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Laboratory and Field Measurements of Bridge Contraction Scour

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While some field studies of bridge contraction scour have been undertaken in the past as well as laboratory studies of scour in long contractions, somewhat less attention has been paid to hydraulic modeling of contraction scour using the full bridge geometry and river bathymetry, not to mention the interaction between contraction scour and local pier scour. This study focuses specifically on contraction scour at a bridge on the Ocmulgee River in Macon, Georgia. A 1:45 scale model of the bridge, its embankments, and the approach and exit river bathymetry were constructed in the Hydraulics Laboratory at the Georgia Institute of Technology in 2005. Several flow rates were modeled including the 50–year peak flood discharge and the 100–yr peak flood discharge as well as a 1998 historical flood discharge for which field measurements were made by the U. S. Geological Survey. Comparisons are made between contraction scour measurements in the laboratory and in the field, and a procedure for hydraulic modeling of contraction scour is suggested.

I. INTRODUCTION

While flood damages typically involve widespread inundation of agricultural land, destruction of homes and businesses, and disruption of economic activity, a less obvious threat is the vulnerability of bridges over waterways that cause flow obstruction and scour around the bridge foundations leading to possible bridge failure during floods. Two types of scour that can lead to bridge failure are local scour, which occurs at the base of abutments and piers and is attributed to flow obstruction, downflow, and formation of a horseshoe vortex that wraps around the obstruction, and contraction scour, which occurs across the entire channel and is attributed to the flow contraction caused by the bridge opening and deflection of floodplain flow into the main channel.

In recent years, flood waters have closed many highways and local roads as well as interstate highways in the United States and caused scour that damaged many bridges and even resulted in loss of life. For example, intense thunderstorms in Iowa in 1992 caused 6 m of contraction scour at the State Highway 14 bridge over Wolf Creek [1]. One thousand bridges have collapsed over the last 30 years in the United States, and the leading cause is hydraulic failure which has resulted in large financial losses. In Georgia, the total financial loss from tropical storm Alberto in 1994 was approximately $130 million because more than 100 bridges had to be replaced and repaired due to flooding [2]. During the 1993 upper Mississippi River basin flooding, more than 258 million dollars in federal assistance was requested for repair and/or replacement of bridges, embankments, and roadways [3]. Bridge failures can also lead to loss of life such as in the 1987 failure of the I–90 bridge over Schoharie Creek near Albany, New York, the U.S. 51 bridge over the Hatchie River in Tennessee in 1989, and the I–5 bridges over Arroyo Pasajero in California in 1995 [4].

The engineering design of a hydraulic structure such as a river bridge requires consideration of both safety and cost with respect to the depth of the foundation relative to predicted scour depths. Engineering experience seems to indicate that computation of scour depth using current scour formulas tends to overpredict scour in comparison to field measurements. The result can be overdesigned bridge foundations that increase the cost of the bridge. In fact, achieving a balance between safety and cost is a very difficult problem which is one reason why the Federal Highway Administration in the U. S. has mandated the use of scour prediction formulas that have a large factor of safety to compensate for a lack of complete understanding of the complex physics of the scour process. These scour prediction formulas are based primarily on idealized laboratory experiments in rectangular flumes (steady, uniform flow and non–cohesive sediments). To predict more accurate scour depths and to suggest more economical methods of designing bridge foundations, physical models that reproduce the pier and abutment geometry as well as the river bathymetry can be used but only in a few cases has this been done [5].

In addition to idealized laboratory experiments, another possible reason for scour depth overprediction is the current practice of adding separate estimates of contraction scour and local scour when in fact these processes occur simultaneously and interact. Local scour occurs at the location of a bridge pier or abutment due to obstruction of the flow and the development of complex, three–dimensional horseshoe vortices at the base of the foundation that entrain and carry sediment away. Contraction scour, on the other hand, tends to occur across the entire bridge section due to contraction of the flow. During a flood, velocities increase as depths increase but they are also affected by changes in the distribution of discharge between the main channel and floodplain, especially within the contracted bridge section. In addition, the time history and time development of contraction scour and local scour are not the same. As a result, the influence of local scour on contraction scour, for example, is time dependent. Some researchers have studied the relationship between local scour and contraction scour [6, 7]. However, those studies were limited to the interaction between abutment scour and contraction scour and so did not consider the relationship between pier scour and contraction scour. In fact, very few hydraulic modeling studies have been conducted on contraction scour which is the focus of this paper.

Many contraction scour prediction formulas are based on the theory of an idealized long contraction in which sediment continuity is satisfied between the approach and the contracted sections for equilibrium scour in the case of live–bed scour, while for clear–water scour, critical conditions for incipient motion are assumed to have been reached in the scoured contracted section at equilibrium [8, 9, 10]. Laursen [11] also developed contraction scour formulas based on this conceptual model for both the live–bed and clear–water scour cases, and these formulas are currently recommended by the Federal Highway Administration (FHWA) for estimating contraction scour. Laursen's live–bed scour formula includes the effect of contraction of the approach floodplain flow due to the bridge embankments as well as the contraction in the channel width itself.

Several laboratory studies have been performed on long contractions in laboratory flumes. Formulas for contraction scour prediction have been proposed based on the experimental results as a function of approach Froude number, the width contraction ratio, and the nonuniformity of the sediment size distribution, for example [12, 13].

Mueller and Wagner [14] have summarized available field data on contraction scour and have compared scour prediction results from formulas such as those of Komura and Laursen with field observations. Overall, the results were mixed with several cases of overprediction and even severe overprediction, while some cases resulted in underprediction of contraction scour. Their conclusion was that application of contraction scour formulas based on idealized long contractions or experimental data from long contractions in rectangular flumes were difficult to apply in the field partly because of difficulties in assessing nonuniform flow distributions in the approach and contracted channels and in separating contraction and local scour.

In this study, a 1:45 scale model of the bridge, its embankments, and the approach and exit river bathymetry for the Ocmulgee River bridge in Macon, GA were constructed in the Hydraulics Laboratory at the Georgia Institute of Technology in 2005. Several flow rates were modeled including the 50–year peak flood discharge and the 100–yr peak flood discharge as well as a 1998 historical flood discharge for which field measurements were available from the U. S. Geological Survey (USGS). The laboratory model measurements were taken in the clear–water scour range up to the maximum clear–water scour case with Froude number similarity and compared with measured live–bed contraction scour in the field. Local pier scour was separated from the measured cross sections in both the model and the field to obtain values of contraction scour alone. In addition, the contraction scour was determined relative to a reference scour surface. Continuous field measurements of scour at the main bridge pier bent were obtained with fathometers attached to the piers. These data were analyzed and compared with cross sections measured during floods to better understand the dynamic nature of the live–bed scour process.

II. EXPERIMENTAL PROCEDURE

A. Laboratory Model

The experimental studies were conducted in an undistorted geometric scale model constructed in a laboratory flume, which is 24.4 m long, 4.3 m wide and 0.8 m deep. The existing flume consists of a level concrete bed with vertical steel walls bolted to the floor and water–sealed. All of the prototype data, including discharge, stage, velocity distributions and river bathymetry were measured by the USGS. Dynamic similarity was obtained by equating Froude numbers in the model and prototype. A geometric scale ratio of 1:45 was selected based on the limiting dimensions of the flume. The model sediment size of d_{50} = 1.1 mm with σ_g = 1.3 was chosen such that the ratio of pier size to sediment size, b/d_{50}, was in the range of 25–50 where it has negligible influence on pier scour [15]. In addition, the value of the sediment mobility parameter, given by the ratio of approach velocity to critical velocity for incipient sediment motion, V/V_c, was close to unity for the occurrence of maximum clear water scour [16].

The complete river bathymetry was modeled with a fixed–bed approach channel followed by a mobile–bed working section in which the bridge piers, embankments and abutments were placed. The approach section was approximately 9.1 m long with a 6.1 m long mobile–bed section followed by an approximately 3.1 m long exit section for sediment deposition. In the approach section, river bathymetry was modeled by cutting plywood templates that reproduced the surveyed cross sections. The bed material was leveled carefully by hand to match the templates. The templates were left in place in the fixed–bed section, but in the mobile–bed section, they were installed and removed after the bed was shaped for each experimental run. To accomplish this task in the mobile–bed section, the river bathymetry was molded to thin aluminum panels that could be extracted without disturbing the bed. The fixed–bed approach and exit sections were formed from a 3.3 mm gravel bed that was fixed with polyurethane.

Water enters the flume from a 0.305–m diameter pipe, which discharges vertically into the forebay section of the flume. Turbulence at the pipe outlet is reduced by two rolls of chain link fence. An overflow weir, baffles and a perforated steel plate serve to minimize entrance effects and produce a uniform inlet velocity distribution. At the downstream end of the flume, there is an adjustable flap tailgate for controlling the tailwater elevation. The water supply is provided by a constant–head tank. Water flows through the flume and recirculates through the laboratory sump where it is continuously pumped by two pumps with a total capacity of 0.3 m^3/s to the head tank which overflows back to the sump. Discharge is measured by an electromagnetic flow meter.

Adjustable rails on the top of the flume walls provide a level track for an instrument carriage. The instrument carriage is moved along the rails by a system of cables driven by an electric motor. An acoustic Doppler velocimeter (ADV) is used for velocity and bed elevation measurement, and water surface elevation measurements are made by a point gage. Both are mounted on the carriage and can be positioned in three dimensions.

The first set of experiments was conducted with a fixed bed. To determine the initial velocity distribution throughout the flow field before scour, the entire mobile–bed section was fixed by spraying polyurethane on the surface. Point velocities were measured at 8 positions above the bed at each location, and then the depth–averaged velocity at each measuring location was calculated by regression analysis using the logarithmic velocity distribution. An ADV sampling duration of 2 minutes was used at each measuring point.

After completion of the velocity measurements over a fixed bed, the mobile bed was installed, and scour experiments were conducted. The flume was slowly filled with water from a downstream supply hose so that the sand was saturated slowly and the initial bottom contours were unchanged. After complete saturation, the initial bottom elevations of the entire working mobile–bed section were measured by the ADV and point gage in detail. The required discharge was then set using the magnetic flow meter. A flow depth larger than the target value was set by the tailgate so as to prevent scour while the test discharge was established. Then the tailgate was lowered to achieve the desired depth of flow. The scour depth as a function of time at a fixed point was measured with the ADV to determine when equilibrium had been reached. Then the flow rate was greatly reduced, and the bed elevations were measured by the ADV and a point gage.

Experimental flow conditions in prototype units include the flow events shown in Table I. An additional flow rate was tested in Run 4 to achieve maximum clear–water scour (Max. CWS) as will be discussed subsequently. For comparison, the peak discharge of the flood having a 2–year recurrence interval is 807 m^3/s, and the 25–year peak discharge is 1,970 m^3/s. The maximum peak discharge of record is 3,030 m^3/s which occurred in July 1994 due to Tropical Storm Alberto.

Pier scour depths and contraction scour bed elevations between the pier bents were measured during the course of the experiment to determine when equilibrium was reached. Although pier scour reached equilibrium in approximately 2 days, contraction scour required 4 to 5 days so all experiments were run continuously for the longer duration.

TABLE I. EXPERIMENTAL DISCHARGES

Experimental Run No.	Discharge (m^3/s)	Water Surface Elev. (m)	Description
1	1,840	91.37	1998 flood
2	2,242	91.87	50–year
3	2,500	92.32	100–year
4	2,152	91.37	Max. CWS

B. *Field Measurements*

The field site chosen for this study of contraction scour is the Fifth Street Bridge over the Ocmulgee River at Macon, Georgia. The USGS has been gaging stage and streamflow at this site since 1895. The drainage area at this site is 5,800 km^2. The river channel is relatively straight for about 300 m upstream of the bridge and for about 450 m downstream of the bridge. The streambed is sandy with a median particle size of 0.8 mm at the bridge and with a geometric standard deviation, σ_g = 1.8. The right bank is high and is not subject to overflow. The left bank is subject to overflow at high stages, but the highway embankment confines all flow to the bridge opening. Seven cross sections were surveyed throughout the channel reach and were used to construct the physical model in the laboratory.

The bridge pier bents consist of four cylindrical columns that rest on concrete footings, which are buried below the streambed. The main bridge pier bent, which is shown in Fig. 1, is located in the center of the channel with one bridge pier bent on either side at each of the river banks. All three bridge pier bents are aligned with the flow. The pier columns have a diameter of 1.83 m.

Fixed field instrumentation was deployed at the bridge site to continuously measure bed elevations and stage. Bed elevations were measured by fathometers that were attached to the central bridge pier bent in the main channel in order to monitor the changes over time (30–minute intervals) in bed elevation around the bridge piers. The fathometers measured the bed elevations at a lateral distance of 0.6 m from the pier. With reference to the four cylindrical columns shown in Fig. 1, one fathometer is located on the left side (looking downstream) of the second column. Another fathometer is located on the right side of the third column. A third fathometer is located on the left side of the fourth column. A total of six fathometers were originally attached to the pier bent including one at the pier nose; however, three of the fathometers were damaged due to an abundance of logs and debris floating in the stream during high flows.

Stage and bed elevation data were collected during multiple moderate highwater events from 2001 through 2005. Before the fathometers were deployed in October of 2001, a peak discharge of 1,840 m^3/s occurred in 1998, which is near the 25–year peak discharge for this site. The highest peak discharge during the monitoring period occurred in May of 2003 and had a value of 722 m^3/s, which is just less than the 2–year flood peak.

III. RESULTS

A. *Laboratory Model*

In order to analyze contraction scour, it is necessary to first separate local pier scour from the measured cross section at the bridge and to establish a reference scour

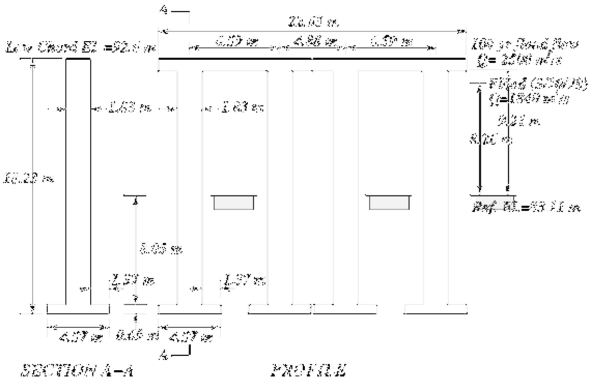

Figure 1. Dimensions of central pier bent in Ocmulgee River at Macon, GA

surface to eliminate residual contraction scour. The local pier scour was eliminated from cross sections at the upstream face of the bridge by the method of concurrent ambient bed level in which average bed elevations are established on each side of the scour hole in the unscoured region [17]. Establishing a reference scour surface for contraction scour is somewhat more difficult because the reference bed level is intended to be the bed elevation that would exist without the bridge obstruction. Historical streambed profiles prior to construction of the bridge were unavailable. Instead, the method used was to establish an average streambed profile from an upstream uncontracted reach to a downstream uncontracted reach using concurrent cross sections that were measured in 2002 as the initial river bathymetry for the laboratory physical model [17]. The reference surface and corresponding flow depths at the upstream face of the bridge were calculated in terms of average or hydraulic depths rather than maximum depths.

The approach cross section for contraction scour was established as the cross section upstream of the bridge with the largest width and smallest velocity at which flow acceleration began into the contracted bridge section. This cross section, referred to as river section 5 (RS 5) was located a distance of approximately 85 m upstream of the bridge.

The laboratory results for contraction scour are summarized in Table II using prototype values. The approach Froude number, $\mathbf{F}_1$, at RS 5 is the same in model and prototype except for Run 4 in which the prototype approach flow depth, y_1, is modeled for the 1998 flood but at a higher velocity. The result is a higher Froude number in order to obtain the contraction scour depth for maximum clear water scour. Because the Froude number is small, the resulting minor increase in Froude number is not likely to affect the results. All of the laboratory results are in the clear–water scour regime since the approach values of velocity in ratio to critical velocity, V_1/V_c, are ≤ 1.0. The reference hydraulic depth at the bridge is given in the table as y_{2ref} which is subtracted from the measured hydraulic depth y_2 at the bridge to produce the measured average contraction scour depth, $d_{sc} = (y_2 - y_{2ref})$.

TABLE II. LABORATORY MODEL RESULTS

Run No.	$\mathbf{F}_1$ *model*	V_1/V_c *model*	y_1 (m)	y_2 (m)	y_{2ref} (m)	d_{sc} (m)	y_2/y_1
1	0.234	0.793	8.15	9.18	8.24	0.94	1.12
2	0.246	0.843	8.60	9.81	8.68	1.13	1.14
3	0.248	0.868	9.14	10.67	9.23	1.44	1.17
4	0.285	0.964	8.15	9.89	8.24	1.65	1.21

B. Field Data

Before the fathometers were deployed in October of 2001, the last high water event greater than the 2–year peak discharge of 807 m^3/s occurred in March of 1998. This event peaked at a discharge of 1,840 m^3/s, which is near the 25–year peak discharge for this site. The channel cross section at the upstream side of the bridge was surveyed during this event. The channel cross section was also surveyed in February, 1998. Comparing these two channel cross sections, both contraction scour as well as local scour were occurring during the March 1998 event as shown in Fig. 2. The channel cross section at the upstream side of the bridge was also surveyed in December 2000. This cross section still showed a remnant pier scour hole from the March 1998 flood.

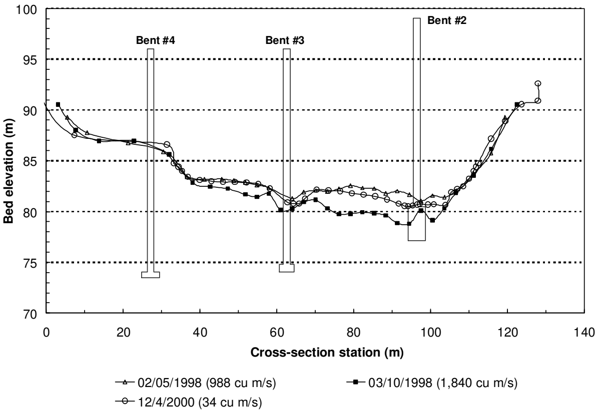

Figure 2. Comparison of bridge cross sections in the field before and after 1998 flood peak of 1,840 m^3/s.

During the period of data collection from October 2001 to July 2005, all the high water events were less than the 2–year peak discharge of 807 m^3/s due to a drought. Fig. 3 shows the fathometer data collected during the period March 12, 2003 to May 29, 2003 on the right side of the third pier column. The other two fathometer locations indicated in the figure inset show very similar results. During the first event of this time record, which occurred on March 22, 2003, all three fathometers measured nearly 1.0 m of fill. A cross section was also surveyed during this event at the upstream side of the bridge as shown in Fig. 4. This cross section verified additional fill of the remnant scour hole from the March 1998 event. From March 22, 2003 to July 10, 2003, the fathometers showed a gradual increase in bed elevation over time that can be seen in Fig. 3. Channel cross sections obtained in July 2003 and October 2005 at the upstream side of the bridge verify the gradual increase in bed elevation throughout the channel cross section as shown in Fig. 4. However, during the high water events above approximately 600 m^3/s for the period of data collection, local scour of nearly 1.0 m was measured by the fathometers. This local scour can be seen in Fig. 3 during the last two events. The local scour hole was immediately filled during the recession of the peak and the gradual fill of the channel cross section continued.

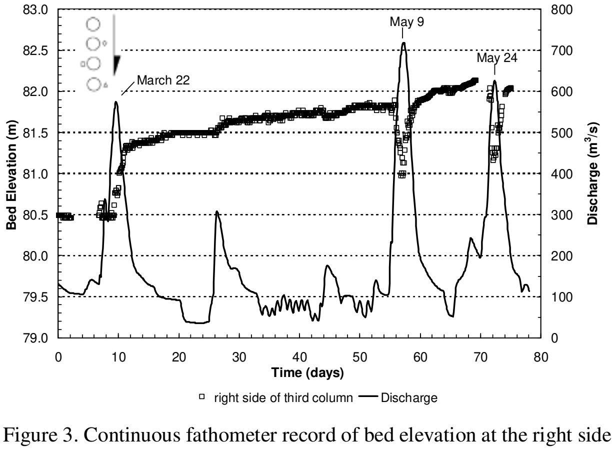

Figure 3. Continuous fathometer record of bed elevation at the right side of the third pier column from March 12 to May 29, 2003.

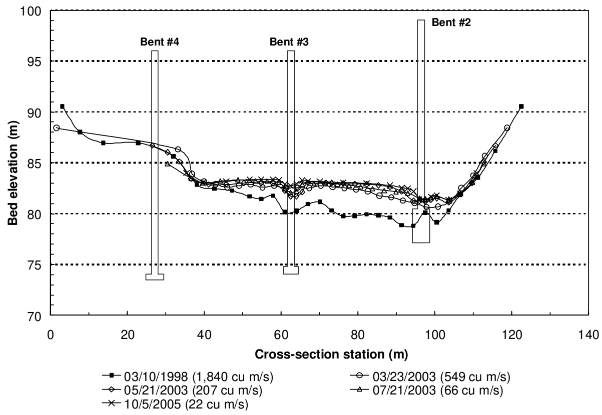

Figure 4. Bridge cross sections during the continuous monitoring period from 2001 to 2005 after the 1998 flood.

C. *Comparison of Laboratory and Field Results*

In Fig. 5, the model and prototype velocities are compared at the upstream face of the bridge for the 1998 flood discharge of 1,840 m^3/s. The prototype velocities were measured just after the peak discharge and so are slightly smaller than the model velocities for the peak flood discharge, but the comparison is consistent with the measured decrease in velocity with stage for the cross section.

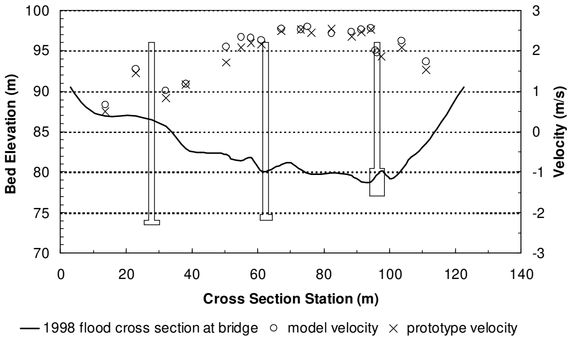

Figure 5. Comparison of measured velocities in the laboratory model and in the field at the upstream face of the bridge for the 1998 flood.

The cross section immediately upstream of the bridge is shown in Fig. 6 at the end of laboratory model run number 1 and as measured in the field for the 1998 flood. For this laboratory run, exact Froude number similarity was used to determine the discharge, and the water surface elevation measured in the field at the downstream face of the bridge was reproduced in the model. However, as shown in Table II, the value of the flow intensity factor for this model run was $V_1/V_c = 0.79$ which is obviously short of maximum clear–water scour. The bed elevations in Fig. 6 show very good agreement for the local pier scour, while the contraction scour is clearly underestimated in the laboratory model. The good comparison with local scour measured in the field is consistent with previous model studies [16]. These studies show that live–bed local scour in the field can be reproduced in the laboratory model by choosing a sediment size such that $V_1/V_c < 1$ to compensate for the decrease in scour observed with large values of the ratio of pier width to sediment size characteristic of field measurements [18].

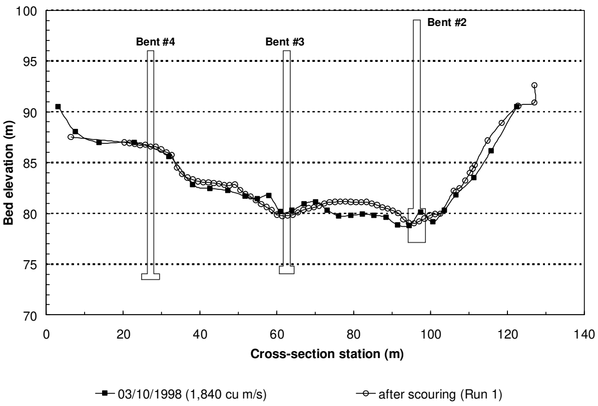

Figure 6. Comparison of laboratory and field cross sections at upstream face of the bridge for 1998 flood.

The laboratory and field contraction scour measurements can be placed in perspective by considering the comparisons shown in Fig. 7. Experimental run 4 as shown previously in Table II was a reproduction of the 1998 flood maximum water surface elevation but at a higher velocity that approached maximum clear–water scour. This should be considered a good estimate of the field live–bed contraction scour for small width contraction ratios [15]. The laboratory value of y_2/y_1 is 1.21 as shown previously in Table II compared with the field value of 1.24. In terms of the reference scour surface, the model value of mean contraction scour is 1.65 m in comparison to the field value of 2.06 m for a difference of about 20 percent. The Laursen contraction scour formulas do a reasonable job of estimating the clear–water contraction scour, but the live–bed contraction scour is underestimated.

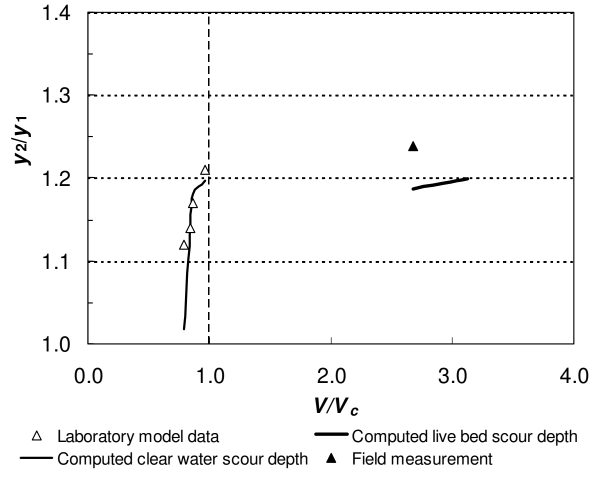

Figure 7. Comparison of laboratory and field measurements of contraction scour along with Laursen formula predictions.

The actual measured cross section upstream of the bridge for laboratory model run 4 and the field cross section for the flood of 1998 are shown in Fig. 8 after removing the local pier scour using the concurrent ambient bed level. This figure gives a better idea of the distribution of contraction scour throughout the cross

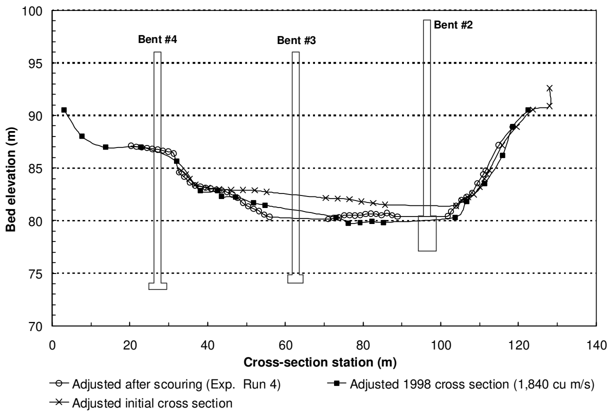

Figure 8. Comparison of adjusted cross sections upstream of bridge with local pier scour removed for 1998 flood.

section. It is not uniformly distributed, but the laboratory model results follow the general trend of the field contraction scour.

IV. SUMMARY AND CONCLUSIONS

A laboratory model study of a bridge over the Ocmulgee River in Macon, GA has been conducted, and the results have been compared with detailed field measurements of contraction scour. Model tests were run for the 1998 flood event having a peak discharge of 1,840 m^3/s as well as for the 50–year and 100–year recurrence interval flood events. Although the prototype contraction scour is live–bed, the model was run in the clear–water regime with a sediment size that resulted in flow intensity values, V_1/V_c, in the range of 0.79–0.96 while maintaining Froude number similarity. Good comparisons were obtained for the prototype values of local pier scour for the 1998 flood at the lowest experimental value of V_1/V_c with exact Froude number similarity in confirmation of a previous model study of a different river bridge [16]. Contraction scour for the 1998 flood, however, was modeled in the laboratory at a discharge approaching maximum clear–water scour, and good agreement was obtained between the laboratory and field values of mean contraction scour depth. This required slight violation of Froude number similarity, but not enough to affect the final results.

Measured field cross sections upstream of the bridge and continuous measurements of scour depths next to the piers illustrate the dynamic nature of the live–bed scour process. Subsequent to the 1998 flood peak of 1,840 m^3/s, no flood discharges in excess of the 2–year recurrence interval discharge of 807 m^3/s occurred. As a result, the contracted section experienced a slow infilling process from 2001 through 2005. The local pier score holes alternately filled and scoured back out for several small floods provided that a threshold discharge of about 600 m^3/s was reached.

Because of the continuously changing streambed at the bridge, occasional snapshot cross–section surveys may not be sufficient to assess live–bed contraction scour. Continuous measurements of scour at the bridge show that the bed responses are quite sensitive to the temporal flow record. Furthermore, both pier scour and contraction scour occur in concert with the flow time history. Under these circumstances, a hydraulic model can be quite helpful in determining contraction scour for realistic field conditions provided that the sediment size is chosen carefully such that Froude number similarity is not seriously violated for maximum clear–water scour conditions, and provided that the pier scour and contraction scour are properly separated relative to reference scour surfaces.

ACKNOWLEDGMENTS

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