Scour at Wide Bridge Piers

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Abstract:

Most empirical, local scour prediction equations over predict scour depths at structures that are wide compared to the water depths where they are located. This paper discusses various researchers attempts to deal with this problem. The methods and equations used by several Western European Countries (obtained during the FHWA, 1998 European Scanning Tour On Bridge Scour) are included along with work done in the United States.

Introduction:

Engineers have long been of the opinion that empirical scour prediction equations based on laboratory data over predict scour depths for large structures. This is true for large offshore gravity structures as well as large coastal and inland bridge piers, and thus the name “wide pier” or “wide structure” problem. It is especially important for large coastal bridges because the local scour equations typically represent the scour depth as a multiple of the pier width. Scour depths of 1.5 to 2.4 times the pier width for a small bridge pier that might be a meter or so wide are not so critical. But they are critical for large bridges that have piers tens of meters wide where over predictions lead to very costly foundation designs. The problems are compounded for most coastal and large river bridges because lateral loads computed for ship impact drive the foundation costs even higher when the lateral support provided by the soil is reduced by excessive scour depth estimates.

There are a number of methods and equations in the literature for estimating local scour at bridge piers located in cohesionless sediment. Most, if not all, of these equations are empirical and were derived using laboratory data from steady flow experiments. Due to the complexity of the flow and sediment transport associated with local scour processes there are a number of dimensionless groups needed to fully characterize the scour. Many of these groups, such as the ratio of water depth to structure diameter, can be maintained constant between the laboratory model and the prototype structure. However, since there is a lower limit on the sediment particle size before cohesive forces become important, those groups involving sediment size cannot be maintained constant between the model and the prototype. In fact, most laboratory experiments are performed with near prototype scale sediment. If the sediment to structure length scales are not properly accounted for in the predictive equations then problems arise when the equations are applied to situations different from the laboratory conditions on which they are based. The problems associated with not being able to maintain the proper scale between model and prototype sediment increases with the size of the prototype structure. Engineers have long recognized the problem of predicting local scour depths at large structures (using equations based on laboratory data) and refer to it as the “wide pier scour problem” or the “large structure scour problem”. These equations tend to over-predict scour depths under these conditions.

An important part of this discussion is a consideration of the HEC-18 (1) pier scour equation and the data set from which it was derived to determine what conditions that equation reasonably represents. The data set that was used to derive the original CSU/HEC-18 pier scour equation was assembled as part of the work for this paper. This data is available from the authors.

This paper outlines several methods that are available for dealing with the so-called wide pier problem including methods that were discovered during the FHWA, 1998 European Scanning tour on bridge scour. Research in the U.S. reported by Johnson resulted in a “wide pier” correction to the HEC-18 equation. Researchers in the Netherlands and the UK use a hyperbolic tangent function that essentially shifts the characteristic length dimension from the pier width to the flow depth as the pier width gets large relative to the flow depth. Researchers in Switzerland developed a method for estimating building scour that seemed pertinent to the “wide pier” problem.

Sheppard (2), the first author of this paper, has concluded that the pier width impacts the equilibrium scour depth in two ways. First, the pier size to flow depth ratio is important and can best be represented by a hyperbolic tangent function, which makes the scour depth primarily a function of the pier size for relatively slender piers but a function of the flow depth for relatively wide piers. Second the pier size to sediment size ratio can have an even greater impact on the scour prediction. Large-scale laboratory tests being performed by the authors were designed to test Sheppard’s hypothesis and to provide clearwater scour data for larger structures. Live bed scour tests are scheduled to be conducted after the clearwater tests are completed.

Literature Review

The wide pier problem is usually considered to be a concern when the relative depth, y/b, is too small to allow the vortices to fully develop where “y” is the flow depth and “b” is the pier width. Earlier investigations of the dependence of scour depth on y/b were performed with small piles and very small water depths, Ettema (1980). Melville (3) established an upper threshold at y/b = 3 beyond which the scour depth is relatively independent of the relative depth. Recent data from the authors’ tests with the large piers indicates that this threshold should be closer to 2. However, this ratio can be modeled and data below these thresholds is included in a number of the existing empirical equations that over predict prototype scour depths. Most practitioners would associate the wide pier problem with relative depths around 1.0.

HEC-18 Pier Scour Equation

FHWA’s HEC-18 (1) is the standard used by most highway agencies for evaluating scour at bridges. The pier scour equation was derived from laboratory data by researchers at Colorado State University and was presented as the CSU equation in an earlier FHWA publication, “Highways in the River Environment” (4). It is prudent to look at the data used to derive that equation to determine its range of applicability.

The CSU equation was derived from laboratory data published by Chabert and Engeldinger (5) CSU data published by Shen, Schneider and Karaki (6). Although the sources of the data used in the derivation are well documented, the actual data had not been tabulated, prior to this paper, and it was difficult to support notions about the characteristics of the data set. After a number of inquiries and investigations the authors were able to assemble the data used to develop the CSU equation. A regression analysis of this data produced an equation very close to the original equation as shown in Figure 1. All of the data used for the original equation was for circular piers in relatively uniform fine grain sands. Correction factors were added later to account for various pier shapes, angle of attack, bed forms, and coarse bed material fractions to produce the familiar pier scour equation that is currently in HEC-18;

$$\frac{y_S}{y} = 2.0 K_1 K_2 K_3 K_4 \left(\frac{b}{y}\right)^{0.65} F_r^{0.43}$$

Where, y_S is the equilibrium scour depth, y is the flow depth, b is the pier width, F_r is the Froude number and K_1, K_2, K_3, and K_4 are the correction factors. Examination of that data reveals that there were several data points with y/b less than 1.0. From that point one could argue that the equation could apply to wide piers. The second part of the question, though, is whether the data for small relative depths was consistently below the regression line. The data points for y/b less than 1.0 are plotted with different symbols in Figure 1 and almost all of them do fall below the regression line, which suggests that the equation could at least be adjusted for wide piers or low relative depths.

Johnson's Adjustment

Johnson (7) defined a wide pier as one situated in shallow, low velocity flows so that $y/b < 0.8$ and $F_r < 0.8$. She isolated the data that met these conditions in the original data set used in the CSU equation and added data from other sources to derive a new equation for wide piers using the same parameters. That equation could be written:

$$\frac{y_S}{y} = 2.08 K_1 K_2 K_3 K_4 \left(\frac{b}{y}\right)^{0.504} F_r^{0.639}$$

Then she divided the wide pier equation by the HEC-18 equation to express the difference as another correction factor, K_W, for the HEC-18 equation.

$$K_W = 1.04 \left(\frac{b}{y}\right)^{-0.15} F_r^{0.21}$$

which can be applied to the HEC-18 equation when $y/b<0.8$ and $F_r<0.8$. If both of these conditions are just met, K_W is approximately 0.95 which means there would be a 5% reduction in the estimated scour depth. But if $y/b = 0.5$ and $F_r = 0.5$, which could occur, then $K_W = 0.81$ which is a 19% reduction.

Application of Building Scour Research:

Researchers in Switzerland developed equations to estimate scour around buildings that obstruct waterways. That situation seemed somewhat analogous to a very wide pier and the equations are worthy of consideration for estimating scour at wide piers. Results of this research were presented to the Oct. 1998 US Bridge Scour Scanning team as a lecture by Dr. Willi Hagar at the Swiss Federal Institute of Technology in Zurich. The equation for estimating building scour is:

$$\frac{y_s}{\sqrt{b \times y_0 / \cos\theta}} = 0.10 \times F_d^2 \times \log(0.10T)$$

$$T = \frac{\sqrt{(S_S - 1)gD_{50}}}{y_0} \times t \qquad F_d = \frac{V_0}{\sqrt{(S_S - 1)gD_{50}}}$$

where: F_d = densimetric Froude number
y_s = scour depth,
b = building width
y_0 =flow depth
S_S = specific density of sediment
D_{SED} = characteristic sediment size
T = scaled time
t= time, units consistent with units of acceleration of gravity, g
θ = skew angle of approach flow

$$D_{SED} = D_{50} + \left[1 - \frac{1}{e^{10^3 T^2}}\right](D_{90} - D_{50})$$

This procedure is limited by the experimental range of the densimetric Froude number which was apparently from approximately 0 to 3.0. This number could easily be 15 to 20 for many bridge sites and extrapolating the equation that far beyond the range of experimental data would be a gross misapplication of the results.

The U K Equation

Richard May of H.R. Wallingford presented the U.K. version of a wide pier equation as

$$\frac{y_s}{y} = k\left[0.55\left(\frac{b}{y}\right)^{0.40}\right]_{MAX=1.0}\left[0.6\left(\frac{2.07\times V_0}{V_C} - 1\right)\right]_{MAX=1.0}$$

where k= 3.2 for rectangular piers, k=2.4 for round piers and the maximum value in either of the bracket terms is 1.0. That means they assume no additional scour for increases in b/y above 4.45 (y/b=0.22) and that peak scour occurs at $V_0/V_C = 0.80$.

The Netherlands Equation

Breusers pier scour equation is preferred in the Netherlands as noted in draft notes on "Scour Experience of Delft Hydraulics Abroad" prepared for the scour scanning tour by Henk Verheij dated 10/30/98, page 8. That is

$$y_s = k \times b \times \tanh\left(\frac{y}{b}\right)$$

The hyperbolic tangent function seems to reflect the pier width relationship very well. For slender piers, *b/y* <1, the hyperbolic tangent of *y/b* approaches 1, and

$$y_s \approx k \times b$$

For wide piers, *b/y*>1, the hyperbolic tangent of *y/b* approaches *y/b*, and

$$y_s \approx k \times y$$

Predictive Equations Developed by Sheppard at the University of Florida

The first author of this paper has conducted a number of site specific model studies for very large piers located in fine sands and has studied the literature to determine why there are inconsistencies in the scour prediction equations. He concluded that the wide pier problem is not so much with the relative water depth, y/b as it is with the lack of sediment scaling in the laboratory tests. The laboratory data on which most, if not all, empirical local scour depth equations are based, scale the relative water depth properly. The quantity that is not scaled in the model tests is the sediment size. Since cohesive forces between the particles become significant when the sediment particle size is less than 0.074 mm (#200 sieve), model sediment is seldom smaller than 0.1 mm in laboratory experiments. Many laboratory experiments have been conducted with much larger sediments, as large as 5 mm while the structures' widths have been relatively small due to the widths of the laboratory flumes. For local scour it is reasonable to normalize the sediment size with the structure length scale, i.e. the structure width. Thus D_{50}/b or more conveniently b/D_{50} has been used by a number of researchers. Note that if prototype sediment is used in the model tests this parameter is vastly different for model and prototype.

The range of the b/D_{50} ratio included in the data used to derive the HEC-18 pier scour equation was from 96 to 633 and two thirds of the data had values less than 200. For 384 field measurements tabulated by Landers and Mueller (8), b/D_{50} ratios ranged from 8.5 to 19,763 with an average value of 2,145 with a median value of 1,024. Sheppard (2) has shown that the maximum relative clear water scour occurs when the b/D_{50} ratio is about 46, and that scour tends to diminish on both sides of this value for constant values of V/V_c and y/b, as illustrated in Figure 2. Since b/D_{50} cannot be properly scaled in the laboratory, the equilibrium scour depths' dependence on this quantity must be established if prototype scour depths are to be predicted from equations developed from laboratory data. The range of this ratio obtainable in the laboratory is limited due to size limitations of existing flumes. Experiments by the authors have extended the range of experimental data by conducting clear water local scour experiments using 0.91 m (3 ft) diameter piers in sand with a D_{50} of 0.22 mm (b/D_{50} =4136).

Even though there is a significant quantity of local scour data for circular piles reported in the literature much of this data is not useable. For example, the duration of many experiments were not sufficient for the scour depth to reach (or even be extrapolated to) an equilibrium value. In other situations vital information about the flow, sediment and/or structure is missing. A thorough review of the literature resulted in 215 useable data points from nine different sources for clear water scour conditions and 244 data points for live bed scour conditions. Included in this data set are data from recent tests conducted by the authors at the USGS-BRD Conte Research Center using 0.11 m, 0.305 m, and 0.914 m diameter piles in 0.22 mm, 0.8 mm and 2.9 mm diameter sand. These data have been used in the development of Sheppard's local scour equations.

Sheppard's equations include the structure width to sediment size ratio and thus should be directly applicable to large structures (wide piers). This equation works well for the range of structure to sediment size ratios obtainable in the laboratory, which now extends to values as high as 4,168. These equations have also been applied to prototype structures from the USGS measurement program that range in width from 1 m to 10 m with good agreement. Of the numerous dimensionless groups that affect local equilibrium scour depths Sheppard found three of the groups y/b, V_0/V_C, and b/D_{50} to be the most important for circular piles, i.e.

$$\frac{y_s}{b} = f\left\{\frac{y}{b}, \frac{V_0}{V_C}, \frac{b}{D_{50}}\right\},$$

where: $y \equiv$ upstream water depth,
$b \equiv$ diameter of pile,
$V_0 \equiv$ velocity upstream of the pile,
$V_c \equiv$ critical velocity upstream of the pile and
$D_{50} \equiv$ median sediment diameter.

The critical velocity, V_c, is that velocity required to initiate movement of the median diameter sediment on the flat bed upstream of the structure. In the live bed scour range there is one additional parameter, V_{LP}/V_C, where V_{LP} is the velocity at which the bed upstream of the structure flattens and becomes a plain bed (see Figures 3 and 5). This is assumed to be the velocity at which the live bed peak scour occurs.

Note that the magnitude of the scour depth at transition from clearwater to live bed conditions (clearwater peak) is highly dependent on the b/D_{50} ratio as opposed to the scour peak in the live bed range which appears to be independent of this ratio. However, the value of V_0/V_C where the live bed peak occurs does depend on the sediment and flow parameters. There are several papers on bedforms in the literature that give the conditions under which dunes disappear and the bed becomes planar [see e.g. Simons and Richardson (1966), Snamenskaya (1969), van Rijn (1993)]. The values for the bed planing velocities predicted by these various methods differ in magnitude. The results given in Snamenskaya (1966) have been used in Sheppard's equations and have resulted in good agreement with field measurements as stated above.

The normalized equilibrium scour depth's (y_s/b) dependence on the three dimensionless groups b/D_{50}, V_0/V_C and y/b is illustrated in Figures 2, 3 and 4, respectively. Note that in each case two of the groups are held constant while the third is varied.

For design purposes the local scour depth can be reduced to the simple relationship shown in Figure 5 and given in the equations below.

For Clearwater Scour ($0.4 \le \frac{V_0}{V_c} \le 1.0$)**:**

$$\boxed{\frac{y_s}{b} = c_1\left[\frac{5}{2}\left(\frac{V_0}{V_c}\right) - 1.0\right],}$$

where $c_1 = \frac{2}{3}k$ and

$$k \equiv tanh\left[2.18\left(\frac{y}{b}\right)^{0.66}\right]\left[-0.279 + 0.049\, exp\left(log_{10}\frac{b}{D_{50}}\right) + \frac{0.78}{log_{10}\frac{b}{D_{50}}}\right]^{-1}.$$

If the design velocity is in the live bed regime then the velocity at the live bed scour peak (V_{LP}) must be determined (point 3 in Figure 5). Determination of V_{LP} requires knowledge of the sediment properties and the water depth. The equilibrium (live bed) local scour depth can then be computed using the following equations.

Live Bed Scour $\left(1.0 < \frac{V_0}{V_c} \le \frac{V_{LP}}{V_c}\right)$

$$\boxed{\frac{y_s}{b} = c_2\left(\frac{V_{LP}-V_0}{V_c}\right)+c_3}$$

where

$$c_2 = \frac{k - 2.4\,tanh\left[2.18\left(\frac{y}{b}\right)^{0.66}\right]}{\left(\frac{V_{LP}}{V_c}-1\right)}, \text{ and} \qquad c_3 = 2.4\,tanh\left[2.18\left(\frac{y}{b}\right)^{0.66}\right]$$

If $\frac{V_0}{V_c} > \frac{V_{LP}}{V_c}$, then

$$\boxed{\frac{y_s}{b} = 2.4\,tanh\left[2.18\left(\frac{y}{b}\right)^{0.66}\right]}$$

The scour depth for a noncircular single pile can be computed by multiplying the scour depths computed by the above equations by the appropriate shape coefficient in HEC-18.

The following information is needed to evaluate the scour using Sheppard's equations:

1. Sediment properties (median size, mass density),
2. Water properties (mass density and viscosity),
3. Design water depth and depth averaged flow velocity, and
4. Diameter of the structure (in the case of single piles) or the effective diameter in the case of complex structures (see paper in these proceedings by Jones and Sheppard).

CONCLUSIONS:

- Although the HEC-18 equation was derived from data that included wide piers by any definition, the subset of data for the wide piers does plot below the best fit to the data.
- At this point the most recognized wide pier adjustment in the US is the relationship derived by Johnson.
- Several equations in the literature use a hyperbolic tangent function to define a continuous function for wide to slender piers. Researchers in the Netherlands explained the benefit of this function for the wide pier problem during the 1999 scanning tour.
- Sheppard's pier scour equations include the hyperbolic tangent function for y/b as well as a sediment scale parameter, b/D_{50} that explains variations in scour measurements at incipient motion velocities. Predictions of prototype pier scour depths for piers as large as 10 m in width in water depths as large as 22 m using these equations are in good agreement with measured values. Current research by the authors is aimed at validating the live bed portion of the equations in the laboratory.

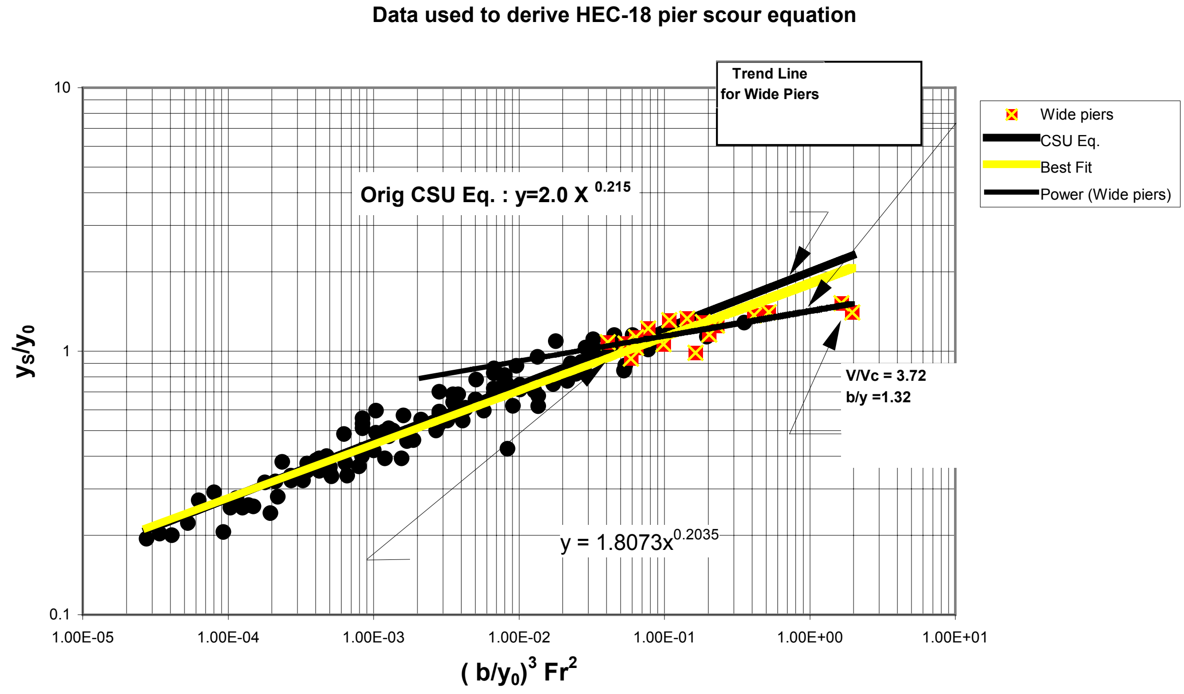

Figure 1. Data used to derive the CSU Equation in HEC-18.

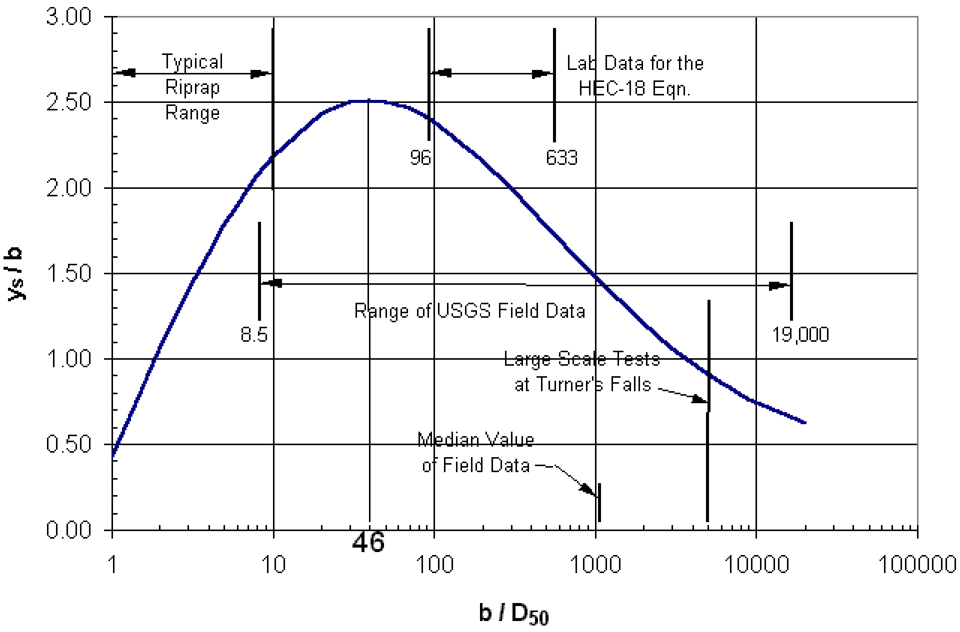

Figure 2. Dependence of normalized scour depth on $b/D_{50}$for a circular pier. For the curve shown $V_0/V_C = 1$, and $y_0/b > 2$.

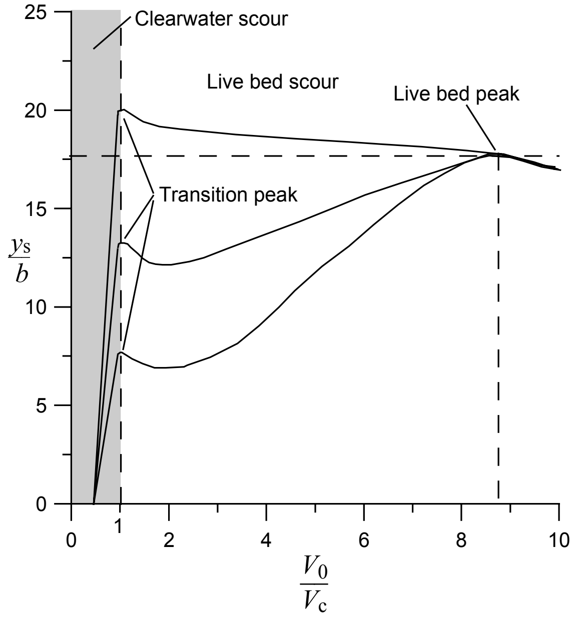

Figure 3. Dependence of normalized scour depth on velocity ratio and b/D_{50} for a circular pile. Each curve is for a different value of b/D_{50} and y_0/b is constant and greater than 2.

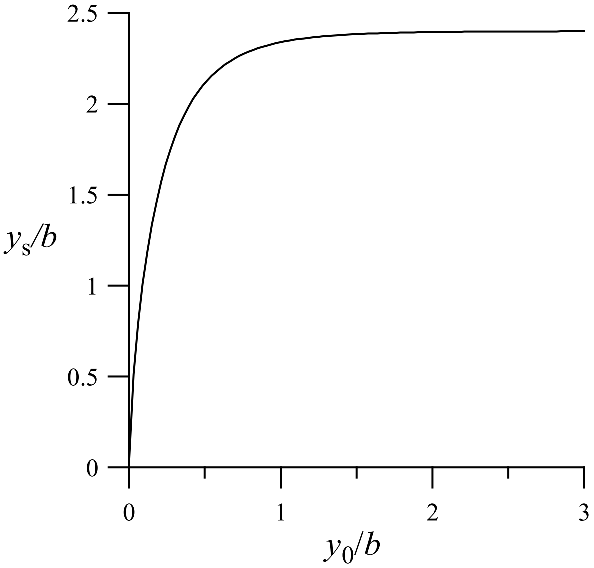

Figure 4. Dependence of normalized scour depth on the aspect ratio (water depth normalized by pier diameter for a circular pile. In this case $V_0/V_C = 1$ and $b/D_{50} = 46.4$.

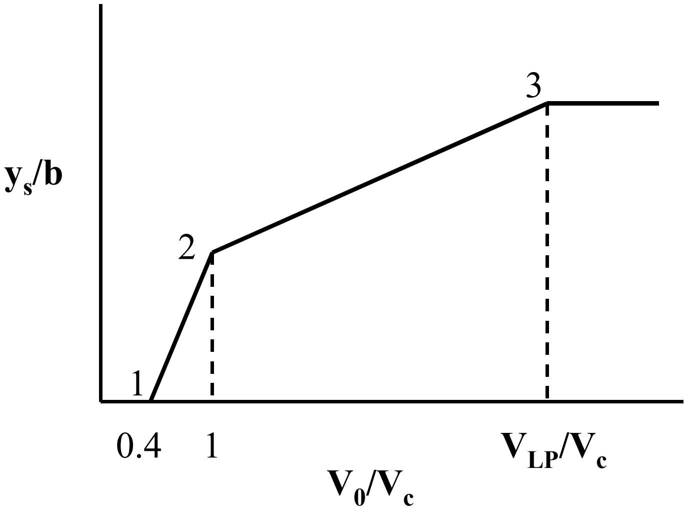

Figure 5. The plot of normalized scour depth versus velocity ratio presented in Figure 3 has been simplified for use in design in this figure. Sheppard's scour equations are the equations of the three straight lines in this figure.

References:

Chabert, J. and Engeldinger, P.(1956) "Etude des affouillements autour des pilesdes ponts," Laboratoire National d'Hydraulique, Chatou, France.

Ettema, R. (1980), "Scour At Bridge Piers", Dissertation, Department of Civil Engineering, University of Auckland, New Zealand.

Johnson, Peggy A.(1999), "Scour at Wide Piers Relative to Flow Depth," Stream Stability and Scour at Highway Bridges, Compendium of ASCE conference papers edited by E. V. Richardson and P. F. Lagasse, pp280 – 287,.

Landers, Mark N., and Mueller, David S.(1986), "Channel Scour at Bridges in the United States," Report No. FHWA-RD-95-184, August.

Richardson, E.V and S.R. Davis(1995), "Evaluating scour at Bridges," Hydraulic Engineering Circular No. 18 (HEC-18), Publication No. FHWA-IP-90-017, Third Edition, Federal Highway Administration, Washington, D.C.,.

Melville, B.W. and Sutherland, A.J.,(1988), "Design Method for Local Scour at Bridge Piers," American Society of Civil Engineers, Journal of the Hydraulic Division, Vol 114,No. 10, Oct. 1988.

Richardson, E.V., Simons, D.B., Karaki,S., Mahmood,K. and Stevens,M.A., (1975),"Highways in the River Environment Design Considerations" Training and Design Manual Prepared for the Federal Highway Administration, May 1975.

Shen, H.W., Schneider, V.R. and Karaki, S.S.(1966), "Mechanics of Local Scour, Data Supplement," Prepared for Bureau of Public Roads by the Civil Engineering Research Center, Colorado State Univ., Fort Collins, CO. June, 1966.

Sheppard, D. Max, Budianto Ontowirjo and Gang Zhao, (1999), "Local Scour Near Single Piles in Steady Currents,"Stream Stability and Scour At Highway Bridges, Compendium of Papers, ASCE Water Resources Engineering Conferences 1991 to 1998, Edited by E.V. Richardson and P.F. Lagasse.

Simons, D.B. and Richardson, E.V.(1966), "Resistance to Flow in Alluvial Channels," Geological Survey Prof. Paper 422-I, Washington, USA.

Snamenskaya, N.S.(1969),"Morphological Principles of Modeling of River Bed Process"International Association of Hydraulic Research, pp195-200.

van Rijn, Leo C., (1993), "Principles of Sediment Transportin Rivers, Estuaries and Coastal Seas", Aqua Publications, P.O. Box 9896, 1006 AN Amsterdam, The Netherlands.