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David S. Mueller and Chad R. Wagner[1]

ABSTRACT

The variability and complexity of site conditions make the development of methodology for predicting scour at bridge piers difficult. Laboratory investigations often oversimplify or ignore many of the complexities that are common in the field. The U.S. Geological Survey, in cooperation with the Federal Highway Administration and many State highway agencies, has collected and compiled 493 field measurements of local pier scour at 79 sites located in 17 States. The pier-scour measurements were used to evaluate 26 published pier scour equations. No single equation conclusively was better than the others, but the top six equations generally appear to be the Froehlich Design, HEC-18, HEC-18-K4, HEC-18-K4Mu, HEC-18-K4Mo (>2 mm), and Mississippi equations. However, comparison of the scour predicted from these equations with the observed scour clearly shows that there is variability in the field data that is not correctly accounted for in the equations. Analysis of laboratory and field data indicated the importance of bed-material characteristics as an explanatory variable in the predictive equations. A new correction to the HEC-18 equation to account for the relative bed-material size is presented.

INTRODUCTION

The lack of and need for reliable and complete field data on scour at bridges has been a recurring conclusion of many researchers (Shen and others, 1969; Melville and others, 1989; Richardson and Davis, 1995). Froehlich (1988), Zhuravljov (1978), Gao and others (1992), and others have compiled field measurements on local pier scour. These historical data sets contain valuable information, but most do not contain information on all of the major variables known to affect scour. Froehlich (1988) was unable to include the effect of sediment gradation in his analysis because many data sets did not include this information. Johnson (1995), in a comparison of seven published pier-scour equations with field data, assumed uniform sediment size because sediment-gradation information was not available for most of the data.

Cooperative research among the Federal Highway Administration (FHWA), State highway departments, and the U.S. Geological Survey (USGS) has allowed the collection of scour data at bridges during floods and has resulted in an extensive data base of local pier-scour measurements. This paper provides a summary of research completed for the FHWA (Mueller and Wagner, in press). A complete evaluation of all equations for the prediction of local scour around bridge piers is beyond the scope of this paper; however, 26 commonly cited pier-scour equations are compared with field measurements of scour to evaluate their potential to be used as

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design equations. A design equation should predict scour accurately; however, predicting sediment transport and scour accurately is difficult. If a design equation predicts too little scour the bridge could be under-designed and the traveling public put at risk. A good design equation should be as accurate as possible, but when in error, the equation should overpredict scour to ensure that the design always is safe. In addition, comparison of the field data with commonly published relations from laboratory investigations are presented. Finally, the importance of bed material properties on the depth of scour is shown and a new correction term introduced.

SUMMARY OF FIELD DATA

The 493 local pier-scour measurements in the Bridge Scour Data Management System (BSDMS) (Landers and others, 1996) were filtered, to ensure that the data were representative of the maximum scour that occurred for the recorded hydraulic conditions. The data collection techniques typically limited the data to cross sections along the upstream and downstream edges of the bridge. All measurements where the flow was not aligned with the pier were removed from the data set, because data were seldom collected along the sides of the piers. Where there were measurements along the upstream and downstream edges of the bridge, only the maximum depth of scour was used. All measurements where the effect of debris on the depth of scour was rated "substantial" were removed from the data set. Observations with scour in cohesive material also were removed from this analysis.

The hydraulic parameters measured should be the hydraulic conditions that caused the measured depth of scour. It is difficult to exactly associate hydraulics with a depth of scour because of the temporal development of the scour hole. Except at a few sites, the temporal development of the scour holes reported in the BSDMS is not available. It was rationalized that if the scour hole can be associated reasonably with the reported hydraulic conditions, the velocity at the pier must be competent to erode the bed material. Gao and others (1992) published an equation to compute the critical approach velocity for transport of the bed material at the pier. All measurements having an approach velocity (V_o) less than the critical approach velocity for transport at the pier (V_c') were removed from the data set.

Of the 493 pier scour measurements in the BSDMS, 266 were selected for this analysis. These 266 measurements represent 106 different piers at 53 bridges located in 15 States. A summary of the selected data and commonly used dimensionless variables are provided in Table 1. The maximum and minimum values of the data and of the dimensionless variables represent a range equal to or greater than most laboratory investigations. Unlike laboratory investigations, the distribution of the data cannot be precisely controlled in the field, and the data tend to be grouped near the low end of most of the variables.

DISCUSSION OF EQUATIONS

Local pier scour has been a popular topic of study by many laboratory researchers. A literature review by McIntosh (1989) found that more than 35 equations had been proposed for predicting the scour depth at a bridge pier. Most local-scour equations are based on research in laboratory flumes with noncohesive, uniform bed material and limited verification of results with field

Table 1 - Summary statistics for selected pier-scour measurements.

[D_x is the grain size for which x percent is finer; g is the acceleration of gravity; V_c is the velocity for incipient transport; -- is not applicable]

Variable	Units	Number of Points	Minimum	25^{th} Quartile	Median	75^{th} Quartile	Maximum	Mean	Standard Deviation	Coefficient of Variation	Skewness
Depth of scour (y_s)	m	266	0.00	0.43	0.61	1.19	7.65	1.06	1.19	1.13	2.68
Pier width (b)	m	266	0.38	0.88	1.13	1.52	5.52	1.53	1.11	0.73	1.88
Approach velocity (V_o)	m	266	0.18	0.66	1.14	1.89	4.48	1.36	0.90	0.66	0.94
Approach depth (y_o)	m	266	0.12	2.45	4.39	6.45	20.03	4.86	3.24	0.67	1.18
D_{16}	mm	262	0.03	0.20	0.35	3.78	68.00	5.48	13.26	2.42	3.45
D_{50}	mm	266	0.15	0.48	0.74	8.00	108.00	10.61	20.74	1.95	2.75
D_{84}	mm	262	0.26	1.30	2.35	29.00	233.00	22.36	39.71	1.78	2.91
D_{95}	mm	262	0.28	2.08	7.45	44.00	350.00	34.87	58.85	1.69	2.78
Gradation coefficient (σ_g)	--	262	1.20	2.03	2.30	3.65	21.80	3.21	2.27	0.71	3.17
Drainage area (DA)	km^2	192	166	1197	3680	9402	1805222	32706	135836	4.15	11.80
Slope (S)	m/m	219	0.00010	0.00016	0.00050	0.00105	0.00500	0.00090	0.00103	1.14	1.96
y_o / b	--	266	0.12	1.87	3.05	5.31	13.84	3.91	2.81	0.72	1.21
b / D_{50}	--	266	8.47	129.54	1024.54	1828.80	14224.00	2219.03	3401.47	1.53	2.33
y_s / b	--	266	0.00	0.40	0.58	0.88	2.09	0.68	0.41	0.61	1.01
V_o / V_c	--	266	0.43	0.75	1.14	1.53	4.92	1.32	0.84	0.64	2.15
V_o / $(gy_o)^{0.5}$	--	266	0.04	0.11	0.17	0.33	0.83	0.23	0.16	0.70	1.17

data (McIntosh, 1989). In evaluating and applying scour-prediction equations, it is valuable to know the limitations of the equations, the conditions for which they were developed, how the underlying data were interpreted, and the methods used to develop the equations. Such information about each equation has been published previously in Landers and Mueller (1996), Mueller (1996), and Pritsivelis (1999).

Three approaches have been used to develop equations that predict the maximum depth of scour at a pier. The first approach is to predict the maximum depth of scour that could occur at the bridge pier under any condition. The second approach is to predict, as accurately as possible, the maximum depth of scour for a given set of hydraulic and bed-material conditions. The equations from this approach often are developed by multiple regression analysis and, by definition, underpredict the depth of scour for about one-half of the observations used in the equation development. The third approach is to develop a design equation. A good design equation should predict accurately the scour depth for a given set of site and flood conditions, but when in error, always should error by predicting too much scour.

Analysis of how each equation addresses pier width, approach velocity, approach depth, and bed-material properties provides an indication of the effect of these variables on the depth of scour. The selected equations are formulated into two patterns. The regime equations are written to compute the total depth of flow including local scour. Nonregime equations are written to compute the depth of local scour only. The equation name, reference, and a summary of the basic variables included in the equation are listed in Table 2. The pier width is included in over 75 percent of the equations. The regime equations have an exponent on pier width between 0.2 and 0.25. The exponent on pier width ranges from 0.6 to 0.75 in over one-half of the nonregime equations when the pier width could be isolated. The smaller exponents on pier width for the regime equations are justified because pier width should have less effect on the total depth than on the depth of local pier scour. The exponents on approach velocity range from 0.2 to 0.68 (except for Shen-Maza with an exponent of 2) and on approach depth from 0.135 to 0.75. This variability indicates that there is a lack of agreement among the equations on the effect of approach depth and velocity on the scour depth. The median grain size only is included in 11 equations; it only can be isolated in four equations where it has a small negative exponent.

COMPARISON OF PREDICTIONS WITH FIELD DATA

This evaluation of the selected equations focuses primarily on the capability of the equations to be used as design equations for different site and flood conditions. The objective is to find an equation that accurately predicts the scour depth for the specified conditions, but when in error, overestimates the depth of scour. The capability of the equations to accurately predict the scour depth for the variety of field conditions represented in this data set varies greatly. Some of the equations (Ahmad, Breusers-Hancu, Chitale, Inglis-Poona I, Melville and Sutherland, and Shen-Maza) displayed trends away from the line of equality, indicating those equations do not properly represent the processes responsible for local pier scour in the field. Several equations (Arkansas, Blench-Inglis I, Blench-Inglis II, Froehlich, Shen, and Simplified Chinese) underpredict the scour depth for a large number of the observations and probably should not be considered for design equations. The other equations displayed some trend along the line of

Table 2 - Summary of exponents for variables used in selected equations.
[D_{50} is the median grain size, $\mathbf{F}_p$ is the pier Froude number]

Equation (Reference)	Pier Width	Approach		D_{50}	Other Bed Material
		Velocity	Depth		
Ahmad (1953)		0.667	0.667		
Arkansas (Southard, 1992)		0.684		-0.117	
Blench-Inglis I (Blench, 1962)*	0.25		0.75		
Blench-Inglis II (Blench, 1962)*	0.25	0.5	0.5	-0.125	
Breusers (1965)	1.0				
Breusers-Hancu (Pritsivelis, 1999)	X		X		
Chitale (1962)		X	X		
Froehlich (1988)	0.62	0.2	0.36	-0.08	
Froehlich Design (Froehlich, 1988)	X	0.2	0.36	-0.08	
HEC-18 (Richardson and others, 1993)	0.65	0.43	0.135		
HEC-18-K4 (Richardson and Davis, 1995)	X	X	X	X	X
HEC-18-K4Mo (Molinas, 2000)	X	X	X	X	X
HEC-18-K4Mu (Mueller, 1996)	X	X	X	X	X
Inglis-Poona I (Inglis, 1949)*	0.22	0.52	X		
Inglis-Poona II (Inglis, 1949)*	0.22		X		
Larras (1963)	0.75				
Laursen I (Neill, 1964)	0.7		0.3		
Laursen II (Laursen, 1962)	X		X		
Laursen-Callander (Melville, 1975)	0.5		0.5		
Melville and Sutherland (1988)	X	X	X	X	X
Mississippi (Wilson, 1995)	0.6		0.4		
Molinas (Molinas, 2000)	0.66	X	X	X	X
Shen (Shen and others, 1969)	0.62	0.62			
Shen-Maza $\mathbf{F}_p$<0.2 $\mathbf{F}_p$>0.2 (Shen and others, 1969)	 0.67	2.0 0.67			
Sheppard (Sheppard, University of Florida, written communication, 2001)	X	X	X	X	
Simplified Chinese (Gao and others, 1992)	X	X	X	X	

*Regime equation that in its original form computed total depth including pier scour and approach depth.

X - Equation uses this variable but the equation is complex, and this variable cannot be algebraically isolated.

equality with few underpredictions, but they display a broad scatter of data and often do not accurately predict the observed scour.

Ranking the performance of scour-prediction equations is difficult because of the tradeoff between accuracy and underpredictions. If only accuracy is considered, the sum of squared errors can be used to evaluate the equations performance (Table 3). This statistic shows the Froehlich equation to be the most accurate equation; however, the Froehlich equation is a regression equation and underpredicted the scour depth for 129 of 266 field observations. If the smallest number of underpredictions is used to evaluate the equations, the Froehlich Design equation is the best equation because it underestimated only four observations. The Froehlich Design equation, however, ranked 19^{th} based on the sum of squared errors criteria. The magnitude of the underpredictions is just as important, if not more so, than the number of underpredictions; thus, the sum of squared errors for those observations that were underpredicted is another factor that should be considered in the analysis. The Melville and Sutherland equation had the lowest sum of squared errors for the underpredicted observations, but this equation ranked 26^{th} in overall sum of squared errors. The Melville and Sutherland equation slightly underestimated scour in a few case, but grossly overestimated scour for many cases. The Froehlich Design, HEC-18-K4, HEC-18, HEC-18-K4Mu, and HEC-18-K4Mo (>2 mm) equations all had low sum of squared errors for the underpredicted observations. If all ranks for each equation are totaled, the Froehlich Design equation appears to be the best equation, followed by the HEC-18-K4Mu, HEC-18-K4, HEC-18, Mississippi, and HEC-18-K4Mo (>2 mm) equations; however, the Froehlich Design equation had the largest sum of squared errors for this group. If only the ranks based on the two sum of squared error categories are totaled for each equation, the HEC-18-K4Mu equation is favored and the Froehlich Design equation drops to a rank of 8.5. No single equation conclusively is better than the rest, but the top six equations generally appear to be the Froehlich Design, HEC-18, HEC-18-K4, HEC-18-K4Mu, HEC-18-K4Mo (>2 mm), and Mississippi equations.

Because no single equation was superior to the others and none of the equations accurately predicted the scour for all site and hydrologic conditions, it is important to assess where the equations failed. Residuals of selected equations were compared with Froude number ($V_o/(gy_0)^{0.5}$), relative velocity (V_c/V_o), median grain size (D_{50}), pier width (b), relative bed material size (b/D_{50}), and relative depth (y_o/b) to assess where the equations may fail to properly account for the scour processes (Mueller and Wagner, in press). The Froehlich equation displayed no clear patterns. The Froehlich equation, which is a regression equation, fit the data reasonably well; however, to convert the Froehlich equation from a regression equation to a design equation Froehlich added the pier width as a safety factor. The safety factor increases the scatter in the data. A comparison of residuals versus pier width showed that the safety factor became too large as the pier width increased. The HEC-18-K4 equation showed patterns of increasing overprediction as Froude number (0-0.4), median grain size, and pier width increased. The K_4, proposed by Mueller (1996), reduced the effect of the Froude number and median grain size, but patterns still were evident in the pier width. Only pier width displayed a pattern in the residuals of the Mississippi equation. Another revised HEC-18 equation, HEC-18-K4Mo, (Molinas, 2000) also showed patterns in the residuals with Froude number and median grain size, but the most dominant pattern was the bottom envelope on the pier width. Most underpredictions

Table 3 - Summary of the performance of the selected pier-scour equations.
[SSE, sum of squared errors]

				Number of Under Predictions				Summation of Ranks			
				Count		SSE		All Ranks		SSE Ranks	
Equation	Number of Observations	SSE Magnitude	Rank	Number	Rank	Magnitude	Rank	Total	Rank	Total	Rank
Ahmad	266	7536.86	27	61	14	159.48	22	63	23	49	25.5
Arkansas	266	239.52	4	74	20.5	165.61	23	47.5	20	27	16
Blench-Inglis I	266	265.83	5	74	20.5	52.14	17	42.5	18	22	11
Blench-Inglis II	266	954.55	17	174	27	824.60	27	71	25	44	23
Breusers	266	670.40	13	18	9.5	7.14	9	31.5	7.5	22	11
Breusers-Hancu	266	1205.60	21	77	22	201.18	25	68	24	46	24
Chitale	266	2299.40	25	90	23	169.37	24	72	26	49	25.5
Froehlich	266	160.67	1	129	26	98.24	21	48	21	22	11
Froehlich Design	266	1067.77	19	4	1	1.51	2	22	1	21	8.5
HEC-18	266	822.38	15	13	7	2.16	4	26	4.5	19	4.5
HEC-18-K4	262	791.54	14	15	8	1.93	3	25	3	17	2
HEC-18-K4Mo (All)	266	495.18	11	65	16	17.01	13	40	15.5	24	13
HEC-18-K4Mo (> 2 mm)	266	608.79	12	21	11	2.47	6	29	6	18	3
HEC-18-K4Mu	266	448.53	9	18	9.5	2.23	5	23.5	2	14	1
Inglis-Poona I	266	1758.81	24	119	25	597.74	26	75	27	50	27
Inglis-Poona II	266	229.68	3	72	19	45.67	16	38	12	19	4.5
Larras	266	311.13	7	48	13	72.09	20	40	15.5	27	16
Laursen I	266	1277.71	23	6	2	5.20	8	33	10	31	21
Laursen II	266	930.57	16	9	3.5	10.95	12	31.5	7.5	28	18
Laursen-Callendar	266	960.55	18	9	3.5	10.39	11	32.5	9	29	19.5
Melville & Sutherland	262	3092.08	26	28	12	1.45	1	39	13.5	27	14
Mississippi	266	465.05	10	12	6	7.90	10	26	4.5	20	6
Molinas	262	199.79	2	103	24	55.96	18	44	19	20	7
Shen	266	300.77	6	69	18	37.00	15	39	13.5	21	8.5
Shen-Maza	266	1133.23	20	67	17	36.90	14	51	22	34	22
Sheppard	262	1276.04	22	11	5	3.89	7	34	11	29	19.5
Simplified Chinese	254	344.46	8	62	15	56.21	19	42	17	27	16

occurred for grain sizes less than 2 mm. Two thirds of the under predictions by HEC-18-K4Mo occur at grain sizes less than 2 mm (Table 3). Limiting the K_i and K_4 bed material corrections to median grain sizes greater than 2 mm, improves the performance of the Molinas correction.

COMPARISON OF LABORATORY EXPERIMENTS WITH FIELD DATA

Laboratory research has been the primary tool in defining the relation among variables affecting the depth of pier scour. The validity of these relations has not been proven in the field. Landers and Mueller (1996) evaluated many relations developed in the laboratory by use of transformed data (to obtain a more normal distribution) and smoothing techniques to assess general trends in the data. They found only minimal agreement between the field data and laboratory-based relations. The assessment presented herein investigates the relations in the field data for variable combinations commonly reported by laboratory investigations. Unlike the data set used by Landers and Mueller (1996), all data at skewed piers were removed to prevent bias by these data, as previously discussed. No transformations were applied unless necessary for consistency with published relations. Whereas this lack of transformation results in a less uniform distribution of the data, this approach benefits from a more direct comparison with laboratory work.

Relative Velocity

Through a series of laboratory experiments, Chiew (1984) found relative scour depths (y_s/b) were less for ripple-forming sediments than for nonripple-forming sediments at relative velocities (V_o/V_c) ranging from 0.6 to 2. He determined that this reduction in scour depth was caused by the roughness and sediment transport associated with the formation of ripples near incipient motion. The upper envelope of the field data generally fit the curves developed by Chiew (1984) (Fig. 1). The maximum relative scour depth observed in the field does not appear to be strongly affected by whether the sediment is ripple forming or nonripple forming. The scatter of data below the envelope curves indicates that the relation between relative scour depth and relative velocity developed in the laboratory does not explain adequately the scour processes in the field.

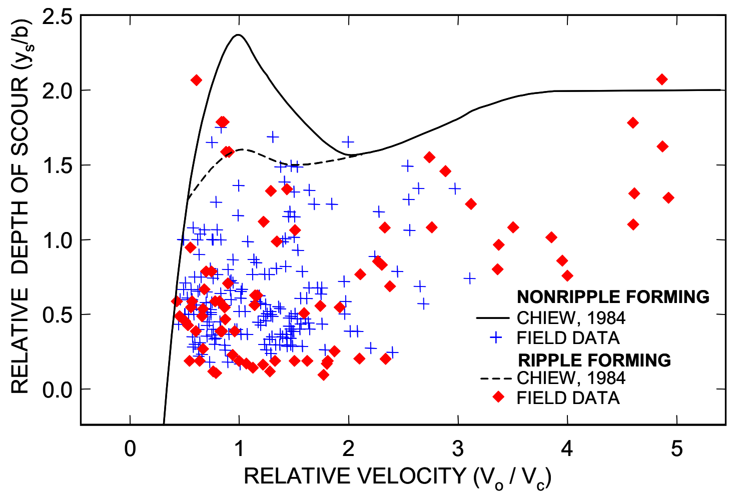

Fig. 1 - Comparison of field observations with the curves developed by Chiew (1984) showing the effect of sediment size and relative velocity on relative depth of scour.

Baker (1986) also investigated the effect of bed-material properties on the relation between relative scour depths and relative velocity, in the laboratory. Baker (1986) used nonuniform bed material characterized by the coefficient of gradation. He found that as the coefficient of gradation increased, the relative scour depth was reduced and the maximum scour occurred at a relative velocity greater than one. The field data categorized by the coefficient of gradation are shown in Fig. 2 with hand-drawn envelope curves for the four categories of gradation. The effect of gradation has no consistent pattern in the relation between normalized scour depth and relative velocity for the field observations.

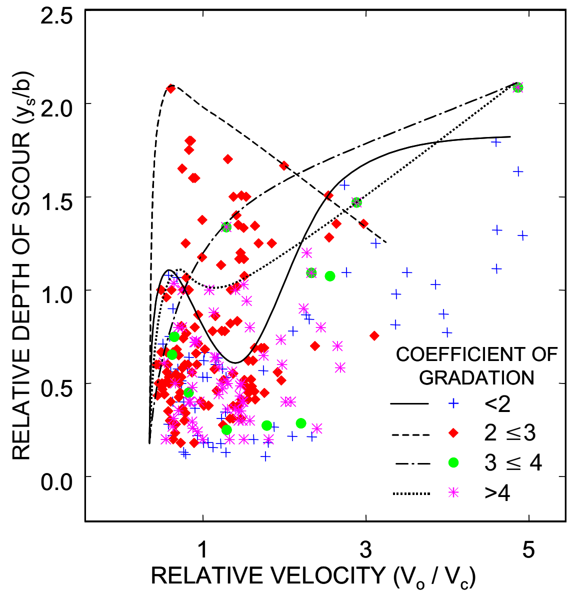

Fig. 2 - Effect of gradation and relative velocity on relative depth of pier scour for field data, with hand-drawn envelope curves for selected gradation classes.

Baker (1986) changed the gradation while maintaining a constant D_{50} during his experiments. To simulate a constant D_{50} in the field data, Mueller (1996) used partial residuals to remove the effect of D_{50} from the field data. Mueller's approach did not improve the comparison between the field data and the laboratory observations by Baker (1986).

Bed-Material Parameters

The scale of laboratory experiments prevents the effect of relative sediment size (b/D_{50}) on relative scour depth from being directly compared with field conditions. The maximum relative sediment size obtained in the laboratory was about 800. In the laboratory, ripple-forming sediments had lower relative scour depths than nonripple-forming sediments for relative sediment sizes ranging from 100 to 800. The field data do not contain ripple-forming sediments with a relative sediment size less than 900 (Fig. 3); therefore, there is insufficient overlap between laboratory and field data to make a valid comparison. The field data show a cluster of ripple-forming sediments near a relative sediment size of 1,000 that is below the maximum relative scour for nonripple-forming sediments; however, the maximum relative scour depth for ripple-forming sediments with relative sediment sizes of 4,000 exceeds the nonripple-forming sediments.

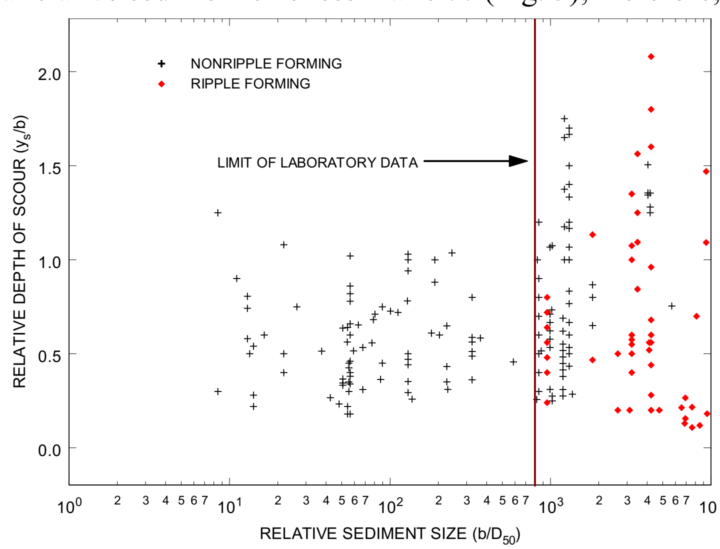

Fig. 3 - Effect of relative sediment size on relative depth of pier scour for field data.

Ettema (1980) recognized that although maximum scour depth was 2.4 times the pier width for uniform sediments; this maximum depth was affected by the gradation of the bed material for nonuniform bed materials. Ettema used a series of laboratory experiments to develop a correction factor to account for the gradation of the bed material on the maximum scour depth. Hand-drawn envelope curves in Fig. 4 show that the relative scour depth for field data is greater for ripple-forming sediments than for nonripple-forming sediments when the gradation coefficient is less than about 2.5. For gradation coefficients greater than 2.5, there is a reduction in the relative scour depth for all observations. The reduction in the relative scour depth is larger for ripple-forming sediments than for nonripple-forming sediments. An increase in the coefficient of gradation for a constant median grain size results in an increase in the coarser size fractions of the bed material. An increase in the coarse size fractions of the bed material reduces the scour depth, thus, the scour depth is dependent on the size distribution of nonuniform bed material. The larger reduction in scour for ripple-forming sediments may be caused by armoring of the scour hole by the coarser size fractions; however, the small amount of ripple forming data for the larger gradations may make any conclusions questionable.

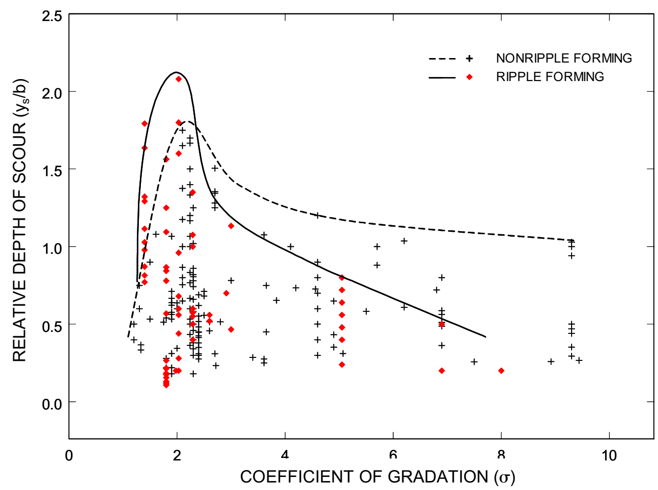

Fig. 4 - Effect of the coefficient of gradation on relative depth of pier scour for field data with hand-drawn envelope curves of ripple and nonripple forming sediments.

Depth of Approach Flow

Most researchers agree that for constant velocity intensity, local pier scour increases as depth of flow increases, but as the depth of flow continues to increase, the scour depth becomes almost independent of flow depth (Breusers and others, 1977; Ettema, 1980; Chiew, 1984). Chiew (1984) plotted data that he collected along with experimental data from Shen and others (1969), Ettema (1980), and Chee (1982) and concluded that the flow depth does not affect scour if the depth is greater than four times the pier width. From this research, Melville and Sutherland (1988) developed a correction factor for the relative depth of flow, $K_{y,}$. The relation between relative flow depth and relative scour depth for the field data is shown in Fig. 5. Although the curve for the K_y factor envelops the data to the right, the data do not follow the trend of the curve. Most laboratory data are collected at or near incipient motion. To better compare the field data with the laboratory data, sediment transport conditions near incipient motion ($0.8 < V_o/V_c < 1.2$) were selected and compared to the curve. Again, the field data did not follow the trend observed in the laboratory data; the data indicated that the relative scour depth tends to increase with increasing relative flow depth.

EVALUATION OF THE K_4 FACTOR

An evaluation of the performance of the HEC-18 equation for various sediment transport conditions and sediment sizes clearly show the need to provide a correction to the HEC-18 equation for coarse bed materials, K_4. An idealized K_4 was computed as the observed scour depth divided by the HEC-18 computed scour depth and compared to the armor potential, the sediment transport in the approach, and to the general size class of the median grain size (Fig. 6). The flow capacity to transport the D_{95} sediment size at the pier (estimated using Gao and others, 1992) was used to estimate armor potential. The armor potential was assumed to be high if the D_{95} sediment size could not be transported. It is clear that the HEC-18 equation tends to overpredict the scour depth for the larger size classes of sediment more than the sand-size class for which it originally was developed (Fig. 6). Therefore, the addition of a K_4 factor to account for grain size in the HEC-18 equation is justified.

The K_4 factor in the HEC-18-K4 equation was introduced in the third edition of HEC-18 (Richardson and Davis, 1995) to account for the bed material size characteristics that were missing from the original HEC-18 equation. The relation for that version of K_4 was derived by the FHWA from preliminary laboratory data provided by Molinas and it was intended as an interim adjustment factor until more detailed analyses were available. The sum of squared errors only was reduced from 822 to 791 (Table 3) by the inclusion of the K_4 term presented in the third edition of HEC-18.

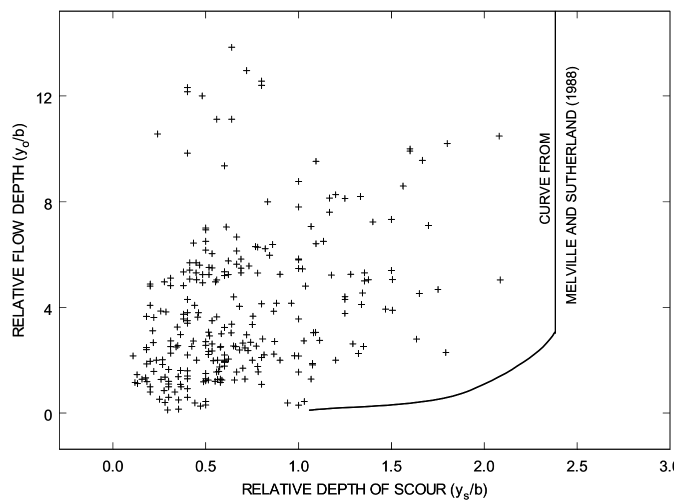

Fig. 5 - Effect of relative flow depth on relative depth of pier scour with field data compared to the relation presented by Melville and Sutherland (1988).

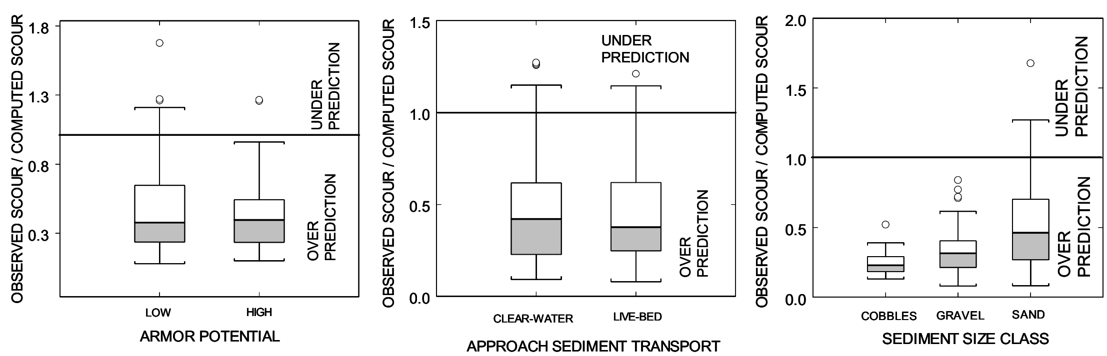

Fig. 6 - Box plot of the variation in the ratio of the observed scour to computed scour from the HEC-18 equation (idealized K4) for armor potential conditions, approach sediment transport conditions, and sediment size classes.

Molinas (2000) derived a new correction to the HEC-18 equation from his final laboratory data set (HEC-18-K4Mo equation). Although this new correction provided a significant decrease in the sum of squared errors (from 822 to 495), it also increased the number of observations that were underpredicted (from 13 to 65). Most of these underpredictions occurred at D_{50} less than 2 mm. If the correction developed by Molinas only is applied to D_{50} greater than 2 mm (HEC-18-K4Mo (>2 mm) equation), its performance was enhanced greatly. The sum of squared errors rose to 609 but the number of observations underpredicted dropped from 65 to 21 and the sum of squared errors for the underpredictions was reduced from 17 to 2.47.

Mueller (1996) developed a relationship for K_4 based on field data. The fourth edition of HEC-18 (Richardson and Davis, 2001) adopted Mueller's K_4 (HEC-18-K4Mu equation) but restricted the lower limit to 0.4 and required a value of 1 if D_{50} was less than 2 mm or D_{95} was less than 20 mm. These restrictions were applied to the evaluation of this factor in Table 3 (HEC-18-K4Mu). Table 3 indicates that Mueller's K_4 factor as adopted in the fourth edition of HEC-18 reduced the sum of squared errors significantly from 822 to 448 (Table 3). Although Mueller's 1996 K_4 factor worked well for the available field data, the formation of the equation causes it to be indeterminate for some situations and behave contrary to logic in others. The equation becomes indeterminate if the velocity for incipient motion of the D_{50} grain size is smaller than the approach velocity needed to scour the D_{95} grain size at the pier. The equation behaves contrary to logic if the D_{50} grain size is held constant and only the D_{95} is varied. In this situation, K_4 increases as D_{95} increases. In the field, variables tend to change together as a system, whereas in the laboratory selected variables can be held constant and other variables can be changed arbitrarily. For the field data used by Mueller (1996) to develop the K_4 factor, an increase in D_{95} always corresponded to an increase in D_{50}. Under these conditions, the relation for K_4 proposed by Mueller (1996) provides a reasonable envelope curve but it can produce illogical results caused by the arrangement of the variables.

In an attempt to better define a bed material correction factor, K_4, numerous combinations of variables were investigated to accurately describe the variation identified in the idealized K_4. Overall, the best correlation was found with the relative bed material size (b/D_{50}). The equation for the envelope curve using this variable combination is:

$$K_4 = 0.35\left(\frac{b}{D_{50}}\right)^{0.19}$$

The envelope curve for K_4 developed from the b/D_{50} ratio is shown in Fig. 7. This curve is applicable for all grain sizes and appears to explain some of the underprediction for the HEC-18 equation for the sand sizes. If this correction curve is applied to all observations, the 13 observations that HEC-18 originally

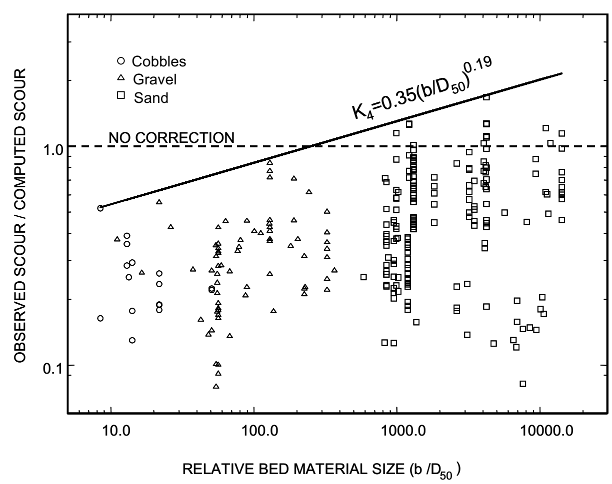

Fig.7 - Relation between relative errors in computed scour using the HEC-18 equation and relative bed material size.

underpredicted (Table 3) are corrected, but the sum of squared errors increases to over 2,800. The large increase in the sum of squared errors is caused by the large scatter below the curve for values of K_4 above 1. If the correction is limited to reducing the scour depth ($K_4 \leq 1$), the sum of squared errors is reduced to 611 but 14 observations are underpredicted. The sum of squared errors for the 14 observations underpredicted is 2.16, which is the same as the HEC-18 equation had prior to this correction (Table 3).

Although the K_4 based on b/D_{50} does not perform as well as the HEC-18-K4Mu equation in table 3, the basis for this new approach is supported to an extent by the work of Sheppard (University of Florida, written communication, 2001) and Ettema (1980) who found that b/D_{50} was an important parameter based on their laboratory research. In addition, although this new K_4 lacks the effect of the coarse size fraction, it does not behave illogically as does the HEC-18-K4Mu approach.

SUMMARY AND CONCLUSIONS

The USGS, in cooperation with the FHWA and State highway departments, has compiled and extensive data base of field measurements of local pier scour. These measurements contain bed-material parameters that have been missing from other previously compiled data sets. A comparison of these data with 26 pier-scour prediction equations showed that none accurately predicted the scour for all site and hydrologic conditions. No single equation conclusively was better than the rest, but the top six equations generally appear to be the Froehlich Design, HEC-18, HEC-18-K4, HEC-18-K4Mu, HEC-18-K4Mo (>2 mm), and Mississippi equations. These field measurements also were compared with the results of various laboratory investigations. This comparison showed that often the laboratory investigations do not cover the same range of variable combinations represented in the field data. Where comparisons between the laboratory investigations and the field data could be made, the laboratory experiments were able to envelope the field data but were unable to explain much of the variation in observed scour depths. The effect of bed-material properties on the scour depth was evident in both the laboratory and field data. Various equations for a bed-material correction (K_4) to the HEC-18 equation have been proposed. Evaluation of these K_4 equations showed that most of them improved the performance of the HEC-18 equation but none of them could fully explain all of the variation in the residuals of the HEC-18 equation. A new relation for K_4, based on the relative bed-material size, was introduced and shown to provide good corrections to the HEC-18 equation. However, much of the variation in the field data remains unexplained.

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