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REPORT 682

Scour at Wide Piers and Long Skewed Piers

TRANSPORTATION RESEARCH BOARD
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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

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Scour at Wide Piers and Long Skewed Piers

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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

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Dr. D. Max Sheppard, President of OEA, is the Principal Investigator. Co-investigators on the project were Dr. Bruce Melville, Professor and Chair of the Civil and Environmental Engineering Department at the University of Auckland in Auckland, New Zealand, and Dr. Huseyin Demir, Hydraulics and Coastal Engineer with OEA, Inc. The authors thank the NCHRP Project 24-32 panel for their helpful questions, comments, and suggestions and the many researchers and practitioners for their contributions to this study.

FOREWORD

By Amir N. Hanna
Staff Officer
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This report presents recommendations for (1) a predictive equation for equilibrium local scour and (2) a potential equation for predicting scour evolution rates at wide piers and skewed piers. These equations provide better estimates of local scour and scour evolution rates than those predicted by currently available equations. Such estimates will reduce overpredictions and the unwarranted need for countermeasures. The material contained in the report should be of immediate interest to state hydraulic engineers and others involved in the design, operation, and maintenance of highway bridges.

Current methods for predicting local scour at bridge piers, including those described in *Hydraulic Engineering Circular No. 18* (Publication No. FHWA NHI 01-001, "Evaluating Scour at Bridges"), were developed on the basis of small-scale laboratory studies with limited consideration of the factors relevant to wide piers and long skewed piers. Because of these limitations, the current methods generally overpredict local scour at such piers, leading to the use of unwarranted and costly foundations or countermeasures. Therefore, research was needed to evaluate current methods for predicting local pier scour and their applicability to wide piers and long skewed piers and to develop improved methods for use by highway agencies in the design, operation, and maintenance of highway bridges.

Under NCHRP Project 24-32, "Scour at Wide Piers and Long Skewed Piers," Ocean Engineering Associates, Inc. of Gainesville, Florida, worked with the objectives of developing methods and procedures for predicting time-dependent local scour at wide piers and at long skewed piers. The research was limited to noncohesive soils and steady flow.

The research included a review of the existing laboratory and field data and predictive methods relevant to time-dependent and equilibrium local scour around piers. As part of this review, methods/equations that appeared applicable for predicting time-dependent local scour at wide piers and at long skewed piers were identified and subjected to an initial screening. This screening included an assessment of the laboratory and field data that were used in developing these methods/equations and the practicality of predictions. The methods/equations that were found to be relevant to this research were identified for further analysis; others were excluded from further consideration. Following further analysis, the research recommended modified forms of existing equations for use in predicting equilibrium local scour and scour evolution rates at wide and skewed piers as well as at piers of other widths. Using the recommended methods/equations will reduce local scour overpredictions that are often obtained using currently available equations and thus reduce unwarranted need for costly countermeasures.

Appendixes A through E contained in the research agency's final report provide further elaboration on the work performed in this project. These appendixes are not published herein; they are available on the *NCHRP Report 682* summary web page at http://www.trb.org/Main/Blurbs/164161.aspx.

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Note: Many of the photographs, figures, and tables in this report have been converted from color to grayscale for printing. The electronic version of the report (posted on the web at www.trb.org) retains the color versions.

SUMMARY

Scour at Wide Piers and Long Skewed Piers

Current methods for predicting local scour at bridge piers, including those described in Federal Highway Administration (FHWA) Hydraulic Engineering Circular No. 18 (Richardson and Davis 2001), were developed on the basis of small-scale laboratory studies and do not consider factors relevant to wide piers and long piers that are skewed to the flow. Because of these limitations, the current methods generally overpredict local scour at such piers, leading to the use of unwarranted and costly foundations or countermeasures. Research was needed to evaluate current methods for predicting local pier scour and their applicability to wide piers and long skewed piers and to develop improved methods for highway agencies to use in the design, operation, and maintenance of highway bridges.

The objective of this research, conducted under National Cooperative Highway Research Program (NCHRP) Project 24-32, was to develop methods and procedures for predicting time-dependent local scour at wide piers and at long skewed piers that are suitable for consideration and adoption by American Association of State Highway and Transportation Officials (AASHTO). The research was limited to noncohesive soils and steady flow.

This objective was accomplished by (1) conducting an extensive literature and information search that included emailing questionnaires to 176 researchers, federal and state department of transportation (DOT) engineers, and practicing engineers; (2) identifying and acquiring published predictive equations/methods and pertinent laboratory and field data for testing the equations/methods; (3) developing methods for evaluating the equations and data; and (4) modifying and evaluating the equations using the compiled laboratory and field database. For the purpose of this study, "wide pier" was defined as piers equal to or greater than 10 ft in width and having a pier width to sediment diameter ratio greater than 100. Thirty-seven responses to the questionnaire were received.

The literature search revealed that there is very little information (predictive equations and data) explicitly on scour at wide piers and long skewed piers. However, the predictive equations in the literature are intended to apply equally well to large as well as small piers. For this reason all local scour equations located by the information search were considered in this study. Twenty-three of the more recent and commonly used equilibrium local scour equations were identified and assembled. As part of the initial screening process, the scour depths predicted by these equations for a wide range of laboratory and field conditions were compared. Six of the equations yielded unrealistic (extremely large or negative) results and were eliminated, leaving seventeen equations for further analysis in this project. The data search resulted in a significant quantity of both laboratory and field equilibrium scour data. However, only a portion of these data was relevant to this study.

Researchers have devoted less effort to the understanding and prediction of local scour evolution rates than to equilibrium scour depths. Only 10 scour evolution methods/equations

were located and obtained. These equations/methods were evaluated for a range of hypothetical laboratory and field conditions for the purpose of identifying those that produce unrealistic results. This exercise showed significant differences between the methods; four methods were eliminated from further consideration.

A total of 195 laboratory local scour evolution data sets were located and obtained. All of these data are for single, simple shaped piers founded in cohesionless sediments and subjected to constant-in-time flow velocities. Only one completed local scour field study, where scour evolution rates and the associated flow parameters were measured, was obtained. The structure was a small, 2 ft square pile located on the seaward end of a bent on a bridge over a tidal inlet on the northern Gulf Coast of Florida.

The predictive equations/methods were tested using both laboratory and field data. Because the maturity of the scour hole at the time of measurement for the field data was unknown, the field data were only used to evaluate underprediction by the equations. If the measured scour depth was that produced by the measured flow (and not from a previous, more severe event), the predicted depths should be greater than the measured values. There is little information regarding the measurement and data reduction techniques (e.g., how local scour was distinguished from the other forms of scour, how the measurements were made, etc.) for two of the data sets (Zhuravlyov 1978 and Gao et al. 1993). The Zhuravlyov report contains both laboratory and field data from several sources but without any information regarding methods used to obtain the data. Field data from one of the sources were eliminated as being inconsistent with data for similar conditions from other sources that document instrumentation and data acquisition information.

After the initial evaluation of both the equilibrium scour and scour evolution equations, improvements were made to the best-performing equations/methods. A melding of Sheppard and Miller's (2006) and Melville's (1997) equilibrium equations resulted in the single best-performing equation, referred to here as the Sheppard/Melville or S/M equation.

Melville and Chiew's (1999) scour evolution equation, which contains an expression for equilibrium scour depth, was modified by adjusting some of the coefficients and replacing the equilibrium scour term with the S/M equation. This equation, referred to here as the Melville/Sheppard or M/S equation, proved to be the best-performing scour evolution equation with the laboratory data. No scour evolution field data for steady (or quasi-steady) flows was located in the data search.

Findings

This research produced (1) comprehensive equilibrium scour and scour evolution quality-controlled laboratory and field databases, (2) a compilation of predictive equations for equilibrium local scour depth and scour evolution rates, (3) an evaluation of the accuracy of the equations and the data in the databases, (4) an evaluation of the methods used to account for the effect of flow skew angle on local scour depth, (5) a recommended equation for equilibrium scour prediction, (6) a best-performing equation for scour evolution prediction, and (7) a list of data gaps and recommendations for future local scour research.

Conclusions

The ability to predict equilibrium scour depths at structures of relatively simple geometry is relatively good. There are, however, practical conditions where little or no laboratory data exist. In particular, experiments with large structures founded in relatively fine sand and subjected to high-velocity, live-bed flows are needed. More research and data are needed to improve the accuracy of scour evolution predictions. In addition, equilibrium scour and scour evolution data are needed (1) for long skewed piers subjected to a range of water depths, flow velocities, and sediment sizes; (2) to better determine the effects of sediment gradation on equilibrium scour and scour evolution rates; (3) for local scour at low-velocity flows; and (4) for local scour with unsteady flows.

Recommended Predictive Equations

This study has produced recommendations for predicting (1) equilibrium local scour depths at piers with simple geometries of all widths, (2) the effect of flow skew angle on equilibrium scour depth, and (3) scour evolution rates at structures with simple geometries.

This information in conjunction with the methods described in the Florida DOT Scour Manual (Sheppard and Renna 2005) can be used for estimating local scour depths at piers with more complex geometries.

The recommended equilibrium local scour equation resulting from this study is a melding of equations developed by Sheppard and Miller (2006) and Melville (1997). This equation, which performed best of those tested with both laboratory and field data, contains parameters that account for the primary scour mechanisms.

The best-performing scour evolution equation is a modification and combination of previous works by Melville and Chiew (1999) and Sheppard and Miller (2006). However, the data used in the development and testing of this equation in the live-bed scour range are limited to experiments with small laboratory structures and, therefore, the predicted scour evolution rates may not be appropriate for use in the development of design scour depths at this time. The recommended equilibrium scour depth equation, the best-performing scour evolution equation, and the method to account for flow skew angle are presented in this report.

CHAPTER 1

Introduction

Background

Current methods for predicting local scour at bridge piers, including those described in Hydraulic Engineering Circular No. 18 (HEC-18; Richardson and Davis 2001), were developed on the basis of small-scale laboratory studies and do not consider factors relevant to wide piers and long piers that are skewed to the flow. Because of these limitations, the current methods generally overpredict local scour at such piers, leading to the use of unwarranted and costly foundations or countermeasures. Research was needed to evaluate current methods for predicting local pier scour and their applicability to wide piers and long skewed piers and to develop improved methods for highway agencies to use in the design, operation, and maintenance of highway bridges. NCHRP Project 24-32 was initiated to address this need.

Objectives

The objective of this research was to develop methods and procedures for predicting time-dependent local scour at wide piers and at long skewed piers that are suitable for consideration and adoption by the AASHTO. The research was limited to noncohesive soils and steady flow.

Project Description

Some level of awareness of sediment scour at bridge piers is as old as bridges themselves. The piers on many early stone arch bridges over rivers were rounded or pointed on the upstream end to streamline the flow and reduce scour. It was not until the 20th century, however, that engineers attempted to quantify and predict scour depths. The lowering of the sediment bed at a bridge pier can be caused by a number of mechanisms including degradation, channel or stream migration, man-made or natural stream contraction, and local structure-induced scour as described in a number of papers and reports including HEC-18. This project is limited to the structure-induced component of the scour, referred to here as local scour. Several approaches have been taken to predict equilibrium and evolution rates of local scour depths including analytical, dimensional analysis (using laboratory and/or field data to determine the functional relationships between the dimensionless groups), and numerical analysis (two- and three-dimensional modeling of the flows and sediment transport). The most successful attempts to date, from a practitioner's point of view, have been those based on dimensional analysis techniques and laboratory data.

This project is concerned with two aspects of the local scour problem, namely (1) the prediction of equilibrium scour depths at wide and long skewed piers and (2) the rate at which scour occurs at these piers. Historically, these problems have been addressed separately. Most local scour research has been directed at predicting equilibrium scour depths at structures with simple geometries, with some work in recent years on structures with more complex shapes. Less work has been reported on the rate at which local scour occurs. Most of the scour rate (scour evolution) predictive methods require knowledge of the equilibrium scour depths as well as the flow, sediment, and structure parameters.

Both researchers and practitioners have observed that local scour depths at prototype structures with large projected widths (i.e., wide piers or long skewed) are less than those predicted by some of the equations developed using small-scale laboratory data. Researchers have attempted to account for this discrepancy in different ways. One attempt (Johnson and Torrico 1994) was to single out and analyze the larger-scale laboratory and field data and apply a correction factor to the predictive equation currently in HEC-18. Other researchers have included terms in the equation to account for scour depth dependence on structure size (and have conducted large-scale laboratory experiments to establish this relationship) and concluded that their empirical equations are applicable for the full range of structure sizes (Sheppard et al. 2004). The data from the larger-structure laboratory tests clearly show a decreasing dependence of equilibrium scour depth on structure size as the structure size increases. The physics of why this occurs remains unproven. Some attempts have been made to explain this phenomenon (e.g., Ettema et al. 2006 and Sheppard 2004). Ettema et al. investigated the differences in the scale of the turbulence in the wake region with increasing pier size and associated this with the decreasing dependence of scour on increasing pier width. Sheppard gave a theoretical explanation involving the pressure-gradient field surrounding the structure. According to this hypothesis, pressure gradients in the vicinity of the structure due to the presence of the structure are much larger for smaller structures than for larger ones. The forces on the sediment grains produced by these pressure gradients are larger near small structures than for larger prototype structures. This explains why predictive equations based on small-scale laboratory data overpredict scour depths at prototype-scale structures. Stated another way, for a given sediment size, some local scour mechanisms diminish in magnitude with increasing structure size. Therefore, predictive equations, based on laboratory data, that do not consider this decreased influence overpredict scour depths at prototype-scale structures. This has implications regarding (1) estimating prototype scour depths from physical model test data and (2) interpreting laboratory-scale scour rate data.

The rate at which local scour occurs depends on all the parameters that control sediment transport rate over a flat bed as well as the structural parameters (size, shape, orientation to the flow). Improvements in instrumentation technology (miniature video cameras, high frequency, narrow beam acoustic transponders, etc.) in recent years have led to a more accurate rate of erosion measurements in both the laboratory and the field. A reasonable quantity of scour evolution laboratory data exists in the literature (Oliveto and Hager 2002, Rajasegaran 1997, Grimaldi 2005, Melville and Chiew 1999, Sheppard et al. 2004, and Sheppard and Miller 2006).

A number of methods for computing local scour evolution rates are also available (Chang et al. 2004, Melville and Chiew 1999, Mia and Nago 2003, Miller and Sheppard 2002, Roulund et al. 2005, and Zaghloul and McCorquodale 1975). The more promising methods were identified and evaluated using a laboratory scour evolution data set assembled as part of this project.

Report Organization

The general approach to the project is described in Chapter 2. Equilibrium scour and scour evolution data acquisition and analyses are covered in Chapter 3. Chapter 4 covers the initial screening, modification, and final evaluation of the equilibrium scour prediction equations. Chapter 5 covers the initial screening, modification, and final evaluation of the scour evolution equations. Chapter 6 covers the predictive equations for scour at piers skewed to the flow. Chapter 7 summarizes the results of this project regarding the best equations/methods for predicting equilibrium local scour depths and scour evolution rates for wide piers and long skewed piers and outlines recommendations for future research. The appendices (available on the *NCHRP Report 682* summary web page: www.trb.org/Main/Blurbs/164161.aspx) contain detailed information that supplements and supports the information presented in the report including the equilibrium scour data compiled as part of this project.

CHAPTER 2

Research Approach

An extensive information and data search was conducted at the onset of the project. The search included (1) questionnaires to state DOT engineers, consulting engineers, FHWA and U.S. Geological Survey (USGS) engineers, and university researchers; (2) electronic literature searches; and (3) emails and telephone calls to personal contacts working in this field in Japan, Portugal, India, Malaysia, Singapore, United Kingdom, Canada, New Zealand, Australia, and the United States. The questionnaire and some of the response statistics are presented in Appendix A (available on the *NCHRP Report 682* summary web page: www.trb.org/Main/Blurbs/164161.aspx).

The search resulted in the acquisition of 569 laboratory equilibrium scour data points, 943 field data points, and 142 laboratory scour evolution data sets. The important variables were grouped in dimensionless groups that represent ratios of the pertinent physical phenomena. For example, the Froude number, $V_1/\sqrt{y_1 g}$, which is the ratio of flow velocity to the propagation speed of a shallow water surface wave, is important in open channel flow. For sediment transport and local sediment scour, the ratio of flow velocity to the velocity required to initiate sediment movement on a flat stream bed, V_1/V_c, is important, etc. The range of the dimensionless groups more commonly used to characterize local scour covered by the compiled data sets is given in Table 1.

The search also produced 23 equilibrium local scour and 10 scour evolution predictive equations/methods.

Analysis of the search results showed that there is only limited information on local (equilibrium and evolution) scour depths for wide or long skewed piers. Most of the scour prediction equations do, however, state or imply that they are applicable for these conditions. For this reason, all equilibrium and evolution scour equations/methods that were obtained in the search were analyzed in this study.

The next step was to perform a preliminary screening of the predictive equations to exclude those equations/methods that yielded predictions significantly different from those for the remaining equations. This screening reduced the number of equilibrium and scour evolution equations from 23 and 10 to 17 and 6, respectively.

A method for assessing the quality of the measured data was developed. The measurement of local scour depths and the sediment and flow parameters on which these depths depend is not straightforward. For example, the bed shear stress, which is one of the important parameters, is usually estimated (or inferred) from the depth-averaged approach velocity. It is assumed that the flow is fully developed and that the depth-averaged velocity can be obtained from a point measurement or that the sectional averaged velocity can be obtained from the volumetric discharge rate in the flume. If the distance from the flume entrance to the test section is too short, the flow will not be fully developed and the bed shear stress will most likely be larger than computed for a fully developed flow. Even small errors in discharge or velocity measurement in the clear-water scour regime can have major effects on equilibrium scour depths and scour depth predictions. These examples illustrate potential problems associated with making accurate local scour measurements in the laboratory. Accurate scour measurements at prototype structures in the field are even more difficult to make. In addition to the measurement problems resulting from the temporal and spatial variations in flow velocities, the soil properties can vary spatially in all directions as well. Perhaps the greatest problem with most field data is the lack of information regarding the level of maturity of the scour hole at the time of measurement, i.e., how near the measured scour depth is to its equilibrium value for the flow, sediment, and structure conditions at the time of measurement.

Publications in professional journals often present insufficient detail regarding measurement techniques, instrumentation, etc., which makes assessing the quality of the reported data more difficult. It was necessary to develop a data evaluation scheme based on deviations from mean values computed using all the data. This procedure worked well for the equilibrium scour data. Refined laboratory and field data sets were created for use in evaluating the predictive equations.

Table 1. Range of values of the dimensionless groups covered by the compiled data sets.

Data Type	y_1/a	a/D_{50}	V_1/V_c	$V_1/\sqrt{y_1 g}$
Equilibrium Laboratory	0.05 to 21.05	3.65 to 4159	0.40 to 5.99	0.07 to 1.50
Equilibrium Field	0.18 to 9.67	8.33 to 65047	0.13 to 7.58	0.03 to 1.95
Laboratory Scour Evolution	0.09 to 11.11	6.72 to 4159	0.46 to 5.99	0.07 to 1.76

y_1 = the approach water depth
a = the structure width
D_{50} = the median sediment grain diameter
V_1 = the depth-averaged velocity
V_c = the sediment critical depth-averaged velocity
g = the acceleration of gravity.

Evaluation of the equilibrium scour equations was a two-step process. The first step involved using all of the equations to evaluate the scour for a range of hypothetical (but practical) structure, sediment, and flow conditions and comparing their results. Equations that produced results that significantly deviated from the mean values were eliminated from further consideration. The refined laboratory and field data sets were then used to evaluate the remaining equations.

An initial screening procedure similar to that used for the equilibrium scour data was used for the scour evolution data. An initial screening of the scour evolution equations was performed by simply evaluating and plotting the predictions for a range of input conditions and omitting the equations producing drastically different results from the mean produced by all of the equations. The remaining equations were then evaluated using the scour evolution laboratory data and errors were computed and presented in graphs.

Based on the performance of the equations in these tests, the best-performing equations/methods were identified and recommended for predicting equilibrium scour depth and scour evolution rates at wide piers and long skewed piers.

CHAPTER 3

Data Acquisition and Analyses

Details of the data acquisition and the quality control procedures used to identify the final data sets are presented in this chapter. As stated earlier, assessing the accuracy of the scour evolution data required introducing assumptions about the maturity of the scour holes at the end of the tests. Therefore, this data was used as published. Only field data for piers of simple shape (round, square, rectangular, etc.) were included in the field data set.

Equilibrium Local Scour Data

Relatively large quantities of equilibrium local scour data have been published (943 field and 569 laboratory data points). The sources and quantities of these data are listed in Table 2; however, it includes only data where all the relevant parameters are known and the sediment is cohesionless. Only 15 field data points were excluded due to missing information.

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, scour depths, etc.) given. There are, however, potential scale effects when the laboratory results are used 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. However, the measurement accuracy for both independent (flow velocity and duration, sediment properties, etc.) and 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 is significant suspended sediment in the water column. In some of the reported cases, the substructure shape and dimensions were not known (Zhuravlyov 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. Therefore, the potential errors associated with field data must be considered when verifying predictive equations.

The available laboratory and field equilibrium scour data are presented in matrix plots in Figures 1 through 4. Each of the independent parameters are plotted versus the other independent parameters, for example, a or a* versus V_1; y_1 versus D_{50}; V_1 versus y_1, a, D_{50}; etc. 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 illustrate the distribution of existing data and thus where data gaps exist. Figures 1 through 4 provide a qualitative view of the range and distribution of the variables covered in the laboratory and field data sets compiled in this study. The information in the matrices can be interpreted as follows. In Figure 1 the top row in the matrix has four elements. Starting from the left, the first element is a histogram showing the distribution of laboratory data with water depth. The vast majority of the data is for water depths less than 1 ft with only a small number of tests conducted at depths beyond 2 ft. The second element shows the values of water depth and pier size covered by the data. The 3 ft diameter pier tests were performed at water depths ranging from about 1 ft up to 6 ft. There is a data gap for pier diameters between 1 and 3 ft. The third element in the top row shows the values of water depth and flow velocity for the laboratory data. All of the high-velocity (greater than 2 ft/s) tests were performed with water depths less than or equal to 2 ft. The fourth element shows the values of water depth and sediment size. The horizontal axis is logarithmic so the value of −0.5 corresponds to a sediment diameter of 0.32 mm, 0.5 to a diameter of 3.2 mm, etc. The sediment diameters range from 0.1 to 7.0 mm, but only a few tests were conducted at water depths greater than 2 ft. The other elements in Figures 1 through 4 can be interpreted in this manner.

Table 2. Equilibrium local scour data sources and quantity.

Data Source	Number of Data Points	
	Clear Water	Live Bed
Field Data		
Zhuravlyov (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, personal communication)	6	0
Jones (unpublished, personal communication)	15	2
Sheppard et al. (2004)	12	2
Sheppard and Miller (2006)	4	20
Total laboratory	334	235

A significant data gap exists in the available laboratory data for $a/D_{50} > 1{,}800$. At present the largest laboratory value for a/D_{50} is 4,159. The histogram in the lower right corner of Figure 4 shows the distribution of a/D_{50} in the field data. This illustrates the range of this parameter for prototype piers. Because the horizontal axis in this plot is logarithmic, the "4" corresponds to $a/D_{50} = 10^4$. A gap in available laboratory data also exists for $a/y_1 > \sim 10$.

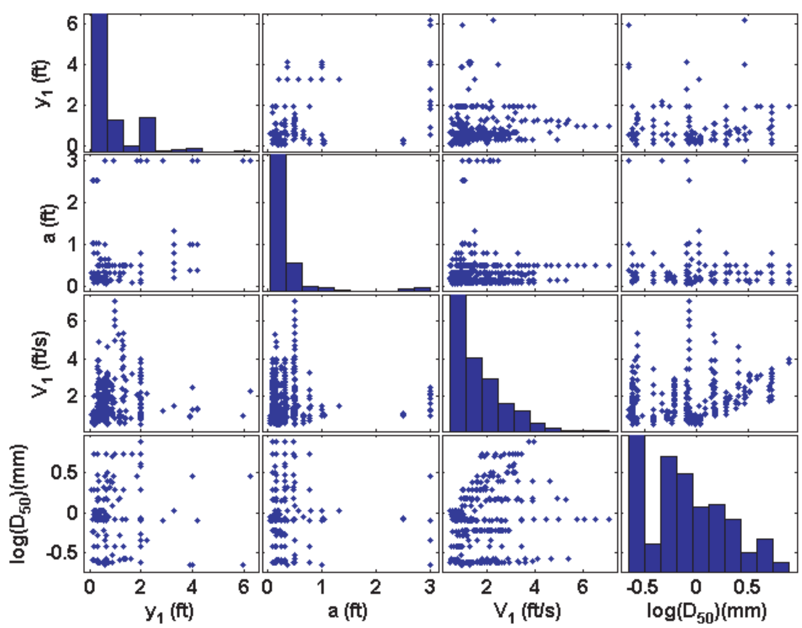
Figure 5 shows the distribution of normalized scour depth, y_s/a, and V_1/V_c for the field data set. The largest value of y_s/a is approximately 1.8.

Assessment of Data Quality

The quality of the data cannot be assessed by using the descriptions of the experimental conditions mainly because the information in the publications is insufficiently detailed. All of the Yanmaz and Altinbilek (1991) laboratory data were discarded due to the short durations of the tests (from 4 to 6 h), which were significantly less than that required for the development of equilibrium scour depths.

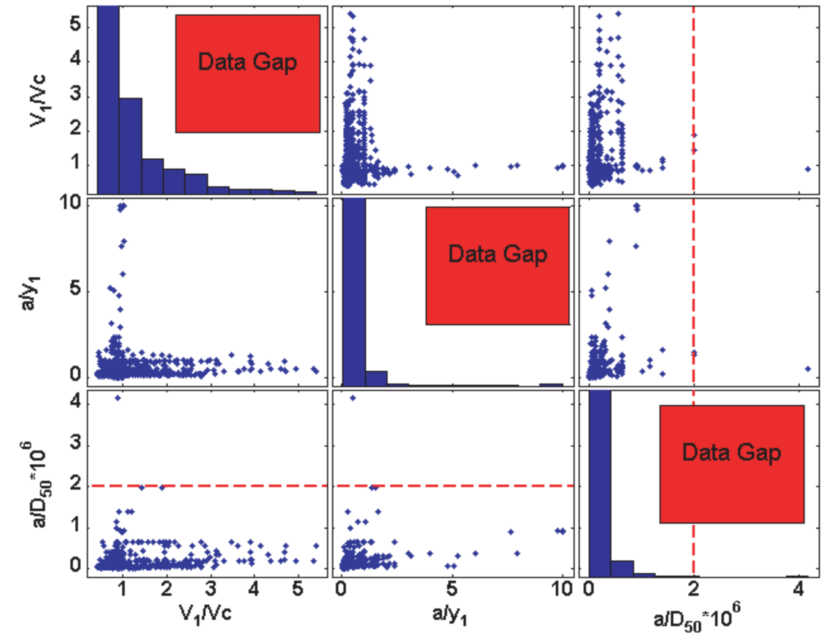
The method developed and used to identify and eliminate outliers in the data sets included the following steps:

1. Place the data in a three-dimensional Euclidean space with coordinates $\log(a/D_{50})$, V_1/V_c, and y_1/a.
2. Compute the variance of the data in each direction.



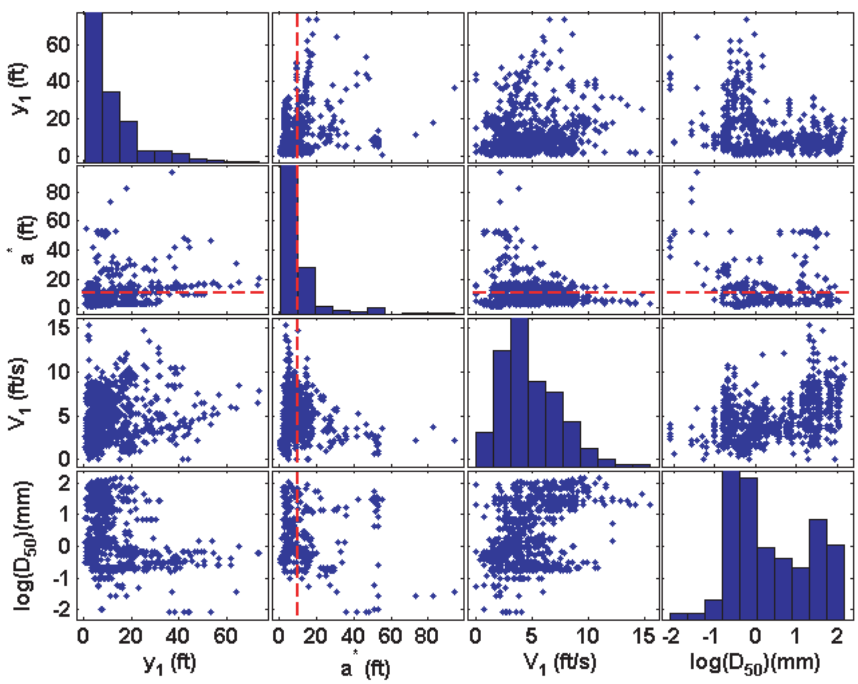
Note: Many of the photographs, figures, and tables in this report have been converted from color to grayscale for printing. The electronic version of the report (posted on the TRB website at http://www.trb.org/Main/Blurbs/164161.aspx) retains the color versions.

Figure 1. Dimensional plots of laboratory local equilibrium scour data.



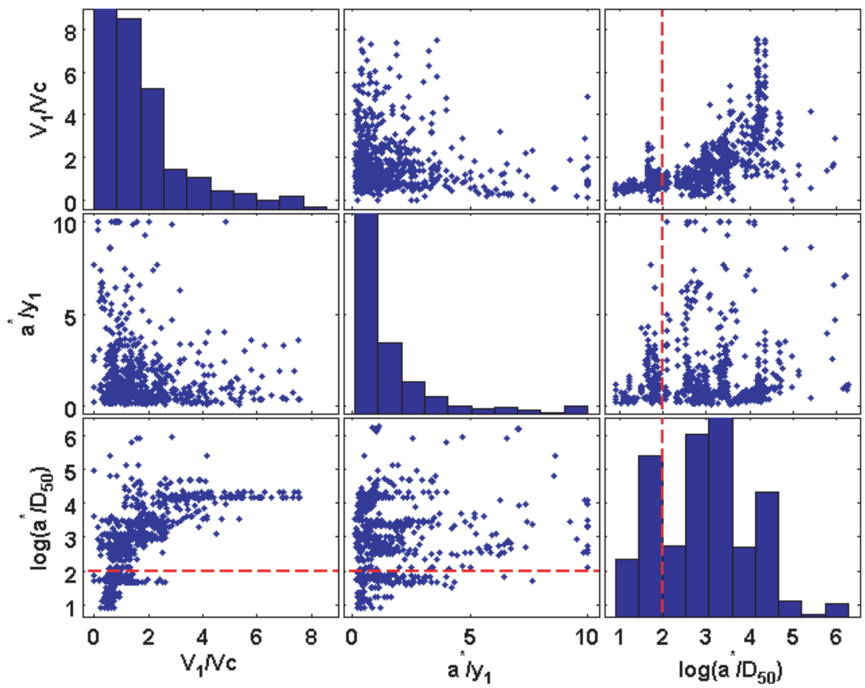
Note: The dashed lines indicate the wide-pier boundary.

Figure 2. Plots of normalized laboratory local scour data.



Note: The dashed lines indicate the wide-pier boundary.

Figure 3. Dimensional plots of field local scour data.



Note: The dashed lines indicate the wide-pier boundary.

Figure 4. Plots of normalized field local scour data.

3. Normalize the data values by the variances [i.e., the value of $\log(a/D_{50})$ for a data point was divided by the variance of the data in the $\log(a/D_{50})$ direction, etc.].
4. Compute the three-dimensional distance between data points.
5. For each data point, determine its four closest neighbors that are not from the same experimental data set.
6. Determine the variance in measured scour depths for the five data points (scour variance).
7. Determine the variance in the distances from the point in question to its neighboring four points (distance variance).
8. Compute the ratio of scour variance to distance variance. This ratio is referred to here as the "proximity parameter."
9. Plot the proximity parameter versus experiment number.
10. Establish a cutoff criterion.
11. Identify the data that exceed the cutoff criteria. These data are considered outliers and eliminated from the data sets.

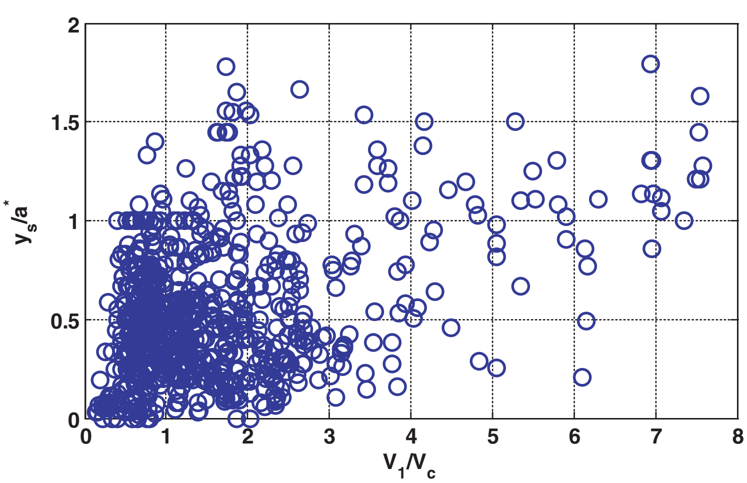


Figure 5. Normalized scour versus normalized velocity for field data.

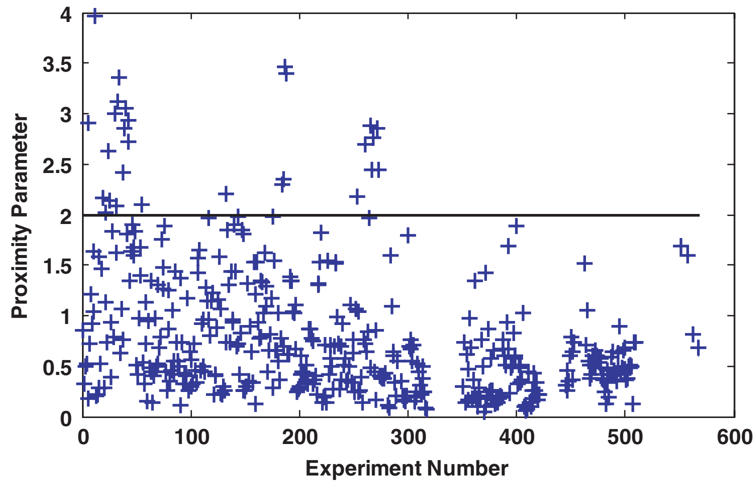


Figure 6. Proximity parameter for all laboratory data.

The laboratory data were analyzed following the above procedure and the results presented in Figure 6. Many of the data points with a proximity parameter value greater than 2.0 were from one source: Chabert and Engeldinger (1956). These data were removed from the data set, the process repeated, and the proximity parameter for the other points recalculated. The results shown in Figure 7 indicate that removing these data changed the values of the proximity parameter to below 2.0 for most of the remaining data. A cutoff value of 2.0 was selected, which resulted in the removal of two additional data points as shown in Figure 7. Most of the outliers had V_1/V_c values less than 0.8 and very large equilibrium scour depths.

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 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 Zhuravlyov (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

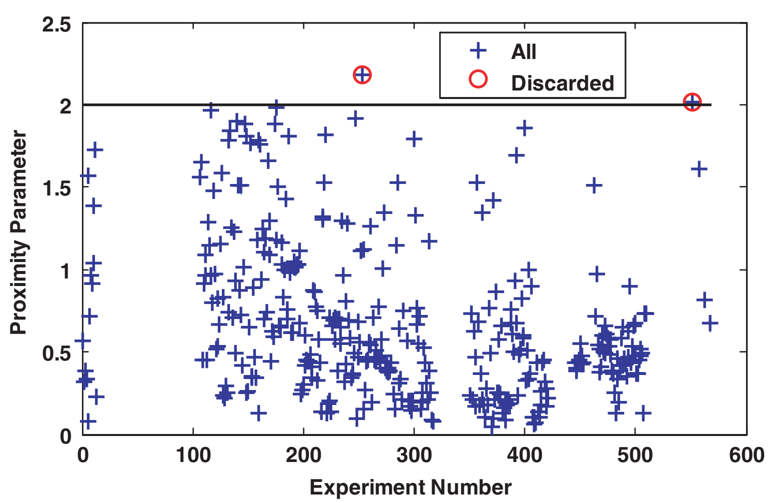


Figure 7. Proximity parameter for laboratory experiments [excluding data reported by Chabert and Engeldinger (1956)].

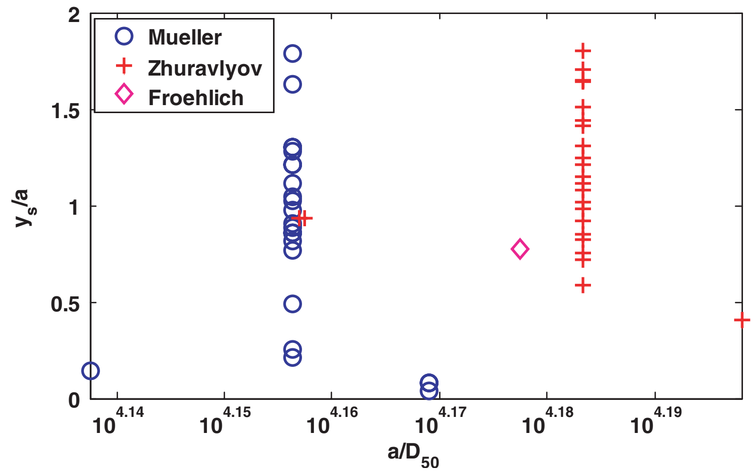


Figure 8. Normalized scour depth versus a/D_{50}.

in the measured scour depth values. Data points from the three sources are shown in Figures 8 and 9. Figure 8 shows the similarity in their a/D_{50} values. Figure 8 shows that the Mueller and Wagner data and Froehlich data have larger values of y_1/a than that 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. That is, all of the scour depths should have been near equilibrium values. However, as can be seen in Figure 10, the scour depth measurements from the Amu Darya River site are much larger. It is very difficult to make accurate 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 and 1997 (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 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 Zhuravlyov report (including the Amu Darya River data) are not given. However, all of the data in the 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 Zhuravlyov report.

Of the conflicting data sets, the Mueller and Wagner (2005) and Froehlich (1988) data were considered to be the more accurate and credible due to the information provided in their reports regarding instrumentation and methods used. For this reason the Amu Darya River data were eliminated from the field data set.

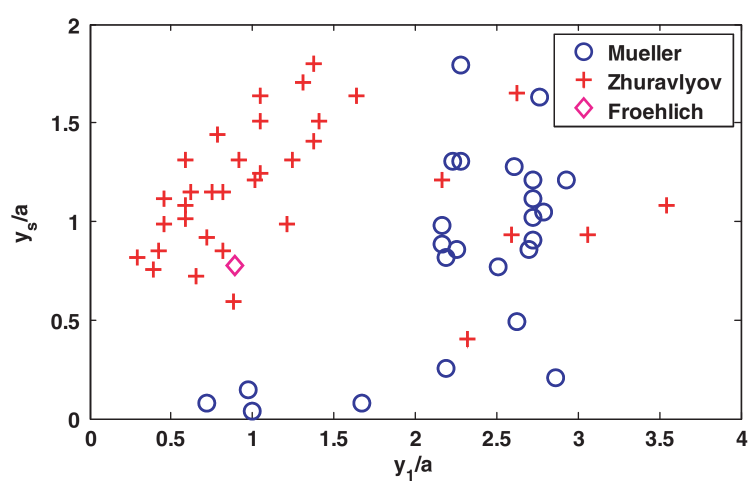


Figure 9. Normalized scour depth versus y_1/a.

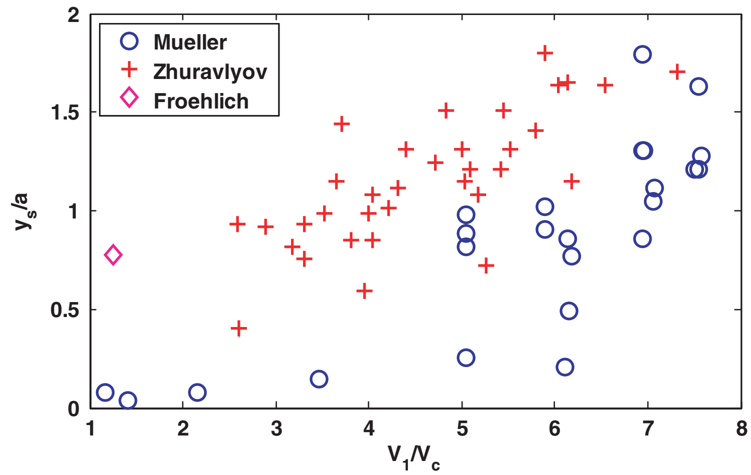


Figure 10. Normalized scour depth versus V_1/V_c.

Local Scour Evolution Data

Laboratory Data

A relatively large number of laboratory-scale local scour evolution rate experiments, with simple shaped structures, has been conducted and reported in the literature. A total of 195 scour time series data sets was compiled for circular or square piles. A list of contributing researchers with their number of reported clear-water and live-bed experiments is presented in Table 3. Figures 11 and 12 show the distribution of local scour evolution data collected in laboratory experiments. The matrices in these figures show the ranges and distribution of variables covered by the scour evolution data. For example, the third row from the top in Figure 11 shows the values of velocity and three of the other variables for the data. The first plot from the left shows that the data covers a wide range of velocities from 1 ft/s up to 7 ft/s but that with few exceptions the water depths are less than 1 ft. Also, there are no data for high-velocity flows and large depths. The second plot shows that most of the tests were performed with piers less than 1.5 ft in width. The third plot is a histogram showing the distribution of velocities for the tests, the majority being around 1 ft/s. The last plot in this row shows velocities and sediment size for the tests. The sediment sizes are grouped into three ranges: 1 mm and smaller, 3.0 to 3.5 mm, and the remainder in the 5.0 to 5.5 mm range. The higher-velocity tests were conducted with the smaller sediment.

A limited number of laboratory experiments have been performed with complex shaped piers (i.e., piers composed of a pile group, pile cap, and a column). Methods have been developed to estimate scour depths at complex piers using the equations developed for single cylindrical piers (Richardson and Davis 2001 and Sheppard and Renna 2005). The effective diameter of a complex pier is obtained using known pier, sediment, and flow values. The effective diameter is the diameter of a single circular pile that will experience the same local scour as the complex pier under the same flow and sediment conditions. This approach seems to work well for equilibrium scour depths for the limited data that exist. However, this approach has not been tested for scour evolution rates. Also, it is not known how scour evolution rates for complex piers compare with those for their equivalent circular piers.

Table 3. Sources and number of scour evolution data sets.

Data Source	Number of Data Sets
Oliveto and Hager (2002)	80
Rajasegaran (1997)	14
Grimaldi (2005)	3
Melville and Chiew (1999)	21
Sheppard et al. (2004)	14
Sheppard and Miller (2006)	24
Total	156

Field Data

The only time-dependent local scour field data obtained in the information and data search portion of this study were that reported by Walker (1995). In that study, the scour hole at a 2.0 ft wide square pile on a bridge over a tidal inlet on the Northwest Florida Coast (East Pass near Destin, Florida) was filled with the surrounding sand and the redevelopment of the scour hole monitored for a period of approximately 10 days. The unsteady (tidal) flow at this site, which exceeded sediment critical velocities at peak flow, reversed direction approximately every 14 h. After 10 days the scour depth was near the original value.

The laboratory and field equilibrium scour data compiled during this project are given in Appendix D (available on the *NCHRP Report 682* summary web page: www.trb.org/Main/Blurbs/164161.aspx).

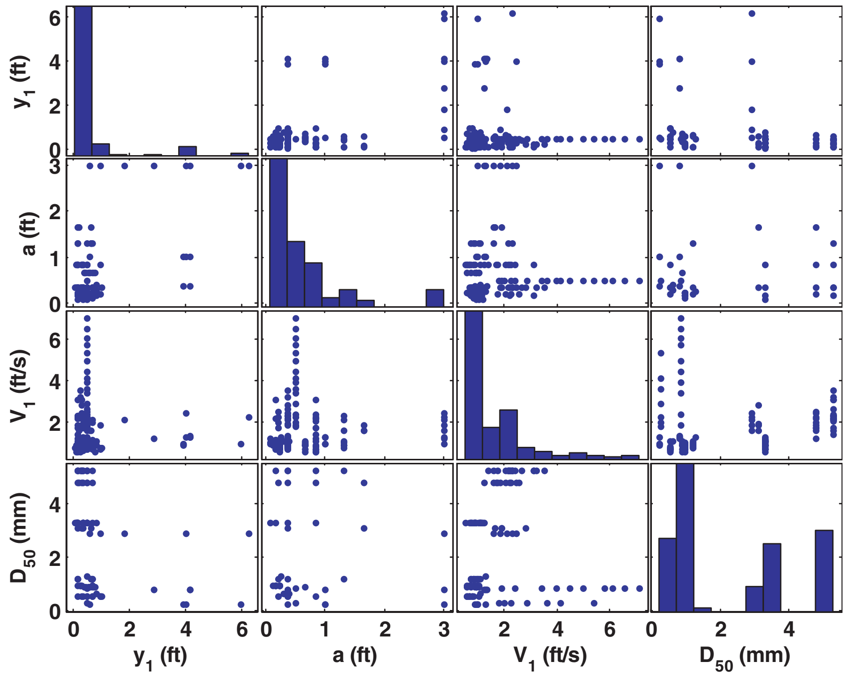
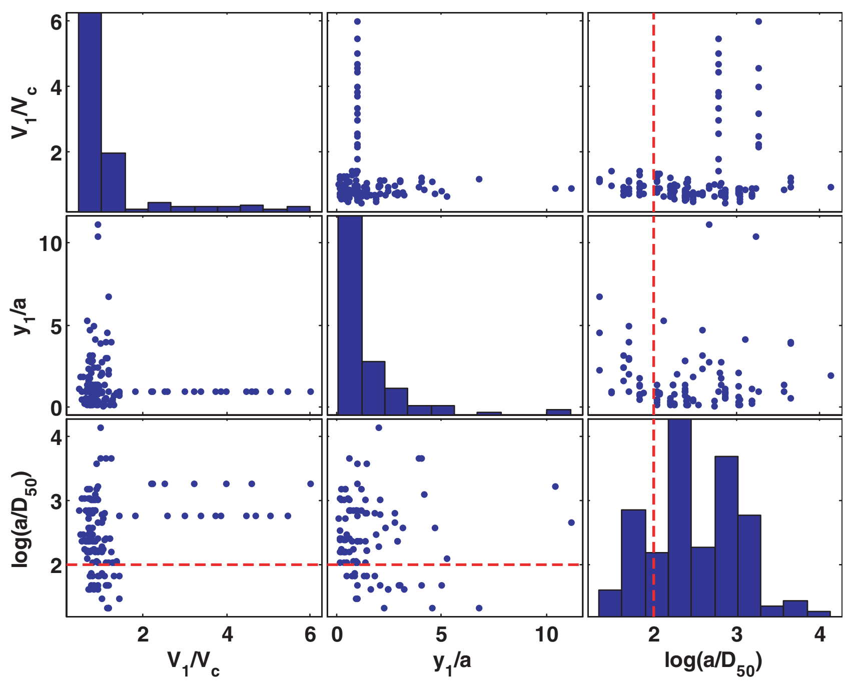


Figure 11. Plots of the data for local scour evolution rates.



Note: The dashed lines indicate the wide-pier boundary.

Figure 12. Plots of normalized data for local scour evolution rates.

CHAPTER 4

Equilibrium Local Scour Predictive Equations

Introduction

A large number of equations has been proposed for estimating equilibrium local scour depths at bridge piers. Detailed descriptions of the data used in the development of the equations are not usually available. However, the equations can be compared with each other for hypothetical, but practical, laboratory and field situations. This procedure was used for the initial screening of the equilibrium scour equations.

A selection of the more widely used and recently published equations is given in Table 4. A brief description of the equations is given in the following paragraphs.

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 using 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, leading to Equations 3 and 5 in Table 4.

The equation in HEC-18 (Richardson and Davis 2001), Equation 22 in Table 4, was determined 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 are the same as those used by Shen et al. (1969) in the derivation of Equation 9. Equation 22 has been progressively modified over the years and is currently recommended by the FHWA for estimating equilibrium scour depths at simple piers (Richardson and Davis 2001). 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.

Equation 18, 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 for local scour at bridge piers, including 137 live-bed data points and 115 clear-water data points. The equation was tested using field data obtained prior to 1964.

Several of the equations are based on field data, including the regime equations (Inglis 1949, Ahmad 1953, Chitale 1962, and Blench 1969) and the relations by Froehlich (1988), Ansari and Qadar (1994) and Wilson (1995). Equation 15 by Froehlich (1988) 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 (numbered 19 in Table 4) 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 Equation 6 by Larras (1963), Equation 7 by Breusers (1965), Equation 12 by Neill (1973), Equation 17 by Breusers and Raudkivi (1991), and an equation by Melville and Sutherland (1988) that is the forerunner of Equation 21.

The May and Willoughby (1990) equation (numbered 16 in Table 4) was derived from data produced by a laboratory study of local scour around large obstructions such as caissons and cofferdams for the construction of bridges across rivers and estuaries. The laboratory study, which focused on cases where the width of the structure was large relative to the flow depth, is especially relevant to this study. May and Willoughby noted that existing design formulae tended to overestimate the amount of scour.

Melville (1997) presented a physically justified method (Equation 21) to estimate local scour depth at piers based on

Table 4. Equilibrium scour predictive equations.

Reference	Equation	Notes	No.
Inglis (1949)	$\frac{y_s + y_1}{a} = 1.70\left[\frac{q^{2/3}}{a}\right]^{0.78}$	q = average discharge intensity upstream from the bridge (ft^2/s) a = pier width	1
Ahmad (1953)	$y_s + y_1 = 0.45 K_s q_2^{2/3}$	q_2 = local discharge intensity in contracted channel (ft^2/s)	2
Laursen (1958)	$\frac{a}{y_1} = 5.5\frac{y_s}{y_1}\left[\left(\frac{y_s}{11.5\,y_1}+1\right)^{1.7} - 1\right]$	Applies to live-bed scour	3
Chitale (1962)	$\frac{y_s}{y_1} = 6.65\,Fr - 0.51 - 5.49\,Fr^2$	Fr = Froude Number of the approach flow $= V_1/(gy_1)^{0.5}$	4
Laursen (1963)	$\frac{a}{y_1} = 5.5\frac{y_s}{y_1}\left[\frac{\left(\frac{y_s}{11.5\,y_1}+1\right)^{7/6}}{\left(\frac{\tau_1}{\tau_c}\right)^{0.5}} - 1\right]$	Applies to clear-water scour τ_1 = grain roughness component of bed shear τ_c = critical shear stress at threshold of motion	5
Larras (1963)	$y_s = 0.43 K_s\, K_\theta\, a^{0.75}$	a is in ft	6
Breusers (1965)	$y_s = 1.4\,a$	Derived from data for tidal flows	7
Blench (1969)	$\frac{y_s + y_1}{y_r} = 1.8\left(\frac{a}{y_r}\right)^{0.25}$	y_r = regime depth $=1.48(q^2/F_B)^{a/3}$ where F_B=1.9 $(D)^{0.5}$, D is in mm and q in m^2/s	8
Shen et al. (1969)	$y_s = 0.000223\left(\frac{V_1 a}{\nu}\right)^{0.619}$ $y_s = 0.000223\left(\frac{V_1 a}{\nu}\right)^{0.619}$	ν = kinematic viscosity	9
Coleman (1971)	$\frac{V_1}{\sqrt{2gy_s}} = 0.6\left(\frac{V_1}{a}\right)^{0.9}$		10
Hancu (1971)	$\frac{y_s}{a} = 2.42\left(\frac{2V_1}{V_c}-1\right)\left(\frac{V_c^2}{ga}\right)^{1/3}$	$(2V_1/V_c - 1) = 1$ for live-bed scour	11
Neill (1973)	$y_s = K_s a$	K_s = 1.5 for round-nosed and circular piers; K_s = 2.0 for rectangular piers	12
Breusers et al. (1977)	$\frac{y_s}{a} = f\left(\frac{V_1}{V_c}\right)\left[2.0\,tanh\left(\frac{y_1}{a}\right)\right]K_1\,K_2$	$f(V_1/V_c) = 0$ for $V_1/V_c \le 0.5$ $= (2V_1/V_c - 1)$ for $0.5 < V_1/V_c < 1$ $= 1$ for $V_1/V_c > 1$	13
Jain (1981)	$\frac{y_s}{a} = 1.84\left(\frac{y_1}{a}\right)^{0.3} Fr_c^{0.25}$	Applies to maximum clear-water scour	14
Froehlich (1988)	$\frac{y_s}{a} = 0.32\,K_s Fr^{0.2}\left(\frac{a_p}{a}\right)^{0.62}\left(\frac{y_1}{a}\right)^{0.46}\left(\frac{a}{D_{50}}\right)^{0.08} + 1$	a_p = projected width of pier	15
May and Willoughby (1990)	$y_s = 2.4\,f_s\left(\frac{y_s}{y_{sc}}\right)\left(\frac{y_{sc}}{y_{sm}}\right)$	For circular cylinder: f_s = 1.0 $\frac{y_s}{y_{sc}} = 1 - 3.66\left(1 - \frac{V_1}{V_c}\right)^{1.76}$ $\quad 0.52 \le \frac{V_1}{V_c} \le 1.0$ $= 1.0$ $\quad \frac{V_1}{V_c} > 1.0$ $\frac{y_{sc}}{y_{sm}} = 0.55\left(\frac{y_1}{a}\right)^{0.6}$ $\quad \frac{y_1}{a} \le 2.7$ $= 1.0$ $\quad \frac{y_1}{a} > 1.0$	16

(continued on next page)

Table 4. (Continued).

Reference	Equation	Notes	No.
Breusers and Raudkivi (1991)	$\frac{y_s}{a} = 2.3 K_y K_s K_d K_\sigma K_\theta$	For an aligned pier, $y_s = 2.3 K_s K_d K_\sigma b$	17
Gao et al. (1993)	$y_s = 0.46 K_\zeta a^{0.60} y_1^{0.15} D^{-0.07} \left[\frac{V_1 - V_c'}{V_c - V_c'}\right]^\eta$ $V_c = \left(\frac{y_1}{D}\right)^{0.14} \left[17.6\left(\frac{\rho_s - \rho}{\rho}\right) D + 6.05\text{x}10^{-7}\left(\frac{10 + y_1}{D^{0.72}}\right)\right]^{0.5}$ $V_c' = 0.645\left(\frac{D}{a}\right)^{0.053} V_c$ where y_s, a, y_1, D, V_1, V_c, V_c' are in S.I. units.	V_c' = incipient velocity for local scour at a pier K_ζ = shape and alignment factor η = 1 for clear-water scour < 1 for live-bed scour i.e., $\eta = \left(\frac{V_c}{V}\right)^{9.35 + 2.23 \log_{10} D}$	18
Ansari and Qadar (1994)	$y_s = 0.024 a_p^{3.0} \quad a_p < 7.2$ ft $y_s = 2.238 a_p^{0.4} \quad a_p > 7.2$ ft		19
Wilson (1995)	$\frac{y_s}{a^*} = 0.9\left(\frac{y_1}{a^*}\right)^{0.4}$	a^* = effective width of pier	20
Melville (1997)	$y_s = K_{ya} K_I K_D K_s K_\theta$ $K_{ya} = 2.4a \quad$ for $\quad a / y_1 < 0.7$ $K_{ya} = 2(y_1 a)^{0.5} \quad$ for $\quad 0.7 < a / y_1 < 5$ $K_{ya} = 4.5 y_1 \quad$ for $\quad a / y_1 > 5$ $K_I = \frac{V_1 - (V_{lp} - V_c)}{V_c} \quad$ for $\quad \frac{V_1 - (V_{lp} - V_c)}{V_c} < 1.0$ $K_I = 1 \quad$ for $\quad \frac{V_1 - (V_{lp} - V_c)}{V_c} \geq 1.0$ $K_D = 0.57 \log_{10}\left(2.24 \frac{a}{D_{50}}\right) \quad$ for $\quad \frac{a}{D_{50}} \leq 25$ $K_D = 1 \quad$ for $\quad \frac{a}{D_{50}} > 25$		21
Richardson and Davis (2001)	$\frac{y_s}{a} = 2 K_s K_\theta K_3 K_4 K_w \left(\frac{y_1}{a}\right)^{0.35} Fr^{0.43}$	K_3 = factor for mode of sediment transport K_4 = factor for armoring by bed material K_w = factor for very wide piers after Johnson and Torrico (1994) $y_{s(max)} = 2.4b$ for $Fr \leq 0.8$ $y_{s(max)} = 3b$ for $Fr > 0.8$	22

Table 4. (Continued).

Reference	Equation	Notes	No.
Sheppard and Miller (2006)	$\frac{y_s}{a^*} = 2.5 f_1 f_2 f_3 \quad \text{for } 0.47 < \frac{V_1}{V_c} < 1.0$ $\frac{y_s}{a^*} = f_1\left[2.2\left(\frac{\frac{V_1}{V_c}-1}{\frac{V_{lp}}{V_c}-1}\right)+2.5 f_3\left(\frac{\frac{V_{lp}}{V_c}-\frac{V_1}{V_c}}{\frac{V_{lp}}{V_c}-1}\right)\right] \quad \text{for } 1<\frac{V_1}{V_c}<\frac{V_{1p}}{V_c}$ $\frac{y_s}{a^*} = 2.2 f_1 \quad \text{for } \frac{V_1}{V_c} > \frac{V_{1p}}{V_c}$ $f_1 = tanh\left[\left(\frac{y_1}{a^*}\right)^{0.4}\right]$ $f_2 = \left\{1-1.75\left[ln\left(\frac{V_1}{V_c}\right)\right]^2\right\}$ $f_3 = \left[\frac{\left(\frac{a^*}{D_{50}}\right)}{0.4\left(\frac{a^*}{D_{50}}\right)^{1.2}+10.6\left(\frac{a^*}{D_{50}}\right)^{-0.13}}\right]$ $V_{lp1} = 0.8\sqrt{g\, y_0}$ $V_{lp2} = 29.31\ u_{*c}\ log_{10}(4y_1/D_{90})$ $V_{1p} = \begin{cases} V_{lp1} \text{ for } V_{lp1} \geq V_{lp2} \\ V_{lp2} \text{ for } V_{lp2} > V_{lp1} \end{cases}$	a^* = effective diameter = projected width * shape factor Shape factor = 1, circular $= 0.86 + 0.97\left(\left\lvert \alpha - \frac{\pi}{4}\right\rvert\right)^4$, square α = flow skew angle in radians	23

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).

A similar rationally based method is given by Sheppard and Miller (2006) equations (numbered 23 in Table 4). 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} increases until the value of a/D_{50} equals approximately 40, at which point dependence begins to decrease. One possible explanation for this behavior was given by Sheppard (2004).

Ettema et al. (2006) conducted experiments for local scour at cylindrical piers placed in a sand bed. The authors contend that the experiments show the importance of considering similitude of large-scale turbulence structures when conducting flume experiments on local scour at cylinders. They proposed a correction factor, a_o, to adjust scour-depth estimates obtained from small-scale cylinders. Ettema et al. (2006) used the largest cylinder size (1.3 ft) as the reference size. It is not known if this equation can be applied to wider piers and, if so, how to select a_o.

Initial Screening of Equilibrium Scour Predictive Equations

Twenty-three equations were assembled for evaluation and assessment. These equations are presented in Table 4. Some of these equations are a function of critical velocity. If the equation did not specify a method to calculate the critical velocity, it was calculated using Equation 24.

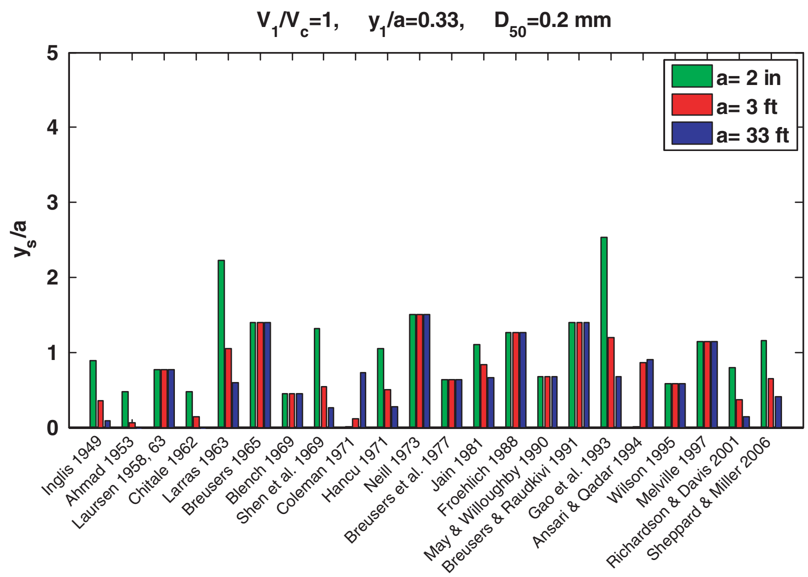
$$\frac{V_c}{u_{*c}} = 5.75 log\left(1685\frac{y_1}{D_{50}}\right)$$

$$u_{*c} = 0.377\,\text{ft/s} + 0.410 D_{50}^{1.4} \qquad 0.1\text{ mm} < D_{50} < 1\text{ mm} \qquad (24)$$

$$u_{*c} = D_{50}^{0.5} - 0.0213\, D_{50}^{-1} \qquad 1\text{ mm} < D_{50} < 100\text{ mm}$$

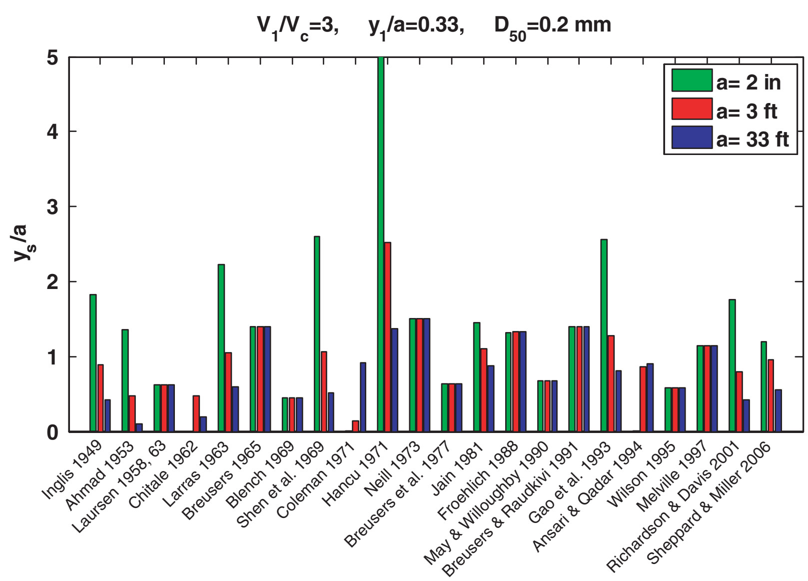
where D_{50} is in mm, u_{*c} & V_c are in ft/s, and y_1 in ft

The first screening procedure consisted of solving all of the equations for a range of input values and comparing the results. The values of the parameters used in Figures 13 through 20 are



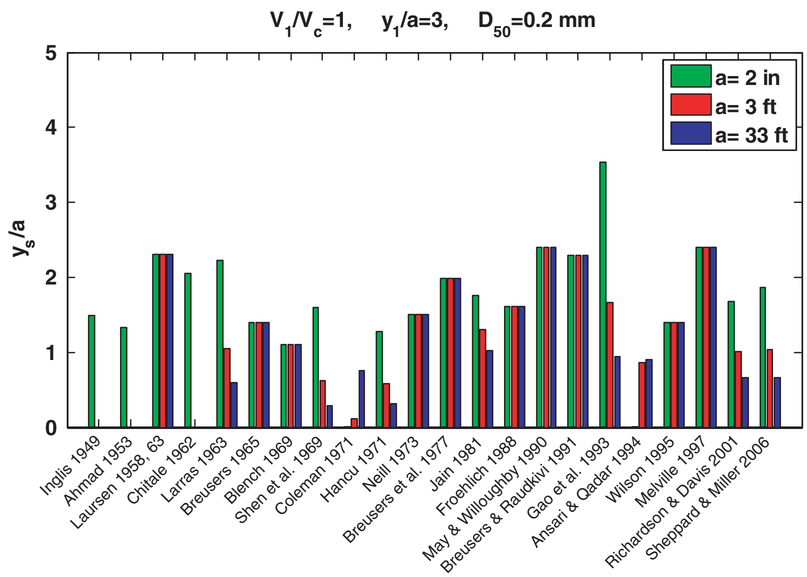
Note: The pier width is large compared to the water depth, and the sediment is fine sand.

Figure 13. Comparison of normalized local scour depth predictions using 22 different methods for transition from clear-water to live-bed scour conditions.



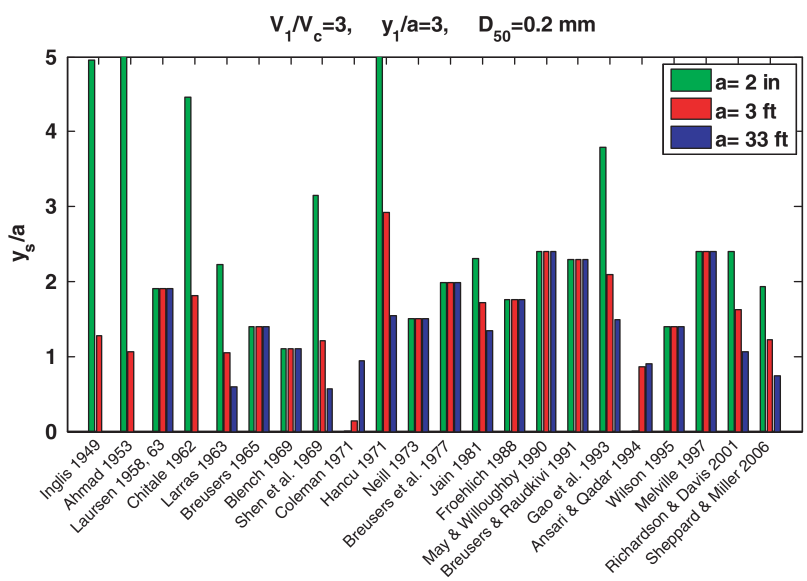
Note: The pier width is large compared to the water depth, and the sediment is fine sand.

Figure 14. Comparison of normalized local scour depth predictions using 22 different methods for a particular live-bed scour condition.



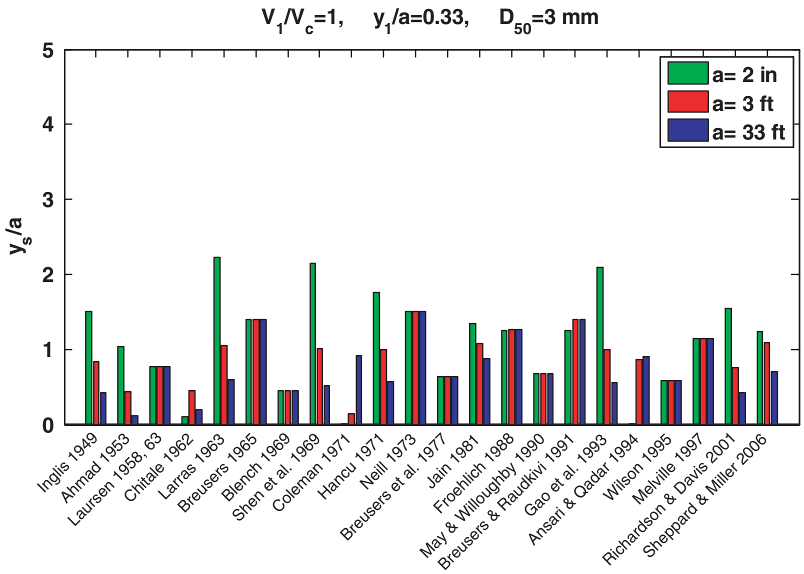
Note: The water depth is deep relative to pier width, and the sediment is fine sand.

Figure 15. Comparison of normalized local scour depth predictions using 22 different methods for transition from clear-water to live-bed scour conditions.



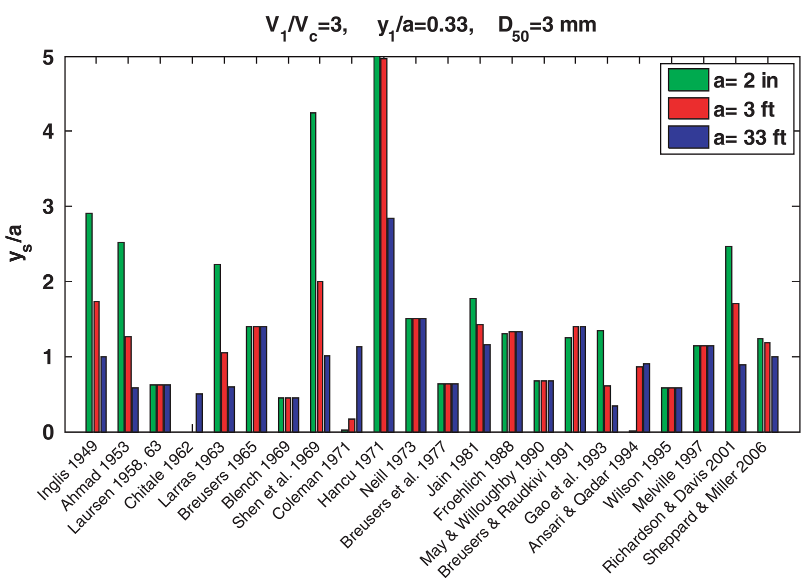
Note: The water depth is deep relative to pier width, and the sediment is fine sand.

Figure 16. Comparison of normalized local scour depth predictions using 22 different methods for a particular live-bed scour condition.



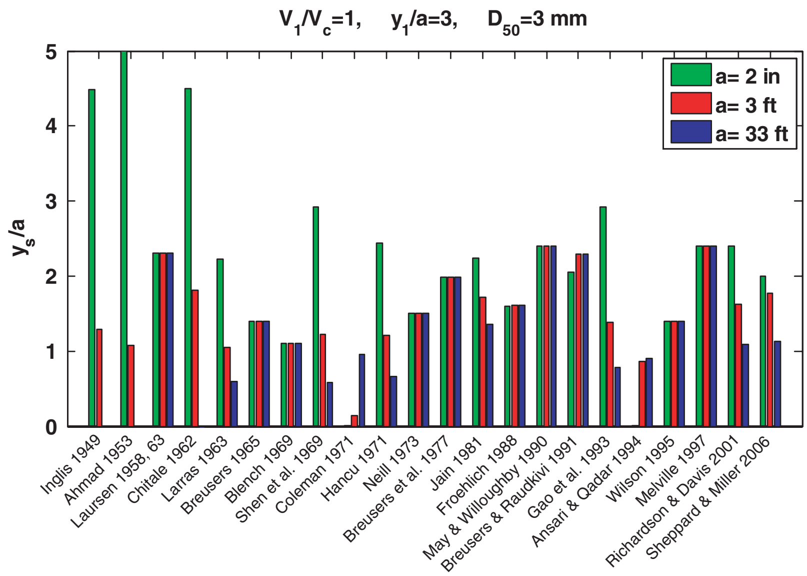
Note: The pier width is large compared to the water depth, and the sediment is very coarse sand.

Figure 17. Comparison of normalized local scour depth predictions using 22 different methods for transition from clear-water to live-bed scour conditions.



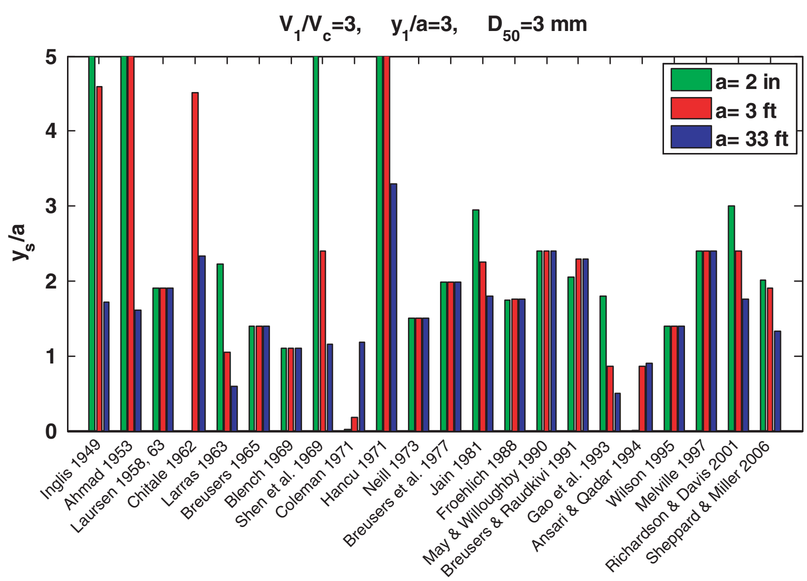
Note: The pier width is large relative to the water depth and the sediment is very coarse sand.

Figure 18. Comparison of normalized local scour depth predictions using 22 different methods for a particular live-bed scour condition.



Note: The water depth is deep relative to the pier width, and the sediment is very coarse sand.

Figure 19. Comparison of normalized local scour depth predictions using 22 different methods for transition from clear-water to live-bed scour conditions.



Note: The water depth is deep relative to the pier width, and the sediment is very coarse sand.

Figure 20. Comparison of normalized local scour depth predictions using 22 different methods for a particular live-bed scour condition.

V_1/V_c = 1 and 3; y_1/a = 0.33, 1, and 3; D_{50} = 0.2 and 3 mm; and a = 2 in., 3 ft, and 33 ft. The results from this evaluation are presented in the form of bar charts in Figures 13 though 20. Negative scour depth predictions were set equal to zero in the charts.

Figures 13 and 15 show scour depth predictions for scenarios comprising clear-water to live-bed transition (threshold) flows ($V_1/V_c = 1$), fine sand (D_{50} = 0.2 mm), and two different flow depth to pier width ratios (y_1/a = 3, 0.33). Figures 14 and 16 are a parallel set of results for live-bed conditions ($V_1/V_c = 3$). Similarly, Figures 17 through 20 apply to situations with coarser sediment (D_{50} = 3 mm).

The equations used in producing the results shown in Figures 13 through 20 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 equilibrium scour 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.

These plots help identify those equations that produce unrealistic results for prototype-scale piers and thus aid in eliminating such equations 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, and Shen et al. 1969) and were eliminated. This process left 17 methods/equations for the final analysis.

Modifications to Equilibrium Scour Predictive Methods

One of the objectives of this study was to determine if any of the predictive equations could be modified to improve their accuracy. The overall accuracy of most of the equations could be improved by adjusting one or more of their coefficients. However, in almost every case this adjustment increased underprediction, which for design equations is not acceptable. The Sheppard and Miller (2006) equation was modified to create the new S/M equation.

Sheppard/Melville (S/M) Equation

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. The modifications consisted of:

1. Changing the 1.75 coefficient to 1.2 in the term for f_2 in Equation 23,
2. Changing the value of V_1/V_c where local scour is initiated from 0.47 to 0.4, and
3. Modifying/simplifying the manner in which the live-bed peak velocity is computed.

The resulting equation is presented in Table 5.

These changes improved the accuracy of the predictions for both laboratory and field data. However, this equation underpredicts some of the measured field data at very low velocities (i.e., low values of V_1/V_c), most likely due to relatively large sediment size distributions (large σ_g). The underpredictions are illustrated in Figures 21 and 22, which show before- and after-modification upper bound curves for laboratory and field data, respectively. The scour depths in this range of flow velocities are, however, very small and therefore are not likely to affect prediction of design scour depths. Also, the reported scour depths in this range of V_1/V_c seem large for the magnitude of the flow velocities (i.e., the accuracy of these data is questionable).

Equation in HEC-18

No attempt was made to modify the scour equation in the current version of HEC-18 (Richardson and Davis 2001) because it does not properly account for the physics of the local scour processes. That is, all of the known local scour mechanisms are not accounted for with the dimensionless groups in this equation. The equation does, however, contain a wide-pier correction factor developed by Johnson and Torrico (1994). Predicted versus measured scour depth plots using this equation are shown in Figure 23 (laboratory data) and Figure 24 (field data). In general, the wide-pier correction decreases the magnitude of the predicted scour depths. The wide-pier correction does, however, increase the number of underpredictions in both the laboratory and field data. The overall error for the dimensional scour is reduced with the wide-pier correction factor, but the error for the normalized scour is increased. The wide-pier correction factor also creates

Table 5. The S/M local scour equations.

Reference	Equation	Notes	No.
S/M	$\frac{y_s}{a^*} = 2.5 f_1 f_2 f_3$ for $0.4 \le \frac{V_1}{V_c} < 1.0$ $\frac{y_s}{a^*} = f_1\left[2.2\left(\frac{\frac{V_1}{V_c}-1}{\frac{V_{1p}}{V_c}-1}\right)+2.5f_3\left(\frac{\frac{V_{1p}}{V_c}-\frac{V_1}{V_c}}{\frac{V_{1p}}{V_c}-1}\right)\right]$ for $1.0 \le \frac{V_1}{V_c} \le \frac{V_{1p}}{V_c}$ $\frac{y_s}{a^*} = 2.2 f_1$ for $\frac{V_1}{V_c} > \frac{V_{1p}}{V_c}$ $f_1 = tanh\left[\left(\frac{y_1}{a^*}\right)^{0.4}\right]$ $f_2 = \left\{1-1.2\left[ln\left(\frac{V_1}{V_c}\right)\right]^2\right\}$ $f_3 = \left[\frac{\left(\frac{a^*}{D_{50}}\right)}{0.4\left(\frac{a^*}{D_{50}}\right)^{1.2}+10.6\left(\frac{a^*}{D_{50}}\right)^{-0.13}}\right]$ $V_{1p1} = 5V_c$ $V_{1p2} = 0.6\sqrt{g\,y_1}$ $V_{1p} = \begin{cases} V_{1p1} \text{ for } V_{1p1} \ge V_{1p2} \\ V_{1p2} \text{ for } V_{1p2} > V_{1p1} \end{cases}$	a^* = effective diameter = projected width * shape factor Shape factor = 1, circular $= 0.86 + 0.97\left(\left\|\alpha - \frac{\pi}{4}\right\|\right)^4$, square α = flow skew angle in radians	25

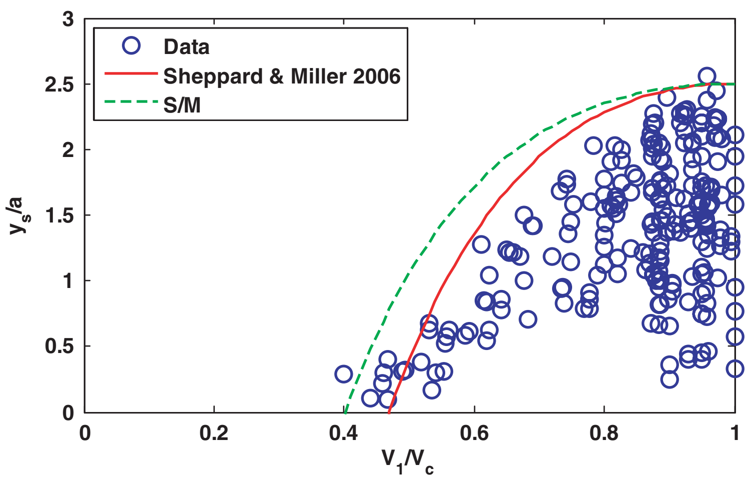


Figure 21. Measured laboratory data at low velocities compared to the upper limit of Sheppard and Miller (2006) and S/M equations.

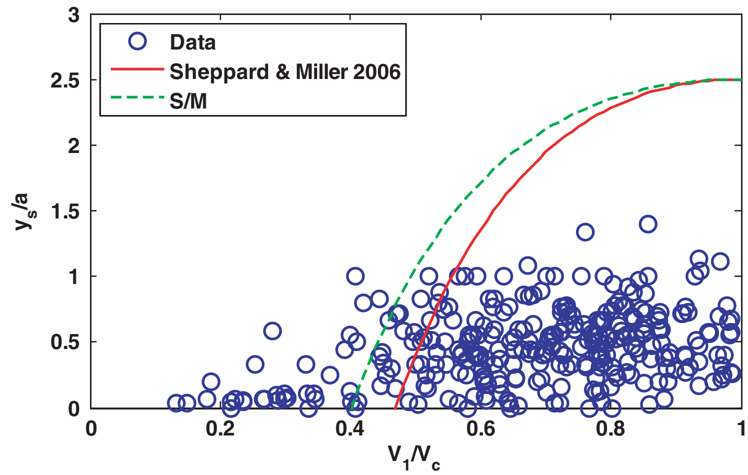


Figure 22. Measured field data at low velocities compared to the upper limit of Sheppard and Miller (2006) and S/M equations.

a discontinuity in predicted scour depth with increasing pier width as shown in Figure 25.

Evaluation of Equilibrium Scour Predictive Methods

Evaluating predictive equations using laboratory data is relatively straightforward because, in most cases in the database, either the scour has reached equilibrium or the measured depth has been extrapolated to an equilibrium value. In addition, the input values (water depth, flow velocity, sediment properties, etc.) are all accurately known. Obtaining accurate measurements of input parameters in the field is much more difficult and the maturity of the scour hole is almost never known. Several of the scour depths in the field data set are extremely small for the pier size, water depth, and flow velocity. This observation suggests that the duration of the flow at the reported velocity was short; that the bed material was cohesive although reported as cohesionless; 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 (contraction, degradation, etc.). One exception is the case where the measured scour depth is due to a previous, more severe, flow event. Figure 26 gives some insight into the flow duration problem for field

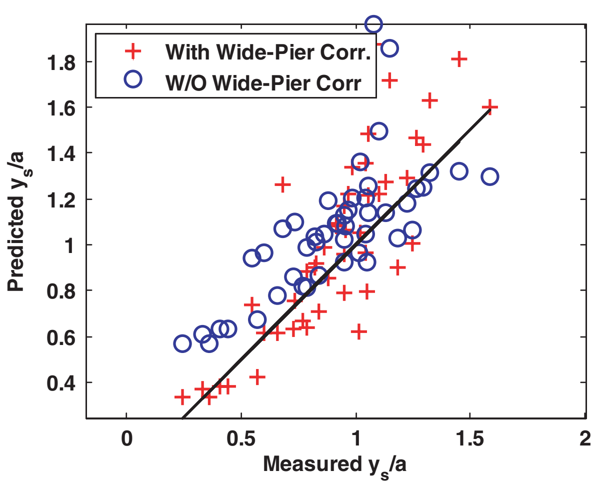


Figure 23. Effect of wide-pier correction on HEC-18 normalized scour depth predictions for laboratory data.

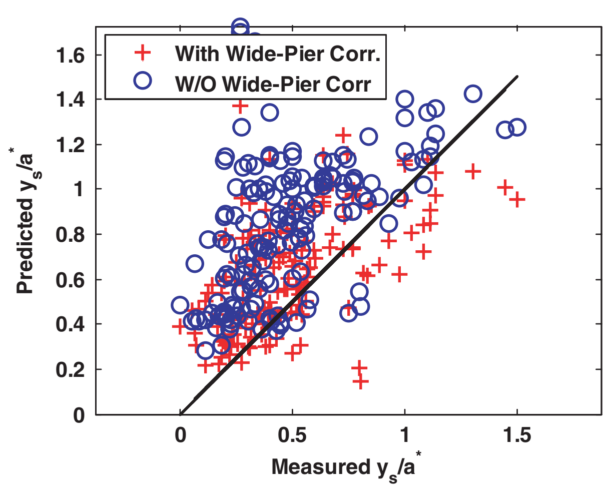


Figure 24. Effect of wide-pier correction on HEC-18 normalized scour depth predictions for field data.

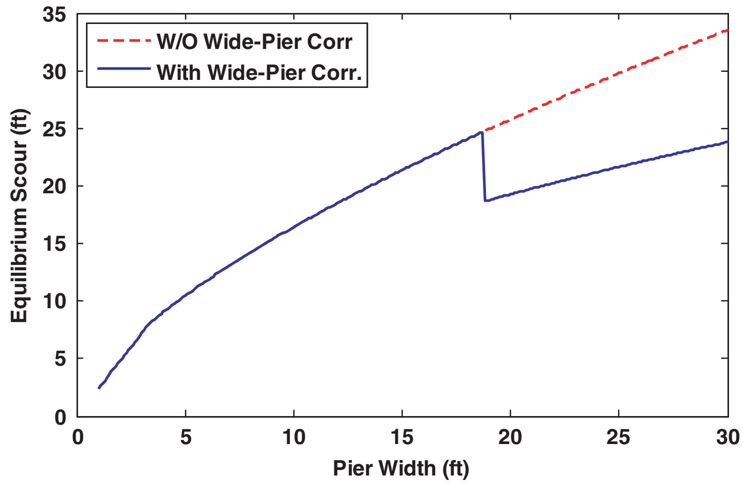
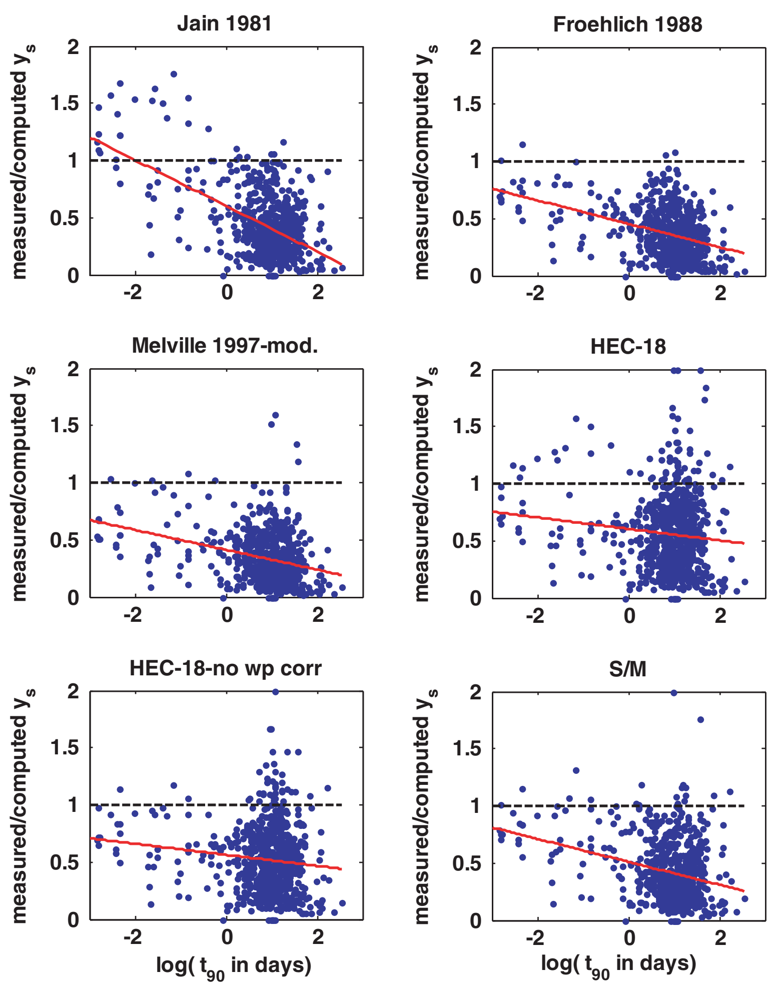


Figure 25. An example of HEC-18 scour predictions (y_1 = 15 ft, D_{50} = 0.3 mm, V_1 = 8 ft/s).



Note: The lines are best linear fits to the data.

Figure 26. Measured/predicted versus predicted time to reach 90% of equilibrium scour depth for the field data.

conditions. In this figure, the ratio of measured divided by predicted scour is plotted versus t_{90} (time required to reach 90% of equilibrium) for six equilibrium scour equations. Best-fit lines to the data are also shown. The time to reach 90% of equilibrium scour depth is computed using the M/S equation discussed later in this report. Note that t_{90} is more than 100 days for some situations. Underpredictions increase for all equations with increasing t_{90}. This result suggests that a large portion of the field cases have not reached equilibrium.

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

$$SSE\% = \frac{\sum\left(y_s^{measured} - y_s^{computed}\right)^2}{\sum\left(y_s^{measured}\right)^2} \times 100 \qquad (26)$$

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

$$SSEn\% = \frac{\sum\left(\frac{y_s^{measured}}{a} - \frac{y_s^{model}}{a}\right)^2}{\sum\left(\frac{y_s^{measured}}{a}\right)^2} \times 100 \qquad (27)$$

The desired method/equation is the one that has the least overall error and least underprediction. Because 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.

Table 6 gives percentage errors (SSE and SSEn) for the laboratory and field data sets. Underpredictions are much smaller compared to the total error for all predictive equations because they are all conservative by design. For the reasons discussed previously, total errors for the field data are not presented because 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. However, 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.

Six different measures of error were used for each method/equation. The overall fit of all equations can be improved by modifying their coefficients, but, in general, such modification increases their underpredictions as can be seen between Sheppard and Miller (2006) and its modified form, S/M. The

Table 6. Absolute and normalized errors for predictive equilibrium scour equations.

Reference	Laboratory (441 points)				Field (760 points)	
	SSE%		SSEn%		SSE%	SSEn%
	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 et al. (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 & 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 & 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
Melville (1997)–mod.	34.9	0.2	24.8	0.1	0.2	0.1
HEC-18	7.9	1.8	21.0	0.3	1.1	1.1
HEC-18–no wp corr	9.5	1.2	21.1	0.3	0.4	0.5
Sheppard & Miller (2006)	5.9	0.1	11.7	0.3	1.9	2.6
S/M	6.8	0.1	13.0	0.3	0.3	0.2

Table 7. Ranking of all predictive equilibrium scour equations.

Reference	Laboratory (441 points)					Field (760 points)		
	SSE		SSEn			SSE	SSEn	
	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	11	**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 et al. (1977)	9	15	5	15	**14**	17	16	**18**
Jain (1981)	5	4	12	8	**6**	11	8	**9**
Froehlich (1988)	11	6	1	10	**5**	1	1	**1**
May & Willoughby (1990)	7	13	8	11	**11**	16	14	**15**
Gao et al. (1993)	19	16	20	17	**18**	19	20	**20**
Ansari & Qadar (1994)	18	22	19	24	**21**	8	19	**13**
Wilson (1995)	4	14	7	13	**9**	12	10	**10**
Melville (1997)	15	5	13	2	**8**	4	4	**4**
Melville (1997)–mod.	16	3	14	1	**7**	3	3	**3**
HEC-18	3	10	9	4	**3**	9	9	**8**
HEC-18–no wp corr	6	8	10	3	**4**	7	7	**7**
Sheppard & Miller (2006)	1	2	4	6	**1**	10	12	**11**
S/M	2	1	6	5	**2**	6	6	**6**

prediction of the absolute scour depth is important because the design scour depth will be computed using the dimensional form of the equation.

The results of the error statistics are presented in Table 6 for all equations. The error statistics confirm the screening process in that the equations eliminated are the ones with the greatest errors. Table 7 gives the ordering of the equations according to the values given in Table 6. There are also two columns for overall error order for field and laboratory data. Each overall error order was calculated by averaging the columns to its left and ordering the results. Field data errors are not very informative by themselves because they do not include total errors. Total errors for the field data are also not meaningful because so many of the reported scour depths are not 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 6 and 7: Jain (1981), Froehlich (1988), modified Melville (1997), HEC-18, HEC-18 without wide-pier correction, and S/M. Only the modified/final versions of the equations were considered. However, both forms of HEC-18 are presented because they are currently widely used in the United States. The error statistics and rankings for these six equations, based on performance with all data, are given in Tables 8 and 9, respectively (statistics are the same as those given in Table 6, but they are repeated for easier access). Tables 10 and 11 give the error

Table 8. Errors for selected predictive equations.

Reference	Laboratory (441 points)				Field (760 points)	
	SSE%		SSEn%		SSE%	SSEn%
	Total	Under	Total	Under	Under	Under
Jain (1981)	9.1	0.2	24.5	0.6	2.2	1.1
Froehlich (1988)	21.0	0.6	10.3	1.7	0.1	0.0
Melville (1997)–mod.	34.9	0.2	24.8	0.1	0.2	0.1
HEC-18	7.9	1.8	21.0	0.3	1.1	1.1
HEC-18–no wp corr	9.5	1.2	21.1	0.3	0.4	0.5
S/M	6.8	0.1	13.0	0.3	0.3	0.2

Table 9. Ranking of selected predictive equations based on performance with all data.

Reference	Laboratory (441 points)					Field (760 points)		
	SSE		SSEn			SSE	SSEn	
	Total	Under	Total	Under	Overall	Under	Under	Overall
Jain (1981)	3	3	5	5	**5**	6	5	**5**
Froehlich (1988)	5	4	1	6	**6**	1	1	**1**
Melville (1997)–mod.	6	2	6	1	**3**	2	2	**2**
HEC-18	2	6	3	3	**2**	5	6	**6**
HEC-18–no wp corr	4	5	4	2	**4**	4	4	**4**
S/M	1	1	2	4	**1**	3	3	**3**

Table 10. Errors for selected predictive equations for wide piers ($a/D_{50} > 100$, $a/y_1 > 2$).

Reference	Laboratory (17 points)				Field (142 points)	
	SSE%		SSEn%		SSE%	SSEn%
	Total	Under	Total	Under	Under	Under
Jain (1981)	15.4	0.0	10.9	0.0	5.6	5.4
Froehlich (1988)	94.8	0.0	55.2	0.0	0.0	0.0
Melville (1997)–mod.	3.3	1.3	7.8	0.4	0.7	1.0
HEC-18	4.2	3.9	2.4	1.9	3.6	6.2
HEC-18–no wp corr	8.7	0.6	4.9	0.2	0.3	0.9
S/M	5.1	0.0	8.5	0.0	0.5	1.5

Table 11. Ranking of selected predictive equations based on performance for wide piers ($a/D_{50} > 100$, $a/y_1 > 2$).

Reference	Laboratory (17 points)					Field (142 points)		
	SSE		SSEn			SSE	SSEn	
	Total	Under	Total	Under	Overall	Under	Under	Overall
Jain (1981)	5	1	5	1	**1**	6	5	**5**
Froehlich (1988)	6	2	6	2	**6**	1	1	**1**
Melville (1997)–mod.	1	5	3	5	**3**	4	3	**3**
HEC-18	2	6	1	6	**5**	5	6	**6**
HEC-18–no wp corr	4	4	2	4	**4**	2	2	**2**
S/M	3	3	4	3	**2**	3	4	**4**

statistics and ordering among these six equations based on performance for wide piers.

Figures 27 through 30 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 a multiplicative constant. The symbols indicate the errors produced by the method with a multiplier of one. As the multiplier changes from one, the symbol simply moves along the curve on which the symbol lies. Note that shifting the position of the symbol along its line for one data set does, however, shift its position on the other plots. For example, if the HEC-18 equation is multiplied by 1.2, its position moves from that shown with the left-pointing open triangle to that with the closed triangle. Note that even though there is improved performance for the dimensional scour (Figure 27), the normalized scour performance is significantly reduced (Figure 28).

Figures 31 through 34 are plots of predicted versus measured scour depths for six of the predictive equations for the various data sets.

Based on these analyses, 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 example plots are presented in Figures 35 through 37. The HEC-18 equation is also presented in these equations.

Figures 38 through 40 are additional comparisons between the S/M and HEC-18 equations for three different prototype design conditions ($\sigma = 2.7$, $a/D_{50} = 10{,}000$).

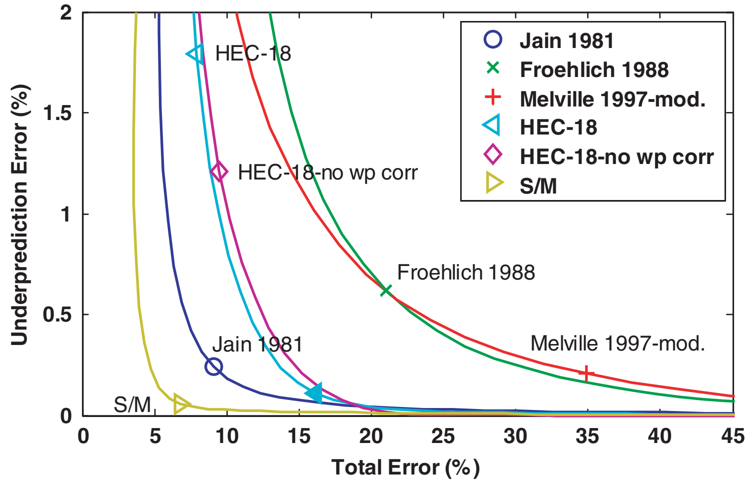


Figure 27. Underprediction scour error versus total error for laboratory data.

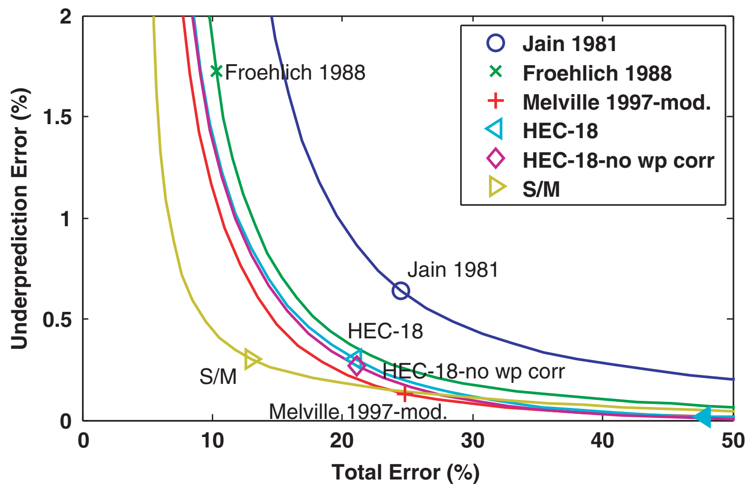


Figure 28. Underprediction normalized scour error versus total error for laboratory data.

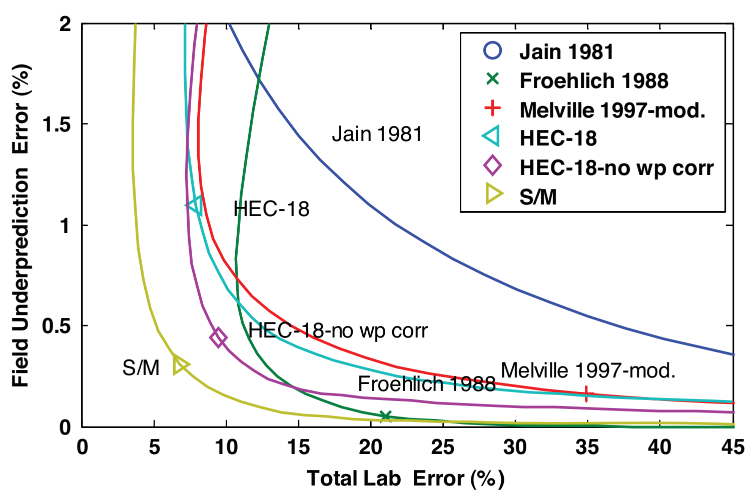


Figure 29. Underprediction scour error for field data versus total error for laboratory data.

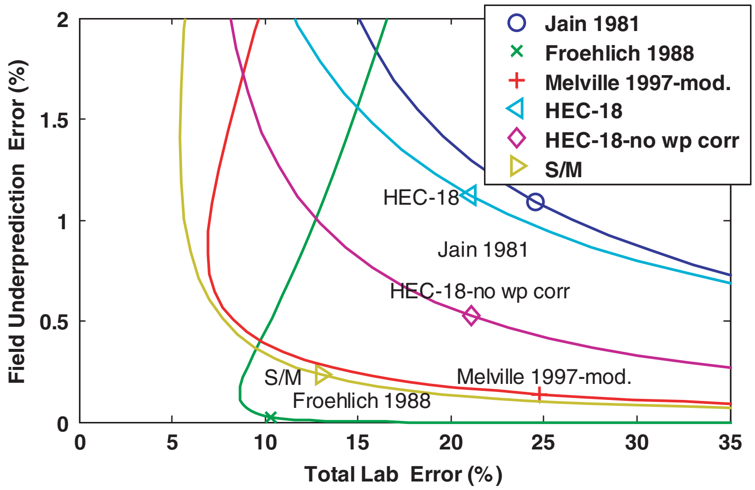
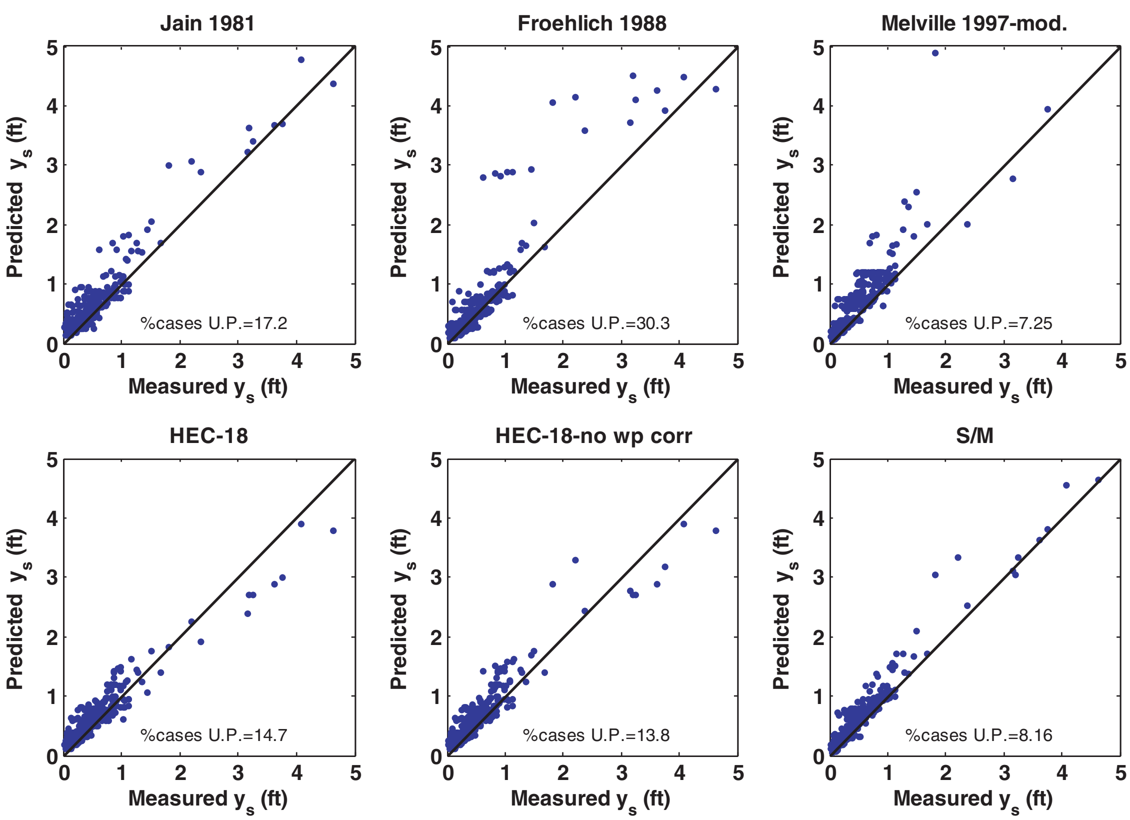
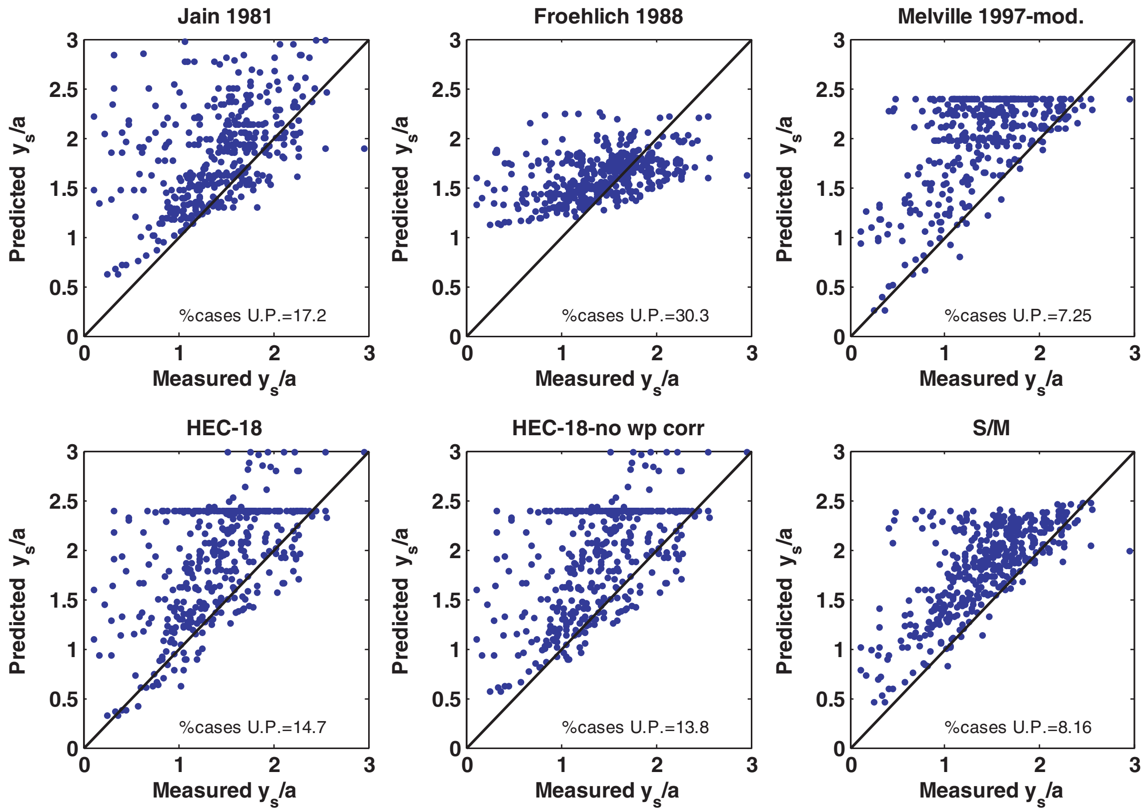


Figure 30. Underprediction normalized scour error for field data versus total error for laboratory data.



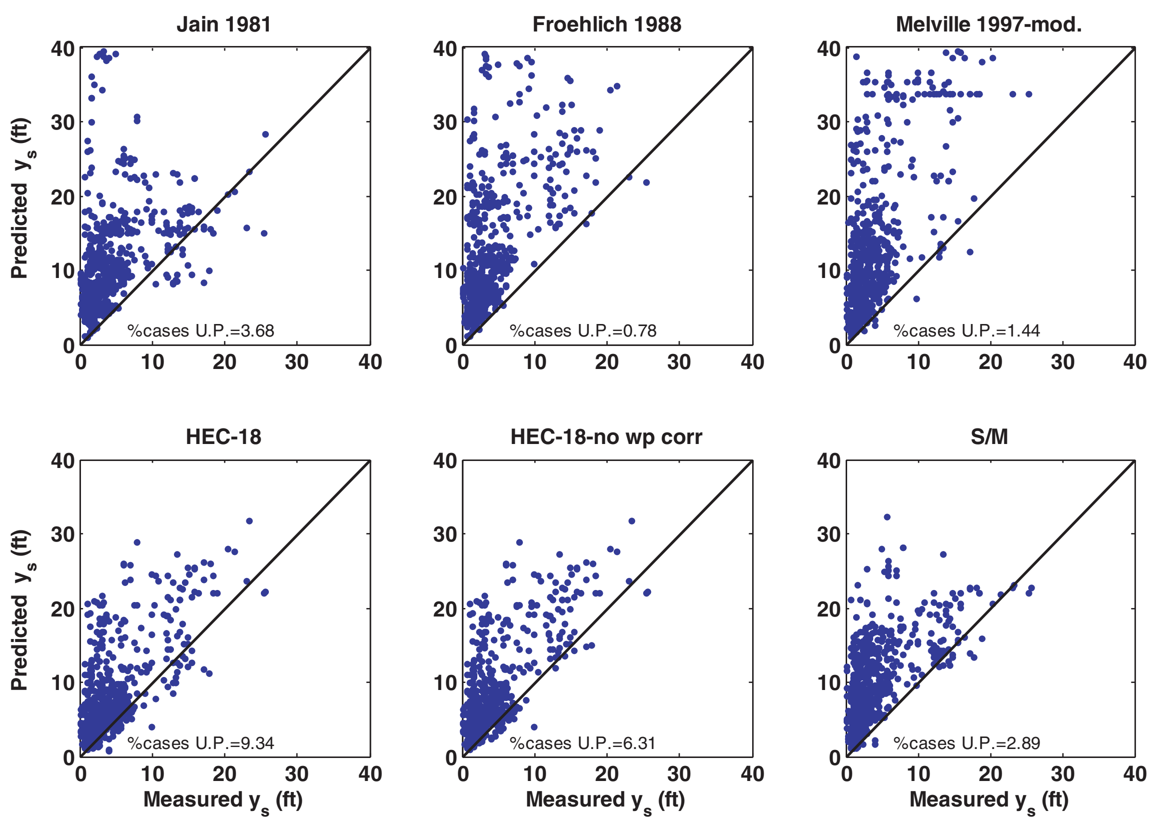
U.P. = underpredicted

Figure 31. Predicted versus measured equilibrium scour depths for six predictive equations for laboratory data.



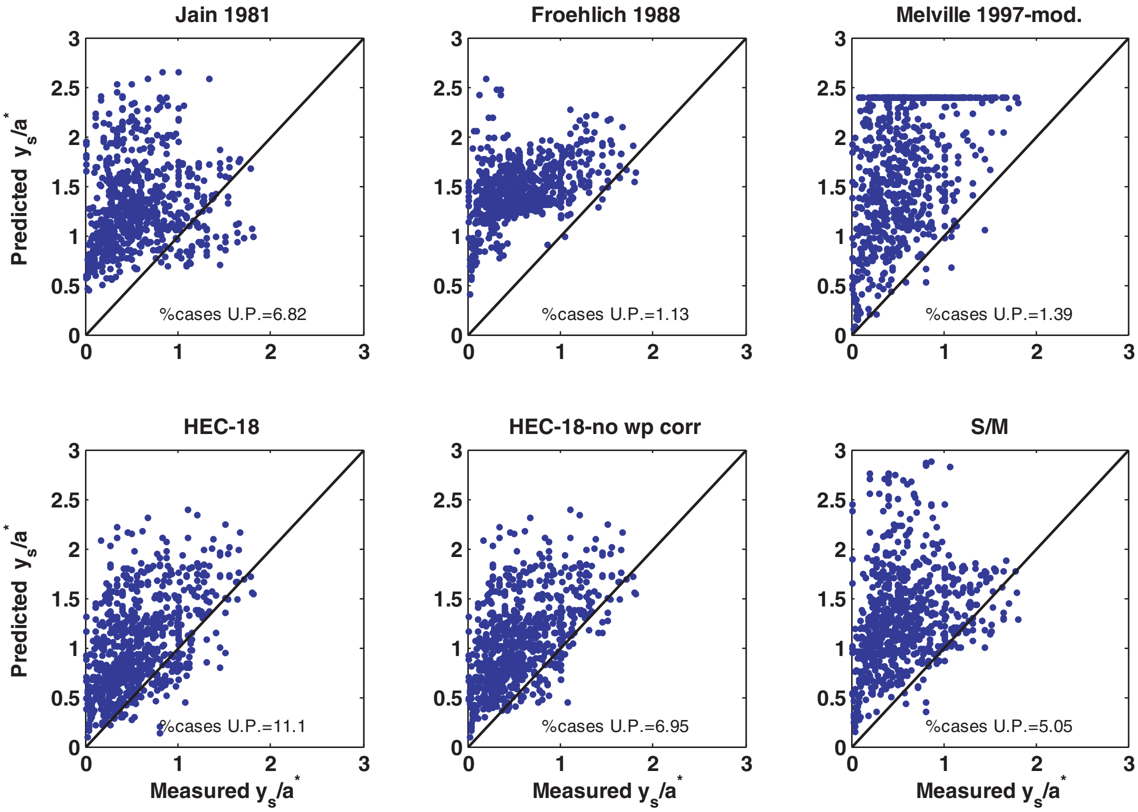
U.P. = underpredicted

Figure 32. Predicted versus measured normalized equilibrium scour depths for six predictive equations for laboratory data.



U.P. = underpredicted

Figure 33. Predicted versus measured equilibrium scour depths for six predictive equations for field data.



U.P. = underpredicted

Figure 34. Predicted versus measured normalized equilibrium scour depths for six predictive equations for field data.

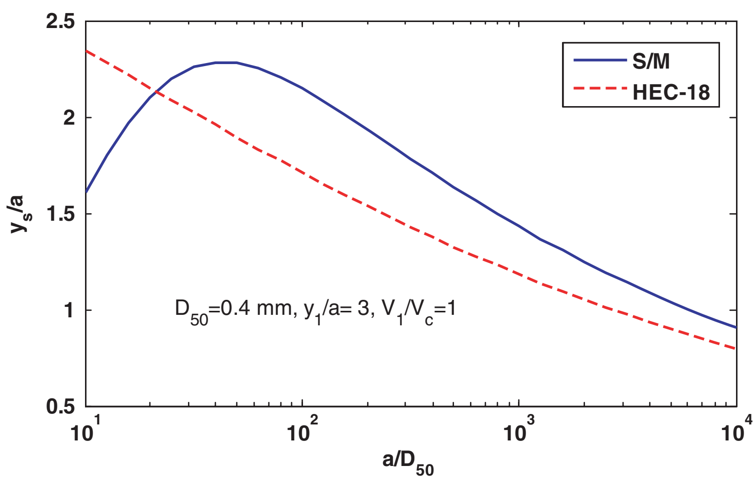


Figure 35. Comparison of S/M and HEC-18 predictions of normalized scour depth versus a/D_{50}.

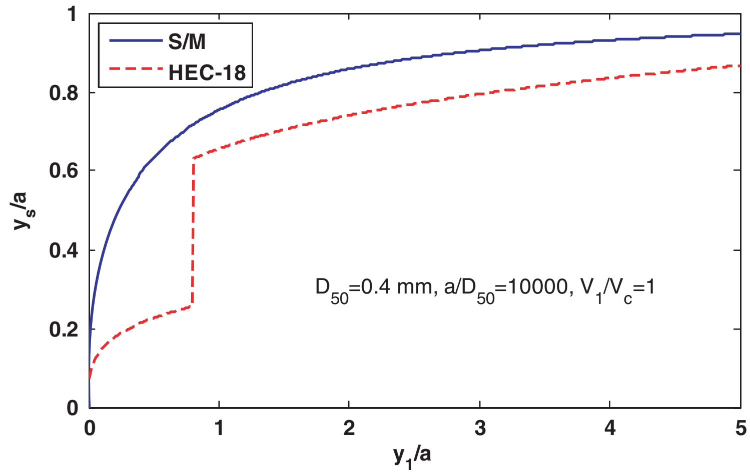


Figure 36. Comparison of S/M and HEC-18 predictions of S/M normalized scour depth versus y_1/a.

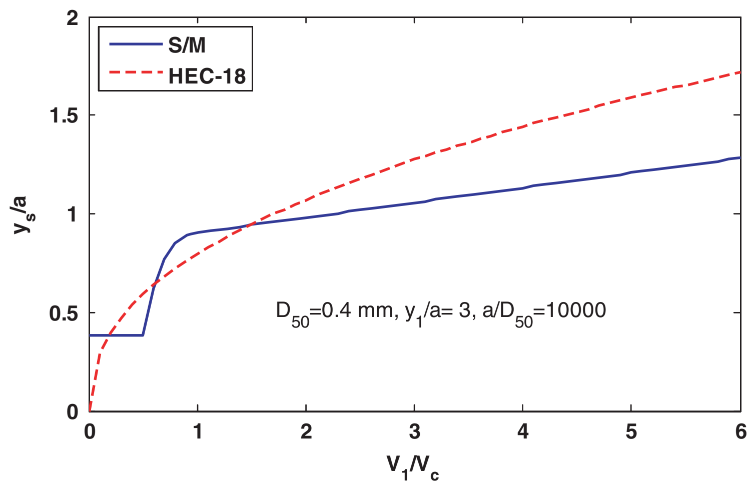


Figure 37. Comparison of S/M and HEC-18 predictions of normalized scour depth versus V_1/V_c.

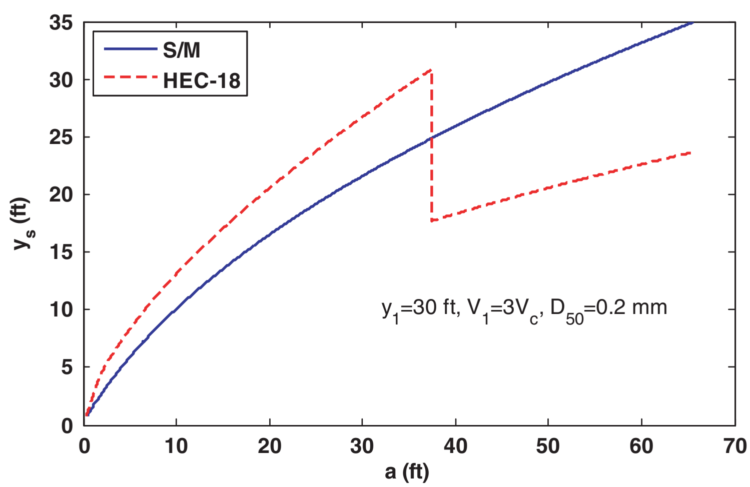


Figure 38. Comparison of S/M and HEC-18 equation predictions of equilibrium scour depth as a function of pier diameter (for D_{50} = 0.2 mm).

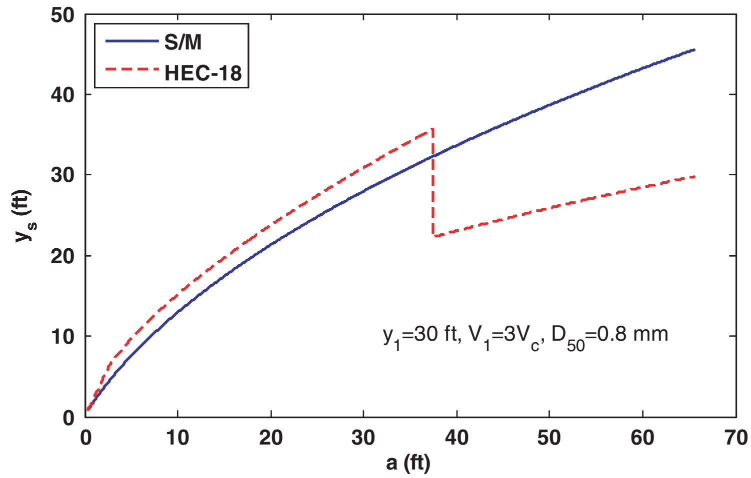


Figure 39. Comparison of S/M and HEC-18 equation predictions of equilibrium scour depth as a function of pier diameter (for $D_{50} = 0.8$ mm).

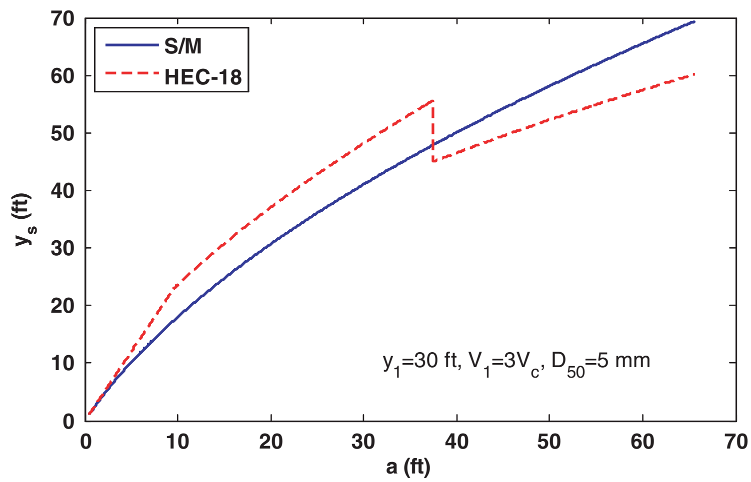


Figure 40. Comparison of S/M and HEC-18 equation predictions of equilibrium scour depth as a function of pier diameter (for $D_{50} = 5$ mm).

CHAPTER 5

Local Scour Evolution Predictive Methods

Introduction

Several methods have been proposed for predicting local scour evolution rates at bridge piers. Some of these methods and, where possible, the associated equations are shown in Table 12. The methods/equations vary in complexity. Some require computer programs to evaluate and therefore cannot be displayed in the table. In all cases considered, the computer programs were obtained from the developer and used in the evaluation process. A brief description of each of the 10 methods is presented in the following paragraphs.

Shen et al. (1966)

Shen et al. (1966) fitted the Chabert and Engeldinger (1956) data to an exponential function, Equation 29, to obtain an expression for scour depth as a function of time. The equation is based on a narrow range of flow and sediment conditions and was developed for circular piers.

Sumer et al. (1992)

Sumer et al. (1992) used measurements from 18 experiments of local live-bed scour at cylindrical piers to determine the exponent of an exponential function, Equation 30, for predicting scour evolution rates. The equilibrium scour depth must be known a priori. If this value is not known, the authors recommend a value of 1 to 1.5 times pier width based on the results of Breusers et al. (1977).

Kothyari et al. (1992)

Kothyari et al. (1992) based their method on the scouring potential of the horseshoe vortex, which decreases as the scour hole enlarges. They assumed that the shear stress under the vortex at time t is a function of the initial shear stress, the initial area of the vortex, and the area of the vortex at time t. The initial shear stress is assumed to be 4 times the shear stress on the approach flow bed. Sediment nonuniformity and stratification are shown to have a significant effect on the scour depth. The effects of these elements, as well as that of unsteadiness of flow, are taken into account in the proposed method. The method applies to scour development at circular piers and is based on experiments with pier widths ranging from 0.21 to 0.56 ft, uniform sediments with D_{50} equal to 0.4 to 4 mm, and sediment mixtures with D_{50} equal to 0.5 and 0.71 mm and standard deviations up to 7.8.

Melville and Chiew (1999)

Melville and Chiew (1999) proposed Equation 32 for the temporal development of local scour at cylindrical piers in uniform sand beds. The method was based on the data of Ettema (1980), together with additional data collected at the University of Auckland and Nanyang Technological University. They defined an equilibrium time scale for the scour process and showed that the equilibrium time scale, t*, is subject to the same influences of flow and sediment parameters as the equilibrium scour depth, y_s. That is, t* is dependent on y_1/a, V_1/V_c, and a/D_{50}. According to their method, the maximum time (in days) for the development of equilibrium scour depth is equal to 28.96 a/V_1.

Miller and Sheppard (2002)

The method comprises a semi-empirical mathematical model for the time rate of local scour at a circular pile located in cohesionless sediment and subjected to steady or unsteady water flow. The model is intended for use for both clear-water and live-bed scour conditions. A knowledge of the structure dimensions, flow conditions, sediment properties, and the equilibrium scour depth for the instantaneous flow conditions is required as input to the model. The scour hole is assumed to have the idealized geometry of an inverted frustum of a

Table 12. Equations/methods for estimating local scour depth evolution with time.

Reference	Equations	Notes	No.
Shen et al. (1966)	$\frac{y_{st}}{a} = 2.5Fr^{0.4}\left(1 - e^{mE^2}\right)$	$m = 0.026e^{-2.932y_1}$, y_1 in ft $E = \left(\frac{a}{y_1}\right)^{0.33} Fr^{0.33}\, ln\left(\frac{V_1 t}{y_1}\right)$	29
Sumer et al. (1992)	$y_{st} = y_s\left(1 - e^{-\frac{t}{T}}\right)$ $T = 0.0005\left(\frac{a^2}{\sqrt{g(S_s-1)D_{50}^3}}\right)\left(\frac{y_1}{a}\right)\left(\frac{u_*^2}{g(S_s-1)D_{50}}\right)^{-2.2}$	y_{st} = time-dependent scour $S_s = \frac{\rho_s}{\rho}$	30
Kothyari et al. (1992)	Computer program [see the discussion in the section "Kothyari et al. (2007)"]	Computer Program	31
Melville and Chiew (1999)	$y_{st}(t) = K_t y_s$ $K_t = exp\left\{C_1\left\|\frac{V_c}{V_1}\, ln\left(\frac{t}{t_e}\right)\right\|^{1.6}\right\}$ $t_e(\text{days}) = C_2\frac{a}{V_1}\left(\frac{V_1}{V_c} - 0.4\right)$ $\quad\frac{y_1}{a} > 6, 1.0 > \frac{V_1}{V_c} > 0.4$ $t_e(\text{days}) = C_3\frac{a}{V_1}\left(\frac{V_1}{V_c} - 0.4\right)\left(\frac{y_1}{a}\right)^{0.25}$ $\quad\frac{y_1}{a} \le 6, 1.0 > \frac{V_1}{V_c} > 0.4$	y_{st} = time-dependent scour y_s = Melville's equilibrium equation $C_1 = -0.03$ C_2 = 48.26 days/sec C_3 = 30.89 days/sec	32
Miller and Sheppard (2002)	Computer program [see the discussion in the section "Miller and Sheppard (2002)"]	Computer Program	33
Oliveto and Hagar (2002, 2005) **Oliveto et al. (2007)**	Clear water: $\frac{y_{st}}{(y_1a^2)^{1/3}} = 0.068\, K_s \sigma_g^{-0.5} F_d^{1.5}\, log\left(\frac{t}{t_R}\right)$ Live bed: $\frac{y_{st}}{(y_1a^2)^{1/3}} = 0.44\sigma_g^{-0.5}\left(F_d - F_{di}\right)^{1/4} log\left(\frac{t}{t_R}\right)$ $\quad\frac{t}{t_R} \le 300$ $\frac{y_{st}}{(y_1a^2)^{1/3}} = \sigma_g^{-0.5}\left(F_d - F_{di}\right)^{1/4}\left[0.80 + 0.12\, log\left(\frac{t}{t_R}\right)\right]$ $\quad 300 \le \frac{t}{t_R} < 10^5$	$F_d = \frac{V_1}{\sqrt{(S_s-1)gD_{50}}}$ $t_R = \frac{(y_1a^2)^{1/3}}{\sigma_g^{1/3}\sqrt{(S_s-1)gD_{50}}}$ F_{di} = densimetric particle Froude number for inception of scour	34
Mia and Nago (2003)	Computer program [see the discussion in the section "Mia and Nago (2003)"]	Computer Program	35
Chang et al. (2004)	Computer program [see the discussion in the section "Chang et al. (2004)"]	Computer Program	36
Yanmaz (2006)	$\frac{dS}{dT_s} = \frac{\alpha S^{0.37}\left(2S\, cot\,\varphi + 1\right)}{T_s^{0.95}\left(S^2 cot\,\varphi + S\right)}$ $S = \frac{y_{st}}{a}$ $T_s = \frac{t D_{50}\left[(S_s-1)gD_{50}\right]^{0.5}}{a^2}$ $\alpha = 0.231(tan\,\varphi)^{0.63}\left(\frac{u_* a}{D_{50}\sqrt{(S_s-1)g D_{50}}}\right)^{-0.95} TD_*^{0.24}\sigma_g^{1.9}$ $D_* = D_{50}\left[\frac{(S_s-1)g}{\nu^2}\right]^{1/3}$	y_{st} = time-dependent scour φ = angle of repose of bed sediment S_s = specific gravity of bed sediment σ_g = geometric standard deviation of particle size distribution u_* = shear velocity T = transport-stage parameter T_s = dimensionless time ν = kinematic viscosity	37

Table 12. (Continued).

Reference	Equations	Notes	No.
Kothyari et al. (2007)	$\frac{y_{st}}{(y_1 a^2)^{1/3}} = 0.272\sigma_g^{-0.5}(F_d - F_{d\beta})^{2/3} log\left(\frac{t}{t_R}\right)$ $F_{d\beta} = \left[F_{di} - 1.26\beta^{0.25}\left(\frac{R}{D_{50}}\right)^{1/6}\right]\sigma_g^{1/3}$ $log\left(\frac{t_e}{t_R}\right) = 4.8F_d^{0.2}$	β = a/B B = rectangular channel width R = hydraulic radius t_e = time to "end scour" t_R = reference time $F_d = \frac{V_1}{\sqrt{(S_s - 1)gD_{50}}}$ F_{di} = F_d for inception of scour	38

right circular cone that maintains a constant shape throughout the scour process. The slope of the sides of the scour hole is uniform and equal to the submerged angle of repose for the sediment. Removal of sediment from the scour hole is limited to a narrow band adjacent to the cylinder where the effective shear stress is greatest. The sediment transport function used in the model is based on commonly used functions for transport on a flat bed.

The effective shear stress in the scour hole, used in the sediment transport equation, is a function of the normalized scour depth (scour depth/equilibrium scour depth) and the structure, flow, and sediment parameters. The function for the shape of the effective shear stress versus normalized scour depth and its dependency on structure, flow, and sediment parameters was determined empirically using data from a number of clear-water and live-bed scour experiments conducted at the Universities of Florida and Auckland and the USGS Laboratory in Turners Falls, Massachusetts. These experiments cover a wide range of structure, flow, and sediment conditions. This method must be programmed to obtain the time history of the scour depth.

Oliveto and Hagar (2002, 2005) and Oliveto et al. (2007)

Oliveto and Hager (2002, 2005) proposed a method for the evolution of clear-water scour, while Oliveto et al. (2007) gave a method for the development of scour under live-bed conditions. The methodology, which is given as Equation 34, is based on an extensive set of experiments conducted at ETH Zurich, Switzerland. In formulating the equations, Oliveto et al. assumed that scour depth varies logarithmically with time. The clear-water equation is based on data for uniform sediments ranging from D_{50} equal to 0.55 to 5.3 mm and cylindrical pier widths ranging from 0.066 to 1.64 ft. Their live-bed equation is based on Chabert and Engeldinger (1956) and Sheppard and Miller (2006) data.

Mia and Nago (2003)

This method comprises a mathematical model for the development of local scour at cylindrical piers in cohesionless sediment subjected to steady flows in the clear-water scour regime. Input parameters to the model are structure dimensions, flow conditions, and sediment properties. The scour hole is assumed to be the frustum of an inverted cone with the angle of the frustum being the angle of repose of the bed sediment. The change in shear stress at the nose of the pier with increasing scour depth is estimated using a modified form of an equation by Kothyari et al. (1992) for the temporal variation of bed-shear velocity. The bed-load sediment transport function used is attributed to Yalin (1977). This method does not require knowledge of the equilibrium scour depth but rather, according to the authors, can compute the equilibrium scour depth and the time required to reach this depth.

This model was able to predict the data obtained by the model developers but did not accurately predict the data from other researchers.

Chang et al. (2004)

This method comprises a mathematical model for the development of local scour at circular piers in cohesionless non-uniform diameter sediments subjected to steady or unsteady flows in the clear-water scour regime. Input parameters for this model are structure dimensions, sediment properties (size, size distribution, mass density), and flow parameters. A sediment mixing layer thickness is computed along with an equivalent sediment size in the mixed layer. The dimensionless scour depth is expressed in terms of time normalized by Melville and Chiew's expression for time to equilibrium. The scour rates are divided into three normalized time intervals as the scour depth progresses toward an equilibrium time. This method was developed for steady flows, but according to the authors can be applied in a finite step-wise manner to unsteady flows. As with the two previous models, this model must be programmed in order to produce scour depth time histories. Chang et al. (2004) provided the computer program for this model, but it yielded unreasonable results for a number of conditions in the data sets and, therefore, was eliminated in the final analysis.

Yanmaz (2006)

Yanmaz's (2006) method for temporal variation of clear-water scour depth at cylindrical bridge piers is based on a common assumption that the shape of the scour hole can be approximated by an inverted cone having a circular base and slope equal to the angle of repose of the bed sediment. In applying the method, Yanmaz used initial measured scour depths as the starting point for the integration of Equation 37. The resulting equation has the form

$$y_{st} \propto t^{0.05}, \qquad (28)$$

which renders the results very sensitive to the choice of initial conditions. If the equation is integrated from time equals zero, the results are quite different from those presented by Yanmaz (2006), which started the integration from measured values in his experiments.

Kothyari et al. (2007)

Kothyari et al. (2007) undertook additional experiments to extend the methods of Oliveto and Hagar (2002, 2005) for evolution of clear-water scour at bridge piers. They developed a new relationship for the temporal scour evolution at piers based on the similitude of Froude by relating the scour depth to the difference between the actual and the entrainment densimetric particle Froude numbers. The new relationship is validated by the complete ETH Zurich data set and verified using data from Chabert and Engeldinger (1956), Ettema (1980), and Melville and Chiew (1999). An expression is given for the time to "end scour," which is equivalent to time to equilibrium scour.

Initial Screening of Scour Evolution Predictive Methods

An initial assessment of the selected scour evolution equations was performed to see if any of the methods yielded results that were clearly unreasonable. All of the methods were evaluated for combinations of values of the pertinent independent variables (and dimensionless groups).

This analysis showed that the methods do not yield consistent results, leading to a wide range of predictions of scour depth development with time. The comparison yielded several interesting results. The method by Shen et al. (1966) can give very high, or very low, predictions relative to the other methods. The methods of Kothyari et al. (1992, 2007) lead to very large scour depths under live-bed conditions. Similarly, the methods of Oliveto et al. (2007) and Oliveto and Hager (2002, 2005) yield relatively deep scour predictions. At this point in the study, the various predictive methods were not tested for the conditions of the laboratory and field data, thus only those producing unrealistically large or small scour values were eliminated from further consideration. The methods eliminated were Shen et al. (1966), Yanmaz (2006), Chang et al. (2004) and Sumer et al. (1992) due to their unrealistic predictions.

Modifications of Scour Evolution Predictive Methods

The possibility of improving the accuracy of the better performing predictive equations was investigated. Some of the methods, such as the Miller and Sheppard (2002) model, are complex and modifications would require significant effort. The Melville and Chiew (1999) model is less complex and easy to use and modify. By adjusting the coefficients in Melville and Chiew's model and replacing the equilibrium scour depth equation with the S/M equation, its accuracy was improved.

The recommended equation is given as Equation 39 (Table 13) with y_s being evaluated using the S/M equation.

Table 13. Modified Melville and Chiew equation (M/S equation).

Reference	Equations	Notes	No.
Melville/ Sheppard (Recommended)	$y_{st}(t) = K_t y_s$ $K_t = exp\left\{C_1 \left\lvert \frac{V_c}{V_1} ln\left(\frac{t}{t_e}\right)\right\rvert^{1.6}\right\}$ $t_e(days) = C_2 \frac{a}{V_1}\left(\frac{V_1}{V_c} - 0.4\right)$ $\quad \frac{y_1}{a} > 6, \quad \frac{V_1}{V_c} > 0.4$ $t_e(days) = C_3 \frac{a}{V_1}\left(\frac{V_1}{V_c} - 0.4\right)\left(\frac{y_1}{a}\right)^{0.25}$ $\quad \frac{y_1}{a} \le 6, \quad \frac{V_1}{V_c} > 0.4$ $t_{90}(days) = exp(-1.83\frac{V_1}{V_c})t_e$	y_{st} = time-dependent scour y_s = S/M equilibrium scour equation $C_1 = -0.04$ C_2 = 200 days/sec C_3 = 127.8 days/sec t_e = reference time t_{90} = time to reach 90% of equilibrium scour depth	39

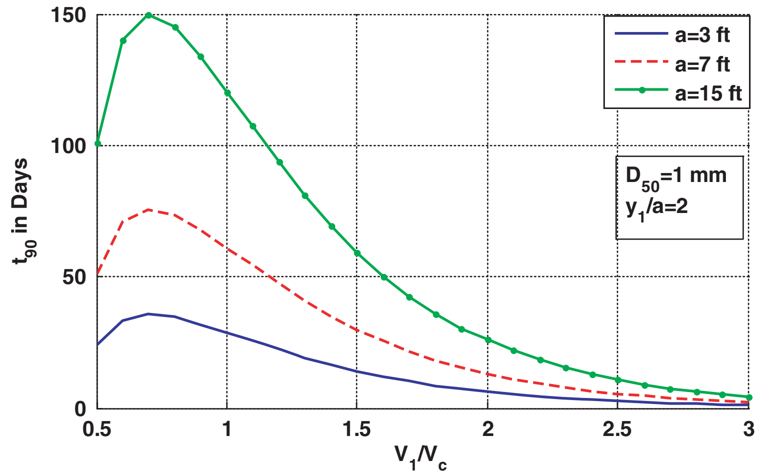


Figure 41. Plot of t_{90} versus V_1/V_c for different pier diameters.

This modified equation is referred to here as the Melville/Sheppard (M/S) equation.

Note that the original Melville and Chiew equation was developed for clear-water scour, while the M/S equation seems to work equally well for the live-bed scour data. Scour approaches an equilibrium value asymptotically; thus "time to equilibrium" is misleading at best and has no practical value. Time to a value like 90% of equilibrium is, however, useful and thus an expression for t_{90} is included with the M/S Equation. The expression for t_{90} in terms of the reference time t_e and V_1/V_c is given in Equation 40.

$$t_{90} = exp\left(-1.83\frac{V_1}{V_c}\right)t_e \qquad (40)$$

Plots of t_{90} versus V_1/V_c for one sediment size and normalized depth and three pier widths are shown in Figure 41.

Final Evaluation of Scour Evolution Predictive Methods

The scour evolution data are reported with different time steps. To calculate prediction errors, the following procedure was used. Each time series was divided into 100 equal time steps and the scour depths interpolated to these points in time. All of the predictive methods were then evaluated at each of the 100 times for the conditions of the experiment and compared with the measured values. The prediction error was computed using the following equations:

$$SSE\% = \frac{\sum_i \sum_j \left({}^i_j y_s^{measured} - {}^i_j y_s^{computed}\right)^2}{\sum_i \sum_j \left({}^i_j y_s^{measured}\right)^2} \times 100 \qquad (41)$$

The normalized SSE then becomes:

$$SSEn\% = \frac{\sum_i \sum_j \left(\frac{{}^i_j y_s^{measured}}{a} - \frac{{}^i_j y_s^{computed}}{a}\right)^2}{\sum_i \sum_j \left(\frac{{}^i_j y_s^{measured}}{a}\right)^2} \times 100 \qquad (42)$$

where i is the index for the time step and j is the index for the experiment. Seven different scour evolution predictive equations were evaluated (six from the literature review plus the recommended M/S equation). The total and underprediction errors for the various data sets were computed and the results are presented in Figures 42 through 45. Note that the scales for total and underprediction are substantially different in these plots in order to emphasize the underprediction. The Mia and Nago (2003) equation errors are not shown in the wide-pier plots (Figures 43 and 45), because they are very large.

The computed scour evolution errors include the differences between the equilibrium scour depth that each experiment would achieve and the predicted value using the S/M equation, as well as the errors for the scour rate. However, not all of the scour evolution tests were conducted for a sufficient duration; therefore, differences between predicted and measured equilibrium values could not be determined and used to assess the quality of the data.

Based on these results, the M/S equation performed the best of the seven in that it has the least total error and nearly the lowest underprediction error. However, as can be seen from the plots, all of the existing and modified methods have relatively large normalized errors. Note that the M/S equation has been optimized using the S/M equilibrium equation. The M/S equation should not be used with any other equilibrium scour equation.

It is important to note that the only live-bed scour evolution data in the data set is for small laboratory structures (maximum 1.0 ft for 1.3 > V_1/V_c >1.1 and 0.5 ft for V_1/V_c >1.3). The

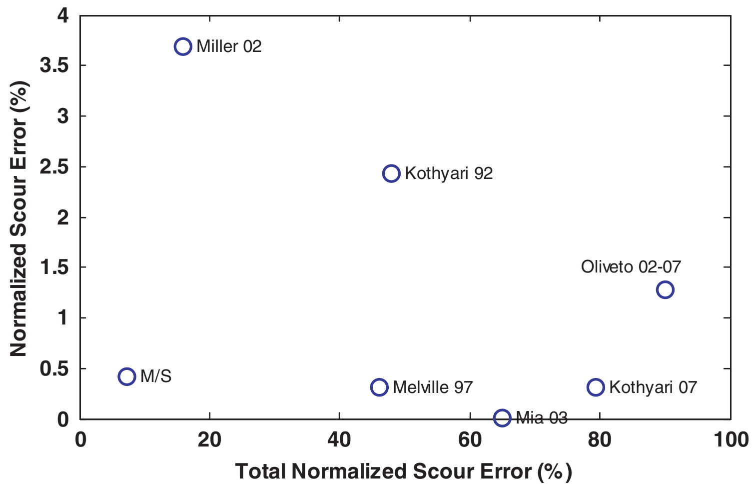


Figure 42. Underprediction versus total normalized scour evolution error.

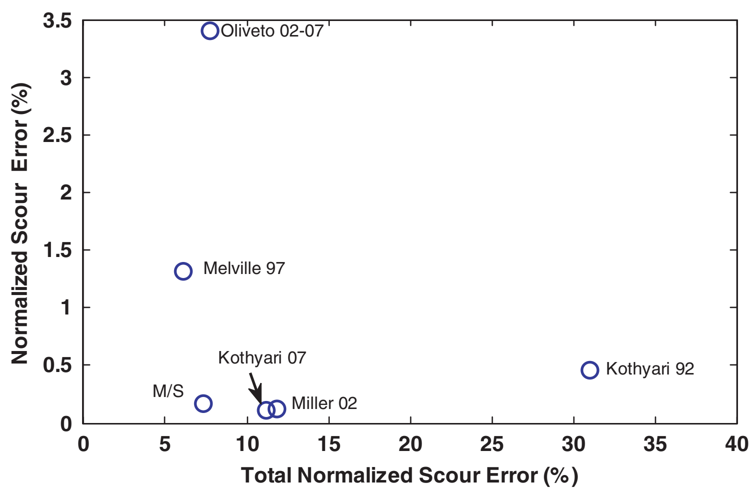


Figure 43. Underprediction versus total normalized scour evolution error for wide piers (defined as $y_1/a < 0.5$ and $a/D_{50} > 100$).

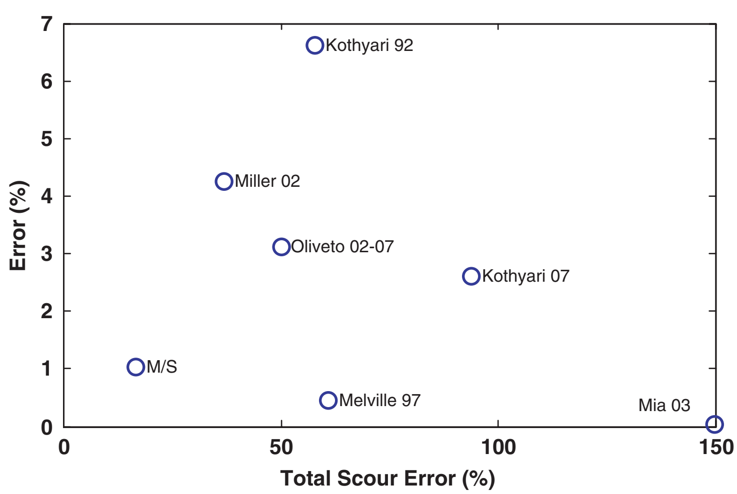


Figure 44. Underprediction versus total scour evolution error.

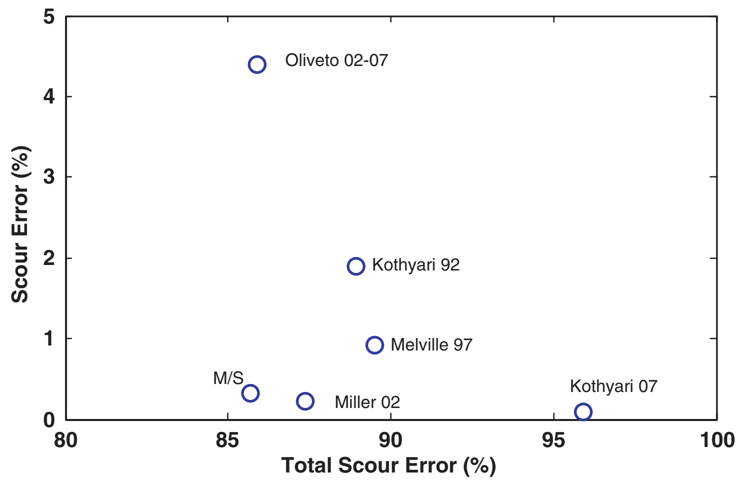


Figure 45. Underprediction versus total scour evolution error for wide piers (defined as $y_1/a < 0.5$ and $a/D_{50} > 100$).

best-performing equation with existing data, the M/S equation, yields, what appears to be, very conservative results for large prototype structures (conservative in the sense of predicting scour rates much higher than seems reasonable); however, there are no large-structure data in the live-bed scour range with which to test the predictions.

To illustrate the effects of sediment size on scour rates, plots of predicted time to reach 50%, 75%, and 90% of equilibrium scour depths versus flow velocity for a 30 ft diameter circular pier in 30 ft water depth are shown in Figure 46.

An example problem with a large, long skewed pier, founded in fine sand and subjected to live-bed flow conditions is presented in Appendix D. This example illustrates, among other things, the conservativeness of the scour evolution equation.

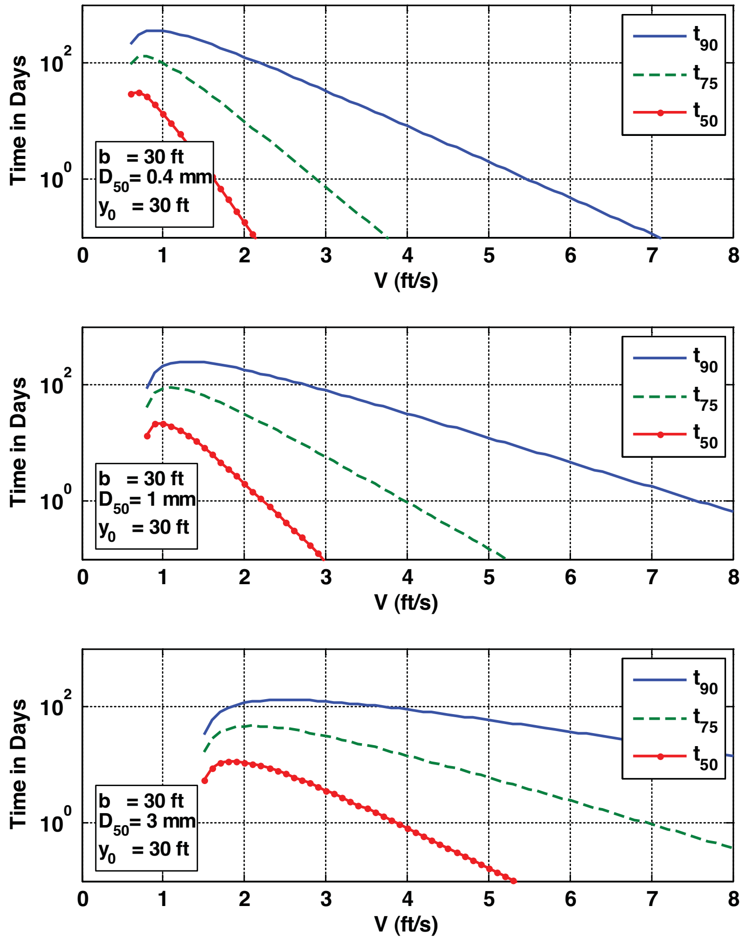


Figure 46. Time to 50%, 75%, and 90% of equilibrium scour versus flow velocity for 0.4, 1.0, and 3.0 mm sediment diameters.

CHAPTER 6

Scour at Piers Skewed to the Flow

The local scour data for long piers skewed to the flow is extremely limited. Most of the scour equations use similar methods to predict the effects of skewness on the equilibrium scour depth. These equations use either the curves proposed by Laursen and Toch (1956) to correct for flow skew angle or equations based on these curves. HEC-18 recommends adjusting the scour depth computed for zero skew angle by the expression in Equation 43.

$$K_2 = \left(cos(\alpha) + \frac{L}{a} sin(\alpha) \right)^{0.65}, \qquad (43)$$

where L is the pier length in the flow direction, α is the flow skew angle relative to the axis of the pier, and a is the width of the pier. The term in the parentheses is basically the ratio of the projected width to the pier width. This term is multiplied by the scour depth computed for zero skew angle to obtain the total scour. Sheppard and Renna (2005) use a different approach where the projected width replaces the pier width in the equations as shown in Equation 44 and Figure 47.

$$a^* = \frac{W\, cos(\alpha) + L\, sin(\alpha)}{W} \qquad (44)$$

Laursen and Toch (1956) do not give the sources for the data that was used to develop the curves in their paper. Schneible's doctoral dissertation (1951) contains the results from laboratory tests performed with piers of various shapes (oblong, elliptical, and lenticular) and skew angles from 0° to 30°. Plots of normalized scour depth versus flow skew angle are given in Figures 48 and 49 for different pier lengths. The measured and predicted scour depths are normalized by Schneible's measured scour depth for a circular pile whose diameter was equal to the width of his piers (0.2 ft). The equations used for the predictions in Figures 48 and 49 are from Sheppard and Renna (2005) and HEC-18. Note that both equations overpredict the effect of skewness and pile shape for all skew angles (including the zero angle). The HEC-18 curves for square and sharp piles are discontinuous because the shape factor applies only for skew angles less than 5°.

Mostafa (1994) provides another data set for skewed piers. In these experiments, measurements were repeated at different water depths. The skewness effect was found to be a function of the relative water depth (y_1/a). These measurements are shown in Figure 50 along with the predictions by the HEC-18 and the Sheppard and Renna (2005) methods. In the HEC-18 method, like other methods based on Laursen and Toch (1956), the skewness factor is not a function of water depth; therefore, only one HEC-18 prediction is plotted. The Sheppard and Renna method takes the effect of depth on the skewness factor into account so two predictions are shown. Note that the Sheppard and Renna method correctly predicts the fact that the skewness effect increases with increasing water depth. Both methods are conservative for skew angles smaller than 45°, but underpredict for angles between 45° and 85°. Flow skew angles greater than 45° are, however, rare.

Ettema et al. (1998) showed the effect of pier length on scour (Figure 51). Pier length also has a bearing on scour depth predictions for skewed piers. The effect of pier length is not taken into account by either of the skew angle methods. Note that for very short (in the flow direction) piers the scour depth increases.

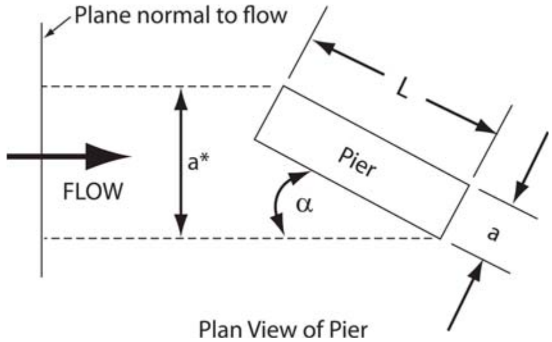
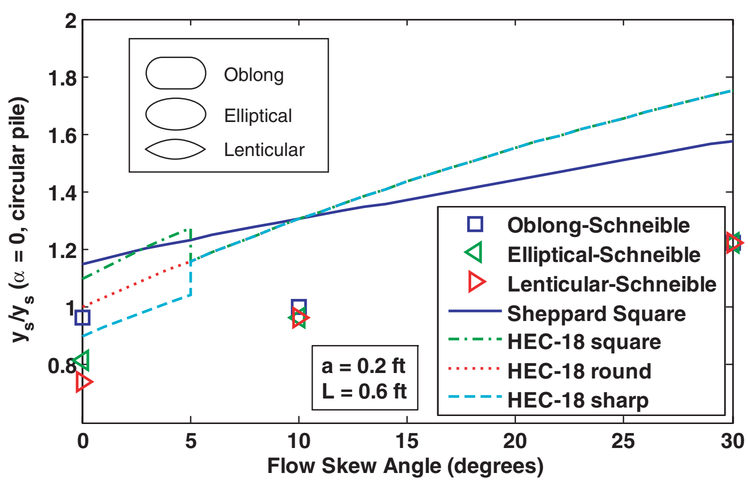
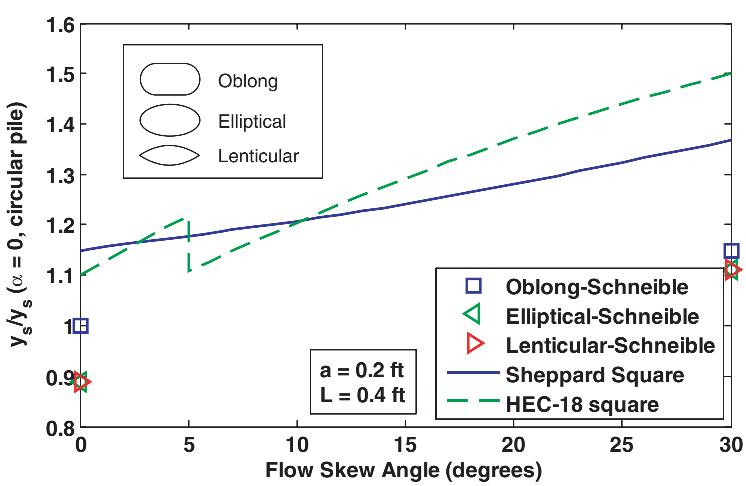


Figure 47. Diagram showing effective width of a long pier skewed to the flow (Sheppard and Renna 2005).



a = pier width, L = pier length

Figure 48. Predicted and measured scour depths as a function of flow skew angle.



a = pier width, L = pier length

Figure 49. Predicted and measured scour depths as a function of flow skew angle.

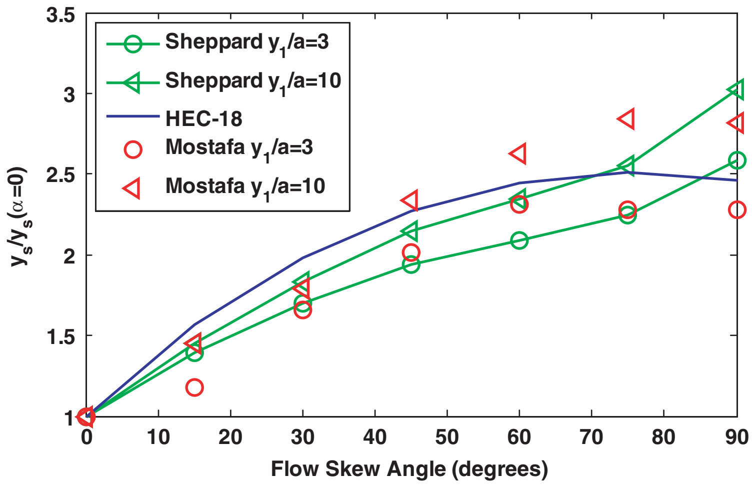
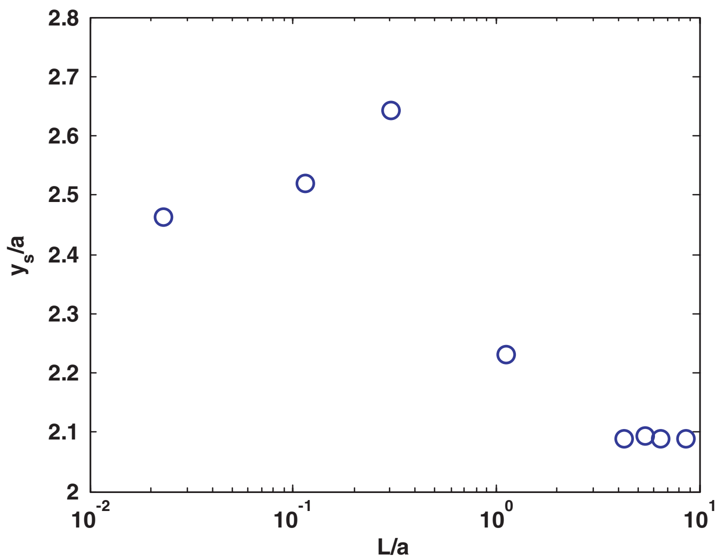


Figure 50. Normalized scour depth versus flow skew angle for rectangular piers [based on data from Mostafa (1994)].



a = pier width, L = pier length

Figure 51. Effect of pier length on scour for flows with zero skew angle [reproduced from Ettema et al. (1998)].

CHAPTER 7

Summary and Recommendations for Future Research

Summary

The objective of this research was to develop methods and procedures for predicting time-dependent local scour at wide piers and at long skewed piers, suitable for consideration and adoption by AASHTO. Most predictive methods/equations for equilibrium local scour in the literature do not place limits on the size of the structure and thus they may or may not apply to piers of all practical widths. There is, however, one published equation that provides a multiplier (Johnson and Torrico 1994) for the predictive equation in HEC-18 to account for large pier widths.

Equilibrium Scour

This research identified 23 methods/equations for predicting equilibrium local scour. The information and data search also resulted in 569 laboratory and 928 field equilibrium local scour data points. A method for assessing the quality of the data was developed and applied to the equilibrium scour data set. This procedure reduced the laboratory and field data to 441 and 791 values, respectively.

Laboratory data provide accurate input quantities (water depth, flow velocity, sediment properties, etc.), scour depths, and maturity of the scour hole at the time of measurement, but there are potential problems with scale effects. There are no scale effects with most field data; however, field data are, in general, less accurate. Perhaps the greatest problem with field data is the lack of knowledge regarding the maturity of the scour hole at the time of measurement. In some cases the measured scour hole depth could have resulted from an earlier, more severe flow event. For these reasons laboratory data were used for evaluating the predictive methods/equations. With only a few exceptions the predictive equations should, however, not underpredict the measured values provided care is taken to isolate the local scour from the other types of scour.

An initial quality control screening of the equilibrium scour methods/equations reduced the number of equations from 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 the error statistics calculations assisted in the ranking of the equations. The equations of Sheppard and Miller (2006) and Melville (1997) were melded and slightly modified to provide the best-performing equation in that it yields the least total error and the nearly least underprediction error of those tested.

The recommended equilibrium scour equation for design, referred to as the S/M equation, is a melding and slight modification of equations that have been in use for a number of years, as follows:

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

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

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

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

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

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

$$V_{1p1} = 5V_c$$

$$V_{1p2} = 0.6\sqrt{gy_1}$$

$$V_{1p} = \begin{cases} V_{1p1} \text{ for } V_{1p1} \geq V_{1p2} \\ V_{1p2} \text{ for } V_{1p2} > V_{1p1} \end{cases}$$

where

a^* = Effective Diameter

a^* = Projected Width * Shape Factor

Shape Factor = 1, circular

$$= 0.86 + 0.97\left(\left|\alpha - \frac{\pi}{4}\right|\right)^4 \text{, rectangular}$$

α = skew angle in radians

Flow Skew Angle

Only limited data exist for the effects of flow skew angle on equilibrium local scour depths. Most predictive methods for the effects of flow skew angle on local scour use some form of projected width of the pier (i.e., the horizontal dimension of the projection of the pier onto a plane normal to the flow) in their analysis. The equation in the current HEC-18 and many other equilibrium scour equations multiply the scour depth computed for zero skew angle by the ratio of projected to actual pier width to some power. The pier width is replaced by the projected width in the S/M equation, thus accounting for the observed effect of water depth on the scour depth's dependence on flow skew angle. Both methods give conservative predictions over the practical skew angle range from 0° to 45°. The recommended method for accounting for flow skew angle on equilibrium scour depths is from Sheppard and Renna (2005).

Scour Evolution Rates

Historically, scour evolution rates have received less attention than equilibrium scour. In spite of this, a significant number of laboratory time history local scour records were obtained from several different researchers as part of this study. Only one scour evolution field data set was obtained and it was for a small pile on a bridge over a tidal inlet on the Western Gulf Coast of Florida. Eight scour evolution predictive methods/equations were obtained in the information and data search. Most, but not all, of the scour evolution methods require knowledge of the equilibrium scour depth for their execution. The methods range in complexity from simple algebraic equations to more complex semi-empirical mathematical models that can be applied to unsteady flow conditions. The more complex methods do, however, need more work, especially for live-bed scour conditions. The level of work required for these cases exceeds the time and resources for this project.

A procedure for evaluating the predictive methods/equations using the time series data sets was developed and used to rank the methods according to their accuracy. The results were plotted as underprediction versus total error. For design purposes it is desirable to have minimal underprediction while maintaining total error as small as practical. The best-performing (least error) method was a modified form of Melville's equation in conjunction with the S/M equilibrium equation. The original Melville equation was developed for clear-water scour conditions. The modified equation, referred to as the M/S equation in this report, appears to work equally well for the live-bed data in the database. However, all of the live-bed scour evolution data are for small, laboratory-scale structures. Local scour at small structures, subjected to high-velocity flow, occurs very fast and is difficult to measure accurately. The predictive equations, while based on the physics of the processes, are still empirical and, thus, can be no better than the data on which they are based. The M/S equation predicts, what appear to be, very conservative scour rates for large structures subjected to high-velocity flows. That is, the predicted scour rate is larger than expected based on experience. This overprediction is most likely due to scale effects that are not properly accounted for in the scour evolution equations for live-bed scour conditions. There is, however, no data (laboratory or field) in the database for these conditions with which to test or modify the equations. The M/S scour evaluation equation is given by:

$$y_{st}(t) = K_t y_s$$

$$K_t = exp\left\{C_1\left|\frac{V_c}{V_1} ln\left(\frac{t}{t_c}\right)\right|^{1.6}\right\}$$

$$t_e(\text{days}) = C_2 \frac{a}{V_1}\left(\frac{V_1}{V_c} - 0.4\right) \qquad \text{for } \frac{y_1}{a} > 6, \frac{V_1}{V_c} > 0.4$$

$$t_e(\text{days}) = C_3 \frac{a}{V_1}\left(\frac{V_1}{V_c} - 0.4\right)\left(\frac{y_1}{a}\right)^{0.25} \qquad \text{for } \frac{y_1}{a} \leq 6, \frac{V_1}{V_c} > 0.4$$

$$t_{90}(\text{days}) = exp\left(-1.83\frac{V_1}{V_c}\right)t_e$$

where

y_s = S/M equilibrium scour equation

C_1 = −0.04

C_2 = 200

C_3 = 127.8

t_e = reference time

t_{90} = time to reach 90% of equilibrium scour depth

The M/S equation is the best performing of the equations/methods analyzed. The accuracy and range of structure pier widths for the clear-water scour data far exceeds that for the live-bed scour data. For this reason there is greater confidence in the prediction of scour evolution rates in the clear-water scour range.

There are many situations where the pier is large and the design flow velocity is relatively small and/or of short duration. Scour evolution rates are important for these cases because equilibrium scour depths are not likely to be achieved during the design event. Substantial bridge foundation cost savings could be realized if scour evolution rate were considered when predicting design scour depths. However, due to the lack of data for even moderate size structures in the live-bed scour range even the best-performing scour evolution equation (M/S equation) should not be used for design at this time. It can be used for estimating the level of conservativeness of design scour depths based on equilibrium scour values. More research, including controlled, live-bed tests with larger structures, is required before scour evolution rate predictions can be used in the development of design scour depths.

Recommendations for Future Research

The recommended equations for predicting equilibrium scour depths and scour evolution rate are empirical, although they are based on the physics of the sediment scour processes. As such, they can be no better than the data on which they are based. Because there are gaps in both the laboratory and field data, there are practical combinations of structure, sediment, and flow conditions where the equations have not been tested. Several experiments are proposed to address this problem. Detail regarding the recommended research is given in Appendix B (available on the *NCHRP Report 682* summary web page: www.trb.org/Main/Blurbs/164161.aspx). A list of these experiments is presented below, in ranked order:

1. Laboratory live-bed equilibrium scour and scour evolution rate experiments with uniform, fine sediment, and larger-model pile structures. The data for these conditions are extremely limited and yet many, if not most, bridge piers in the United States fall into this category (i.e., relatively large structures and high-velocity design flows).
2. Experiments to obtain equilibrium scour depths, and scour evolution rates, at rectangular piers, aligned with and skewed to the flow, under controlled laboratory conditions. Reported scour data for piers skewed to the flow is extremely limited. These tests could be performed with moderate size structures.
3. Similar experiments to those described in the first item above, but with much larger piers. These tests will have to be conducted in a large stream where the flows are sufficiently high and controlled and the sediment cohesionless.
4. Experiments to investigate equilibrium scour depths and scour evolution rates at complex and multiple piers. The vast majority of local scour experiments have been performed with circular or square cylinders while most prototype piers are more complex in shape. While methods exist (Richardson and Davis 2001, Sheppard and Renna 2005) for estimating local scour depths at piers with complex shapes, more laboratory data are needed to test the accuracy of these methods.
5. Experiments to investigate influences of sediment gradation, σ_g, on equilibrium scour depths. Armoring of the bed in the vicinity of a structure due to large sediment size distributions (large σ_g) can have a substantial impact on equilibrium scour depths. More data are needed before this effect can be predicted to sufficient accuracy for use in design.
6. Experiments to investigate local clear-water scour at low values of V_1/V_c ($V_1/V_c < 0.7$). Some reported laboratory and field scour depth data for low values of V_1/V_c are larger than would be expected. This investigation will improve scour depths for typical daily flows (which are sometimes used for ship impact analyses).
7. Experiments associated with testing the theory regarding pressure gradient–induced local scour (Sheppard 2004). There are several explanations for why equilibrium scour depends on a/D_{50}. Understanding the underlying mechanisms responsible for this dependence is important for the extrapolation of predictive equations to conditions where laboratory data cannot be easily obtained due to flume size limitations, etc.

The experiments described above are self-contained and can be conducted in parallel. Some could be conducted at more than one location while others, such as the one with large structures in an outside open channel, will require special channels and there will be limited location options.

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LIST OF SYMBOLS

Symbol	Description	Units	Dimensions
a	Pier width	ft (m)	L
a*	Projected width of pier	ft (m)	L
B	Rectangular channel width	ft (m)	L
D_{50}	Median grain diameter	mm	L
F_{di}	Densimetric particle Froude number for inception of scour	—	—
Fr	Froude Number of the approach flow	—	—
Fr_c	Critical Froude Number of the approach flow	—	—
g	Acceleration of gravity	ft/s^2 (m/s^2)	L/T^2
K_3	Factor for mode of sediment transport	—	—
K_4	Factor for armoring by bed material	—	—
K_s	Pier shape factor	—	—
K_θ	Discharge approach angle correction	—	—
K_w	Wide pier correction factor	—	—
q	Average discharge intensity upstream from the bridge	ft^3/s (m^3/s)	L^3/s
q_2	Local discharge intensity in contracted channel	ft^3/s (m^3/s)	L^3/s
R	Hydraulic radius	ft (m)	L
S_s	Specific gravity of bed sediment	—	—
t	Time	s, h, day	T
t_e	Time to "end" scour Kothyari et al. (2007)	s, h, day	T
u*	Shear velocity in the upstream section	ft/s (m/s)	L/T
$u*_c$	Sediment critical shear velocity	ft/s (m/s)	L/T
V_1	Average velocity at upstream main channel	ft/s (m/s)	L/T
V_c	Sediment critical velocity for D50	ft/s (m/s)	L/T
V_{c84}	Sediment critical velocity for D84	ft/s (m/s)	L/T
V_{lp1}	Velocity used in computing "live-bed peak velocity"	ft/s (m/s)	L/T
V_{lp2}	Velocity used in computing "live-bed peak velocity"	ft/s (m/s)	L/T
y_1	Average depth in the upstream main channel	ft (m)	L
y_r	Regime depth	ft (m)	L
y_s	Equilibrium scour depth	ft (m)	L
y_{st}	Time dependent scour depth	ft (m)	L
α	Flow skew angle	radians	Plane Angle
ν	Kinematic viscosity	ft^2/s (m^2/s)	L^2/T

Symbol	Description	Units	Dimensions
ρ	Density of water	$slugs/ft^3$ (kg/m^3)	FT^2/L^4
ρ_s	Density of sediment	$slugs/ft^3$ (kg/m^3)	FT^2/L^4
σ_g	Geometric standard deviation of particle size distribution	–	—
τ_1	Grain roughness component of bed shear stress	lbf/ft^2 (kPa)	F/L^2
τ_c	Critical shear stress at threshold of motion	lbf/ft^2 (kPa)	F/L^2
φ	Angle of repose of bed sediment	radians	Plane Angle

APPENDICES

Appendices A through E are available on the *NCHRP Report 682* summary web page: www.trb.org/Main/Blurbs/164161.aspx. Titles of the appendices are as follows:

- Appendix A: Questionnaire and Respondents
- Appendix B: Future Research Needs
- Appendix C: Additional Measured over Predicted Equilibrium Scour Plots
- Appendix D: Example Problem
- Appendix E: Equilibrium Scour Data

Abbreviations and acronyms used without definitions in TRB publications:

AAAE	American Association of Airport Executives
AASHO	American Association of State Highway Officials
AASHTO	American Association of State Highway and Transportation Officials
ACI–NA	Airports Council International–North America
ACRP	Airport Cooperative Research Program
ADA	Americans with Disabilities Act
APTA	American Public Transportation Association
ASCE	American Society of Civil Engineers
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
ATA	Air Transport Association
ATA	American Trucking Associations
CTAA	Community Transportation Association of America
CTBSSP	Commercial Truck and Bus Safety Synthesis Program
DHS	Department of Homeland Security
DOE	Department of Energy
EPA	Environmental Protection Agency
FAA	Federal Aviation Administration
FHWA	Federal Highway Administration
FMCSA	Federal Motor Carrier Safety Administration
FRA	Federal Railroad Administration
FTA	Federal Transit Administration
HMCRP	Hazardous Materials Cooperative Research Program
IEEE	Institute of Electrical and Electronics Engineers
ISTEA	Intermodal Surface Transportation Efficiency Act of 1991
ITE	Institute of Transportation Engineers
NASA	National Aeronautics and Space Administration
NASAO	National Association of State Aviation Officials
NCFRP	National Cooperative Freight Research Program
NCHRP	National Cooperative Highway Research Program
NHTSA	National Highway Traffic Safety Administration
NTSB	National Transportation Safety Board
PHMSA	Pipeline and Hazardous Materials Safety Administration
RITA	Research and Innovative Technology Administration
SAE	Society of Automotive Engineers
SAFETEA-LU	Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users (2005)
TCRP	Transit Cooperative Research Program
TEA-21	Transportation Equity Act for the 21st Century (1998)
TRB	Transportation Research Board
TSA	Transportation Security Administration
U.S.DOT	United States Department of Transportation