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Research Article

Reproducing Field Measurements Using Scaled-Down Hydraulic Model Studies in a Laboratory

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Little efforts have been made to the value of laboratory model study in closing the gap between results from idealized laboratory experiments and those from field data. Thus, at first, three bridge sites were selected and equipped with fathometers to find the bed elevation change in the vicinity of bridge pier over time. After and during the flooding, the stream flow variables and their bathymetry were measured using current viable technologies at the field. Then, to develop and suggest a laboratory modeling techniques, full three-dimensional physical models including measured river bathymetry and bridge geometry were designed and fabricated in a laboratory based on the scale ratio except for the sediment size, and the laboratory results were compared with the field measurements. Size of uniform sediment was carefully selected and used in the laboratory to explore the scale effect caused by sediment size scaling. The comparisons between laboratory results and field measurements show that the physical models successfully reproduced the flow characteristics and the scour depth around bridge foundations. With respect to the location of the maximum scour depth, they are not consistent with the results as in the previous research. Instead of occurring at the nose of each pier, the maximum scour depths are located further downstream of each pier column in several experimental runs because of the combination of complex pier bent geometry and river bathymetry, and the resulting unique flow motions around the pier bent.

1. Introduction

General purposes of physical hydraulic modeling are reproduction and/or duplication of actual flow phenomena in a laboratory. Thus, with the help of successful physical hydraulic modeling, the effects of selected flow parameters around various hydraulic structures, such as different shape of orifices [1], T-shaped spur dike [2], bridge pier, and so on, can be examined using well-controlled laboratory experiment. This study is an experimental investigation of local pier scour throughout the reach of a bridge section under clear-water scour conditions using scale-down full bridge geometry and river bathymetry. Pier scour is analyzed with reference to its spatial and temporal distribution, and several experimental observations and conclusions are reported.

One thousand bridges have collapsed over the last 30 years in the United States, and 60 percent of those failures stem from hydraulic failure including bridge foundation scour [3]. Thus, the topic of foundation of scour has been attracted by many researchers and scientist since the late 1950s. Although numerous studies for the prediction of bridge scour depths have been conducted using physical modeling in laboratory and also using numerical simulation [4, 5], the topic is still challengeable when the resultant scour depths are applied to large-scale prototype because most of the current scour prediction formula are based on laboratory experiments which have been implemented with simple channel and bridge geometry even though most of bridge foundations in the field have complex geometry and the channel shape is site specific. Even though the earliest laboratory experiment conducted by Durand-Claye [6] used three different shapes of pier (rectangular, round, and triangular) to find local pier scour, since then, most experimental investigations have been conducted with a single cylindrical pier in the laboratory [7–9]. Therefore, relations and estimations of the pier scour depth developed from

laboratory data show inaccurate results compared to the actual pier scour depths measured at field sites [10]. Furthermore, most of the predictive formulas presented in the literatures have not been verified by field data because there are few long-term stations that monitor the scour process at a specific bridge site including real-time velocity measurements [11].

Only a few studies [12–14] show results for scour around scaled model having the same shape as actual field bridge pier including river bathymetry. Prototype bridges usually have complex pier configurations including shapes other than cylindrical, multiple columns with variable spacing along the pier column, and multiple pier bents at variable flow depths across the river that may be skewed relative to the main flow direction. In addition, the measurements of scour depth at complex bridge piers in the field for the validation of lab results are tricky because of the safety and economical reason. Under these circumstances, scale-down physical modeling is suggested that can reproduce the prototype flow characteristics and scour patterns including location of the maximum scour depths, which may not be at the nose of the pier as in idealized laboratory studies.

In this study, laboratory pier scour experiments on particular bridges in Georgia, USA, were conducted and their hydraulic and geometrical conditions were reproduced in the laboratory by equating the Froude numbers in the model and prototype. Based on the Froude number similarity between the model and the prototype, all of the measured prototype data including discharge, stage, velocity distributions, and river bathymetry were reproduced in the laboratory except for the sediment size. The sediment size scaling, which is one of the important hydraulic modeling criteria, will be explained in more detail in the Physical Modeling Strategy. The USGS has been gauging stream flow at the chosen bridge sites for long periods, but detailed monitoring including continuous measurement (30-minute intervals) of pier scour using fathometers and velocity measurements using acoustic velocity meter has been underway since 2002 as part of a large scour study for the Georgia Department of Transportation (GDOT) [15]. The measured temporal variation of scour depth and velocity measurement around the bridge pier for specific flood events were analyzed and compared with laboratory experimental data, and the several experimental observations and conclusions are presented here.

2. Hydraulic Modeling Procedure

2.1. Field Monitoring of Regional Bridge Sites in Georgia. A standard USGS stage-discharge station is located at each of the three bridge sites (a bridge over the Flint River at Bainbridge, a bridge over the Chattahoochee River near Cornelia, and a bridge over the Ocmulgee River at Macon) chosen for modeling. In each bridge sites, bed sediment samples were collected both upstream and downstream of the bridge. Also, continuous velocity data were measured using a cross-channel acoustic Doppler velocity sensor which provided two-dimensional velocity components in the bridge approach section at 15-minute intervals. In addition, temporal variations of channel bed elevations near the bridge pier bent were measured by several fathometers attached to the wall of the bridge piers. The horizontal locations of the bridge pier bents were determined by a kinematic differential Global Positioning System (GPS), which was also used to establish the horizontal positions where elevations and velocity were measured at each cross section. During large flood events, an acoustic Doppler current profiler (ADCP) and a digital fathometer were deployed in a boat to measure three-dimensional velocities and channel bathymetry in more detail [15].

The first bridge site for physical modeling is a bridge over the Flint River at Bainbridge, Georgia. This particular bridge was chosen partly because cross-sectional geometry and velocity data along the bridge deck were measured adequately by the USGS during tropical storm Alberto. Tropical storm Alberto produced peak flood discharges greater than 500-year events in July 1994 and caused numerous bridge failures in southern part of Georgia [16]. One other reason for the selection was the bridge was representative of the Georgia coastal plain. The width of the main channel is approximately 150 m, and there is a very wide and flat floodplain on both sides of main channel. The channel is straight for upstream and has a sharp bend about 150 m downstream of the bridge. The effect of backwater propagated from the Jim Woodruff Reservoir located 40 km downstream of the bridge exists at lower stages, but the backwater can be neglected at higher stages [15]. There are four bridge pier bents, two of which are situated in the main channel, while the other two are located on each bank. As shown in Figure 1, each pier bent has two square concrete pier columns having 1.83 m width and placed on large stepped square concrete footings. The median size of the bed material sample is approximately 0.4 mm, and the geometric standard deviation is 2.17.

The second bridge site is the Georgia Highway 384 (Duncan Bridge Road) bridge over the Chattahoochee River in the Piedmont physiographic province near Cornelia, Georgia. During the 2003 flooding, the USGS measured the bed elevations along the immediate upstream of the bridge deck and also presented mean velocities measured by the in situ acoustic velocity meter at the left side of the central pier. Based on the measurement in 2003, the USGS rated a peak discharge of 385 m^3/s which corresponded with a bank-full flow and found approximately 1.8 m of local scour at the bridge foundation. The channel is fairly straight for several hundred meters upstream and downstream of the bridge. The bridge was supported by three bridge pier bents, and one of them is located in the main channel and the others on each side of left and right banks. As shown in Figure 2, each bridge pier bent consists of four rectangular concrete columns and rectangular concrete footings. Among the four pier columns, two inner pier columns were connected by a web, while two outer pier columns were newly added to widen original Georgia Highway 384 Bridge in 1988. The bridge piers were designed to be aligned with the flow and the width is 1.07 m. The median size of bed material around the center of the channel is about 0.7 mm, and the geometric standard deviation is 1.6.

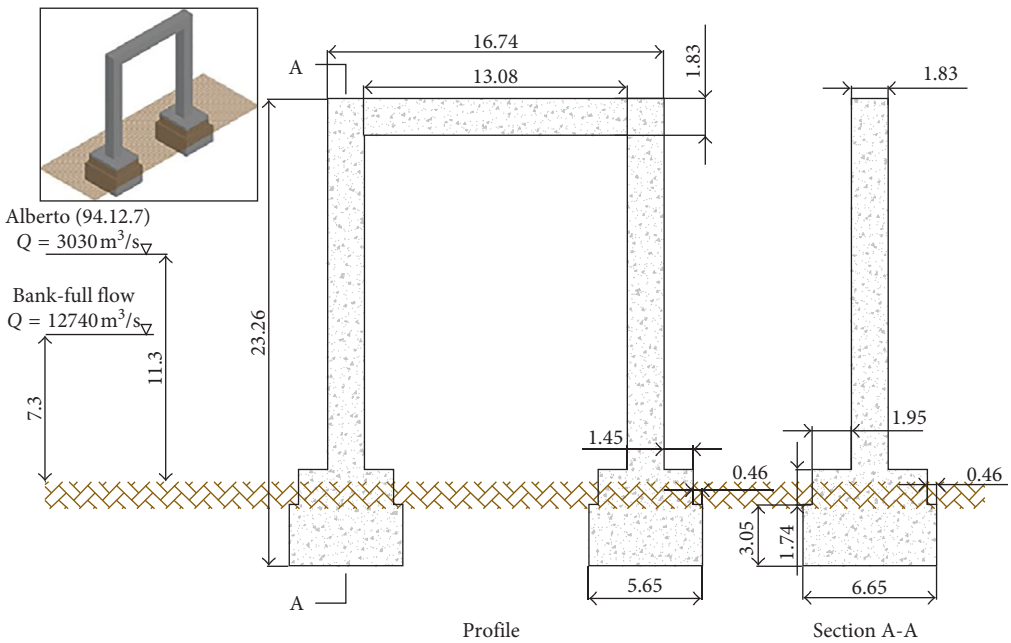

Figure 1: Dimensions of the bridge bent in Flint River at Bainbridge, GA (prototype dimensions in m).

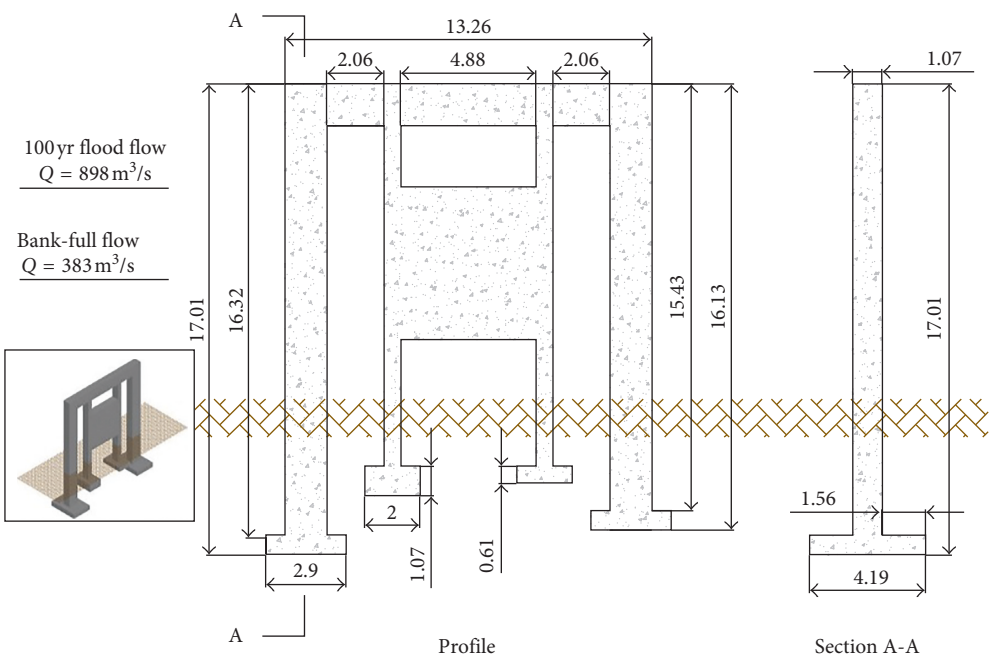

Figure 2: Dimensions of central pier bent in Chattahoochee River Bridge near Cornelia, GA (prototype dimensions in m).

The third bridge site was the Fifth Street Bridge over the Ocmulgee River at Macon, Georgia, located in the physiographic Fall Line region. The historical peak discharge at this site is 1841 m^3/s and measured in March 1998 along with approximately 3.3 m of total scour depth caused by both contraction scour as well as local scour on the upstream side of the bridge pier bent located in the main channel [15, 17]. As shown in Figure 3, the bridge pier bents consist of four circular cylinders each having a diameter of 1.83 m placed on rectangular concrete footings. The median size of bed material is about 0.8 mm, and the geometric standard deviation is 2.13.

As explained in the previous paragraph, temporal variations of bed elevations as well as continuous velocity data were collected for each site. Figure 4 shows example plot of the fathometer data collected for bed elevations during the period of March 25, 2005, to April 14, 2005, on the nose of the front pier columns at a bridge over Flint River, May 5, 2003, to May 12, 2003, on the nose of central pier bent in Chattahoochee River, and February 15, 2003, to March 2, 2003, on the left side of pier bent in Ocmulgee River, respectively. During this time record, the continuous fathometer measurements of scour depth illustrate the

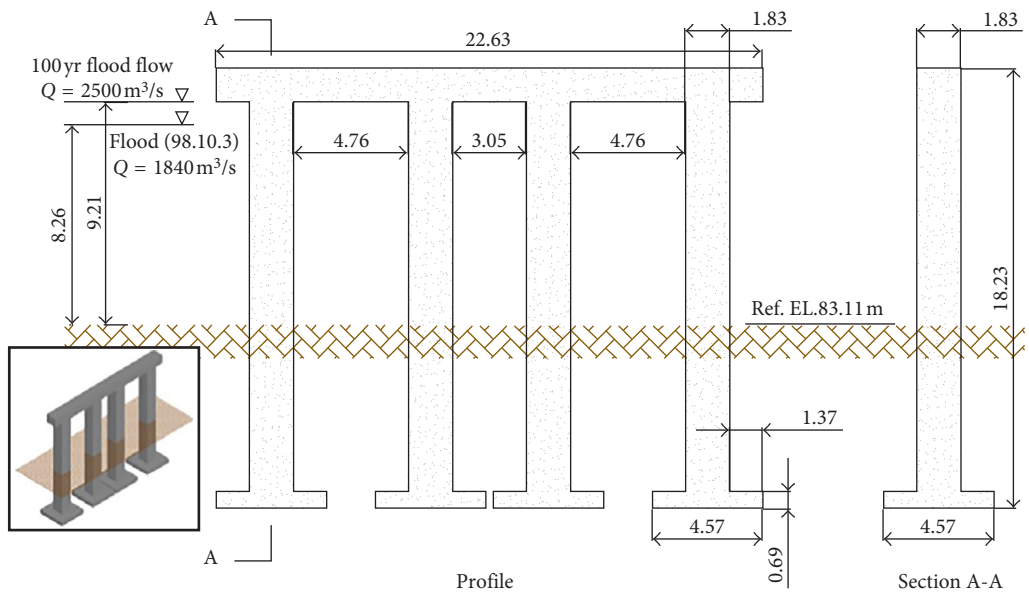

Figure 3: Dimensions of the central bridge pier bent in Ocmulgee River at Macon, Georgia (prototype dimensions in m).

dynamic nature of scour process. For example, Figure 4(a) shows that the fathometer measured almost 0.8 m of scour at the peak discharge of 1,800 m^3/s, but the local pier scour holes alternately filled and scoured back out, even in similar magnitude of the peak discharge amount during a week period (April 1, 2005, to April 7, 2005). A cross section was also surveyed during the flooding event across the bridge for the comparison with laboratory data.

2.2. Physical Modeling Strategy. The local scour around a bridge pier is often governed by multiple parameters as given in the following equation [13, 18, 19]:

$$\frac{d_s}{b} = f\left(K_s, K_\theta, \frac{y_1}{b}, \frac{b}{d_{50}}, \frac{V_1}{V_c}, Fr_1 \text{ or } Fr_b, R_1 \text{ or } R_b\right), \quad (1)$$

where d_s is the scour depth; b is the width (diameter) of bridge pier; K_s is the shape factor; K_θ is the pier alignment factor; d_{50} is the median sediment size; y_1 and V_1 are approach depth and velocity, respectively; V_c is the velocity for initiation of motion of sediment; Fr_1 is the approach Froude number ($V_1/\sqrt{gy_1}$); Fr_b is the approach pier Froude number ($V_1/\sqrt{gb}$); R_1 is the approach Reynolds number ($V_1 y_1/\nu$), and R_b is the pier Reynolds number ($V_1 b_1/\nu$). Firstly, one of the challenging parts in the laboratory modeling is that it is almost impossible to satisfy all requisite similarity criteria simultaneously. The sediment size, for instance, cannot be scaled using same geometric scale ratio in the laboratory because very small model sediment sizes exhibit interparticle forces that are not present in prototype sand-bed streams. Hence, a physically reasonable model strategy is required to predict the prototype behavior effectively.

Second challenging work is "How to reproduce/mimic field scour regime (live-bed scour) in a laboratory?" and "If we cannot reproduce/mimic field scour regime, is there any way of surrogate?" Keulegan's equation for fully rough turbulent flow was used to evaluate the critical velocities of sediment in the field and laboratory [20]. Then, the value of V_1/V_c confirmed that scour regime in the field was certainly live-bed scour. It is difficult to reproduce live-bed scour conditions in a laboratory due to the physical and economic constraints, even though a large scale is selected in a large flume. As a result, a surrogate method of finding maximum scour depth using clear-water scour experiment should be suggested instead of conducting experiment in live-bed conditions.

Among the nondimensional variables in (1), local scour depth relative to the pier width, d_s/b, relative flow depth, y_1/b, nondimensionalized by pier width, and the ratio of pier width to median sediment size, b/d_{50}, are meaningful nondimensional parameters. The effect of Reynolds number can be negligible because the flow around the pier is fully turbulent [8, 21]. Thus, the Froude number similarity can be utilized as a dynamic similarity, and the length scale ratio can be determined based on the constructability of a physical model. The Froude number governs open-channel flow through the bridge and hence the pressure gradient in the vicinity of the piers. Geometric similarity is maintained in terms of y_1/b in order to preserve the relative size and strength of the horseshoe vortex. While maintaining the Froude number similarity and geometric similarity (y_1/b) in between field and laboratory, the sediment size in the laboratory can be selected to produce a value of $V_1/V_c < 1.0$ (clear-water scour condition) as a surrogate to model live-bed scour in a laboratory and concurrently to compensate for the reduction in dimensionless scour depth, d_s/b, at large values of b/d_{50} (maximum scour depth occurs for $V_1/V_c = 1.0$). The laboratory model was constructed using an undistorted scale from the Froude number similarity with equality of y_1/b.

The scale for laboratory models was determined based on the measured field extent versus physical horizontal flume space. Then, discharge, water depth, and velocity were calculated to match Froude numbers between field and laboratory. Finally, possible experimental runs were selected

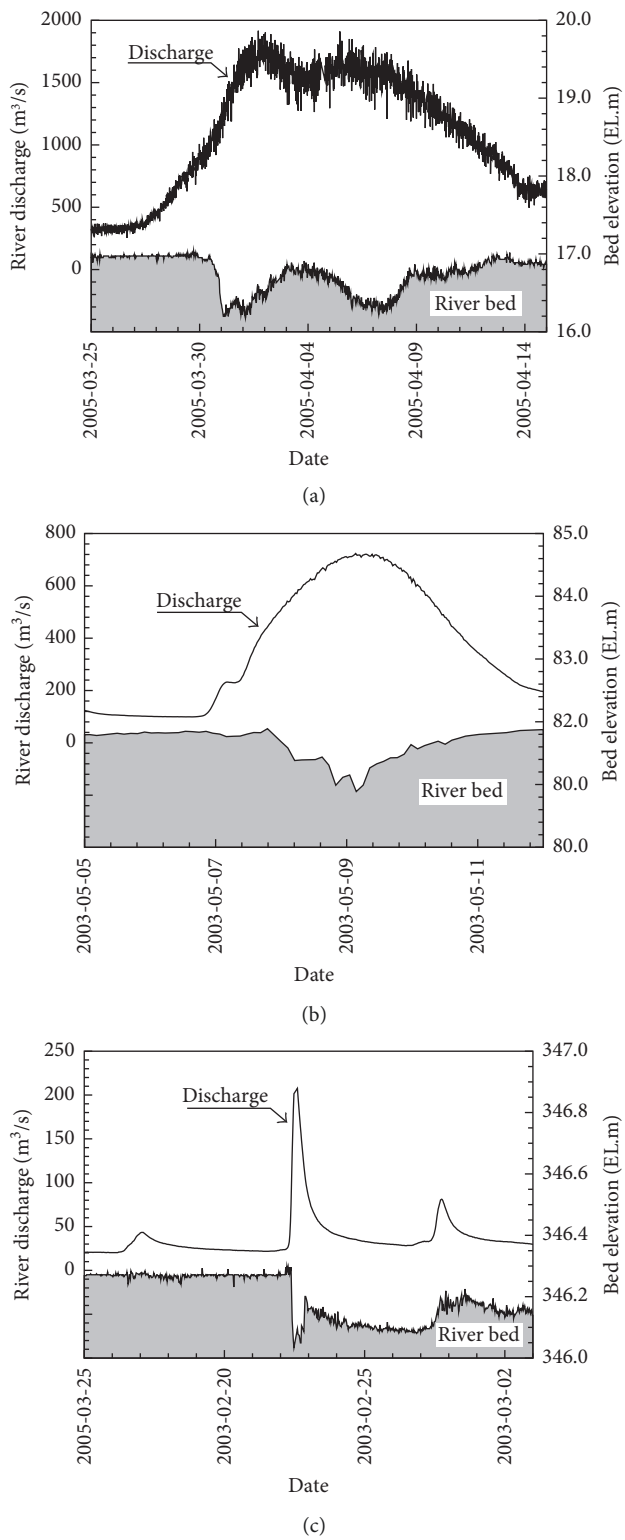

Figure 4: Temporal variation of bed elevation around bridge pier bent with corresponding discharge in (a) Flint River, (b) Chattahoochee River, and (c) Ocmulgee River.

up to where the approach velocity in the laboratory model became close to the critical velocity calculated by Keulegan's equation to conduct the experiment in clear-water scour regime.

2.3. Laboratory Experiments. All of laboratory experiments were conducted in a 4.3 m wide, 24.4 m long, and 0.6 m deep open-channel flume with test section where the models of bridge piers and embankments were built. The templates for cross sections were made of plywood with scaled elevations, and the vertical wooden templates corresponding to the scaled river bathymetry were placed in the flume based on the coordinates determined by a Global Positioning System (GPS). This GPS information was used not only to locate the cross sections and the bridge appurtenances but also to establish corresponding positions where the scour results from the experiments were compared with field measurements.

The test section for the scour in which the bridge pier, embankment, and abutment were placed began at 7.3 m, 7.9 m, and 9.4 m from the inlet of flume for Chattahoochee River model, Flint River model, and Ocmulgee River model, respectively, to create fully developed turbulent flow in the approach section. The approach section (7.3 m long, 7.9 m long, and 9.4 m long) for each model was filled with a sediment having a median grain size of 3.3 mm and a geometric standard deviation of $\sigma_g = 1.3$. The moveable bed test section and the sediment trap section were leveled carefully by hand to match the templates manufactured by thin aluminum panels based on the measured river bathymetry, and the aluminum panels were removed after the bed was shaped for scour experiment. In the test section, the full depth was filled with 1.1 mm sand to measure the bed deformation by scour. Finally, the sediment trap section was filled with 3.3 mm of sand and the surface layer was fixed with spraying polyurethane to trap the sediment transported out of the moveable test section.

The water flows into the head box of the flume vertically from a 0.305 m diameter supply pipe, and the maximum flow rate is up to 0.283 m^3/s. Turbulence at the entrance of the flume is reduced by a flow diffuser, overflow weir, and baffles, and those device produced stilling of the inflow and a uniform flume inlet velocity distribution. A flap tailgate is located at the downstream end of the flume to control the water elevation. Water was recurred through the laboratory sump from which two pumps continuously provided overflow to the constant-head tank. In the supply pipe, discharge was measured by a magnetic flow meter with an uncertainty of $\pm 0.0003\ m^3/s$.

An acoustic Doppler velocimeter (ADV), which is used for measuring instantaneous point velocities and turbulence quantities, is mounted on the carriage and can be moved in three dimensions freely. Three different types of ADV probes, 3D down-looking, 3D side-looking, and 2D side-looking, were used for measurements. When velocity measurements were needed at points close to the free surface and at shallow water depths, the 2D and 3D side-looking ADV probes were used. The ADV with 3D down-looking probe gives the distance from the sampling volume to the bed which can be converted into elevation relative to the datum by reading the point gage vertical scale to which the ADV is attached. The temporal variation of scour depth in front of a bridge pier was measured periodically using the ADV temporarily positioned for a moment above the point of scouring. Each experiment was ended when the local

scour depth reached the equilibrium state at which there are negligible changes in bed elevation with time as guided in literatures [9, 13], but it was never less than 48 hours. Scour depth was measured with a point gage having a ±0.3 mm scale error and an ADV having a ±1 mm scale error.

3. Results and Discussion

Experimental flow conditions and results for each river model are presented in Table 1 including field measurements from the USGS. One of the interesting findings from these experimental studies is that the scour contours show non-symmetrical pattern relative to the bridge pier bent centerline. Experimental results from several other researchers show that the location of maximum local scour depth was in front of the first pier in many cases. However, as shown in Figure 5, the maximum scour depth occurred at the nose of the third pier, not at the first pier, and the footing of the third pier was almost exposed as measured as in the Chattahoochee River Bridge because of the site-specific river bathymetry, angle of attack, and alignment of the bridge pier bent in the main channel. These findings will be discussed in the following sections in more detail.

3.1. Comparison of Velocity Distribution. As shown in Figure 6, the laboratory velocities were compared with available field measurements to examine our laboratory modeling regime which is Froude number similitude. In Figure 6(a), the streamwise, depth-averaged velocity distribution along the bridge deck (FR1 in Table 1) was compared with corresponding field data (FF in Table 1) in Flint River Bridge measured during tropical storm Alberto occurred in 1994. Even though there is some discrepancy in the velocities near the right bank (around station 200) and at the nose of the bridge pier in the main channel, the velocity distribution measured in the laboratory is in good agreement overall with field measurements. For the Chattahoochee River case as shown in Figure 6(b), flow velocities in the field were measured with an acoustic Doppler velocity meter mounted at the side of the upstream pier and pointed in the cross-stream direction during the 2003 flood events. There were three data points at different distances from the side wall of the bridge pier located in the main channel. The velocity comparison shows also good agreement in Figure 6(b). Finally, Figure 6(c) shows the velocity comparison for the case in Ocmulgee River Bridge. Because measurement activities during the flooding are too dangerous in the field, the velocities were measured at a short time after the peak discharge of 1,841 m^3/s. Thus, the actual discharge during the measurements was 1,388 m^3/s. Therefore, the magnitude of each velocity measured by the USGS was slightly smaller than that of laboratory measurement. However, the shape of the velocity distribution for each case is similar enough to verify the validity of the Froude number similitude [17].

3.2. Comparisons of Bed Elevation Upstream of the Bridge Foundations. When the bed elevations for physical modeling of Flint River Bridge were compared with the field data measured during tropical storm Alberto, local pier scour depths upstream of each pier in the main channel were reproduced well in the laboratory model experiment as shown in Figure 7(a). However, the scour profiles in the constricted region between two bridge pier bents in the main channel (between the station 100 m and 150 m) did not agree well with the field cross section possibly because of the lack of sufficient time for full development of the contraction scour in the laboratory which develops more slowly than the local pier scour [17].

For the Chattahoochee River Bridge comparison as shown in Figure 7(b), the measurement across the upstream bridge for bank-full flow conditions that occurred in July 2003 with a peak discharge of 385 m^3/s was compared with the laboratory results. The maximum scour depth occurred at the nose of the upstream pier in both field and laboratory with a 2 percent relative error between the two measurements. It is also interesting to note that a flood of similar magnitude (371 m^3/s) as in July 2003 occurred in December of 1961 and the maximum scour depth is remarkably similar to the value after 2003 flooding with a difference of 0.06 %. The shapes of the scour holes are approximately the same and the maximum scour depths at the nose of the bridge pier despite the intervening time interval of 42 years during which many cycles of alternate scouring and filling occurred. There is some discrepancy between laboratory and field cross sections in the deposition region between the pier bents because the experiment was conducted under clear-water scour conditions while live-bed scour conditions occurred in the field. The measured cross sections upstream of the bridge in Ocmulgee River during the 1998 flood were compared with the experimental run OR1 in Figure 7(c). The pier scour depth showed a good agreement of the bed elevation with field data, while the scour depth between the central pier and pier on the right side (located around 100 m) did not seem to agree with the field data because of the similar reason as in Flint River Bridge through the flow contraction region.

3.3. Comparison of Maximum Scour Depth Upstream of the Bridge Piers. The scour depths measured at the nose of the upstream of pier for each physical model are compared with the commonly accepted scour prediction formulas in the United States, which are HEC-18 [22], Melville [23], and Sheppard et al. [24]. One of the important objectives of writing research paper is suggesting a design practice that determines how their design can best take their interest into account. That is the reason why those three equations are chosen because they are the mostly used equations for the hydraulic engineers. The effect of the flow intensity, V_1/V_c, on the dimensionless scour depth, d_s/b, is observed by comparison with scour prediction formulas having constant values of y_1/b and b/d_{50} for each comparison. The approach Froude number is given as a label on each data point in Figures 8–10.

It is found that the laboratory data for Flint River modeling with $b/d_{50} = 18.8$ agree well with Melville's and Sheppard et al.'s formula, while HEC-18 overpredicts the scour depth for two small Froude numbers as shown in

Table 1: Summary of experimental results and field data for each river.

Name	Scale	Q m^3/s	b m	y_1 m	V_1 m/s	d_s m	Fr_1	V_1/V_c	y_1/b	b/d_{50}	d_s/b
CR[1]1	1/40	0.071	0.027	0.190	0.317	0.060	0.23	0.71	7.04	24.53	2.23
CR2	1/40	0.038	0.027	0.107	0.308	0.052	0.30	0.75	3.95	24.53	1.92
CR3	1/40	0.085	0.027	0.190	0.348	0.059	0.26	0.78	7.04	24.53	2.19
CR4	1/40	0.042	0.027	0.107	0.341	0.060	0.33	0.83	3.95	24.53	2.23
CR5	1/40	0.047	0.027	0.107	0.411	0.068	0.40	1.00	3.95	24.53	2.51
CF[2]	NA	385.0	1.067	4.279	2.140	2.003	0.33	4.39	4.01	1568	1.88
FR[3]1	1/90	0.042	0.021	0.152	0.247	0.022	0.20	0.57	7.35	18.8	1.05
FR2	1/90	0.047	0.021	0.152	0.290	0.037	0.24	0.67	7.35	18.8	1.77
FR3	1/90	0.051	0.021	0.152	0.335	0.058	0.27	0.78	7.35	18.8	2.79
FF[4]	NA	3030	1.829	11.28	2.306	2.908	0.22	5.27	6.17	4813	1.59
OR[5]1	1/45	0.136	0.041	0.181	0.312	0.050	0.23	0.70	4.45	36.9	2.05
OR2	1/45	0.165	0.041	0.191	0.336	0.053	0.25	0.75	4.69	36.9	2.20
OR3	1/45	0.184	0.041	0.203	0.350	0.084	0.25	0.78	4.99	36.9	2.19
OF[6]	NA	1841	1.829	8.230	2.094	0.032	0.23	3.73	4.50	2286	1.78

CR[1] = Chattahoochee River model experiment (d_{50} = 1.1 mm), CF[2] = field data at Chattahoochee River (d_{50} = 0.68 mm), FR[3] = Flint River model experiment (d_{50} = 1.1 mm), FF[4] = field data at Flint River (d_{50} = 0.38 mm), OR[5] = Ocmulgee River model experiment (d_{50} = 1.1 mm), OF[6] = field data at Ocmulgee River (d_{50} = 0.8 mm).

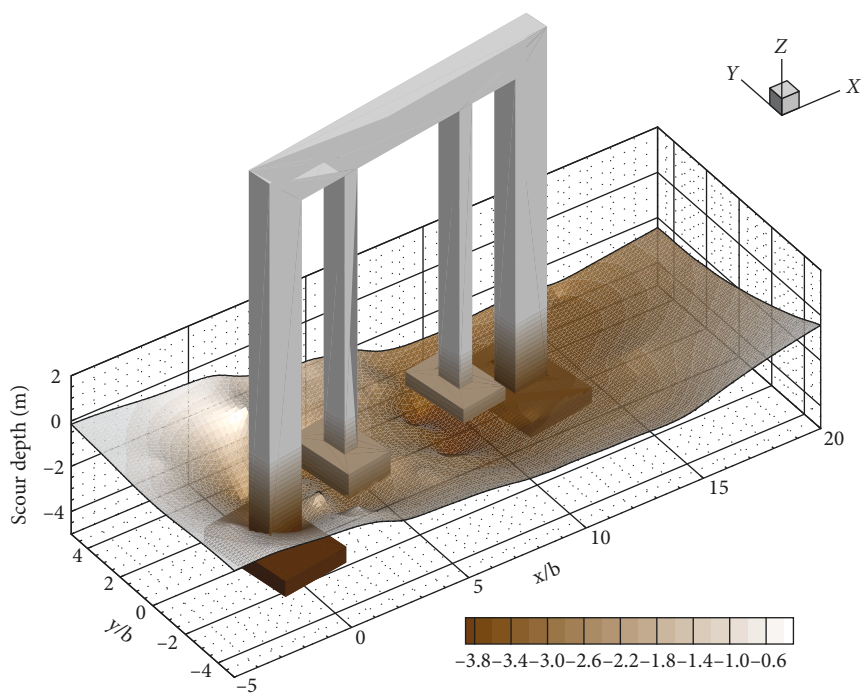

Figure 5: Scour depth contours for experimental run CR4.

Figure 8. The HEC-18 formula includes the effect of the approach Froude number but does not include the parameter bearing the effect of V_1/V_c. Conversely, the other two formulas, the Melville and the Sheppard et al. formulas, include the effect of V_1/V_c but do not consider the approach Froude number. Also, the Melville and Sheppard et al. formulas include a reduction in d_s/b because the relative sediment size, b/d_{50}, is less than 25. The effect of the relative flow depth, y_1/b, has an effect only in the HEC-18 formula because the value of y_1/b is large enough that it has almost no influence in the Melville and Sheppard et al. formulas. The field data of Flint River are in the live-bed scour condition with $b/d_{50} = 1569$ ($d_{50} = 0.38$ mm in the field). The dimensionless scour depths were overpredicted by the HEC-18 and Melville formula, while Sheppard et al.'s formula slightly underestimated the dimensionless scour depth.

For Chattahoochee River modeling as shown in Figure 9, the laboratory data also agree relatively well with all three formulas even though HEC-18 slightly overpredicts the scour depth. With the field data, the Melville and HEC-18 formulas still overpredict the dimensionless scour depths with the value of $b/d_{50} = 1569$ ($d_{50} = 0.68$ mm in the field), while the Sheppard formula shows reasonably good agreement. Finally, as shown in Figure 10, for the Ocmulgee River

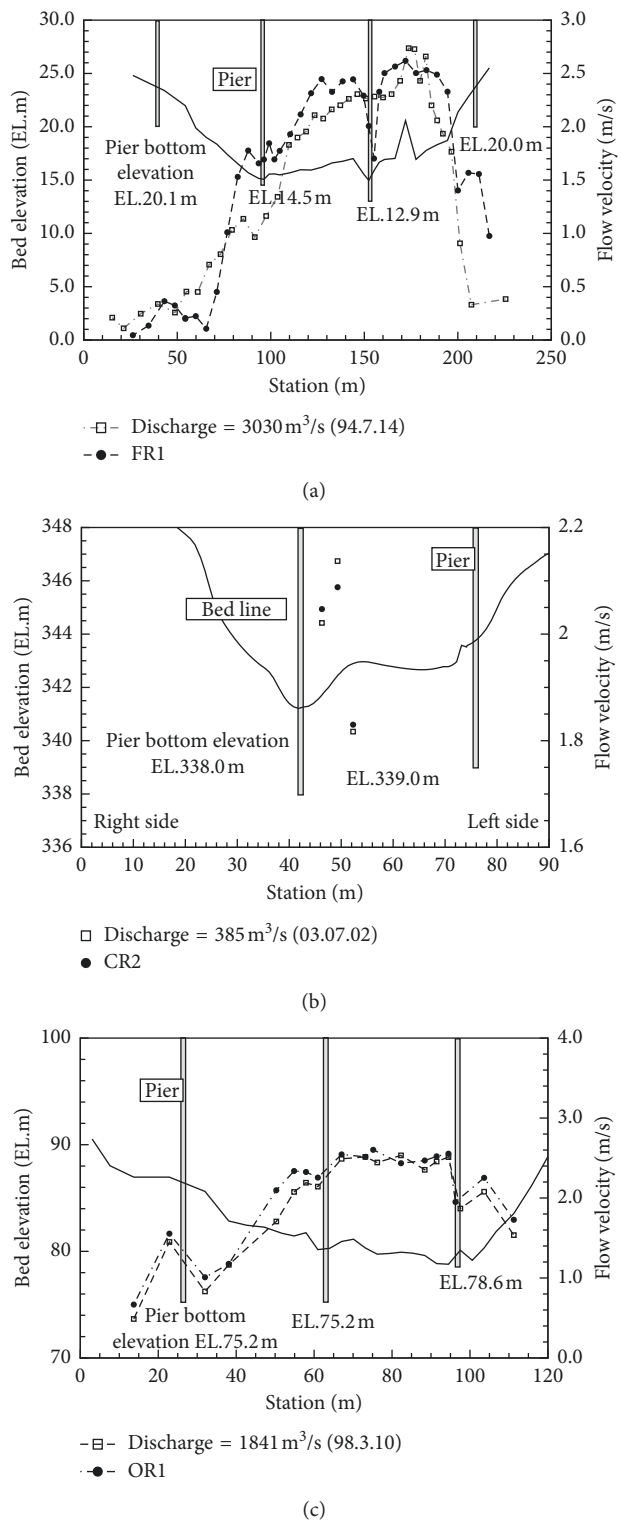

Figure 6: Velocity comparison between laboratory and field measurements for (a) FR1, (b) CR2, and (c) OR1.

field data with the value of $b/d_{50} = 2286$ ($d_{50} = 0.8$ mm in the field), the Sheppard formula underpredicts the dimensionless scour, and the other two formulas shows overprediction even though it agrees relatively well with the laboratory data. These comparisons highlight that the field

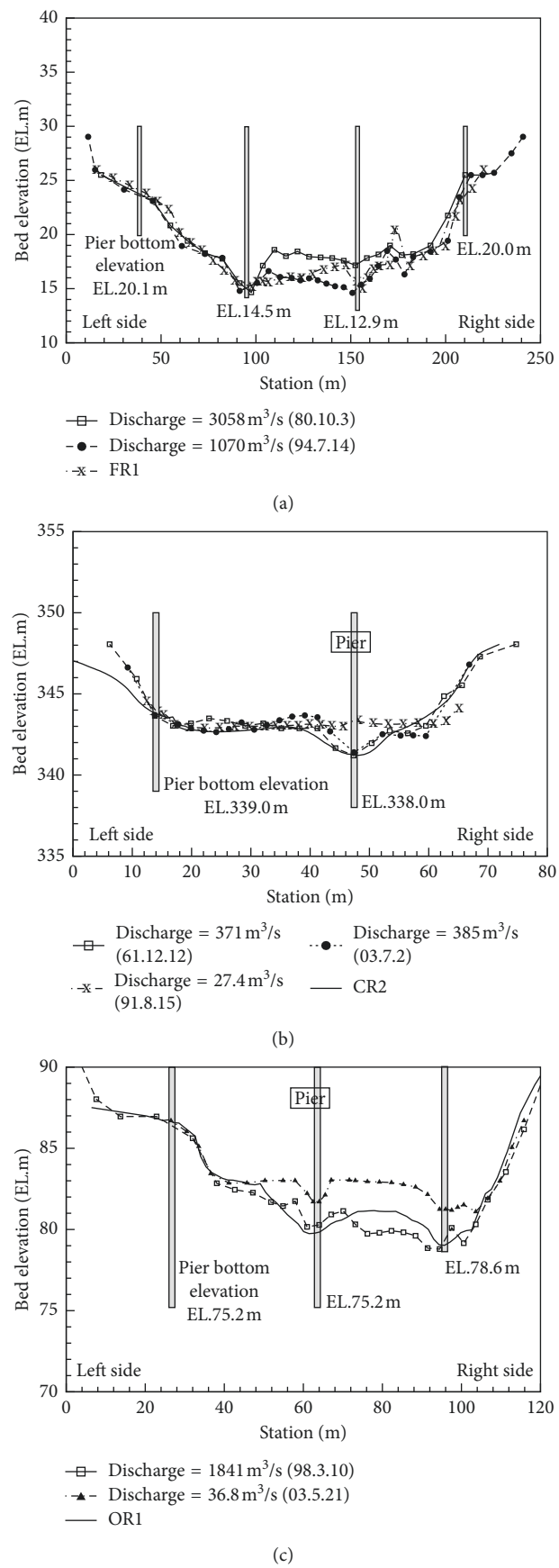

Figure 7: Cross section comparison between laboratory and field measurements for (a) FR1, (b) CR2, and (c) OR1.

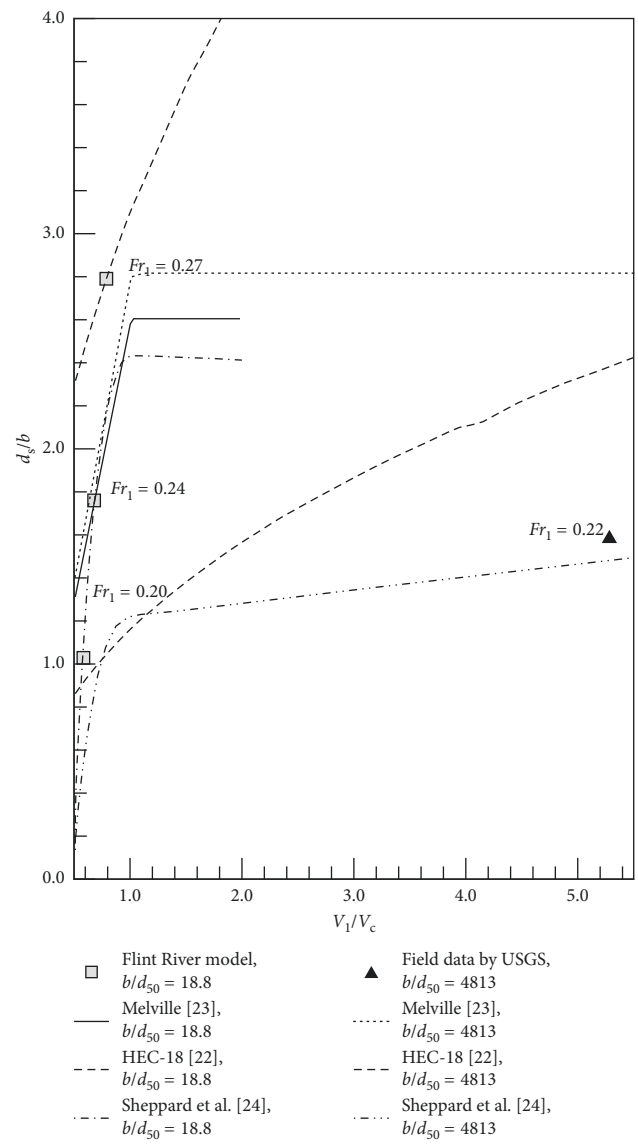

Figure 8: Comparison of field and laboratory measurements of scour depths and scour prediction formulas for Flint River Bridge.

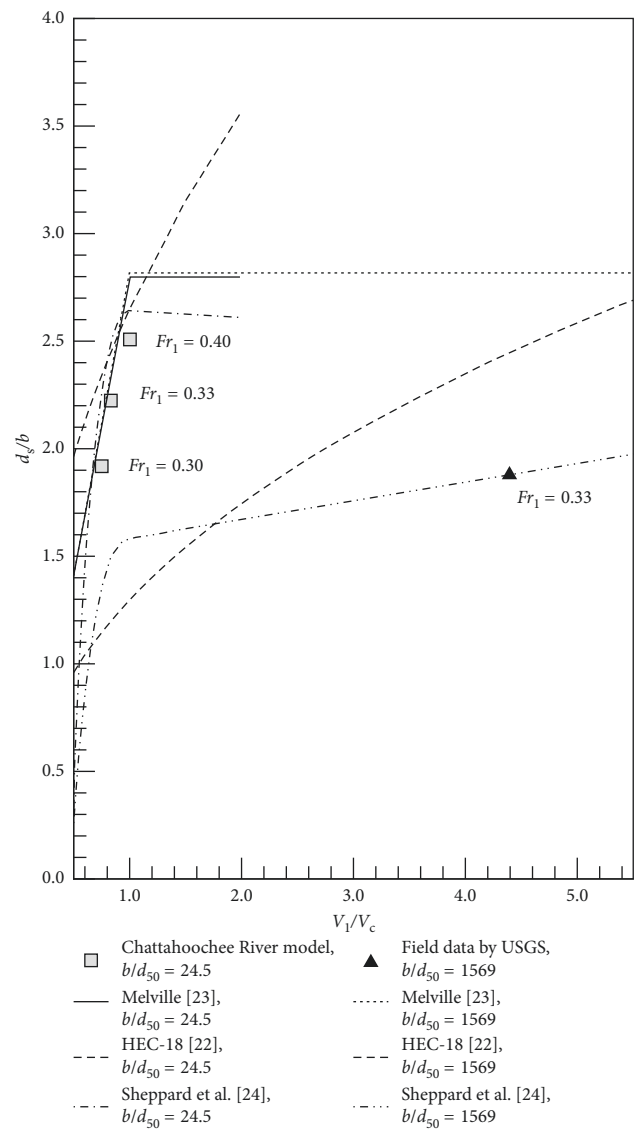

Figure 9: Comparison of field and laboratory measurements of scour depths and scour prediction formulas for Chattahoochee River Bridge.

engineers need to carefully select the scour formulas for their design because the current widely used scour formulas are only based on the idealized laboratory experiments, and sometimes, the results show somewhat unreliable answer.

4. Summary and Conclusions

In this study, scaled physical models were constructed and conducted based on the actual field surveys, and the results have been compared with detailed field measurements of contraction scour and pier scour. Comparisons of velocity distributions for all river models showed good agreement with the field measurements. The shapes of the cross section and bed elevations along the bridge deck were well reproduced in laboratory experiments including the maximum pier scour depths in front of the pier. The close agreement between field and laboratory measurements appears to validate the modeling strategy presented in this study in which the Froude number similarity and the geometric similarity (y_1/b) are maintained while choosing a sediment size in the laboratory that produces the ratio of pier size to sediment size, b/d_{50}, in the range of 25–50 where it has negligible influence on pier scour. Furthermore, the ratio of approach velocity to the critical velocity which concludes the condition of clear scour regime is also an important factor to choose sediment size. Values of b/d_{50} are quite large in the prototype and so they cannot be reproduced in the laboratory because the sediment size satisfied with scale ratio becomes so small that the innerparticle cohesive force acted important role, which do not exist in prototype sand-bed streams. In other words, live-bed scour depths in the prototype can be matched using clear-water scour in the laboratory by compensating for an observed decrease in scour depth due to large prototype values of b/d_{50} with a corresponding decrease in V_1/V_c to a value less than 1.0 at which

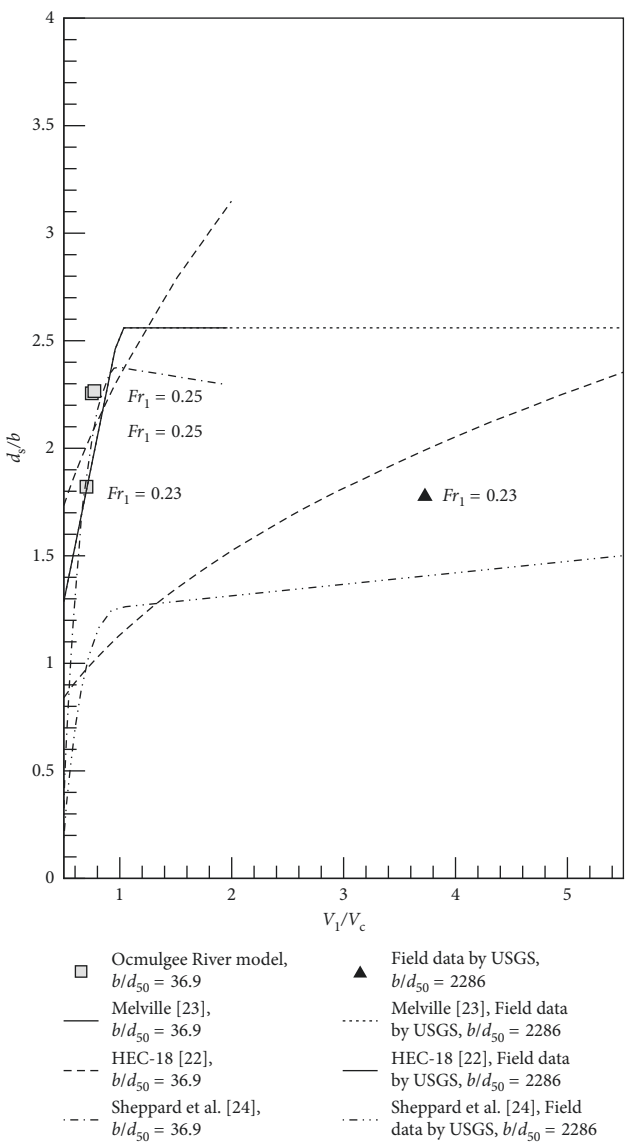

Figure 10: Comparison of field and laboratory measurements of scour depths and scour prediction formulas for Ocmulgee River Bridge.

maximum scour depth occurs. "How this good comparison was achieved?" is one of the important results of this research in that it provides a modeling methodology with scaling laws that can be used to design models of complex pier and bridge geometries, select the appropriate model sediment size, and then translate the results to the prototype. If the relationship for decreases in local scour depth with increasing values of b/d_{50} in prototype and decreasing value of V_1/V_c in laboratory clear-water scour is well known, then it can be used to evaluate the prototype local scour depth from the measured model value of local scour depth. So far, little effort has been made to the value of laboratory model study in closing the gap between results from idealized laboratory experiments and those from field data because of economical and practical reasons. However, the experimental results show that the location of the maximum scour depth around a complex pier is not consistent due to the variability of the horseshoe vortex system and the complexity of bridge geometry and river bathymetry, which gives another essential reason for the need to conduct a physical model study of local scour depth, especially for large, expensive bridges.

The laboratory and field data were compared with several existing pier scour formulas to find their accuracy when the effect of b/d_{50} is included in their comparison. The results show that none of the accepted formulas provided a satisfactory estimate of scour depth because several cases show considerable underprediction as well as overprediction in many cases. These results emphasize the need for improvement in explaining and accounting for the effect of b/d_{50} in order to obtain more accurate scour predictions [25].

In this study, three prototype bridges in Georgia were modeled in the laboratory including the actual bridge and pier geometry as well as the river bathymetry using different geometric scale ratios. The laboratory results were compared with continuous field measurements to provide a more comprehensive collection of realistic local scour data than has been developed in the past.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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