Prediction Methods for Local Scour at Intermediate Bridge Piers

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The ability to establish foundation elevations for intermediate bridge piers that will provide a reasonable degree of assurance that the pier will not be undermined by the flowing stream and to rate existing intermediate bridge pier foundations relative to their risk of being undermined has become a matter of national concern. This paper will document the results of a study that presents and recommends formulae that can be used to predict the anticipated depth of local scour in both uniform-particle, cohesionless streambeds, and graded, armored streambeds. The study incorporated both a literature search and a field verification of the results of the literature search. The Laursen and Toch formula will be recommended to predict anticipated local scour depths at intermediate bridge piers in uniform-particle, cohesionless streambeds, and the University of Aukland formula will be recommended for consideration for graded, armored streambeds. This document will show that these scour prediction formulae, in conjunction with other engineering data, can be a valuable tool to aid the engineer in economically and safely establishing an intermediate bridge pier foundation elevation, or rating the safety of an existing foundation.

For over 100 years, engineers have noted that the intrusion of intermediate bridge piers into a flowing stream causes eddy currents, which in turn may scour and undermine the bridge foundation. Researchers have proposed over 35 different formulae for local scour prediction since 1949. Almost all of this research has focused on streambed materials that are uniform in size and cohesionless; however, many streams in Washington and other states have beds of graded material with some degree of armoring.

An extensive literature search that uncovered over 50 publications dealing with the prediction of local scour at intermediate bridge piers and an investigation of 28 bridge sites in Washington indicate that the use of prediction formulae based on uniform-particle, cohesionless streambeds for estimating scour in graded, armored streams may produce excessive scour depths. Under certain circumstances, though, armored beds may exhibit scour greater than that found in uniform-particle, cohesionless beds.

Scour was predicted and compared for six bridge sites in the state of Washington using four methods of scour prediction formula for uniform-particle, cohesionless streambeds, and one method for graded, armored streams. The method for graded, armored streams indicated anticipated scour depths of about one quarter that of the uniform-particle methods. All these structures had experienced meaningful floods. In-depth investigations of these foundations indicated no significant scour problems.

This paper presents and suggests consideration of a procedure developed by Raudkivi and Ettema at the University of Aukland, with a safety factor suggested by the authors, for estimating local scour at intermediate bridge piers in graded, armored streams. The formula developed by Laursen and Toch is recommended for streams with uniform-particle, cohesionless beds. Caution, and the application of engineering judgment, is suggested in the evaluation of the results of either method. More research is required to further confirm or deny the validity of these formulae.

BACKGROUND

The Washington State Department of Transportation (WSDOT) has traditionally protected both its bridge approach abutments and intermediate bridge piers against erosion with riprap. Riprap has been placed on the end abutments as shown in Figure 1, and over the intermediate piers as shown in Figure 2.

At least 20 percent and not more than 90 percent of stones weighing 300 pounds to 1 ton, at least 80 percent of stones weighing 50 pounds to 1 ton, and at least 10 percent and not more than 20 percent of stones weighing 50 pounds or less are the riprap for both bridge abutments and intermediate piers. Periodic observations by inspection crews indicate that this type of protection has performed adequately on structures experiencing flows as large as the 50-year mean recurrence interval. This apparent adequate performance applies to both end abutments and intermediate bridge piers.

WSDOT has long recognized that the thalweg of the stream can meander across the floodplain; thus, the tops of all foundations in the floodplain were set a minimum of 2 feet below the thalweg. This, with the use of riprap for all erosion, appears to have provided adequate countermeasures for general, constriction, and local scour for structures that have experienced flows as large as the 50-year mean recurrence interval. A quantitative estimate of each type of scour has not been required. This observation, however, is not intended to suggest or recommend continuation of this practice.

In the early 1970s, environmental requirements precluded WSDOT's practical use of riprap at intermediate bridge piers. To excavate for the riprap, cofferdams were needed to prevent the accommodation of silt and the resulting adverse effect on fish. Riprap could still be used to protect the bridge abut-

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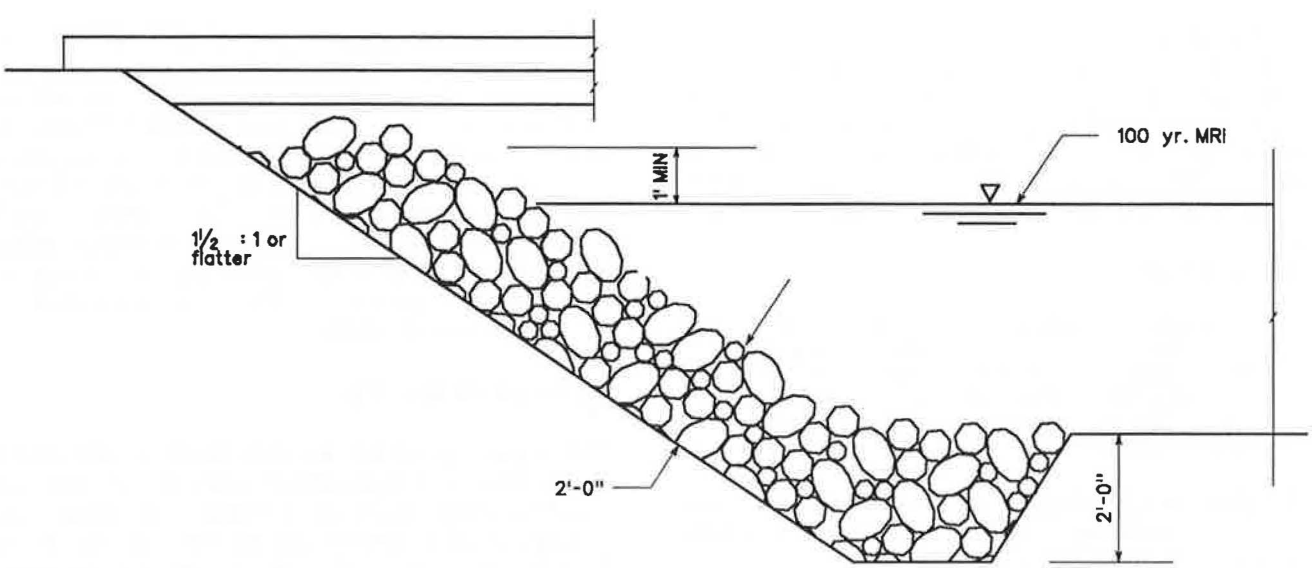

FIGURE 1 Riprap at end abutments.

ments, as the needed excavation normally could be done in the dry. WSDOT then searched for another way to protect the intermediate bridge foundations from undermining.

WSDOT realized that the practical solution was to set the foundations of the intermediate bridge piers at an elevation that would not be undermined. General and constriction scour at most Washington sites were subjectively considered negligible. WSDOT determined that the key to adequately setting the foundation to prevent undermining centered on the knowledge of the meandering thalweg and the ability to predict scour. Foundation elevations could then be established to offer a reasonable assurance that the pier would not be undermined by scour.

Intermediate bridge pier foundations are very costly. As the foundation is lowered to mitigate against scour, the head on the bottom of the cofferdam seal is increased. This increased head requires a thicker seal, which increases the amount of excavation, sheet piling, and concrete required for the foundation. WSDOT recognized that while overly conservative methods of scour prediction should be avoided, loss of the structure because of an inadequate pier foundation is even more costly.

SCOUR PREDICTION RESEARCH

Highway agencies are concerned with the loss of any bridge attributed to undermining of a pier foundation by local scour

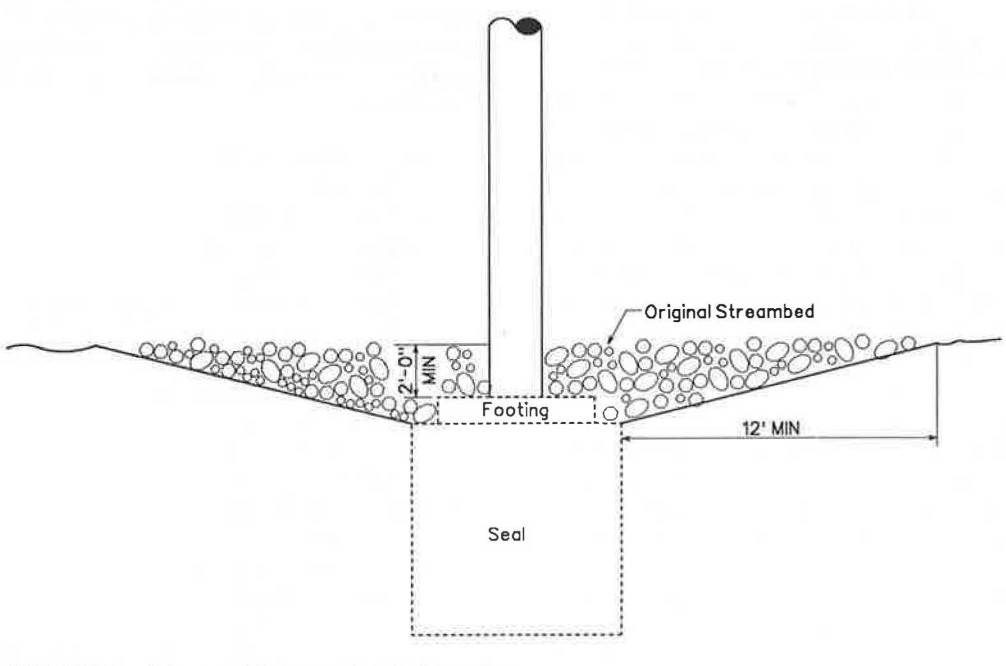

FIGURE 2 Riprap at intermediate bridge piers.

and will sponsor research leading to a more precise ability to predict the depth of anticipated local scour at intermediate bridge piers. For example, considerable bridge losses in Iowa in 1947 resulted in the intensive study by Laursen and Toch (*4*). This was the forerunner of many modern research projects that addressed the issue of predicting local scour depth an intermediate bridge piers in uniform-particle, cohesionless soil.

Hopkins et al. (*3*) stated:

> Over the past century many investigators have attempted to develop a simple scour prediction formula. . . . It appears that a set of variables were arbitrarily selected and data collected over a limited range to determine their relationship to scour depth. . . . This approach has left us with a large number of sometimes conflicting formulas to predict scour.

Hopkins's statement suggests a reason for the many scour prediction formulae uncovered in the literature and the diverse scour depths that they produce.

WSDOT engineers recognized that the majority of the scour research had produced formulae that predicted anticipated local scour at intermediate bridge piers for uniform-particle, cohesionless streambeds. WSDOT also realized that most of the Washington bridge sites consisted of graded, armored material. In most situations, graded, armored material resists erosion much better than uniform-particle, cohesionless soil. Recent work by Raudkivi and Ettema (*6*) indicates that under certain conditions this may not be true. Further research is needed to better describe and quantify this issue. A reliable equation to predict local scour based on graded, armored streams could produce significant cost savings while maintaining a reasonable degree of confidence.

SCOUR PREDICTION IN GRADED, ARMORED STREAMS

WSDOT, in cooperation with the Federal Highway Administration (FHWA), issued a request for a prospectus for a research program dealing with determining the estimated scour depth for intermediate bridge piers in graded, armored streams. Different prediction methodology is required for local scour at end abutments, local scour at intermediate piers, general scour, and constriction scour. Recognizing a need for the ability to predict all these types of scour, it was arbitrarily decided that to narrow the scope of research, only local scour at intermediate piers would be investigated. This decision resulted in a research project award to Washington State University (WSU) in 1986. The principal investigator was Howard D. Copp, who was assisted by Jeffrey Johnson. Their work culminated in the report *Riverbed Scour at Bridge Piers* (*2*).

The study had a single objective. WSDOT was using the Laursen Toch formula to estimate the depth of local scour at intermediate bridge piers under all streambed conditions. WSU was to determine, within the specified limitations, the most appropriate methods for predicting local scour depth at intermediate bridge piers for both uniform-particle, cohesionless and graded, armored streambeds.

The study team was to concentrate on keeping recommended methods practical. Methods of scour prediction that required extensive collection of data or observations of stream characteristics over a period of time were not to be considered. Absolute and rigorous research methods were to be subordinated to practicality. Known methods of scour prediction were to be uncovered by a literature search, and these methods were to be compared and evaluated. Comparisons of known methods of scour prediction with a field investigation were included in the scope of the research. Field investigations, made after a flood, cannot be relied on to show the maximum scour occurring during the flood peak. Combined with historical records of flood flows, they do give a general indication of the present condition of the foundation, i.e., whether it is safe or unsafe.

LITERATURE SEARCH

The literature search revealed 38 formulae developed to predict the anticipated depth of local scour at intermediate bridge piers. Some were based on laboratory experiments, others were developed through field investigations, and some involved both laboratory and field work. All but one pertained to uniform-particle, cohesionless streambeds.

Only the scour prediction formula based on research conducted by Raudkivi and Ettema (*5*) at the University of Aukland incorporates a parameter that recognizes a nonuniform or graded streambed material. It will be referred to as the UAK formula.

The UAK formula includes a geometric standard deviation of size distribution. All other parameters being equal, this one difference predicts an estimated scour depth significantly less than any of the other 37 equations that were developed for uniform-particle, cohesionless beds.

A complete listing of these expressions is contained in *Riverbed Scour at Bridge Piers*.

COMPARISON OF SCOUR PREDICTION METHODS

To compare the many different scour prediction formulae, they first must be rearranged so that the variables are identified and classified in a common manner. The many parameters that influence scour around intermediate bridge piers have been arranged by Breussers (*2*, p. 276) into the following four groups:

1. Stream fluid variables
   a. Density of fluid, p
   b. Viscosity of fluid, v
2. Stream flow variables
   a. Depth of flow, y_0
   b. Velocity of the flow approaching the pier, U
   c. Magnitude of stream discharge, Q
3. Streambed materials
   a. Grain size distribution
   b. Grain diameter
   c. Sediment density, P_s
   d. Cohesive properties
4. Pier size and shape
   a. Pier dimensions
   b. Pier shape in plan view
   c. Surface roughness
   d. Number and spacing of piers
   e. Orientation of piers to approach flow direction
   f. Pier protection (fenders, for example)

In attempting to make this comparison, it was found that because of the complexities and attendant costs of measuring, analyzing, and evaluating all of the above-mentioned variables, many investigators deliberately

1. assumed that the differences between the laboratory and field values for density, viscosity, and the acceleration due to gravity can be neglected;
2. restricted the study to steady, uniform flow fields unconstricted by bridge approach fills;
3. considered only alluvial, noncohesive, uniform particle-sized bed materials; or
4. considered only perfectly smooth, single piers that are perfectly aligned with the approach flow and do not have scour protection systems, such as riprap.

These assumptions and restrictions reduce a long list of variables that affect scour depth to the following eight:

1. Fluid density
2. Kinematic viscosity of fluid
3. Gravitational acceleration constant
4. Sediment grain size diameter
5. Bed sediment density
6. Approach flow depth
7. Mean approach flow velocity
8. Pier width

Many researchers have compared these different categorical arrangements and have determined that under certain conditions several equations would give comparable results. Several of the prediction equations give comparable results and reasonable estimates of scour; however, they are not necessarily valid. This was the conclusion of Raudkivi and Sutherland (*7*) after they had compared 17 prediction equations to actual scour depths measured at four New Zealand bridge sites. A field investigation, while it cannot absolutely verify the validity of a scour prediction equation, can certainly nullify it.

FIELD STUDY

Twenty-eight bridge sites on state highway routes in Washington State were investigated for evidence and magnitude of scour at intermediate bridge piers. The exposed streambed and bank materials at most of these locations were nonuniform in size (graded), and consisted of fines to large gravel, and, in some locations, small to medium boulders. Significant armoring was observed in most cases.

It was recognized that the field measurements would not indicate the maximum scour that had occurred but rather that they would show the general condition that exists. These measurements were not intended to be a verification of any given equation.

Table 1 lists the six sites, gives the date of construction, shows the magnitude of the flood of record, compares the different prediction methods, and gives a general indication of the condition of the foundation with the field measurements.

The field procedure at each of the six sites consisted of

1. documenting the channel geometry, including the identification of the channel pattern and measuring the bridge waterway cross-sectional dimensions;
2. evaluating the type and characteristics of the streambed bank and bed materials; and
3. measuring the apparent depth of local scour at various

TABLE 1 SUMMARY OF SCOUR DEPTHS AT SIX WASHINGTON STATE BRIDGE SITES

	Study Site					
Bridge Site Equation	5/216E Newaukum (1)	507/102 Skookumchuck (2)	507/128 Nisqually (3)	90/82S S. Fk. Snoq. (4)	12/706 Touchet (5)	12/725 Tucannon (6)
Year Built	1952	1971	1917	1975	1966	1967
Flood of Record	50 Year MRI	10 Year MRI	50 Year MRI	15 Year MRI	35 Year MRI	7 Year MRI
C.S.U.	19.6	5.5	24.9[a]	17.3	11.7	12.7[b]
Laursen-Toch 1	25.8	6.5	25.1	13.8	9.3	14.7
Shen II	15.7	6.4	34.0	27.0	16.5	15.7
Neill	17.2	4.5	31.4	14.0	5.7	20.0
UAK	5.2	1.4	8.0	4.3	2.1	5.1
Field Measurements	6.1	1.7	8.0	2.8	1.7	3.3

Note: Units in feet; 1 ft = 0.305 m

[a] Computed using foundation width, 15.7 ft

[b] Computed using pedestal width, 10.0 ft

locations around the piers, which is not intended to represent the maximum depth of scour but to give an indication of the overall condition of the foundation.

WSDOT "as-built" drawings were obtained for each site, and the design flow, from U.S. Geological Survey streamflow records, was listed for each of the six sites. The historical flood of record was determined and expressed in terms of the mean recurrence interval. All sites had experienced meaningful flood flows in their lifetime. Work by Laursen (*4*) and others suggests that a significant parameter influencing depth of scour is the depth of the approach flow. The historical floods at the locations in question were sufficient to produce an approach flow depth that would have the capability to generate meaningful scour. It is not possible to determine, by direct measurements, the amount of deposition, if any, that occurred during the recession of the flood. Further research should center on developing an indirect method based on various field measurements combined with known principles of sediment transport to estimate the maximum depth of scour that has occurred.

CONCLUSIONS AND RECOMMENDATIONS

The comparisons in Table 1 between the four different scour prediction formulae for uniform-particle, cohesionless stream beds at the six structures investigated gave comparable results. As stated elsewhere in this paper, that is no guarantee of their validity. No scour prediction formula has been completely validated by objective, measured means. All the bridges studied had experienced meaningful historical floods, and all were in locations where the beds were graded, armored material. None of the bridge foundations appeared to be in any immediate danger from undermining.

WSDOT has been using the Laursen and Toch equation to predict anticipated scour at all intermediate bridge piers since the early 1970s. This is one of the earliest scour prediction methods, and it has received historical acceptance. This paper recommends the continued use of the method to predict local scour depths in uniform-particle, cohesionless streambeds. The recommendation is not founded on the field investigations made for this study but on the simplicity of the method and its wide historical acceptance.

It has been the subjective opinion of many engineers that the scour prediction formulae for use in uniform-particle, cohesionless streambeds give overly conservative results when applied to graded, armored streams. The work done by Raudkivi and Ettema, under normal conditions, tends to support this subjective opinion. Although their work has not been rigorously substantiated, it is recommended that the UAK formula, with adequate consideration for streambed layering and with a factor of safety, be considered for predicting local scour in graded, armored streams. Again, it should be noted that this recommendation is not founded on any field investigation made for this study but rather the literature review that indicates Raudkivi and Ettema are alone in their studies of graded, armored streambeds.

USE OF THE LAURSEN AND TOCH EQUATION

The Laursen and Toch equation is

$$d_s/b = 1.5\,(y_0/b)^{0.3}$$

where d_s is the anticipated depth of local scour, b is the width of the pier, and y_0 is the depth of flow approaching the pier.

The right-hand side of the above equation is multiplied by a design factor, K_σ, that ranges from 1 to 7 for the angle of attack of the stream to the pier, and by a shape coefficient, K_s, that varies from 1.00 to 0.70, depending on the nose shape of the pier.

The design factor, K_σ, for angle of attack of the stream to the pier, can be found in Figure 3. Table 2 lists the shape coefficient, K_s, for various nose shapes and pier configurations. These same modifiers are applicable to the UAK equation and to all the other scour prediction formulae referenced in this report.

USE OF THE UAK EQUATION

The initial step in using the UAK formula for estimating the scour depth in graded, armored streambed material is to

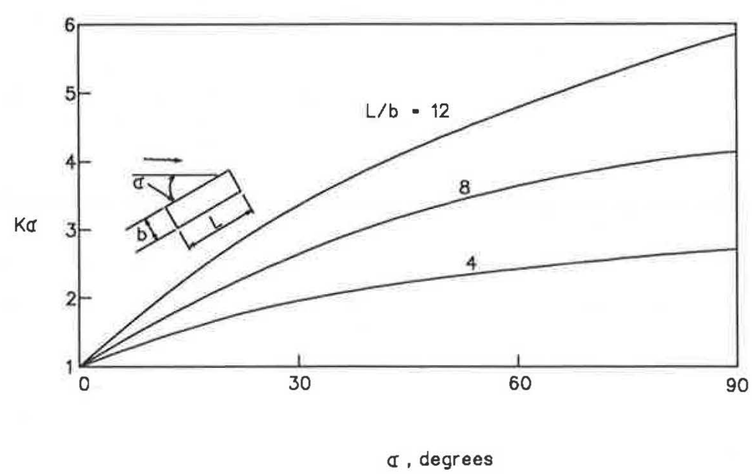

FIGURE 3 Design factor K_α for angle of attack of stream to pier.

TABLE 2 SHAPE COEFFICIENT K_s FOR VARIOUS NOSE FORMS

Nose Form	Length - Width	Shape	Ks
Rectangular		▭	1.00
Semicircular		(	0.90
Elliptic	2:1	⊂	0.80
	3:1	⊂	0.75
Lenticular	2:1	<	0.80
	3:1	<	0.70
Square		▭	1.0
Round		▭	0.9
Cylinder		○	0.9
Sharp		⬭	0.8
Group of Cylinders		○ ○	0.9

determine the characteristics of the riverbed material near the planned bridge. At a minimum, two samples of the streambed material should be obtained from each pier location. The sampling should range from 30 feet upstream to 30 feet downstream of each pier.

Samples should be obtained in a way that will not lose the fines. Special core drill apparatus are available, and they should penetrate the streambed about as deep as a "guess" of the estimated scour depth (about 6 to 10 feet). In some instances, a back hoe may be used.

When obtaining streambed samples, the engineer must ascertain whether the streambed is layered with interstices of fine sand or clay. If layering is present, actual scour may be deeper than predicted by the UAK formula because of stepwise failure in the layers. Predicted scour depths should be increased by 15 percent to 20 percent, depending on the engineer's judgment. This increase for layering is above the recommended safety factor that will be applied later.

The sample of the bed material from each location should represent material for the surface to the maximum depth. These samples should be carefully marked, taken to the laboratory, and analyzed with a sieve. A gradation curve can then be prepared for each sample obtained. A single "site" gradation curve is an average of all the curves of the site. A single average curve may be used if the variation of samples does not exceed 20 percent.

From this "site" curve, the size of sample that corresponds to the 16, 50, and 84 percentiles is determined. These are d_{16}, d_{50}, and d_{84}.

Next, b/d_{50} should be calculated, where b is the anticipated pier width in the direction of the streamflow. With this value of b/d_{50}, use Figure 4 with d_{50} greater than 0.7 mm and find the corresponding value of d_s/b. The mean value of scour depth can now be calculated as $d_{sm} = d_s/b \times b$. This is the

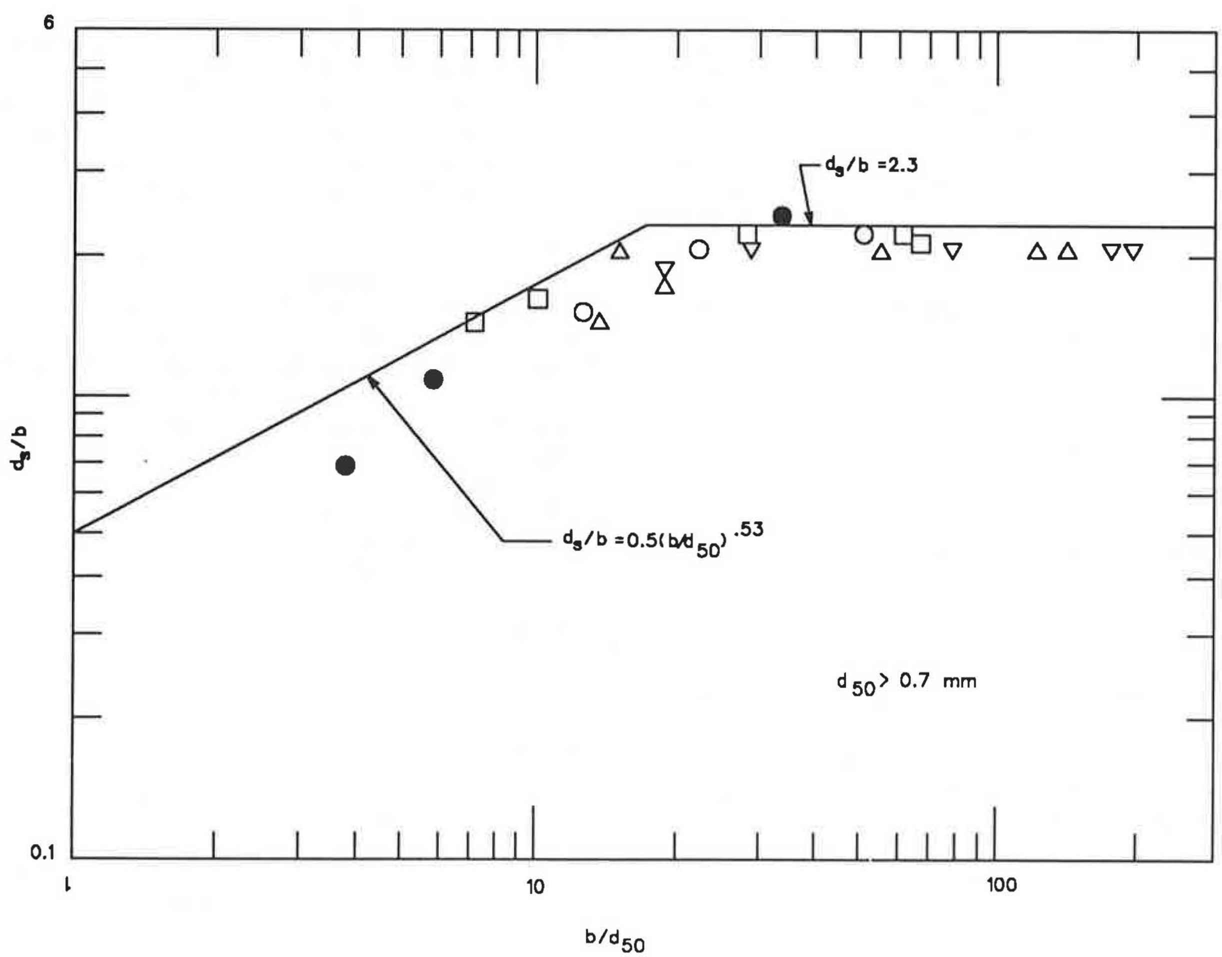

FIGURE 4 Scour-depth-to-pier-diameter ratio as a function of pier-diameter-to-sediment-size ratio.

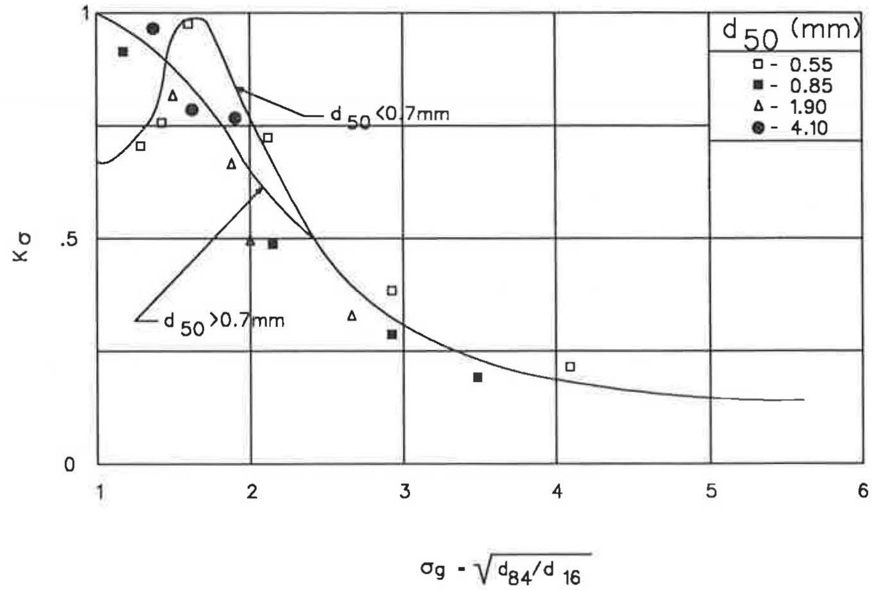

FIGURE 5 Particle size coefficient K_σ related to geometric deviation σg.

predicted scour depth if a rectangular-shaped pier is built and it will be oriented perfectly with the stream flow paths. Adjustments may be necessary.

K_σ is then determined. With the previously determined values of d_{16} and d_{84}, $\sigma g = (d_{84}/d_{16})^{1/2}$ can be computed. Use Figure 5 with this value of 5g and find K_σ. As in Figure 4, the $d \rangle$ 0.7 mm curve is used.

Next, K_α is determined. L/b is calculated (L is the pier length) and used in Figure 3 with the angle α at which the pier will be oriented with the streamflow. These two values will permit the determination of K_α. K_s is then determined from Table 2.

Next, a factor of safety is established, K_{fs}. K_{fs} equal to 1/ K_σ is selected whenever σg is less than 2, and 1.5 when K_σ is greater than 2. The final step is to compute the estimated scour depth as

$$d(\text{est}) = d_{sm}\ K_\sigma\ K_\alpha\ K_s\ K_{fs}$$

USE OF ESTIMATED SCOUR DEPTH

The use of either formula recommended in this report to predict anticipated local scour is only one of many tools that can determine the risk factors associated with the potential undermining of an intermediate bridge pier foundation. In addition to predicting local scour, the engineer must predict and quantify the effect of general and constriction scour and the meandering thalweg. It must also be kept in mind that the validity of all scour prediction formulae has not been conclusively demonstrated.

The degree that other information, such as underwater investigation of nearby bridge foundations on the same stream, soils investigation relating to the nature of the streambed, and the knowledge that can be obtained applying accepted principles of sediment transport to the stream, should be combined and evaluated with the results of the scour prediction formula is a matter of subjective engineering judgement.

Ignoring the potential for scour or relying solely on some form of artificial armoring as protection against undermining is a situation that can no longer be accepted. The engineer's goal is the knowledge that the existing or proposed bridge pier foundation is reasonably safe from undermining by the flow of the stream with the attendant loss of the structure. Scour prediction formulae, properly applied, are a way to help attain this goal.

An initial prediction of anticipated scour depth is made using the formula appropriate for the type of streambed material and the width of the pier, b, that protrudes into the flowing stream. If this predicted scour depth lies above the top of footing or pedestal, the foundation is safe. If this predicted scour depth lies below the top of the footing or pedestal, the predicted scour depth should be recalculated using the width of the seal for b. In a spread footing, if this new predicted scour depth is above the bottom of the seal, the foundation is safe. In a pile-supported footing, the predicted scour depth using the width of the seal for b can be below the bottom of the seal and still result in a safe foundation, provided that sufficient embedment of the piling exists below this predicted depth to fully develop the horizontal and vertical loads that are transmitted to the foundation.

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