Evaluation of Existing Equations for Local Scour at Bridge Piers

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Abstract: Twenty-three of the more recent and commonly used equilibrium local scour equations for cohesionless sediments were evaluated using compiled laboratory and field databases. This investigation assembled 569 laboratory and 928 field data. A method for assessing the quality of the data was developed and applied to the data set. This procedure reduced the laboratory and field data to 441 and 791 values, respectively. Because the maturity of the scour hole at the time of measurement for the field data was unknown, they were only used to evaluate underprediction by the equations. A preliminary quality control screening of the equilibrium scour methods/equations reduced the number of equations from the initial 23 to 17. For this screening procedure the equations were used to compute scour depths for a wide, but practical, range of structure, flow, and sediment parameters. Those methods/equations yielding unreasonable (negative or extremely large) scour depths were eliminated from further consideration. The remaining 17 methods/equations were then analyzed using both laboratory and field data. Plots of underprediction error versus total error for the laboratory data and underprediction error for field data versus total error for laboratory data along with error statistics calculations assisted in the ranking of the equations. Equations from previous publications were melded and slightly modified to provide the best performing equation in that it yields the least total error and close to the least underprediction error of those tested. The new equation is termed the Sheppard/Melville (S/M) equation in this paper. **DOI: 10.1061/(ASCE)HY.1943-7900.0000800.**

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Introduction

The research reported on in this paper was conducted under contract with the National Cooperative Highway Research Program (NCHRP 24-32) and reported in NCHRP Report 682.

A large number of equations have been proposed for estimating equilibrium local scour depths at bridge piers. A brief description of some of the more widely known equations is presented below.

The regime equations of Inglis (1949), Ahmad (1953), Chitale (1962), and Blench (1969) were derived from measurements in irrigation canals in India and are supposed to describe the conditions under which these canals are stable for the existing sediment supply. These equations can lead to negative estimates of local scour.

Laursen (1958, 1963) extended the solutions for the long rectangular contraction to local scour at piers. He used the observation that the depth of local scour does not depend on the contraction ratio until the scour holes from neighboring piers start to overlap. For sand, the width of the scour hole normal to the flow was observed to be about 2.75 times the scour depth ($2.75y_s$). Laursen (1958, 1963) assumed the scour in the contraction, defined by this width, to be a fraction of the scour depth at the pier or abutment. This lead to the Laursen (1958, 1963) equations for live-bed and clear-water scour, respectively.

The so-called Colorado State University (CSU) (or HEC-18) equation in the Federal Highway Administration (FHWA) Hydraulic Engineering Circular No. 18 (Arneson et al. 2012) was developed from a plot of laboratory data for circular piers. The data used were selected from Chabert and Engeldinger (1956) and Colorado State University data (Shen et al. 1966). These data were the same as those used by Shen et al. (1969) in the derivation of the Shen (1969) equation. The HEC-18 equation has been progressively modified over the years and is currently one of those recommended by FHWA for estimating equilibrium scour depths at simple piers (Arneson et al. 2012). The equation includes a multiplying factor, K_w, to be applied to wide piers in shallow flows. The factor was developed by Johnson and Torrico (1994) using laboratory and field data for large piers.

The equation presented by Gao et al. (1993) has been used by highway and railway engineers in China for more than 20 years. The equation was developed from Chinese data of local scour at bridge piers, including 137 live-bed data and 115 clear-water data. The equation was tested using field data obtained prior to 1964.

Several of the equations are based on field data, including the regime equations as discussed above and the relations by Froehlich (1988), Ansari and Qadar (1994), and Wilson (1995). Froehlich's equation was fitted to 83 on-site measurements from bridges in the United States and elsewhere. It includes a safety factor equal to one pier diameter.

Ansari and Qadar (1994) fitted envelope equations to more than 100 field measurements of pier scour depth derived from 12 different sources and several countries, including 40 measurements from India. Ansari and Qadar (1994) also presented a comparison of the field data they used with estimates of scour depth obtained using the equations by Larras (1963), Breusers (1965), Neill (1973),

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Breusers and Raudkivi (1991), and an equation by Melville and Sutherland (1988), which was the forerunner of the Melville (1997) equation.

The May and Willoughby (1990) equation was derived from a laboratory study of local scour around large obstructions, such as caissons and cofferdams used during the construction of bridges across rivers and estuaries. The study focused on cases where the width of the structure was large relative to the flow depth. May and Willoughby noted that existing design formulas tended to overestimate the amount of scour.

Melville (1997) presented a physically justified method to estimate local scour depth at piers based on extensive sets of laboratory data from the University of Auckland and elsewhere (Chabert and Engeldinger 1956; Laursen and Toch 1956; Jain and Fischer 1979; Chee 1982; Chiew 1984; Ettema 1980; Hancu 1971; Shen et al. 1966). The method uses a number of multiplying factors (K-factors) for the effects of the various parameters, which influence scour. The values of the K-factors were determined from envelope curves fitted to the data. The method is, therefore, inherently conservative. The method defines wide piers as those having large values of the ratio a/y_1 (>5), where a is pier width and y_1 is average depth in the upstream main channel.

A similar method is that given by Sheppard et al. (2004) and Sheppard and Miller (2006). The equations are based principally on laboratory data, as well as a few field measurements. The equations include the important observation that normalized local scour depths' dependence on a/D_{50} (where D_{50} is median grain diameter) increase to a value of a/D_{50} equal approximately to 40 where it begins to decrease. One possible explanation for this behavior was given by Sheppard (2004). This finding was also confirmed by laboratory measurements by Ettema et al. (2006) and Lee and Sturm (2009) as well as field measurements by the USGS (Lee and Sturm 2009). Tafarojnoruz (2012) showed that most of the decrease in normalized scour depth observed in Ettema et al. (2006) data can be explained by the Sheppard et al. (2004) method.

A number of local scour depth papers have been published using alternative techniques like artificial neural networks (ANN) (e.g., Bateni et al. 2007; Firat and Gungor 2009; Toth and Brandimarte 2011). These approaches, while having the capability of providing adequate predictions within the range of data on which they are based, are prone to overfitting. The standard practice of independent validation sets are a good way to check for overfitting. However, in most of the reported applications, the validation sets are not truly independent. In most studies, data from the same data set have been used for both training and validation, casting doubt on the independency claim. Overfitted models would perform poorly when used to extrapolate outside the range of data on which they were developed.

The only scour depth data for which there is confidence regarding the maturity of the scour hole at the time of measurement is that obtained in the laboratory where the conditions are controlled and time history measurements are made. This means that predictions of equilibrium scour depths at prototype structures using equations based on laboratory data require extrapolations that can be problematic for these approaches. Additionally, when these techniques are compared to existing scour equations and claim to perform better, the fact that most of the standard equations are design equations that are inherently conservative is ignored. For these reasons and the fact that their use usually requires obtaining the program from the developer, these methods were not considered in this study. The objective of this study is to evaluate recent and commonly used local scour depth prediction methods against reliable laboratory and field data for local scour at bridge piers.

Table 1. Equilibrium Local Scour Data Sources and Number of Scour Data Values (NCHRP Report 682, with Permission from the National Academy of Sciences)

	Number of data points	
Data source	Clear-water	Live-bed
Field data		
Zhuravljov (1978)	40	147
Froehlich (1988)	17	60
Gao et al. (1993)	119	133
Mueller and Wagner (2005)	171	241
Total field	347	581
Laboratory data		
Chabert and Engeldinger (1956)	87	6
Ettema (1976)	19	0
Shen et al. (1969)	2	21
Jain and Fischer (1979)	2	32
Ettema (1980)	90	7
Chiew (1984)	11	90
Chee (1982)	1	36
Yanmaz and Altinbilek (1991)	14	19
Graf (1995)	3	0
Dey et al. (1995)	18	0
Melville (1997)	17	0
Melville and Chiew (1999)	27	0
Ettema et al. (2006)	6	0
Coleman (unpublished)	6	0
Jones (unpublished)	15	2
Sheppard et al. (2004)	12	2
Sheppard and Miller (2006)	4	20
Total laboratory	334	235

Database

Relatively large quantities of equilibrium local scour data have been published (approximately 928 field and 569 laboratory data points). The sources and quantities of these data are listed in Table 1, and the range of the dimensionless groups more commonly used to characterize local scour covered by the compiled data sets are given in Table 2. The tables include only data where all the relevant parameters were known and the sediment is cohesionless; about 15 field data points were excluded due to missing information. In Table 2, a is the structure width, D_{50} is the median sediment grain diameter, V_1 is the depth-averaged velocity, V_c is the sediment critical depth-averaged velocity, and y_1 is the approach water depth.

Laboratory data are derived from experiments that were carefully performed with all pertinent parameters (flow speed and direction relative to the pier, sediment size and size distribution, and scour depths) given. There are, however, potential scale effects when using the laboratory results for prototype piers. Flow regimes are usually different between model and prototype resulting in differences in the relative magnitudes of the forces involved. This is particularly true for such complex mechanisms as sediment transport and scour.

Field studies have the advantage of little or no scale effects provided the structure size is approximately the size of interest.

Table 2. Range of Values of the Dimensionless Groups Covered by the Compiled Data Sets (NCHRP Report 682, with Permission from the National Academy of Sciences)

Data type	y_1/a	a/D_{50}	V_1/V_c	$V_1/(gy_1)^{0.5}$
Laboratory	0.05–21.05	3.65–4,159	0.40–5.99	0.07–1.50
Field	0.18–9.67	8.33–65,047	0.13–7.58	0.03–1.95

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However, the measurement accuracy for both independent (flow velocity and duration, sediment properties, and more) and the dependent (contraction and local scour depths) quantities is, in general, less than that for laboratory conditions. This is especially true for high-velocity flows where there are significant quantities of suspended sediment in the water column. In some of the reported cases the substructure shape and dimensions were not known (Zhuravljov 1978). Another important parameter that is usually missing in field data is the level of maturity of the scour hole at the time of measurement. These potential errors associated with field data were taken into consideration in testing the equilibrium scour equations by only using the field data as lower bounds for the predictions. That is, the predicted scour depths should always exceed the measured values, provided the reported values are correct.

The available laboratory and field equilibrium scour data are presented in matrix plots in Figs. 1–4. Each of the independent parameters are plotted against the other independent parameters, e.g., a or a^* (effective pier width) versus V_1, y_1 versus D_{50}; or V_1 versus y_1, a, D_{50}. The matrix plots are also given in dimensionless form in terms of the ratios a/y_1, V_1/V_c, and a/D_{50}. The histograms in the matrices provide an easy way to show the distribution of existing data and thus, where data gaps exist.

The vast majority of the laboratory data are for water depths less than 0.3 m with only a small number of tests conducted at depths beyond 0.6 m. There is a data gap for pier diameters between 0.3 m and 1 m. All of the high velocity (greater than 0.6 m/s) tests were performed with water depths less than or equal to 0.6 m. The sediment diameters for the laboratory data range from 0.1 to 7 mm, and only a few tests were conducted at water depths greater than 0.6 m.

A significant data gap exists in the available laboratory data in the a/D_{50} range $a/D_{50} > 1{,}800$. At present, the largest laboratory value for a/D_{50} is 4,159. The histogram in the lower right corner of Fig. 1 shows the distribution of a/D_{50} in the field data. In spite of these gaps, the equations that are based on the laboratory data that exists (values of a/D_{50} up to 4,160) predict scour depths equal to or greater than those reported for field situations where a/D_{50} has values as large as 6.5×10^4.

It was not possible to assess the quality of the data by using the descriptions of the experimental conditions mainly due to insufficient detailed information in the publications. All of Yanmaz and Altinbilek (1991) laboratory data were discarded due to the short durations of the tests (ranged from 4 to 6 h), which is significantly less than that required for the development of equilibrium scour depths.

The method developed and used to identify and eliminate outliers in the data sets is described next. First, the data were plotted in a 3D Euclidean space, with coordinates $\log(a/D_{50})$, V_1/V_c, and y_1/a, and then normalized using the variance of the data in each direction. The three-dimensional distance between data points was calculated and, for each data point, its four closest neighbors that were not from the same experimental data set were identified. For the five data points, the variance in measured scour depths and the variance in the distances from the point in question to its neighboring four points were determined. The ratio of these two variances,

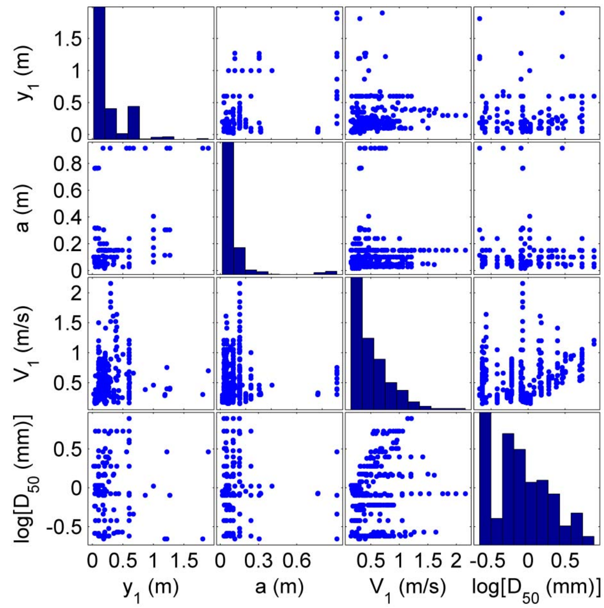

Fig. 2. Plots of dimensional laboratory local scour data

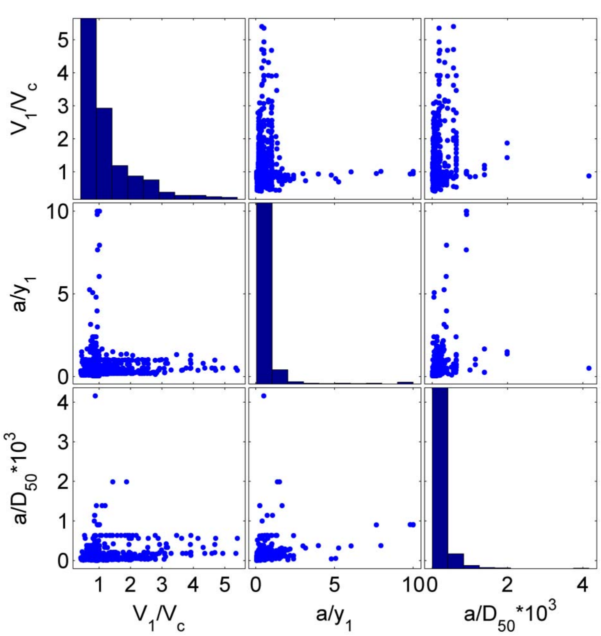

Fig. 1. Plots of dimensionless laboratory local scour data

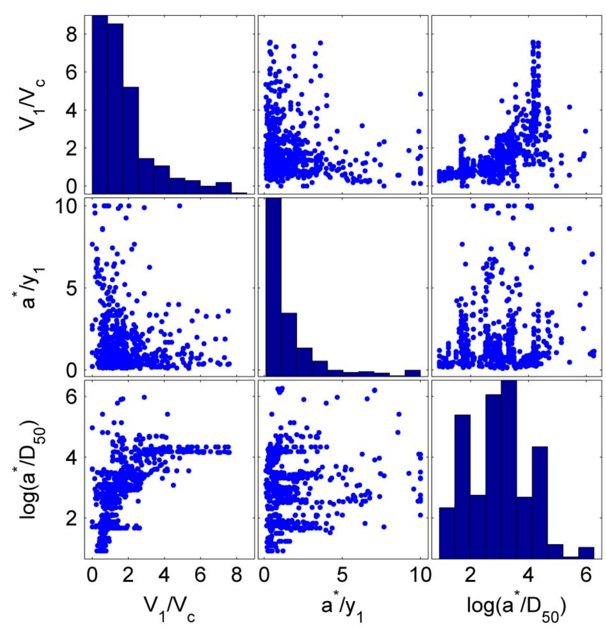

Fig. 3. Plots of dimensionless field local scour data

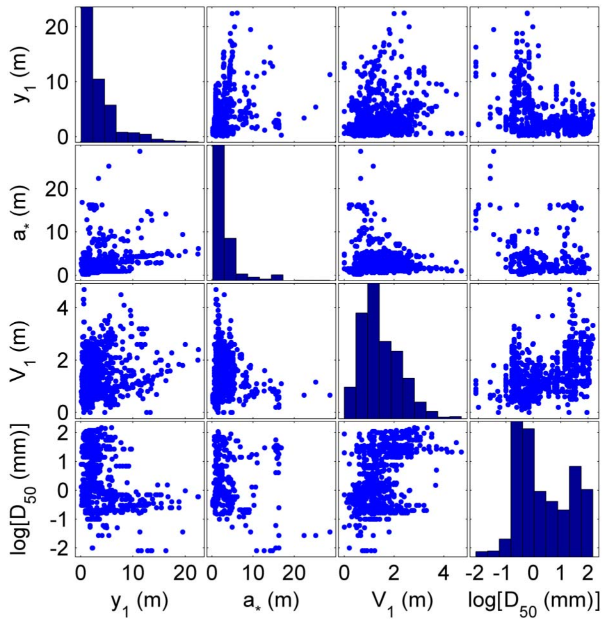

Fig. 4. Plots of dimensional field local scour data

termed the proximity parameter, was used as the criterion for exclusion of outliers in the dataset.

The laboratory data were analyzed following the above procedure, and the results are presented in Fig. 5. A cutoff value of 2.0 was selected. Most of the data points with a proximity parameter value greater than 2.0 had V_1/V_c values less than 0.8 and very large equilibrium scour depths. Many of the outliers were from one source, Chabert and Engeldinger (1956).

This methodology could not be used to determine outliers in the field data because it was not known if the measured scour depths were equilibrium values for the specified flow, sediment, and structure conditions. In some cases, where scour depths were measured at the same pier for different flow events, it appeared that the scour hole had not recovered from a previous, more severe, event at the time of the second measurement. For this reason, field scour depth measurements can be less or greater than the equilibrium depth for the conditions at the time of the measurement.

The Zhuravljov (1978) report included both laboratory and field data from several sources. Data from one field site (denoted as the Amu-Darya River data) appeared to have unusually large scour values for the reported structure, sediment, and flow conditions. A comparison of these data with data from Froehlich (1988) and Mueller and Wagner (2005) with similar values of a/D_{50} clearly showed an inconsistency in the measured scour depth values. The Mueller and Froehlich data have larger values of y_1/a than those from the Amu-Darya River site and therefore should have greater scour depths. The values of V_1/V_c were very large for all of these data so flow duration should not have been a problem, i.e., all of the scour depths should have been near equilibrium values. However, as can be seen in Fig. 6, the scour depth measurements from the Amu-Darya River site are much larger than those obtained by Mueller and Wagner (2005). It is very difficult to make accurate field measurements of flow speed and direction and scour depths during a high velocity flow event, even with today's sophisticated instrumentation. The Mueller and Wagner data were obtained during 1965 through 1998 (with 69% being obtained after 1988) using state-of-the-art instrumentation and methodology. They also made attempts to distinguish between local and other types of scour (i.e., degradation and contraction) by making measurements away from as well as at the piers. There is only one Froehlich (1988) data point in the range of variables of the Amu-Darya River data, and it is in agreement with the Mueller and Wagner data.

The dates and methods used to obtain the data in the Zhuravljov report (including the Amu-Darya River data) are not given. All of the data in this report were obtained prior to 1978 (most likely in the late 1960s and early 1970s). There is also no information available about the review process for the Zhuravljov report.

Of the conflicting datasets the Mueller and Wagner (2005) and Froehlich (1988) data were considered to be the more accurate and credible. For this reason, the Amu-Darya River data were eliminated from the field dataset.

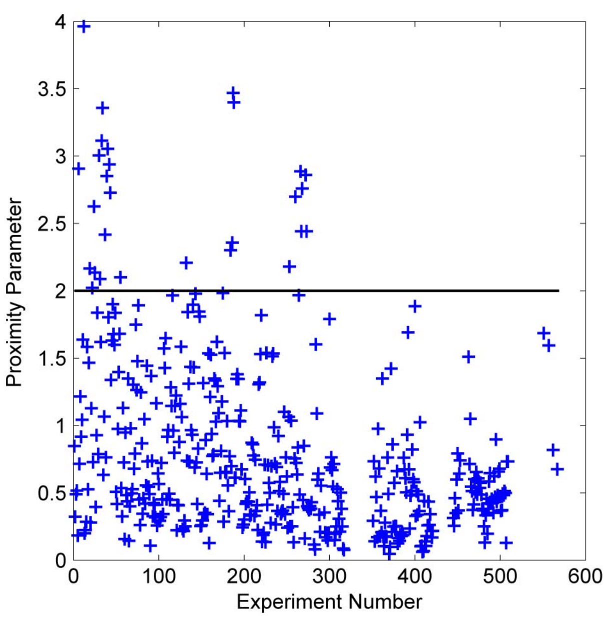

Fig. 5. Plot of the proximity parameter for all laboratory data (NCHRP Report 682, with permission from the National Academy of Sciences)

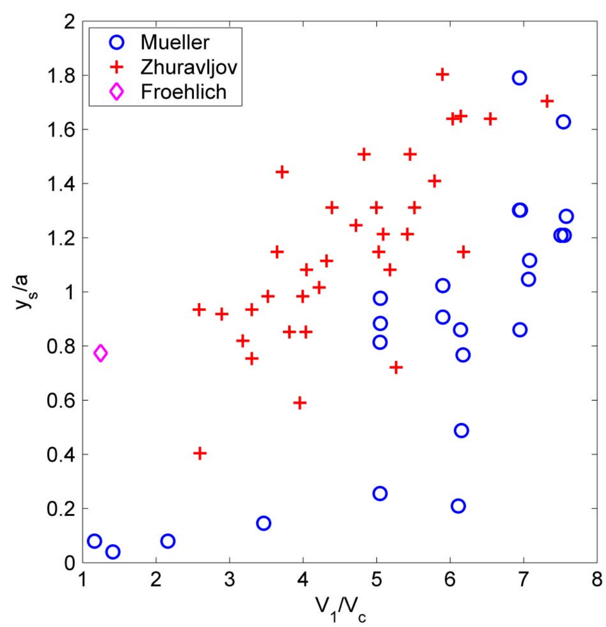

Fig. 6. Dimensionless field local scour depth data versus dimensionless velocity

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Table 3. Values of the Parameters Used in the Initial Screening of Equilibrium Scour Prediction Equations (NCHRP Report 682, with Permission from the National Academy of Sciences)

V_1/V_c	y_1/a	D_{50} (mm)	a (m)
1, 3	0.33, 1, 3	0.2, 3	0.05, 1, 10

Initial Screening of Scour Prediction Equations

Twenty-three equations were assembled for evaluation and assessment. The first screening procedure consisted of solving all of the equations for a range of input values and comparing their results. The input parameters used are given in Table 3. The two Laursen equations are appropriately treated as one method in the analysis.

The results from this evaluation are presented in the form of bar charts in Figs. 7 and 8. For these charts, $V_1/V_c = 3$, $y_1/a = 3$, and $D_{50} = 0.2$ mm and 3 mm, respectively. Negative scour depth predictions were set equal to zero in the charts. The computations are for $a = 50$ mm (laboratory scale), and prototype pier widths of 1 m (typical field) and 10 m (very large field). Thus, the charts cover a wide range of pier sizes.

The equations used in producing the results shown in the charts span the period from 1949 to 2006 in their development and publication. Improvements in the understanding of local scour processes and scour hole development during this time period resulted in improvements to the predictive equations/methods. For example, several of the earlier equations predicted negative scour depths for some of the input conditions. Also, the differences between the predictions become less with time.

Variations in the predictions of local scour for different pier sizes (laboratory to typical field to very large field) are reported. Some methods predict scour depth ratios decreasing with increasing pier size; others show constant values of scour depth ratio from laboratory to field, with one equation by Coleman (1971) showing larger normalized scour depths in the field than in the laboratory.

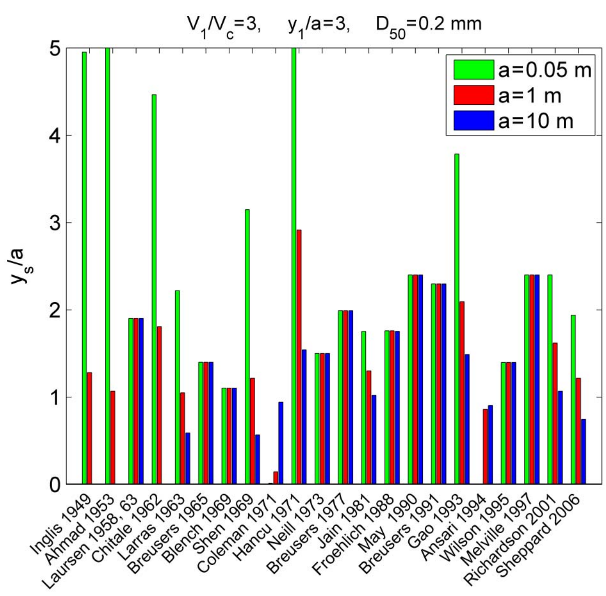

Fig. 7. Comparison of normalized local scour depth predictions using 22 different equations/methods for a particular live-bed scour condition (deep water relative to pier width and fine sand)

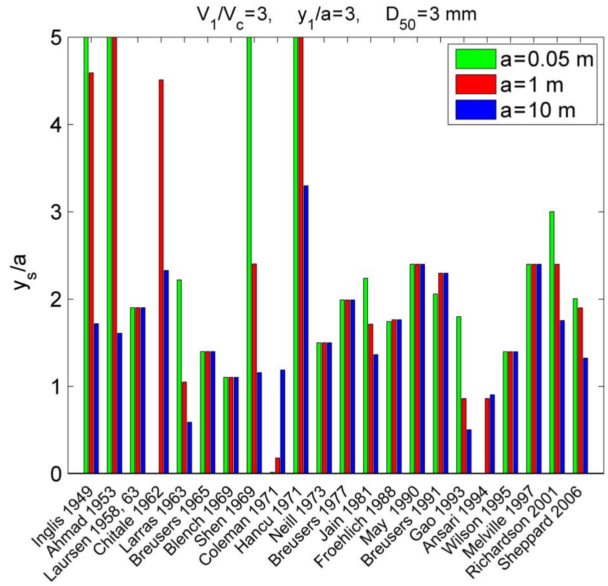

Fig. 8. Comparison of normalized local scour depth predictions using 22 different equations/methods for a particular live-bed scour condition (deep water relative to pier width and very coarse sand)

These plots help identify those equations that produce unrealistic results for prototype scale piers and thus eliminate them from further consideration. The regime equations of Inglis (1949), Ahmad (1953), and Chitale (1962) yield negative scour depths in some cases. The Coleman (1971) equation yields an unrealistic trend with increasing pier size and therefore was eliminated. Several other equations predict unreasonably high normalized scour depths (Inglis 1949; Ahmad 1953; Chitale 1962; Hancu 1971; Shen 1969) and were also eliminated. This left 17 methods/equations for the final analysis.

Due to space limitations it is not practical to present all of the equations analyzed in this study in this paper. The reader is referred to Sheppard et al. (2011) for the complete list and description of equations analyzed. During the course of this investigation it became apparent that a melding of the equations due to Sheppard and Melville would produce better results and be easier to evaluate. The resulting equation is referred to here as the Sheppard/Melville equations or simply the S/M equations. As the study results show, this equation performed best of the equations tested and is recommended by the authors for use in predicting equilibrium local scour depths. These equations are presented below.

Sheppard/Melville (S/M) Equation

Notably, a number of researchers have found that the dimensionless groups (y_1/a^*), (V_1/V_c), and (a^*/D_{50}) are useful for describing the physics of local scour processes (e.g., Sheppard et al. 2004; Sheppard and Miller 2006; Melville 1997; Melville and Sutherland 1988; Ettema et al. 2006; Lee and Sturm 2009. The Sheppard and Miller (2006) and Melville (1997) equations were melded and slightly modified to form a new equation referred to here as the S/M equation. Note that armoring of the scour hole resulting from sediment gradation is not accounted for in these equations. Therefore for situations where the gradation is large, the predictions will be conservative. The resulting equation for normalized scour depth, y_s/a^* is

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$$\frac{y_s}{a^*} = 2.5 f_1 f_2 f_3 \quad \text{for } 0.4 \le \frac{V_1}{V_c} < 1.0 \tag{1}$$

$$\frac{y_s}{a^*} = f_1 \left[2.2 \left(\frac{\frac{V_1}{V_c} - 1}{\frac{V_{1p}}{V_c} - 1} \right) + 2.5 f_3 \left(\frac{\frac{V_{1p}}{V_c} - \frac{V_1}{V_c}}{\frac{V_{1p}}{V_c} - 1} \right) \right] \quad \text{for } 1.0 \le \frac{V_1}{V_c} \le \frac{V_{1p}}{V_c} \tag{2}$$

$$\frac{y_s}{a^*} = 2.2 f_1 \quad \text{for } \frac{V_1}{V_c} > \frac{V_{1p}}{V_c} \tag{3}$$

$$f_1 = \tanh\left[\left(\frac{y_1}{a^*} \right)^{0.4} \right] \tag{4}$$

$$f_2 = \left\{ 1 - 1.2 \left[\ln\left(\frac{V_1}{V_c} \right) \right]^2 \right\} \tag{5}$$

$$f_3 = \left[\frac{\left(\frac{a^*}{D_{50}}\right)}{0.4\left(\frac{a^*}{D_{50}}\right)^{1.2} + 10.6\left(\frac{a^*}{D_{50}}\right)^{-0.13}} \right] \tag{6}$$

$$V_{1p1} = 5 V_c \tag{7}$$

$$V_{1p2} = 0.6\sqrt{g y_1} \tag{8}$$

$$V_{1p} = \begin{cases} V_{1p1} & \text{for } V_{1p1} \ge V_{1p2} \\ V_{1p2} & \text{for } V_{1p2} < V_{1p1} \end{cases} \tag{9}$$

where a^* = effective diameter of the pier = $K_s a_p$; K_s = shape factor; and a_p = projected width of the pier. For circular piers, $K_s = 1$, while for rectangular piers

$$K_s = 0.86 + 0.97\left(\left| \alpha - \frac{\pi}{4} \right| \right)^4 \tag{10}$$

where α = flow skew angle in radians.

Eq. (10) is a curve fit to laboratory equilibrium scour data from experiments with square piles.

The limited data that are available for equilibrium scour depths for very high velocity flows indicate that a maximum scour depth is reached when the velocity is such that the bed planes out and bed forms disappear. This velocity is referred to here as the live-bed peak velocity, V_{lp}. These conditions are associated with hydraulically critical flow ($V/\sqrt{g y_1} \approx 1$).

The sediment critical velocity, V_c, can be estimated from Shields (1936) diagram, using Eqs. (11)–(14)

$$u^* = \left(16.2 D_{50} \left\{ \frac{9.09 \times 10^{-6}}{D_{50}} - D_{50}[38.76 + 9.6 \ln(D_{50})] - 0.005 \right\} \right)^{1/2} \tag{11}$$

$$\mathsf{R} = \frac{u^* D_{50}}{2.32 \times 10^{-7}} \quad \text{for } 5 \le \mathsf{R} \le 70 \tag{12}$$

$$V_c = 2.5 u^* \ln\left(\frac{73.5 y_1}{D_{50}\{\mathsf{R}[2.85 - 0.58 \ln(\mathsf{R}) + 0.002\mathsf{R}] + \frac{111}{\mathsf{R}} - 6\}} \right)$$

for $\mathsf{R} > 70$ (13)

$$V_c = 2.5 u^* \ln\left(\frac{2.21 y_1}{D_{50}} \right) \tag{14}$$

Evaluation of Equilibrium Scour Predictive Equations

Evaluating predictive equations using laboratory data is relatively straightforward since, in most cases in the database, the scour has either reached equilibrium or the measured depth has been extrapolated to an equilibrium value. In addition, the input values (water depth, flow velocity, and sediment properties) are all accurately known. It is much more difficult to obtain accurate measurements of the input parameters in the field, and the maturity of the scour hole is almost never known. A number of the scour depths in the field data set are extremely small for the pier size, water depth, and flow velocity. This suggests that the duration of the flow at the reported velocity was short or that the bed material, reported as cohesionless, was cohesive or perhaps both. With the uncertainty associated with even the most reliable field data, it is not appropriate to use it directly to evaluate the predictive equations. However, with only a few exceptions, the predicted values should not be less than the measured values, assuming the measured values are accurate and do not include other types of scour (e.g., contraction or degradation). One exception is the case where the measured scour depth was due to a previous, more severe flow event.

The errors associated with predicting the measured equilibrium scour depths were computed using the following equation for dimensional scour depths, y_s:

$$\text{SSE\%} = \frac{\sum\left(y_s^{\text{measured}} - y_s^{\text{computed}}\right)^2}{\sum\left(y_s^{\text{measured}}\right)^2} \times 100 \tag{15}$$

where SSE = sum of the squares of the error.

The corresponding equation for normalized scour depths, y_s/a, is

$$\text{SSEn\%} = \frac{\sum\left(\frac{y_s^{\text{measured}}}{a} - \frac{y_s^{\text{computed}}}{a}\right)^2}{\sum\left(\frac{y_s^{\text{measured}}}{a}\right)^2} \times 100 \tag{16}$$

where SSEn = sum of the squares of the normalized error.

The best performing method/equation is the one that has the least overall error and least underprediction. Since these equations are being recommended for design, underprediction errors must be weighted heavier. That is, greater emphasis must be given to reducing underprediction than to total error.

Figs. 9–12 and Table 4 give percent errors (SSE and SSEn) for the laboratory and field data sets. Underpredictions are much smaller compared to the total error for all predictive equations since they are all conservative by design. For the reasons discussed above, total errors for the field data are not presented since the maturity of these data are not known. The fact that all the equilibrium scour equations overpredict many of the measured depths, especially for the larger structures, indicates the need to account for the design flow event duration in the prediction. Unfortunately, even the best scour evolution equations are not sufficiently accurate for this task at this time. Large scale, live-bed scour evolution tests and the development of improved predictive scour evolution equations are definitely needed.

The error statistics confirm the screening process in that the equations eliminated are the ones with the greatest errors. For the values given in Table 4, Table 5 gives the ordering of the equations. There are also two columns for overall order for field and lab

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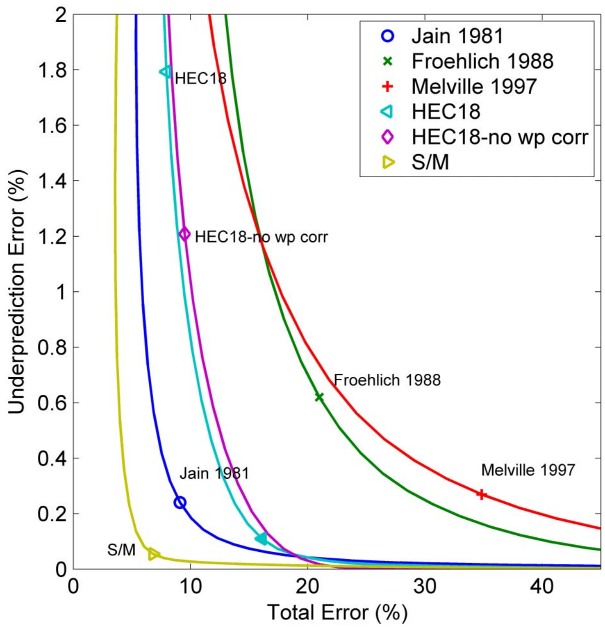

Fig. 9. Underprediction error of dimensional local scour depth versus total error for laboratory data

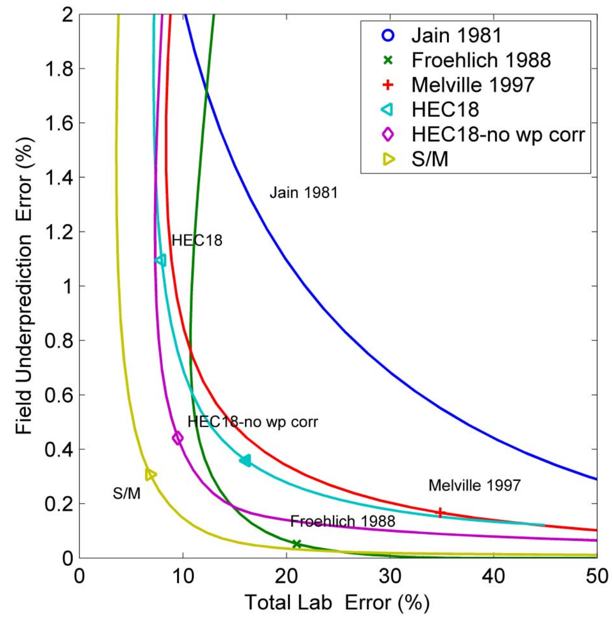

Fig. 11. Underprediction error of dimensional local scour depth for field data versus total error for laboratory data

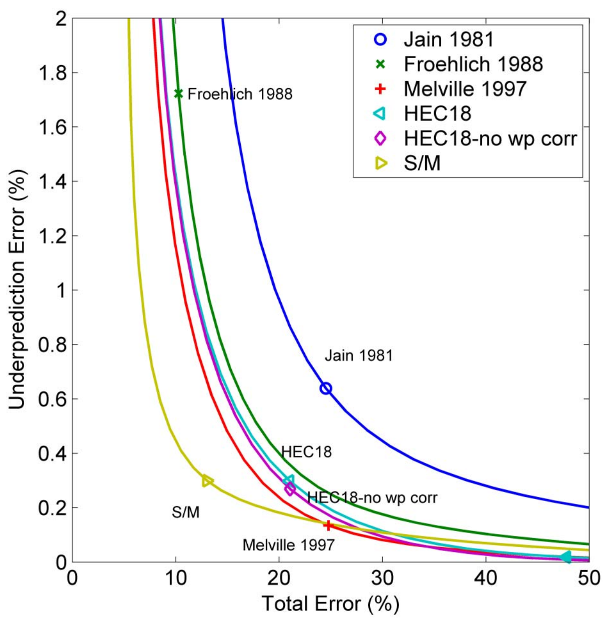

Fig. 10. Underprediction error of dimensionless local scour depth versus total error for laboratory data

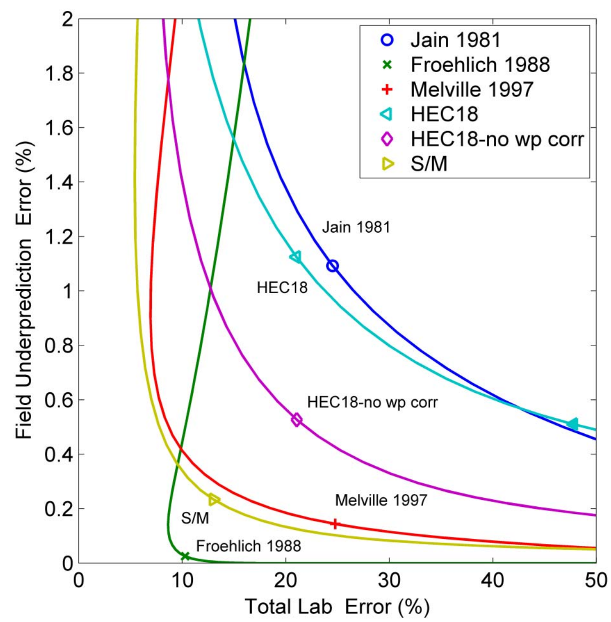

Fig. 12. Underprediction error of dimensionless local scour depth for field data versus total error for laboratory data

data. Each overall order was calculated by averaging the columns to its left and ordering the results. Field data errors are not very informative by themselves since they do not include total errors. Total errors for the field data are also not meaningful due to so many of the reported scour depths not being equilibrium values. Note that an equation that grossly overpredicts can have small underprediction errors.

Six equations were chosen for final evaluation based on their performances listed in Tables 4 and 5. These are Jain (1981), Froehlich (1988), Melville (1997), HEC-18, HEC-18 without wide pier correction and S/M. Both forms of HEC-18 are presented since they are currently widely used in the United States.

Figs. 9–12 show underprediction error versus total error for the six selected methods. These plots show the performance of the different methods and how their errors can be modified by multiplying the resulting scour depth by a constant. The symbols not only identify the method but the location on the curve for a multiplicative constant equal to 1.0 as well. Changing the constant to reduce the error in Fig. 9 increases the error in Fig. 10. For example, if the HEC-18 equation is multiplied by 1.2, its symbol moves from that shown with the open triangle to that with the closed triangle in both figures. Note that even though there is improved performance for the dimensional scour (Fig. 9), the normalized scour performance is significantly reduced (Fig. 10).

Table 4. Absolute and Normalized Errors for Equilibrium Local Scour Prediction Equations (NCHRP Report 682, with Permission from the National Academy of Sciences)

	Lab (441 points)				Field (760 points)	
	SSE (%)		SSEn (%)		SSE (%)	SSEn (%)
Data source	Total	Under	Total	Under	Under	Under
Inglis (1949)	77.0	30.1	297.0	57.3	32.7	106.1
Ahmad (1953)	167.7	56.2	957.1	19.8	70.3	127.8
Laursen (1958, 1963)	24.0	21.4	24.3	12.6	4.1	7.2
Chitale (1962)	123.3	31.1	921.1	19.2	25.8	67.1
Larras (1963)	21.1	1.8	27.2	0.5	8.0	4.2
Breusers (1965)	31.0	1.8	10.9	5.7	0.2	0.2
Blench (1969)	18.6	18.3	60.6	60.0	5.7	7.8
Shen et al. (1969)	19.1	6.4	55.5	0.9	3.0	1.9
Coleman (1971)	87.2	87.2	97.7	97.7	25.2	49.8
Hancu (1971)	130.2	20.8	250.9	7.7	3.1	6.6
Neill (1973)	38.7	1.2	11.1	4.0	0.1	0.1
Breusers (1977)	18.9	13.0	12.5	6.2	4.9	7.2
Jain (1981)	9.1	0.2	24.5	0.6	2.2	1.1
Froehlich (1988)	21.0	0.6	10.3	1.7	0.0	0.0
May and Willoughby (1990)	17.9	6.5	18.4	2.6	4.1	6.2
Gao et al. (1993)	75.7	16.2	158.5	8.1	7.4	12.9
Ansari and Qadar (1994)	52.9	52.5	97.8	97.8	0.6	12.0
Wilson (1995)	9.1	6.9	15.6	5.3	2.8	1.9
Melville (1997)	34.9	0.3	24.8	0.1	0.2	0.1
HEC-18	7.9	1.8	21.0	0.3	1.1	1.1
Sheppard and Miller (2006)	6.8	0.1	13.0	0.3	0.3	0.2
S/M	6.8	0.1	13.0	0.3	0.3	0.2

Table 5. Ranking of All Equilibrium Local Scour Prediction Equations (NCHRP Report 682, with Permission from the National Academy of Sciences)

	Lab (441 points)					Field (760 points)		
	SSE		SSEn			SSE	SSEn	
Data source	Total	Under	Total	Under	Overall	Under	Under	Overall
Inglis (1949)	20	20	22	21	20	23	23	23
Ahmad (1953)	24	23	24	20	24	24	24	24
Laursen (1958, 1963)	13	19	11	18	16	15	17	16
Chitale (1962)	22	21	23	19	22	22	22	22
Larras (1963)	12	9	15	7	13	20	13	17
Breusers (1965)	14	11	2	14	12	5	5	5
Blench (1969)	8	17	17	22	17	18	18	19
Shen et al. (1969)	10	12	16	9	15	13	12	12
Coleman (1971)	21	24	18	23	23	21	21	21
Hancu (1971)	23	18	21	16	19	14	15	14
Neill (1973)	17	7	3	12	10	2	2	2
Breusers (1977)	9	15	4	15	14	17	16	18
Jain (1981)	5	4	12	8	6	11	9	9
Froehlich (1988)	11	6	1	10	5	1	1	1
May and Willoughby (1990)	7	13	8	11	11	16	14	15
Gao et al. (1993)	19	16	20	17	18	19	20	20
Ansari and Qadar (1994)	18	22	19	24	21	9	19	13
Wilson (1995)	4	14	7	13	9	12	11	11
Melville (1997)	15	5	13	2	8	4	4	4
HEC-18	3	10	9	4	3	10	10	10
Sheppard and Miller (2006)	1	1	5	5	1	6	6	6
S/M	2	2	6	6	2	7	7	7

Based on this analysis, the best-performing equation and the one that attempts to account for the most important local scour mechanisms is the S/M equation. To illustrate this equation's dependence on the various dimensionless groups, three plots are presented in Fig. 13. The top, center and bottom plots show how the normalized equilibrium scour depth varies with y_1/a^*, V_1/V_c, and a^*/D_{50}, respectively, while holding the other two ratios constant. As an example, consider the case where the equilibrium local scour depth for a 2-m diameter circular pile founded in sediment with a median diameter of 2 mm, located in a water depth of 6 m and subjected to a steady flow velocity of 2 m/s is desired. For this situation $V_c = 0.79$ m/s, $y_1/a^* = 3$, $V/V_c = 2.35$, and $f_3 = 1,000$. The predicted equilibrium scour depth, y_s, is 3.2 m.

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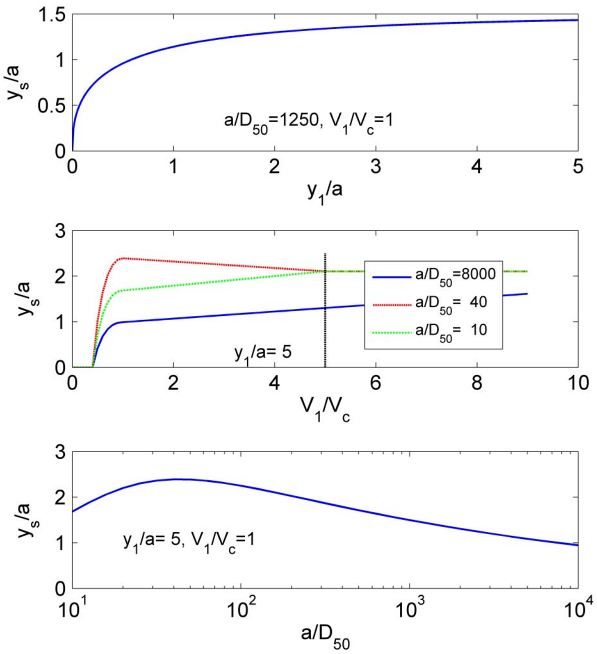

Fig. 13. Illustration of the S/M normalized local scour depth equation's dependence on y_1/a, V_1/V_c, and a/D_{50}

Conclusions

This study compiled perhaps the most comprehensive laboratory and field equilibrium local scour data set to date. These data were used to evaluate 23 predictive equilibrium local scour depth equations/methods intended for use with structures with simple shapes founded in cohesionless sediments. Quality-control screening methods were developed and applied to both the data and the equations. This resulted in 441 laboratory and 791 field data and 17 predictive equations/methods. The predictive methods were found to improve in accuracy over the years with those developed in recent years demonstrating the best performance. The Sheppard/Melville (S/M) method was found to be the most accurate of those tested and is recommended for use in design.

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Notation

The following symbols are used in this paper:

a = pier width (L);
a_p = projected pier width (L);
a^* = effective pier width (L);
D_{50} = median grain size (L);
g = acceleration of gravity (L/T^2);
K_s = pier shape factor (−);
K_w = wide pier correction factor (−);
u^* = friction velocity = $\sqrt{\tau_0/\rho}$ (L/T);
V_1 = average velocity in upstream main channel (L/T);
V_c = sediment critical velocity for D_{50} (L/T);
V_{lp1} = velocity used in computing live-bed peak velocity (L/T);
V_{lp2} = velocity used in computing live-bed peak velocity (L/T);
y_s = equilibrium scour depth (L);
y_1 = average depth in the upstream main channel (L);
α = flow skew angle (radians);
ρ = mass density of water (FT^2/L^4); and
τ_0 = bed shear stress (F/L^2).

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