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SCALING ISSUES FOR LABORATORY MODELING OF BRIDGE PIER SCOUR

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Despite several decades of research on bridge pier scour, one of the more vexing problems remains the one of how to scale pier scour depths measured in the laboratory up to prototype dimensions. This issue has led to mistrust of laboratory-based prediction formulas for pier scour, especially because field measurements of pier scour seem to indicate smaller values measured in the field in comparison to those predicted from laboratory-based formulas. In this paper, scour-depth results from a laboratory physical model that reproduces the prototype stream bathymetry as well as the bridge geometry are compared with some pier scour prediction formulas. The ratio of pier diameter to sediment size is typically not the same in laboratory and prototype because of the small model sediment sizes that would be required, and this model distortion is confirmed to account for differences between measured and predicted scour depths. These observations suggest that reproduction of prototype live-bed pier scour is possible by compensating for the inequality in the ratio of pier diameter to sediment size with the flow intensity factor for laboratory clear-water scour. A possible explanation for the physical importance of the ratio of pier diameter to sediment size in model and prototype is suggested through turbulence scaling arguments.

Key Words : *bridge piers, hydraulic models, scour, sediment transport, turbulence*

1. INTRODUCTION

Bridge scour is a significant transportation problem because of the monetary damage and possible loss of life that it can cause when it results in bridge foundation failure. The damage caused by Tropical Storm Alberto in Georgia, USA in 1994 is a case in point. Tropical Storm Alberto dumped as much as 71 cm of rainfall in parts of central and southwest Georgia from July 3-7, 1994 and caused numerous bridge failures and highway closings as a result of the 100-yr flood stage being exceeded at many locations along the Flint and Ocmulgee Rivers[1)]. Prevention of bridge scour damages and possible loss of life hinges on having the capability of predicting expected bridge scour. Unfortunately, such predictions remain a challenging problem because of the complex interaction of the river flow with the obstruction presented by the bridge foundation and with the erodible bed of the river. Under these circumstances, a number of bridge scour prediction formulas have been developed based on laboratory studies[2)]. This approach introduces the concomitant difficulty of scaling of laboratory measured scour depths up to the prototype scale. When such scaled scour predictions are compared with field observations obtained using the latest in mobile instrumentation techniques by the USGS[3),4)], the overall impression is an overprediction of field scour by laboratory formulas, although the field data exhibit a considerable degree of scatter. Whether this scatter and overprediction of scour depths is due to imprecise knowledge of the flow conditions and degree of time development of scour at the time of the measurements or to laboratory scaling issues, or both, remains to be determined.

The laboratory scaling issue is partly attributable to the choice of model sediment size. Scaling the sediment size according to the geometric scale based on Shields' criterion for fully rough turbulent flow leads to very fine model sediment sizes exhibiting interparticle forces that are not present in sand bed rivers. This state of affairs has led to the practice of reproducing the flow intensity factor (ratio of approach velocity to critical velocity of the model sediment) which can violate Froude number similarity because of the larger critical velocities associated with model sediment sizes that are necessarily too large. An additional model distortion occurs with respect to the ratio of the pier diameter to sediment size due to the constrained choice of model sediment size. These issues are currently being explored by conducting physical model studies of several bridges in Georgia as part of a larger effort to improve the reliability of scour prediction formulas based on field studies and CFD modeling as well. This paper focuses on the laboratory scaling problem using as an example one of the bridges that was modeled in the laboratory at Georgia Tech.

2. PHYSICAL MODEL STUDIES

All experiments on local scour around bridge piers were conducted in the hydraulics laboratory of the School of Civil and Environmental Engineering at the Georgia Institute of Technology, Atlanta, GA. Flat-bed models and river models were built inside a 4.2 m wide by 24.2 m long horizontal flume and a 1.1 m wide by 24.2 m long rectangular tilting flume in the hydraulics laboratory. The flat-bed models had an initially level mobile sediment bed around a single pier bent while the river models had a mobile bed that reproduced the river bathymetry in addition to the complete bridge and pier geometry. All of the river model experiments were conducted in the 4.2 m wide horizontal flume. The approach channel upstream of the bridge was 7.3 m long followed by a working mobile bed section with a length of approximately 6.1 m in which the bridge model was placed. The templates for the river model cross sections in the approach channel were cut from plywood sheets placed vertically at regular intervals with elevations scaled from detailed field measurements of river bathymetry. The spaces between the templates were filled with bed sediment and carefully leveled to the elevations established by the templates. The approach channel bed was then fixed with polyurethane. In the mobile bed section, thin aluminum templates were used to reproduce the bed bathymetry and then removed for the scour tests.

The water supply to the flume was provided from a large constant-head tank through a 30.5 cm diameter pipe that can deliver up to 0.3 m^3/s to the head box of the flume. A flow diffuser, overflow weir, and baffles in the flume head box produced stilling of the inflow and a uniform flume inlet velocity distribution. A flap tailgate controlled the tailwater elevation. Water recirculated 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 ±0.001 m^3/s.

An instrument carriage was mounted on horizontal steel rails and was moved along the flume on wheels driven by a cable system and electric motor. Approach velocities were measured with a SonTek 16 MHz acoustic Doppler velocimeter (ADV) that was attached to the instrument carriage on a mobile point gauge assembly that could be accurately positioned in all three spatial dimensions. A 3D down-looking probe was used to measure velocity profiles across the deeper portions of the cross section while a 2D side-looking probe was selected to measure velocity profiles in shallow floodplain areas in the river models. The water depth and bed elevations before and after scouring were measured by the point gauge and the ADV. The ADV can generally measure the distance from the center of the sampling volume to a solid boundary with ±1 mm uncertainty. The sampling frequency of the ADV was chosen to be 25 Hz with a sampling duration of 2 minutes at each measuring location. More details of the experimental setup and instrumentation are given by Lee[5)].

The full scope of the physical modeling program is summarized in Table 1 for three separate river bridges. Each of the pier bents consisted of either two or four in-line columns. The cross-sectional shapes of the pier columns were rectangular, square, and circular. Relatively uniform sediments with three different median sizes were used in the experiments as shown in Table 1. Flat-bed models refer to models of the central river pier bent placed in a rectangular flume, while river models were constructed with complete geometric similarity of the river cross sections as well as the bridge itself.

Maximum scour depths were measured immediately upstream of the first column in the downstream direction. Detailed measurements are presented in this paper only for the Flint River bridge for the extreme flood event of record (Tropical Storm Alberto in 1994), which exceeded the 100-yr event. The full set of results for all the bridges will be presented in a subsequent paper.

Table 1. Bridge model scales, pier shape and model pier width, *b*, including model sediment sizes, d_{50}.

River Bridge Modeled	Scale	Pier shape	d_{50}, mm	*b*, mm	Type
Chattahoochee	1:23	▭	3.3, 0.5	46	F[1]
Chattahoochee	1:40	▭	3.3, 1.1, 0.5	27	F, R[2]
Flint	1:33	□	0.5	55	F
Flint	1:50	□	3.3, 0.5	37	F
Flint	1:90	□	1.1, 0.5	21	F, R
Ocmulgee	1:45	○	1.1, 0.5	41	F, R

[1]F = Flat bed experiment, [2]R = River model

3. RESULTS AND DISCUSSION

Dimensional analysis of the pier scour problem for relatively uniform sediment produces[6), 7)]:

$$\frac{d_s}{b} = f\left(K_s, K_\theta, \frac{y_1}{b}, \frac{V_1}{V_c}, \frac{b}{d_{50}}, Fr_1 \text{ or } Fr_b, \text{Re}_1 \text{ or } \text{Re}_b\right)$$

in which d_s = scour depth, b = pier width, K_s = shape factor, K_θ = skewness factor, y_1 = approach depth, V_1 = approach velocity, V_c = critical velocity, d_{50} =median sediment size, Fr_1 = the approach flow Froude number, Fr_b = the approach pier Froude number, Re_1 = the approach flow Reynolds number and Re_b = the approach pier Reynolds number. From the dimensional analysis, it is clear that selecting a model sediment that is similar in size to the prototype sediment in order to avoid fine-grained sediment particles necessarily causes distortion of the flow or pier Froude number as well as b/d_{50} if V_1/V_c is held constant in the model and prototype. Larger values of the Froude number in the model than in the prototype can distort the free-surface and pressure gradients around a pier[6)]. Similarly, using larger values of y_1/b in the model than in the prototype can also alter the flow Froude number, even though interaction between the surface roller on the pier and the horseshoe vortex may become unimportant in its effect on pier scour at large values of y_1/b. Dissimilarity of b/d_{50} in the model and prototype was previously thought to be acceptable based on the results of Raudkivi[8)] who showed that dimensionless pier scour depth increases with b/d_{50} up to a value of about 50 beyond which it seemingly becomes independent of the ratio b/d_{50}. However, Sheppard et al.[9)] have suggested that relative scour depth may decrease significantly at very large values of b/d_{50} based on experiments in a large flume.

The pier Reynolds number ($V_1 b/\nu$) has not usually been considered to have a strong influence on scour depth for fully-rough turbulent flow around a bridge pier[6)]. On the other hand, the mean dimensionless distance from the pier to the separation point of the primary horseshoe vortex might be expected to depend on Reynolds number, but in fact it appears to be only weakly dependent on the pier Reynolds number as the values become large based on an extensive literature review of experimental measurements[5)]. Ettema et al.[10)] have shown that changes in either pier Reynolds number or pier Froude number effected by increases in pier diameter while holding all other variables constant results in smaller pier scour depths. (Alternatively, the increase in pier diameter corresponds to an increase in b/d_{50}). They propose that this reduction in scour depth is related to lower frequencies of shedding of wake vortices for piers of larger width.

A different modeling strategy that applies to rivers in live-bed scour has been proposed by Lee et al.[11)]. Instead of arbitrarily choosing a sediment size and holding V_1/V_c constant in model and prototype, flow Froude number similarity and equality of y_1/b in model and prototype are invoked which implicitly assures pier Froude number similarity. Then a model sediment size is chosen such that b/d_{50} is approximately 25 (say 20-40) where it has a known effect on scour depth. Finally, the apparent reduction in scour at large prototype values of b/d_{50} is compensated by clear-water scour values of V_1/V_c < 1.0 in the laboratory. This strategy for physical modeling of the Flint River bridge in Bainbridge, Georgia USA was undertaken for Tropical Storm Alberto which occurred in 1994.

In Fig. 1, the scour depths measured at the nose of the upstream pier for the main Flint River bridge pier bent (third bent from the left in Fig. 2) are compared with some commonly accepted scour prediction formulas, which are referred to as HEC-18[12)], Melville[13)], and Sheppard[9),14)]. The complete formulas can be found in the references cited. The effect of the flow intensity, V_1/V_c, on the dimensionless scour depth, d_s/b, is observed by comparison of the laboratory data with scour prediction formulas having constant values of y_1/b and b/d_{50}.

Field measurement of the maximum scour depth at the main pier bent by the USGS during Tropical Storm Alberto is also compared with the laboratory data and the formula predictions in Fig. 1. The approach flow Froude number is given as a label on each data point.

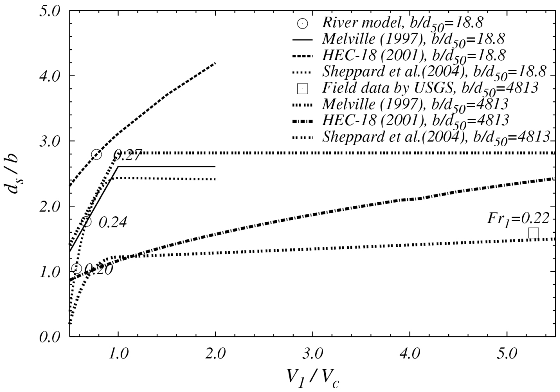

Fig. 1. Comparison of field and laboratory measurements of scour depths and scour prediction formulas for Flint River. (Scale=1:90, y_1/b≈7.0, b/d_{50}=18.8).

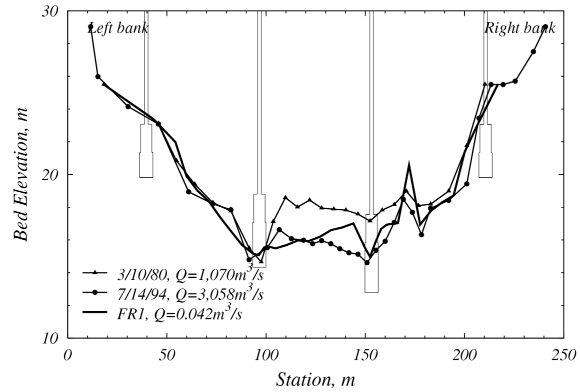

Fig. 2. Comparison of Flint River cross sections upstream of the bridge for prototype flood flows of 1980 and 1994 and for physical model run FR1 (Tropical Storm Alberto).

In Fig. 1, it is observed that the laboratory data from the Flint River model with b/d_{50}=18.8 agree with the Melville and Sheppard formulas for the two smaller Froude numbers, while HEC-18 overpredicts the scour depth for these two data points but agrees very well with the data point for the maximum Froude number. The HEC-18 formula includes the effect of the approach flow Froude number but does not include the flow intensity parameter, V_1/V_c. Conversely, the Melville and the Sheppard formulas include the effect of V_1/V_c but do not consider the approach Froude number. Also, the Melville and Sheppard formulas include a slight reduction in d_s/b because the relative sediment size, b/d_{50}, is less than 25 for the laboratory data. 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 other two formulas. The field data point shown in Fig. 1 for the Flint River is in live-bed scour with b/d_{50}=4813. In this case, the dimensionless scour depth is overpredicted by the HEC-18 and Melville formulas, while the Sheppard formula slightly underestimates it. There is a reasonably good comparison between the field live-bed scour depth and the estimated laboratory clear-water scour depth at the same Froude number. Overall, the results shown in Fig. 1 confirm similar results obtained from the same modeling strategy employed for the Chattahoochee River bridge as reported previously by Lee et al.[11].

When the bed cross section measured in the physical model of the Flint River bridge is compared in Fig. 2 with the field cross sections measured for Tropical Storm Alberto, local pier scour depths upstream of the main pier bent (third from the left in Fig. 2) and the deposition region on the right side of the main pier bent are reproduced well in the laboratory model.

However, the contraction scour in the constricted region between the two middle bridge pier bents does not agree as well with the field cross section possibly because of the lack of sufficient time for full development of the contraction scour in the laboratory where it develops more slowly than local pier scour[15].

The results for the dimensionless scour depth d_s/b from all of the physical model experiments summarized in Table 1 are given in Fig. 3 in which all influences on scour depth except that of b/d_{50} have been normalized using the empirical correction factors from Melville's formula. In addition, data from Sheppard[16] and Ettema[17] have been included in the figure. The data include only those measurements for which the flow Froude number was less than 0.4 to remove large Froude number influences. A two-part best fit curve is shown in the figure with a maximum value of corrected dimensionless scour depth occurring at b/d_{50} = 25. Also shown in the figure are confidence limits of ±2 RMSE where RMSE is the root-mean-square error. This figure confirms the decrease in scour depth with decreases in b/d_{50} for values less than 25 and with increases in b/d_{50} for values greater than 25. Lee and Sturm[18] have suggested that this behavior can be explained by the ratio of the time scale of sediment lifting, estimated from the vertical turbulence fluctuations near the bed in front of the pier, to that of sediment entrainment and transport. The latter processes are shown to be associated with the fluctuations in the phase-averaged streamwise velocity resulting from the large-scale unsteadiness of the horseshoe vortex system as it oscillates back and forth upstream of the pier. It is proposed that this time-scale ratio (or frequency ratio) is essentially represented by b/d_{50} such that for large field values of b/d_{50}, the frequency of entrainment and transport

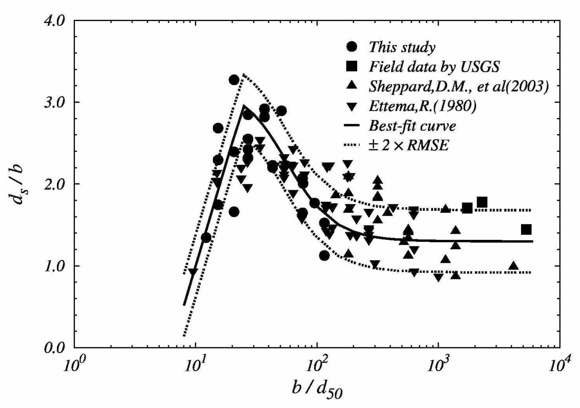

Fig. 3. Effect of b/d_{50} on the corrected d_s/b for Fr_1<0.4.

events occasioned by the intermittent contraction of the horseshoe vortex system is smaller than the frequency of sediment lifting events due to vertical turbulence fluctuations which leads to a reduction in scour depth. The resulting functional variation of scour depth with b/d_{50} shown in Fig. 3 makes possible the physical modeling strategy demonstrated in this paper with the Flint River model.

4. SUMMARY

A physical modeling strategy for prototype live-bed pier scour has been suggested in which flow Froude number similarity and equality of the ratio of flow depth to pier width are required in model and prototype. This approach also ensures pier Froude number similarity. The model sediment size is chosen such that the reduction in scour at large prototype values of b/d_{50} in comparison to chosen laboratory values of the order of 20 to 40 is reproduced by clear-water scour values of V_1/V_c < 1.0 in the laboratory. The functional variation of dimensionless scour depth with b/d_{50} from the laboratory to the prototype scale is demonstrated and a possible explanation for this behavior is offered in terms of the characteristics of the turbulence including the large-scale coherent motions associated with the horseshoe vortex system.

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