LOCAL SCOUR AT COMPLEX PIER GEOMETRIES

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Abstract:

This paper follows a conceptual paper on the same topic presented by the authors at the 1998 Water Resources Engineering Conference held in Memphis, TN. That paper described the hypothesis that local scour depth predictions for the individual components of a complex structure (pier, pile cap and pile group exposed in the flow field) can be combined to obtain a reasonable prediction for the composite structure. At that time there was very little reliable data to back up the hypothesis. Since that time the authors have conducted a systematic series of experiments in three separate laboratories to produce a preliminary set of design curves and a proposed procedure which are presented in this paper. The procedure has been tested on several physical models of complex piers and the computed values are compared to the measured values.

Introduction:

The classic pier for which most of the local scour equations have been developed is envisioned as a simple uniform shaped flow obstruction that extends from the water surface to a depth below the stream bed that exceeds the scour depth. Often the flow obstruction is anything but a simple geometric shape and the foundations including footings or pile caps as well as the supporting pile groups are well into the flow field. We don't necessarily need new equations to handle these complex situations, but we do need a procedure to adapt existing equations to handle them.

Several papers have been written on related topics, but all have been deficient in reliable data to produce a comprehensive design recommendation. Sheppard ,et al (1995) reported on local scour around pile foundations; Salim. and Jones (1996 & 1999[i]) reported on scour around exposed pile foundations. The Salim and Jones paper was later accepted by FHWA (199) as an interim design guideline for estimating scour around complex piers. That paper was based on relatively short duration laboratory experiments and it did not account for additional scour that is produced by an underlying pile group after it is exposed by local scour from structural components above it. Also the suggestion in that paper for combining a pier and pile cap into a weighted average width composite was borrowed from other literature and was not considered a conservative approach.

The authors of this paper decided to combine their resources to produce a practical and supportable recommendation for analyzing local scour around complex structures, especially those typified by a pile foundation, pile cap and a pier component all being exposed to the flow currents in a stream. Figure 1 illustrates the typical situation that was envisioned for this effort. They then developed a conceptual procedure (Sheppard and Jones, 1998) and outlined a series of laboratory experiments to be conducted as a joint effort. All of the laboratory experiments needed to have test durations of at least 46 hours. Most of the laboratory experiments were conducted in the Federal Highway Administration (FHWA) Turner Fairbank Highway Research Center (TFHRC) hydraulic lab or at the University of Florida hydraulic lab. A few of the experiments, which required a wide flume or deeper flow depths, were conducted at the U. S. Geological Survey (USGS) Biological Research Division (BRD) large scale located at Turners Falls Massachusetts

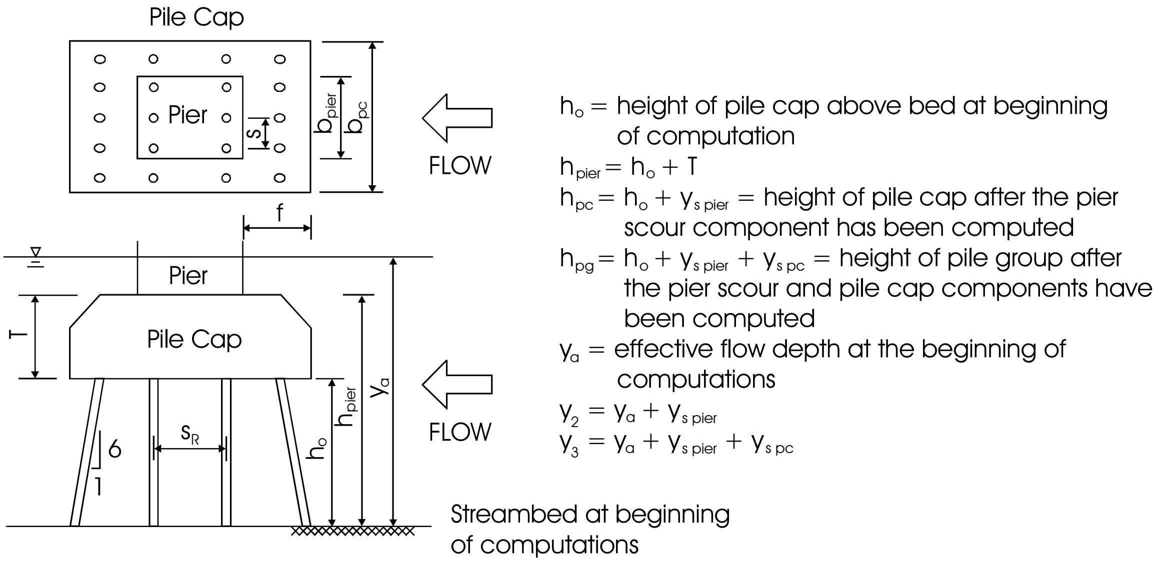
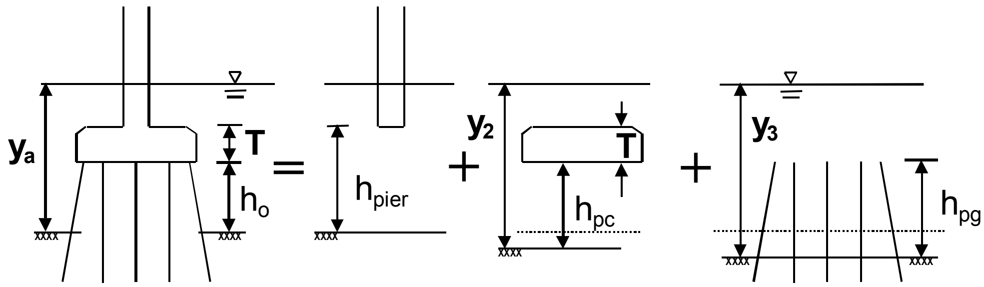


Figure 1. Definition Sketch of a Complex Pier

Conceptual Methodology:

The method proposed in 1998 was based on the simple hypothesis that the individual scour components of a complex structure (pier, pile cap and pile group) can be combined to obtain a reasonable prediction for the composite structure. That hypothesis is illustrated in figure 2. A lot of research has been done on scour around simple geometric shapes such as cylinders and rectangles; so the problem can be reduced to defining the individual structural components as equivalent simple geometric shapes.[ii]

Researchers at the University of Florida have analyzed experimental laboratory data from a number of independent facilities and they have developed a good prediction equation for clear water scour around simple geometric shapes (Sheppard 1999).[iii] The University of Florida equation accounts for the various sediment sizes and relative flow depths used in different experiments. That equation is very useful for determining an equivalent simple geometry size that would produce the same scour depth as one of the individual structural components produced under clear water conditions.



$$y_s = y_{s\,pier} + y_{s\,pc} + y_{s\,pg}$$

$$= K_{h\,pier}\, y_{so\,pier} + y_{s\,pc} + K_{h\,pg}\, y_{so\,pg}$$

($y_{s\,pc}$ using b^*_{PC} as pier)

Figure 2. Conceptual Hypothesis for Superimposing Scour Components

Experimental Procedure and Apparatus:

A series of experiments were conducted to measure clear water scour for each of the isolated structural components at various levels in the flow field to measure the scour components for one. Then a scour reduction factor or an equivalent simple pier size could be obtained to utilize existing scour equations.

The top component is the column or pier, which often contributes a very small amount of scour when it is suspended above the stream bed as illustrated in figure 1. The diving currents and vortices generated by the pier component could be partially blocked by the pile cap if the pile cap extends in front of the pier a distance “f” as illustrated. To simulate this blockage, thin plates of various sizes were attached to the suspended piers during the experiments for this component. The suspended pier experiments were conducted at the TFHRC laboratory.

The middle component is the pile cap. These experiments were conducted by using various thickness caps suspended at various levels above the streambed. The thickness was varied from 0.1 to 0.8 times the flow depths used in the experiments. The pile cap experiments were conducted at the TFHRC lab and at the Univ. of Fl lab

The bottom component is the pile group. The pile group is expected to extend below the deepest scour hole but it does not necessarily extend to the water surface. Experiments were conducted for full-flow-depth pile groups with various spacing between piles and at various skew angles to the flow. Then experiments were conducted for pile groups cut at various levels below the water surface. Extensive experiments for pile groups were conducted at the Univ. of Florida by Smith (1999). A few of the experiments for skewed pile groups required a wider flume and those experiments were conducted at the USGS BRD lab in Massachusetts.

The TFHRC flume is 21.3 m long by1.83 m wide by 0.6 m deep. The tests in the TFHRC flume were conducted at a constant flow depth of 0.305 m with 1.0 mm sand as the bed material. The Univ. of Fl flume is 33 m long by 2.44 m wide by 0.56 m deep; tests were conducted at flow depths of .305 m to 0.38 m with 0.18 mm sand as the bed material. The USGS BRD flume is 39 m long by 6.1 m wide by 6.4 m deep; tests were conducted at flow depths greater than 0.6 m with 0.2 mm sand as the bed material. All of the tests were clear water experiments with the velocities at or slightly below the incipient motion velocity for the bed material used in the flume.

Results:

The results are summarized as design charts shown in figures 3, 4 and 5. Figure 3 provides a scour reduction factor for suspended piers that do not go the full depth of the scour hole. Figure 4 provides an equivalent simple-geometry pier width that would produce the same maximum clear water scour depth as the isolated pile cap would produce. Figure 5 provides a scour reduction factor for a pile group when cut off below the water surface.

The pier component experiments with thin plates did not yield consistent results. In fact suspended piers with a thin plate actually scoured more than a suspended pier without a plate in some of the tests. In retrospect the authors recognized that the thin plates were still relatively thick for the small-scale experiments. A better experimental procedure would have been to test a pier and pile cap suspended in the pier at the positions that the pile caps were located. Then use the difference between the pier and pile cap scour and the scour produced by the pile cap suspended by itself as the pier scour component. Until those types of results are available, the authors chose to use the test results for a simple suspended pier without taking advantage of the front overhang from the pile cap. The procedure for this component is to compute the scour depth , y_{S0}, for a full depth pier with the same dimensions, determine the scour reduction factor $K_{h\ pier}$, from figure 3 and multiply them to predict the pier component scour.

The pile caps can be represented as an equivalent simple full-depth pier with the same geometric shape as the pile cap. The flow depth, height of pile cap and effective flow velocity should be adjusted to include the bed lowering from the pier scour component. That means the flow depth and the pile cap height are increased by the pier component scour depth. The velocity is correspondingly reduced by the ratio of the original flow depth to the adjusted flow depth. Referring to figure 2:

$$y_2 = y_a + y_{s\ pier}$$

$$h_{PC} = h_0 + y_{s\ pier}$$

$$V_2 = V_a\ (y_a/y_2)$$

Where: V_a is the approach velocity at the beginning of the computations
V_2 is the adjusted flow velocity for the pile cap computation.

The equivalent pier width, b^*_{PC} that would produce the same scour as the pile cap component can be determined from figure 4. The pile cap component scour can be predicted using b^*_{PC} as the pier width, y_2 as the flow depth, and V_2 as the approach velocity in a basic pier scour equation.

Smith determined that a full depth pile group can be represented as an equivalent solid that has an effective width, b*pg, equal to a spacing factor, K_{SP}, multiplied by the sum of the non-overlapping projected widths of the piles onto a plane normal to the flow direction. This technique is the same as the collapsed pile group rule suggested in version three of HEC-18 if the pile group is are aligned with the flow and if the rows are not staggered. It varies from the collapsed pile group rule when the pile group is skewed to the flow direction and when the rows of piles are staggered. Smith's procedure can be written as follows

$$b^*_{pg} = K_{SP}\ W_P$$

where: b^*_{pg} = width of a full depth solid pier that would yield the same scour depth as the full depth pile group
W_P= sum of non-overlapping projected widths of the piles onto a plane normal to the flow direction.
K_{SP} = the pile spacing factor

$$K_{SP} = \frac{1 - .003078(1 - \frac{b}{W_P})(\frac{S}{b} - 1)^{3.3}}{e^{0.015(s/b)^2}}$$

The flow depth, effective velocity and height of the pile group can be adjusted to include bed lowering from both of the upper scour components. Again, referring to figure 2

$$y_3 = y_a + y_{S\ pier} + y_{S\ PC}$$
$$h_{pg} = h_0 + y_{S\ pier} + y_{S\ PC}$$
$$V_3 = V_a\ (y_a/y_3)$$

The procedure for this component is to compute the scour depth, $y_{S0\ pg}$ for a full depth pile group using b^*_{pg}, y_3, and V_3 in a base pier scour equation.. The pile group scour component then becomes

$$y_{S\ pg} = K_{h\ pg}\ y_{S0\ pg}$$

where: $K_{h\ pg}$ is the height factor, illustrated in figure 5

$$K_{h\ pg} = -0.0011 + 2.68\left(\frac{h_{pg}}{\psi}\right) - 3.55\left(\frac{h_{pg}}{\psi}\right)^2 + 1.78\left(\frac{h_{pg}}{\psi}\right)^3$$

where: $\psi = y_3$ if $y_3 < 3.5\ b^*_{pg}$
$\psi = 3.5\ b^*_{pg}$ if $y_3 > 3.5\ b^*_{pg}$

The pile group technique described above is considered preliminary because researchers at the Univ. of Florida conducted additional tests on pile groups but the results from those tests are not available at the time this paper is being prepared. Those results will be available by the time the paper is presented.

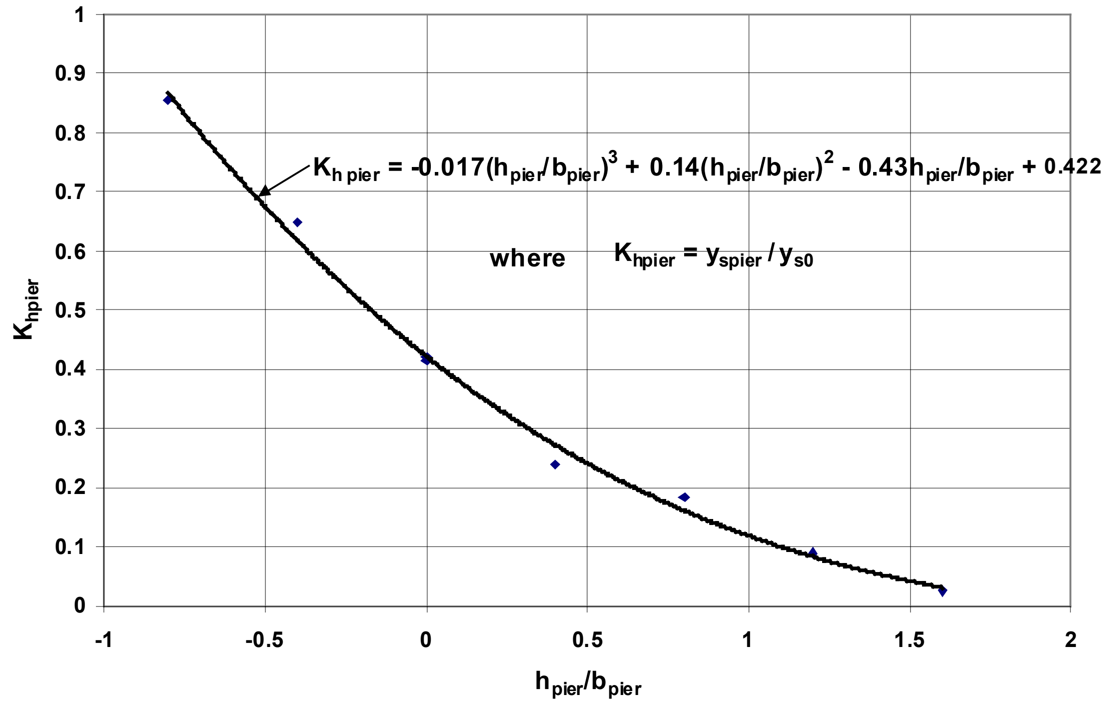


Figure 3. Suspended Pier Height Factor

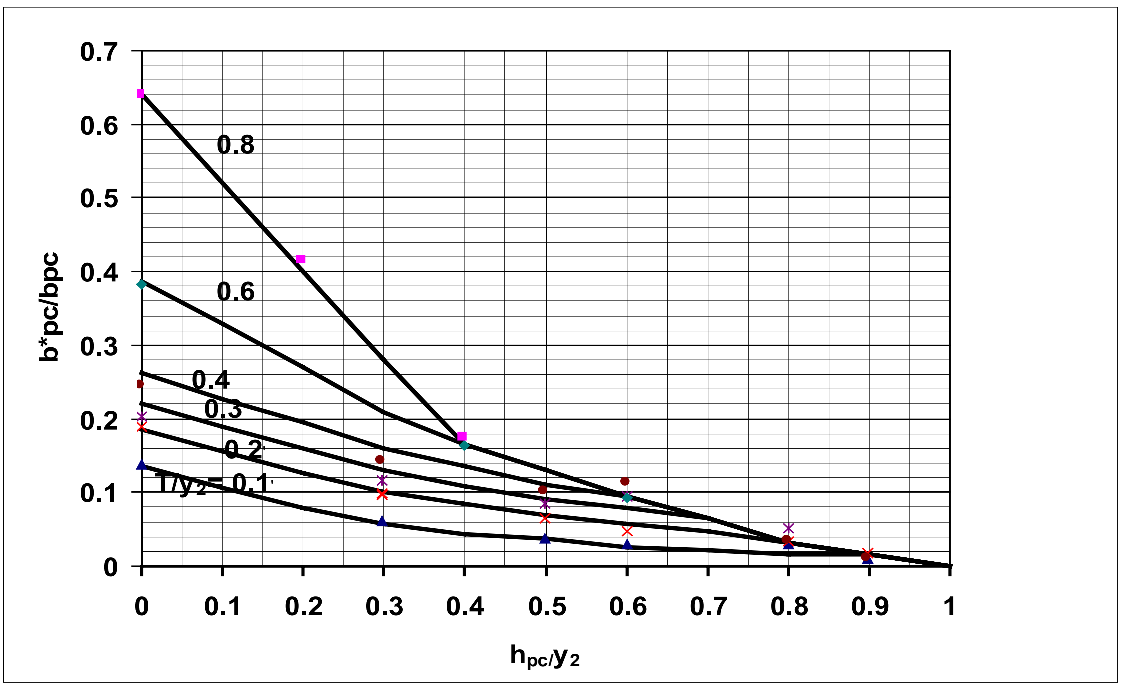


Figure 4. Pile Cap Equivalent Solid Pier Ratio

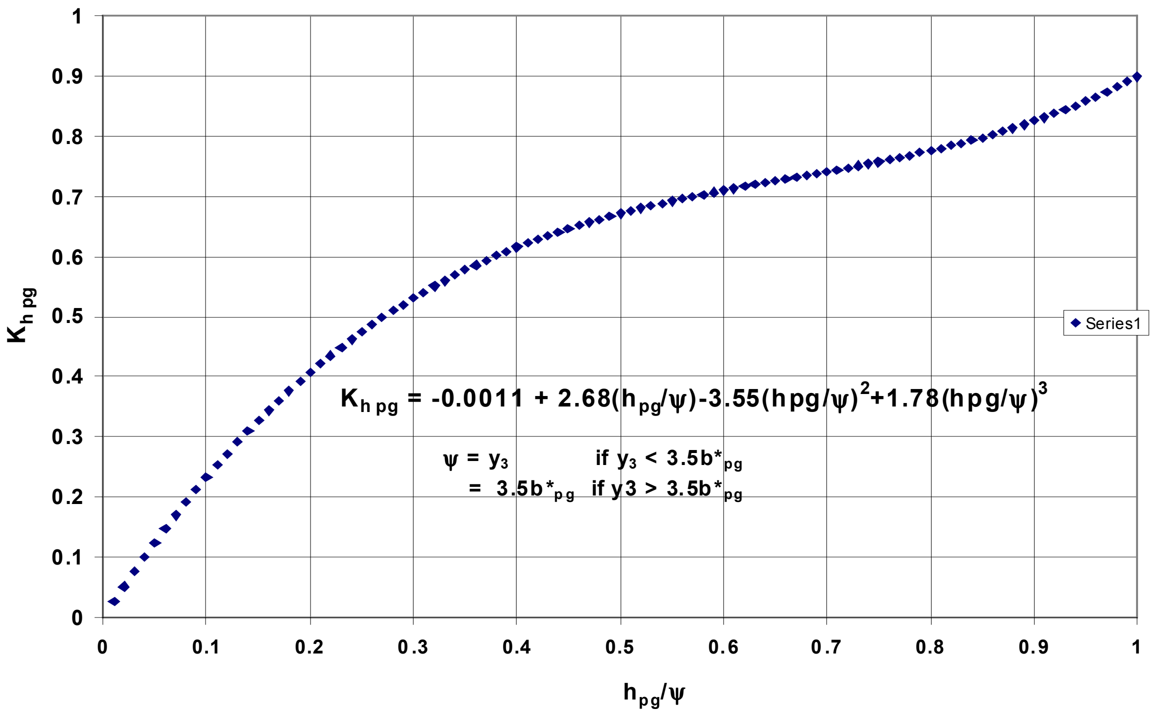


Figure 5. Pile Group Height Factor

Verification:

The procedure described in this paper was tested against several physical model measurements made by the authors. Proposed piers, for the replacement of the Woodrow Wilson Bridge, were modeled at several different model scales. The hydraulic and geometric conditions that were used in the physical model study were used to compute the scour depth by. the described procedure. One of the models was separated into the three components and each component was tested independently in the lab and computed independently by the described procedure. The computed versus the measured scour values are plotted in figure 6. The coordinates for the point labeled "sum of components" were obtained by summing the separate scour measurements and summing the separate computed values for the three components.

The FHWA HEC-18 (see Richardson et al,1995) local scour equation was used to compute the scour components for these comparisons. Using that base equation for the computed values, the procedure consistently over-predicted the measured values.

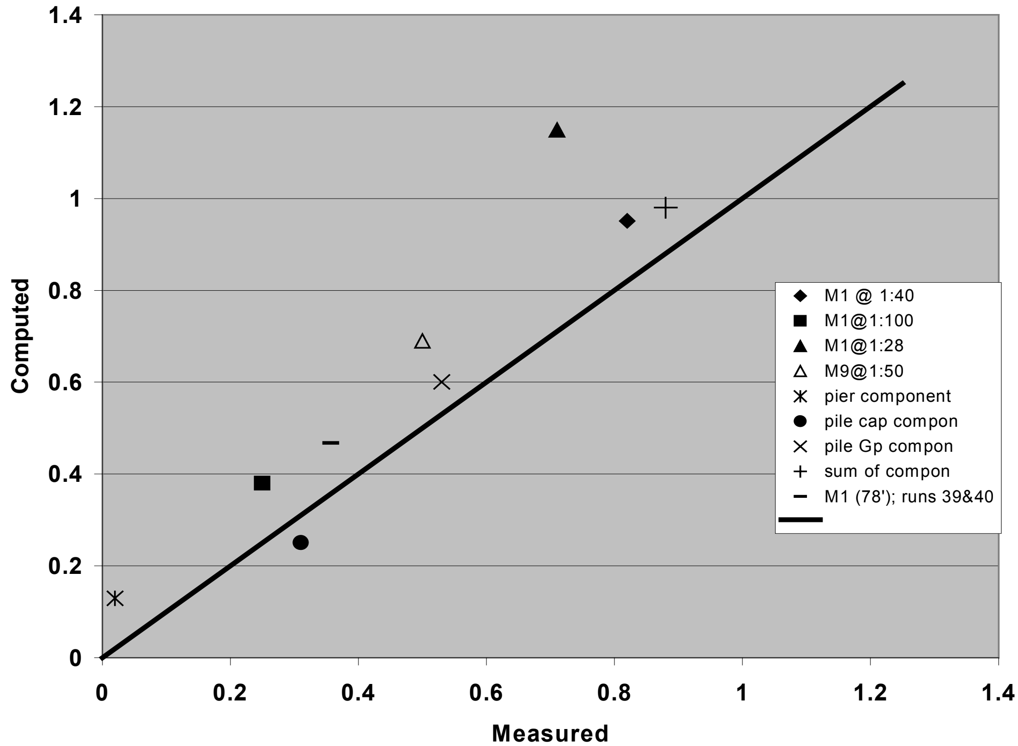


Figure 6. Comparison With Measurements

Conclusions:

- The goal of reducing the complex pier to problem to one that can be evaluated using existing scour equations was accomplished.
- The design charts are based on quality lab data with experiments that had durations of at least 46 hours.
- The procedure consistently over-predicted the measured values when the HEC-18 scour equation was used in the computations, but the amount of over-prediction or under-prediction will depend on which scour equations are used with the described procedure
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