Echo sounder	1.8	0.6	121	1.2	6.7

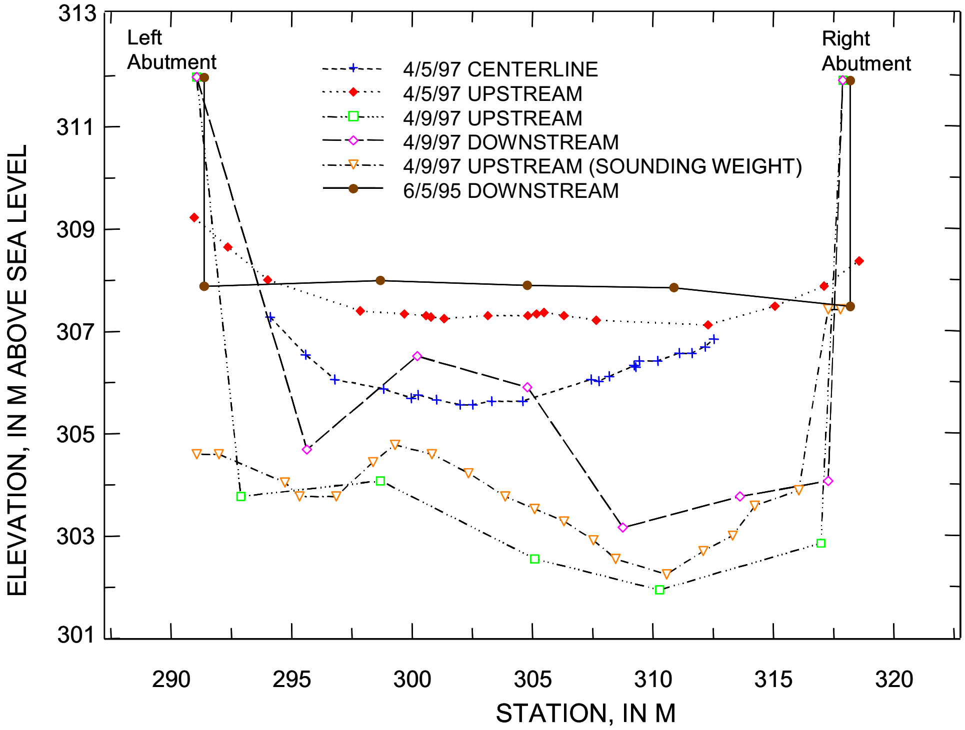

Figure 2. Measured cross sections at U.S. Route 12
over the Pomme de Terre River, Minnesota.

Large ice drifts were observed during both site visits, indicating the potential for the formation of a debris and (or) ice dam downstream of the data-collection area. Analysis of the Appleton gaging-station records was of little assistance since the gage was washed out on 4/6/97 by the failure of a small upstream dam. The water-surface elevation at the upstream side of County Route 22 located about 10 km upstream changed only 0.2 m over the same period; therefore, the model was considered calibrated despite the apparent discrepancy with the water-surface elevation observed on 4/9/97.

One of the most important factors in using one-dimensional models at contracted bridges is the model capablity to accurately represent the velocity distribution laterally across the stream and floodplain. depict how The velocity distributions depicted in figures 3 and 4 show the variation between the model and field measurements, using the geometry from 4/5/97 and 4/9/97. The distribution shown in figure 3 reveals that the measured flow was skewed toward the right abutment. HEC-RAS did not duplicate this skewed flow pattern but rather computed a relatively uniform flow distribution across the cross-section caused by the model assigning flow tubes of equal conveyance through the geometrically uniform bridge section. For the scoured channel bathymetry, HEC-RAS more accurately reproduced the observed velocity distribution (figure 4), although the model does not simulate the region of reverse flow that occurred adjacent to the left abutment. The HEC-RAS computed velocities are greater near the deeply scoured region

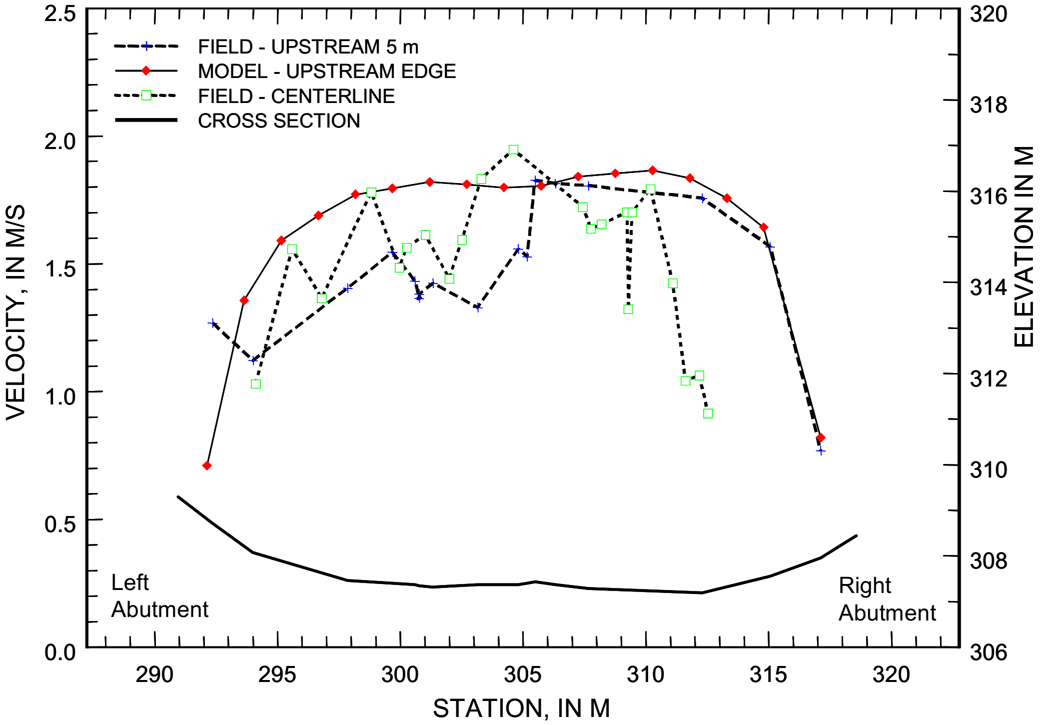

Figure 3. Comparison of observed and model velocity distributions at U.S. Route 12 over the Pomme de Terre River, Minnesota for April 5, 1997.

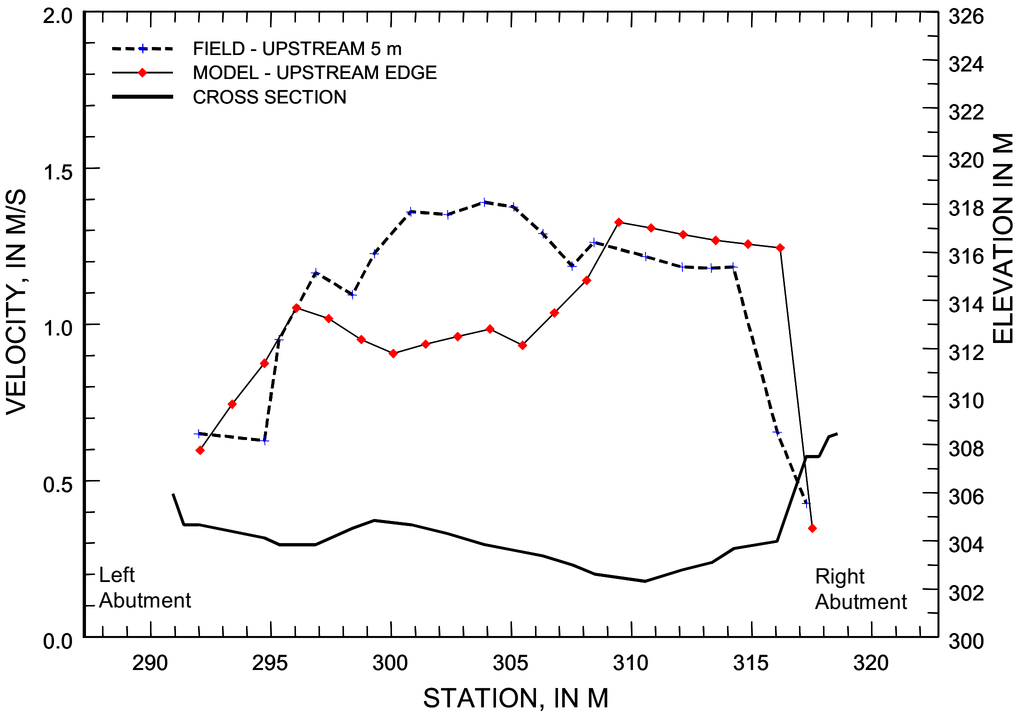

Figure 4. Comparison of observed and model velocity distributions at U.S. Route 12 over the Pomme de Terre River, Minnesota for April 9, 1997.

adjacent to the right abutment because the slope and roughness are constant across the cross section, so the conveyance becomes dependent upon the depth of flow.

Assessment of Scour Computations

The calibrated model was used to assess how accurately the scour for this flood could have been estimated. The bathymetry in the calibrated model was replaced with the original bathymetry extracted from the BRW, Inc. WSPRO model, which represented the pre-flood condition. The discharges from both 4/5/97 and 4/9/97, then were run through the HEC-RAS model with the original bathymetry to determine the hydraulic parameters required to compute bridge scour. The contraction scour was computed in HEC-RAS by allowing the model to use the default equation (live-bed or clear-water) depending upon the hydraulic conditions. A comparison of observed and model-computed contraction scour is shown in table 3.

The computed depth of contraction scour was less than the observed value for all measurements. The contraction scour observed on 4/9/97, may not be typical live-bed contraction scour because depth of contraction scour could be affected by overlapping abutment scour holes. The abutment scour was computed in HEC-RAS using both the Froehlich equation and the HIRE equation. These two equations recommended in HEC-18 (Richardson and Davis, 2001, p. 7.8). The HIRE equation is only applicable (but not required) if the embankment length to flow depth at the abutment (L/a) is greater than 25 (Richardson and Davis, 2001, p. 7.8). In this case the L/a ratio is approximately 33.5. A comparison of the observed and model-computed abutment scour is shown in table 4.

The data summarized in table 4 show the overprediction of scour that is common for abutment scour computations. Although the abutment scour equations overpredicted the local scour and the contraction scour equation underpredicted the contraction scour (table 3), when added together the total scour was estimated with reasonable accuracy and actually underpredicted the scour observed at the upstream edge of the bridge on 4/9/97. These are surprising results that should be viewed with caution because the flow skew through the bridge could not be accounted for in the one-dimensional model, and the individual components were both in error. The agreement may, therefore, be coincidental.

Swift County Route 22 over the Pomme de Terre River

Site Description

Swift County Route 22 crosses the Pomme de Terre River near Artichoke Lake, Minn., and is located 10 km upstream from the U.S. Route 12 bridge. This bridge has two piers in the main channel with the abutments set at the edge of the main channel. The spill-through slopes at the abutments were protected by riprap and formed the banks of the main channel. The bridge is located in a very sinuous reach of the river with two large meanders immediately upstream and downstream of the bridge (figure 5). The floodplains are composed of farmland and forest.

Table 3. Comparison of observed to computed contraction scour at U.S. Route 12 over the Pomme de Terre River in Minnesota.

Date	Location (Edge of Bridge)	Equation	Depth of Scour (m) Computed	Observed
4/5/97	Upstream	Live-bed	0.4	0.9
4/9/97	Upstream	Live-bed	0.6	3.8
4/9/97	Downstream	Live-bed	0.6	1.4

Table 4. Comparison of observed to computed abutment and total scour at U.S. Route12 over the Pomme de Terre River in Minnesota.

				Observed		Based on Froehlich Equation		Based on HIRE Equation	
Date	Abutment	Location (Edge of Bridge)	Equipment	Local Scour Depth (m)	Total Scour Depth (m)	Local Scour Depth (m)	Total Scour Depth (m)	Local Scour Depth (m)	Total Scour Depth (m)
4/9/97	Right	Upstream	Sounding weight	2.4	5.6	4.6	5.2	10.8	11.4
4/9/97	Right	Upstream	Echo sounder	2.1	5.9	4.6	5.2	10.8	11.4
4/9/97	Right	Downstream	Echo sounder	3.4	4.8	4.6	5.2	10.8	11.4
4/9/97	Left	Upstream	Sounding weight	0.9	4.1	4.0	4.6	5.2	5.8
4/9/97	Left	Upstream	Echo sounder	0.5	4.3	4.0	4.6	5.2	5.8
4/9/97	Left	Downstream	Echo sounder	1.8	3.2	4.0	4.6	5.2	5.8

During the flooding in April 1997, the USGS visited this site three times. During all three visits the floodplain flow was concentrated in the right floodplain. This concentration of flow in the right floodplain likely is caused by the channel alignment upstream of the bridge. No defined point of reattachment along the right embankment was found during the flood. Flow was toward the main channel along the entire length of the right embankment. The flow separated from the right embankment, nearly perpendicular to the main channel flow, and joined the main flow just left of the rightmost pier (figure 6). During the measurements made on 4/5/97, the flow from the right floodplain was so intense that a standing wave formed upstream of the bridge where the floodplain and main-channel flow began mixing. The area from the rightmost pier to the right abutment was primarily slack and reverse flow. The depth of flow at the right abutment progressively deepened from 4.5 m on 4/4/97, to 6 m on 4/9/97. On 4/9/97, a portion of the right embankment slumped, forcing Swift County officials to temporarily close the bridge until riprap was placed to protect the bridge.

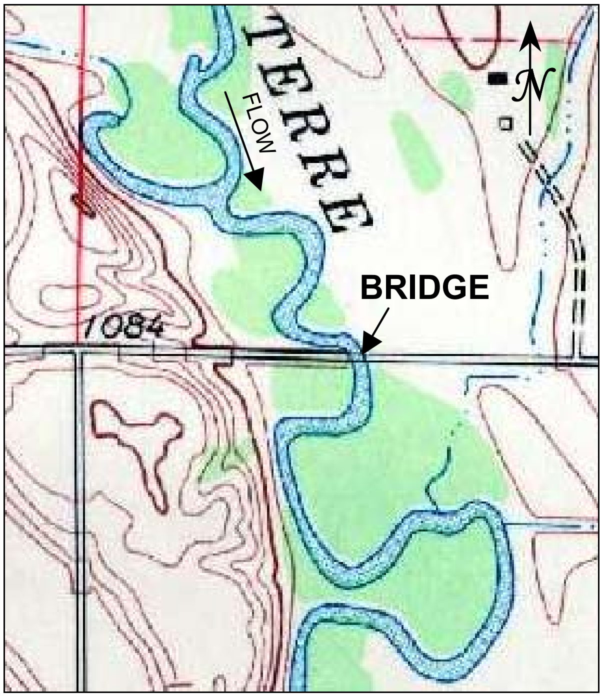

Figure 5. Plan view of Swift County Route 22 over the Pomme de Terre River, Minnesota (no scale).

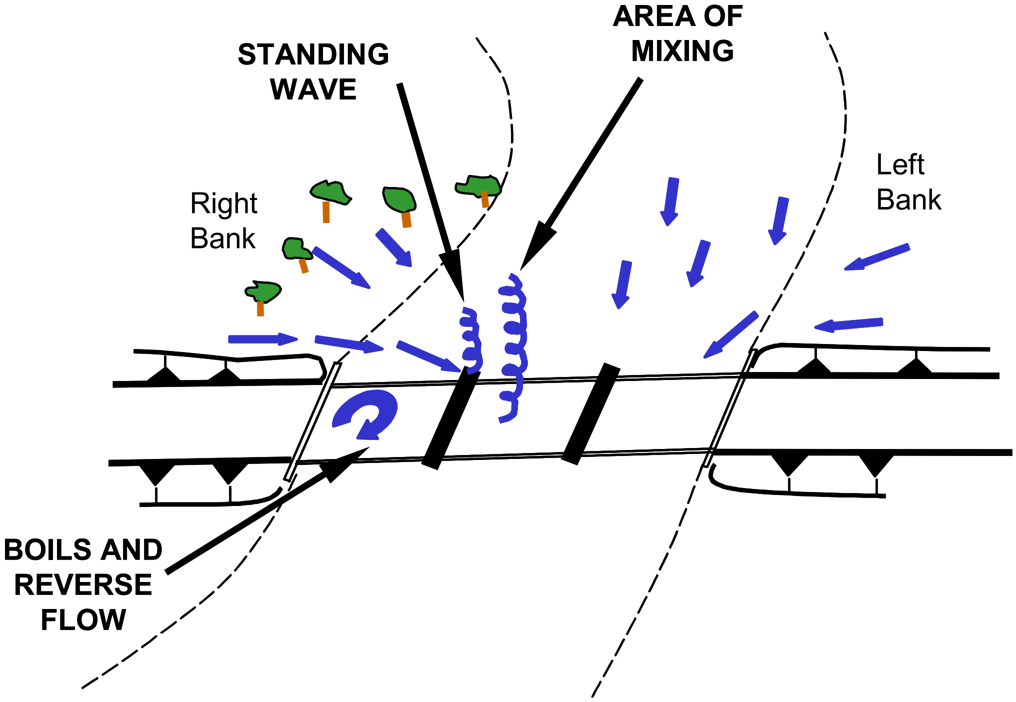

Figure 6. Sketch of flow conditions at Swift County Route 22 over the Pomme de Terre River, Minnesota (not to scale).

Discussion of Field Data

Data-collection efforts were restricted to data that could be collected from the bridge deck for all three site visits during the flood (4/4/97, 4/5/97, and 4/9/97). All bathymetry data were collected by floating an echo sounder attached to a knee-board across the river while being controlled by a hand line from the bridge. The board was allowed to float downstream and streambed elevations were collected as far as 30 m downstream from the bridge. Data collected upstream of the bridge was restricted to the upstream edge of the bridge deck and the area around the upstream end of the right wing wall. Data could not be collected in the floodplains because of heavy vegetation. Velocity magnitudes and water discharge were measured during two of the three site visits using a vertical-axis current meter deployed along the upstream edge of the bridge. Water-surface elevations were measured at the upstream edge of the bridge from the top of the bridge deck between the left most pier and the left abutment. The hydraulic data collected during the flood are summarized in table 5. Additional bathymetry data were collected 21 m upstream from and 30 m downstream from the bridge after the flood during a low-water site visit on July 15, 1997. The elevation and geometry changes experienced by the streambed at the bridge during the period of data collection are shown in figure 7.

The rightmost pier may have had some effect on the depth of scour at the right abutment, yet it is difficult to determine the effect of the pier on the depth of local abutment scour. The effect of the abutment is believed to be the dominant scouring factor; therefore, all scour is credited to the abutment with none reported for the pier. The observed velocity in the area at the right abutment dropped considerably as the scour-hole depth increased. The velocity at the left abutment held steady through the data-collection period, as did the depth and shape of the scour hole. All abutment scour measurements were collected from the upstream edge of the bridge.

Contraction scour typically is computed as the difference in average bed elevation between the uncontracted and contracted sections, adjusted for bed slope. Because of the inability to collect field measurements in the uncontracted section during the flood, a cross section collected in 1991 included in the bridge plans was used as a reference surface. All contraction scour measurements were made along the upstream edge of the bridge. There is less than 0.3 m difference in the bed elevation near the center of the channel (beyond the limits of the abutment scour holes) between the 1991 cross section and those collected during and after the 1997 flood (Figure 7). A value of zero for contraction scour is reported.

The reference surface used to determine the depth of abutment scour was the concurrent ambient bed; therefore, the depth of abutment scour reported is additional local scour below the depth of contraction scour, which for this site was negligible. A reference surface at 313.7 m above NGVD of 1929 was used to measure local abutment scour. A summary of the abutment scour data is presented in table 6.

Table 5. Summary of hydraulic data collected at Swift County Route 22 over the Pomme de Terre River in Minnesota.

Date	Water-Surface Elevation (m, NGVD of 1929) Upstream	Water-Surface Elevation (m, NGVD of 1929) Downstream	Discharge (m^3/s)	Velocity (m/s) Average	Velocity (m/s) Maximum
4/4/97	317.02	316.93	--	--	--
4/5/97	317.15	317.06	132	1.3	2.5
4/9/97	317.34	--	146	1.2	1.8

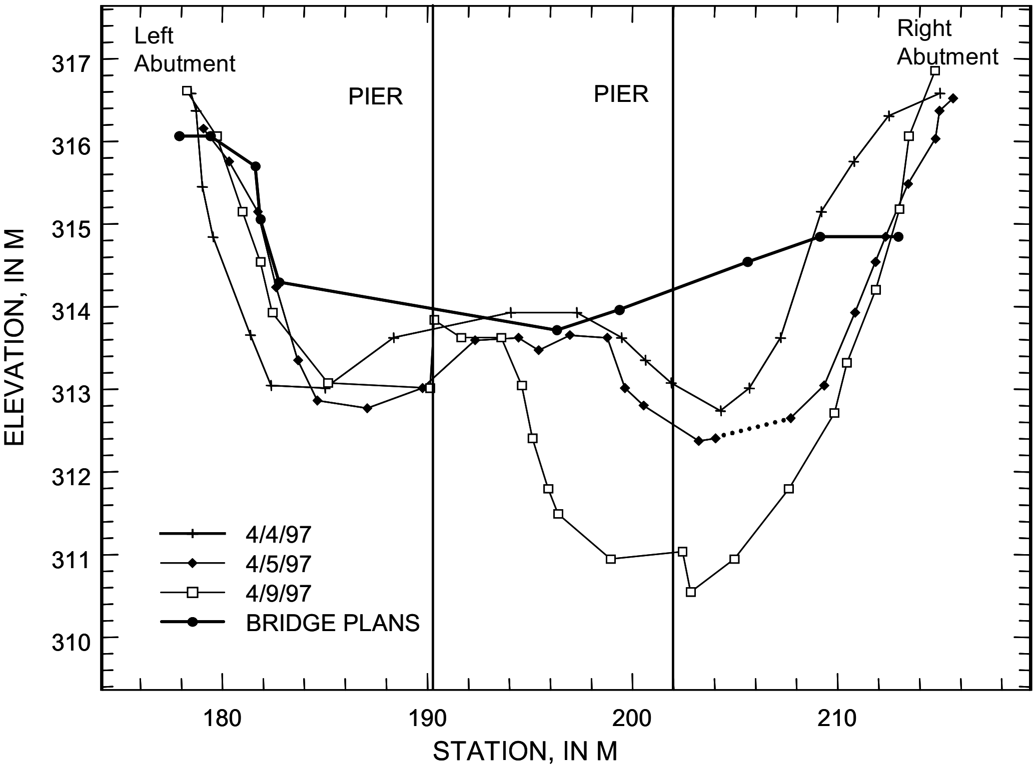

Figure 7. Cross sections collected along the upstream edge of Swift County Route 22 over the Pomme de Terre River, Minnesota.

Table 6. Summary of abutment scour field data for Swift County Route 22 over the Pomme de Terre River in Minnesota.

Date	Abutment	Location	Equipment	Observed Scour Depth (m)	Accuracy (m)	Embankment Length (m)	Velocity At Abutment (m)	Depth At Abutment (m)
4/4/97	Right	Upstream	Echo sounder	1.2	0.3	157	--	4.2
4/5/97	Right	Upstream	Echo sounder	1.2	0.3	162	2.5	4.8
4/9/97	Right	Upstream	Echo sounder	3.0	0.5	166	1.0	6.4
4/4/97	Left	Upstream	Echo sounder	0.9	0.3	44	--	4.0
4/5/97	Left	Upstream	Echo sounder	0.9	0.3	47	1.5	4.4
4/9/97	Left	Upstream	Echo sounder	0.6	0.3	50	1.6	4.3

Model Calibration

The data collected on 4/5/97, 4/9/97, and 7/15/97, were utilized to develop and calibrate the HEC-RAS model. Because no bathymetry data were collected during the flood in either the approach or exit sections, low-flow cross sections measured before and after the flood were used. The bathymetry data collected on 7/15/97, along with geometry taken from the bridge plans, were the basis for the cross sections upstream and downstream of the bridge crossing. Despite the added hydraulic complexities introduced by the meander of the channel near the C.R. 22 bridge, the HEC-RAS model simulated the water surface at the bridge within 0.06 m of field measurements on 4/5/97 and 4/9/97. When an ineffective flow area representing the recirculation zone between the right abutment and the rightmost pier was included, the model simulated the water-surface elevation at the bridge within 0.03 m of the data collected in the field.

The velocity distributions from the model and the field compared favorably, when taking into account that the one-dimensional model is not capable of replicating the two-dimensional features of the flow field. The velocity distributions for the model, using the geometry from 4/5/97 and 4/9/97, and field measurements collected with a vertical-axis current meter along the upstream edge of the bridge are shown in figures 8 and 9. The one-dimensional model results did not accurately compare with the 4/5/97 observations (figure 8). Although model simulated the peak velocity near the rightmost pier reasonably well, the model velocities were too high on near the right bank and in the center of the main channel and too low along the left bank. The model more accurately redistributed the flow after the scour had fully developed. The errors displayed should be expected when using a conveyance method to distribute flow that is complex and dominated by two-dimensional contraction effects. Because data were not available for the approach section, no comparisons could be made upstream from the bridge.

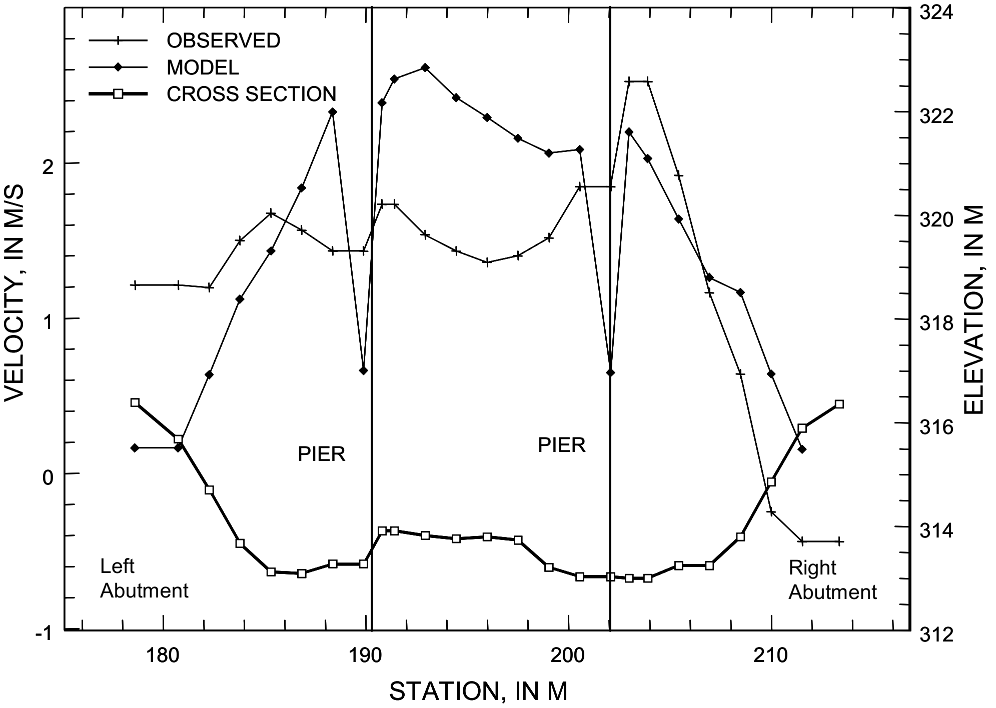

Figure 8. Comparison of observed and model velocity distributions for April 5, 1997, at Swift County Route 22 over Pomme de Terre River, Minnesota.

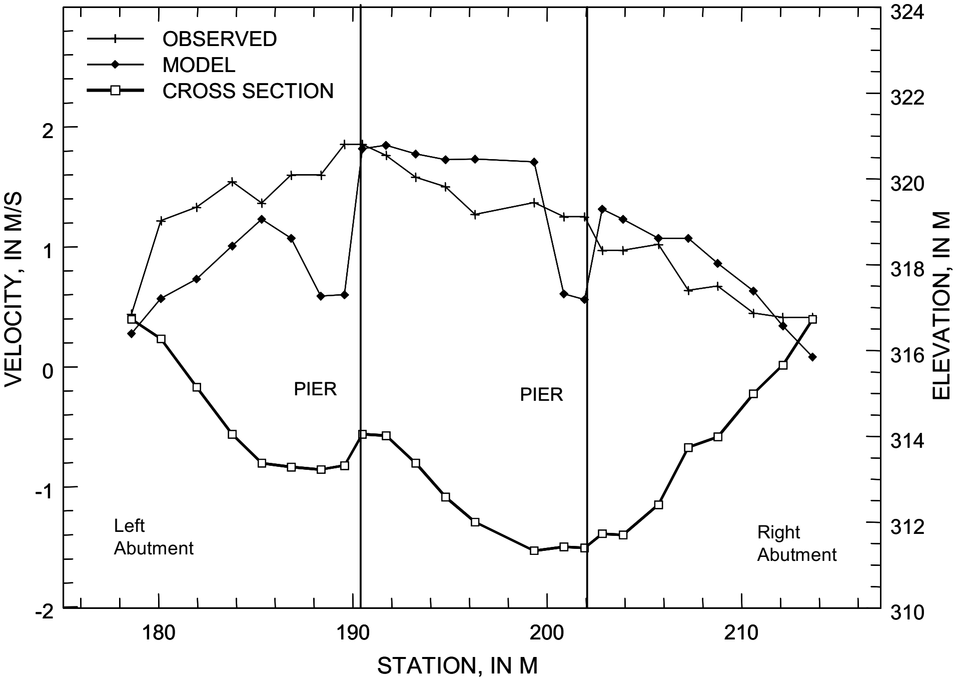

Figure 9. Comparison of observed and model velocity distributions for April 9, 1997, at Swift County Route 22 over Pomme de Terre River, Minnesota.

Assessment of Scour Computations

The calibrated model was used to assess how accurately the scour for this flood could have been predicted. The original geometry of the bridge section was taken from the bridge plans and input into the calibrated HEC-RAS model. The approach and exit cross sections were modified to be consistent with the streambed elevations from the bridge plans. The ineffective flow area between the rightmost pier and the right abutment was assumed to be effective because it is unlikely that it would have been assumed ineffective without field observations. The discharges from both 4/5/97 and 4/9/97, were then modeled with the original bathymetry to determine the hydraulic parameters needed for scour computations. The model analysis did not include the data collected on 4/4/97, because no hydraulic measurements were made during that site visit.

The contraction scour was computed in HEC-RAS by allowing the model to use the default equation (live-bed or clear-water) depending upon the hydraulic conditions computed by the model. The model correctly predicted little or no contraction scour for the prescribed discharges.

Abutment scour was computed in HEC-RAS by both the Froehlich equation and the HIRE equation. The data contained in table 7 show that the Froehlich equation accurately predicted abutment scour, when compared to the fully developed scour holes on 4/9/97. Because the equations predict maximum depth of scour, the Froehlich equation accurately predicted and overpredicted the depth of scour, when compared to the scour holes measured on 4/5/97, which had not fully developed. The HIRE equation overpredicted scour for all hydraulic conditions.

Table 7. Comparison of observed to computed abutment scour at Swift County Route 22 over the Pomme de Terre River in Minnesota.

				Local Scour Depth		
Date	Abutment	Location	Equipment	Observed (m)	Froehlich Equation (m)	HIRE Equation (m)
4/5/97	Right	Upstream	Echo sounder	1.2	2.9	3.8
4/5/97	Left	Upstream	Echo sounder	0.8	0.7	2.8
4/9/97	Right	Upstream	Echo sounder	3.0	3.3	4.1
4/9/97	Left	Upstream	Echo sounder	0.6	0.9	3.1

Summary and Conclusions

In cooperation with the FWHA, the USGS developed a comparison of computed abutment and contraction scour depths with depths measured in the field for U.S. Route 12 and Swift County Route 22 over the Pomme de Terre River in Minnesota provides insight to the capabilities and limitations of using one-dimensional models and the available abutment and contraction scour equations to predict scour at contracted bridge openings. The application of the methods outlined in HEC-18 to these bridges showed a similar variability of results as the comparisons published in the literature. HEC-RAS and the equations recommended in HEC-18 provided reasonable predictions for maximum total scour at the two bridges; however, the magnitudes of the individual scour components (abutment and contraction) did not compare well with the field data. Although field data in the approach sections were inadequate to provide a comprehensive evaluation of the capability of a one-dimensional model to represent a complex two-dimensional flow field, the comparisons that could be made showed the one-dimensional model computed flow distributions that were comparable with the field data for the fully developed scour hole conditions, but were less accurate for initial conditions and in areas of highly curvilinear flow.

The complexity and variability of conditions at bridges make the development of predictive methodology difficult. The equations oversimplify most conditions, but modification of the methodology to account for site complexity and variability is not simple. New methodologies must balance the desire to fully explain complex processes with the need to provide procedures that are time and cost effective to apply. Additional field data and model studies are needed to continue to improve scour prediction methodology.

References

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