Updating HEC-18 Pier Scour Equations for Noncohesive Soils

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FOREWORD

Balancing safety and cost is critical to smart investment when estimating scour at bridge piers in noncohesive soils. This report summarizes a study to improve techniques for estimating scour under a broad range of conditions using quantitative measures of reliability and accuracy. Attention is focused on situations with higher uncertainty including sites with coarse bed materials and bridge designs with pier groups. This study will provide improved guidance to bridge engineers involved with foundation design. The study described in this report was conducted at the Federal Highway Administration Turner-Fairbank Highway Research Center J. Sterling Jones Hydraulics Laboratory.

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Acting Director, Office of Infrastructure
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16. Abstract
A dataset of 594 bridge pier scour observations from two laboratory and three field studies was compiled. The dataset served as the testing ground for evaluating potential enhancements to the pier scour tools for noncohesive soils in Hydraulic Engineering Circular 18 (HEC-18). In the current (fifth) edition of HEC-18, there are two primary equations for pier scour in noncohesive soils. One is the general equation applicable to most situations, including clear water and live bed conditions. The second is a coarse bed material equation recommended only for use under clear water conditions with coarse bed materials. The objective of this research was to determine if the coarse bed materials equation could be used for conditions beyond those under which it is currently limited. A framework for evaluating the two equations was developed using qualitative and quantitative tools.

The coarse bed equation is referred to as the Hager number/gradation coefficient (HN/GC) equation because it references the use of both in the equation formulation. After adjusting the HN/GC equation to a target reliability index of 2.0, it was evaluated on its ability to predict scour for a wide range of conditions in noncohesive soils. Partitioned subsets of the data based on key conditions—including the HEC-18 coarse bed criteria, clear water versus live bed transport conditions, gradation, and median grain size—were used for the evaluation. The equation performed reasonably consistently in all partitioned datasets, leading to the conclusion that it may be used for a broader range of conditions. A subgroup of pier group scour observations was assessed to determine if the equation could also be used for pier groups. The equation performed better for single piers but offered a basis for predicting local scour at pier groups.

Considering these findings, the modified HN/GC equation is recommended for use on a broader range of noncohesive soil conditions for pier scour. Recommended limits for application of the equation are as follows: (1) clear water or live bed conditions ($V_1/V_{c,50} < 5.2$), (2) sands, gravels, and cobbles (0.0079 inches (0.2 mm) < D_{50} < 5 inches (127 mm)), (3) gradation coefficients (σ) less than 7.5, (4) Froude number less than 1.7, and (5) single piers.

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
^oF	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	^oC
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
^oC	Celsius	1.8C+32	Fahrenheit	^oF
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.
(Revised March 2003)

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF SYMBOLS

a	Pier diameter or width, ft (m)
D_{50}	Median grain size of the sediment, ft (m)
D_{84}	Grain size for which 84 percent (by weight) is smaller, ft (m)
Fr_1	Froude number for approach flow, dimensionless
g	Gravitational acceleration, ft/s^2 (m/s^2)
H	Hager number (densimetric particle Froude number), dimensionless
K_1	Correction factor for pier nose shape
K_2	Correction factor for angle of attack of flow
K_3	Correction factor for bed condition
K_w	Correction factor for wide piers in shallow flow
S_g	Specific gravity of the sediment, dimensionless
V_1	Approach flow velocity, ft/s (m/s)
$V_{c,50}$	Critical velocity based on D_{50}, ft/s (m/s)
y_1	Approach flow depth, ft (m)
y_s	Scour depth, ft (m)
$y_{s,m}$	Measured scour depth, ft (m)
$y_{s,p}$	Predicted scour depth, ft (m)
σ	Sediment gradation coefficient (D_{84}/D_{50}), dimensionless

CHAPTER 1. INTRODUCTION

The fifth edition of Hydraulic Engineering Circular 18 (HEC-18) *Evaluating Scour at Bridges* introduced a new equation for pier scour in coarse bed materials.(1) The equation, shown in figure 1, is based on work conducted by the Federal Highway Administration (FHWA) to develop more physics-based relations.(2)

$$\frac{y_s}{a^{0.62} y_1^{0.38}} = 1.1 K_1 K_2 \left[tanh\left(\frac{H^2}{1.97\sigma^{1.5}} \right) \right]$$

Figure 1. Equation. Pier scour in coarse bed materials (HEC-18).

Where:
y_s = Scour depth, ft (m).
y_1 = Approach flow depth, ft (m).
a = Pier diameter, ft (m).
K_1 = Correction factor for pier nose shape, dimensionless.
K_2 = Correction factor for angle of attack of flow, dimensionless.
σ = Sediment gradation coefficient (D_{84}/D_{50}), dimensionless.
H = Hager number (densimetric particle Froude number (Fr)), dimensionless.

As prescribed in HEC-18, this equation is only applicable to clear water flow conditions and to what is described as coarse bed materials. *Coarse bed materials* are defined as those with D_{50} greater than or equal to 0.79 inches (20.1 mm) and a gradation coefficient greater than or equal to 1.5.

The Hager number used in the equation was developed by Oliveto and Hager and is defined in figure 2.(3,4)

$$H = \frac{V_1}{\sqrt{g(S_g - 1)D_{50}}}$$

Figure 2. Equation. Hager number.

Where:
V_1 = Approach velocity, ft/s (m/s).
D_{50} = Median grain size, ft (m).
S_g = Specific gravity of the sediment, dimensionless.
g = Gravitational acceleration, ft/s^2 (m/s^2).

The equation in figure 1 was provided to supplement the primary scour equation in HEC-18, which is shown in figure 3.

$$\frac{y_s}{a^{0.65}y_1^{0.35}} = 2.0K_1K_2K_3[Fr_1^{0.43}]$$

Figure 3. Equation. General pier scour equation in HEC-18.

Where:
K_3 = Correction factor for bed condition, dimensionless.
Fr_1 = Approach flow Fr, dimensionless.

The equation in figure 3 was modified from previous versions by dropping a coarse bed adjustment factor, K_4, when the equation in figure 1 was introduced. Current guidance is to use the equation in figure 1 for conditions to which it is applicable and then to use the equation in figure 3 for most other conditions.

The objective of the research described in this report is to determine if the equation described in figure 1 can be used for conditions beyond those to which it is currently limited.

CHAPTER 2. DATA CHARACTERISTICS

The development of the pier scour equation for coarse bed materials in figure 1 was based on datasets from Colorado State University (CSU), the FHWA Turner-Fairbank Highway Research Center, and the U.S. Geological Survey (USGS), which are listed as the first four datasets in table 1.[2] These data included a range of conditions with observations of clear water and live bed scour. For the previous study, only the clear water data were used for the development of the equation in figure 1.

Table 1. Data sources.

Source	Total Number of Scour Observations	Data Type
CSU[5]	184	Laboratory
FHWA[2]	20	Laboratory
USGS-2011[6]	103	Field
USGS-2004[7]	42	Field
USGS-1995[8]	384	Field
Total*	694	Laboratory/Field

*Thirty-nine observations are included in both the USGS-2004 and USGS-1995 datasets.

In addition, the last dataset shown in the table (USGS-1995) will be used for the analyses in this study. Combined, these datasets provide 694 unique pier scour observations.

Selected data observations were removed from the dataset either because of incomplete data or because of inappropriate data for the study. In total, 12 observations were filtered out of the CSU laboratory dataset, and 88 observations were filtered out of the USGS-1995 dataset for the following reasons:

- **USGS-1995 field data.** The following changes were made:
    - Fifty-eight observations were actually 29 pairs of measured scour depths upstream and downstream of the same pier. The smaller of the two measurements was deleted (29 observations).
    - Scour depths that were minimal (measured scour depth less than 0.2 inches (5.1 mm) or measured scour depths less than the reported error of field observation) were deleted (38 observations).
    - Soils that were cohesive were deleted (7 observations).
    - Observations with unusually high gradation coefficients (5 with a gradation coefficient of 12.1 and 2 with a gradation coefficient of 20.4) were deleted (7 observations).
    - Soils with no gradation information were deleted (7 observations).
- **CSU laboratory data.** Scour depths that were minimal (measured scour depth less than 0.2 inches (5.1 mm)) were deleted (12 observations).

After filtering, 594 pier scour observations remained for further analysis. Of these, 402 were from the 3 USGS field datasets, and 192 were from the CSU and FHWA laboratory datasets.

The remaining data included a variety of pier types. Within the field data, there were 60 observations with pier groups and 342 observations with single piers. The single pier types/nose types were cylindrical (8), round nose (158), sharp nose (141), square nose (27), and unknown (8). The unknown observations were treated as round nose. All of the laboratory data were for single cylindrical piers.

The data contained a broad range of grain size classes for noncohesive soils. Table 2 summarizes the grain size classification and gradation according to the system of Krumbein and Aberdeen.[(9)] The data range from fine sand to cobble sizes based on the D_{50}. The most numerous size range represented in the data is coarse sand (215 observations).

The gradation coefficient ranges from 1.15 to 7.22. For this study, a noncohesive soil is considered uniform when the gradation coefficient is less than 1.5. With the exception of the very fine gravel, nonuniform gradations make up at least half of the observations for each soil class.

The definition of soil gradation coefficient used in this study and in HEC-18 is D_{84}/D_{50}. Another definition used is $(D_{84}/D_{16})^{0.5}$.[(2)] These two definitions are equivalent when $D_{84}/D_{50} = D_{50}/D_{16}$. Landers and Mueller reported gradation coefficients for the 384 data observations included in that study.[(8)] Each gradation coefficient was recomputed using the definition for this study and compared with the reported values. For 123 observations, the recomputed values matched the reported values. However, for 132 observations, the recomputed values exceeded the reported values, but for 129 observations, the recomputed values were less than the reported values. In all cases, the recomputed values were used for this study because they are supported by the data.

Table 2. Noncohesive grain size classification for 594 pier scour observations.

D_{50} Range (mm)	Grain Size Classification	Observation	D_{50} (mm) Minimum	D_{50} (mm) Maximum	D_{50} (mm) Median	D_{50} (mm) Mean	D_{50} (mm) Standard Deviation	Gradation Coefficient, σ Minimum	Gradation Coefficient, σ Maximum	Gradation Coefficient, σ Median	Gradation Coefficient, σ Mean	Gradation Coefficient, σ Standard Deviation
0.125–0.25	Fine sand	13	0.17	0.18	0.18	0.18	0.003	1.47	2.06	2.06	2.01	0.16
0.25–0.5	Medium sand	39	0.28	0.45	0.38	0.36	0.06	1.33	2.47	2.10	1.96	0.46
0.5–1	Coarse sand	215	0.50	0.94	0.75	0.72	0.11	1.28	5.22	2.43	2.53	0.70
1–2	Very coarse sand	74	1.00	1.87	1.80	1.59	0.37	1.15	7.22	3.70	3.56	2.11
2–4	Very fine gravel	6	2.00	2.85	2.00	2.14	0.35	1.35	1.65	1.35	1.40	0.12
4–8	Fine gravel	34	4.00	7.60	6.90	6.67	1.00	2.17	6.50	2.17	2.84	1.11
8–16	Medium gravel	23	8.00	15.00	9.63	10.38	2.60	1.40	4.14	3.75	3.61	0.74
16–32	Coarse gravel	70	16.70	31.30	27.00	24.15	5.41	1.28	4.14	1.94	2.08	0.75
32–64	Very coarse gravel	61	32.00	60.70	49.30	47.18	9.56	1.18	3.98	1.99	2.11	0.52
64–256	Cobble	59	64.70	108.00	73.00	81.68	13.72	1.29	2.56	2.05	1.96	0.38

1 inch = 25.4 mm.

The distribution of the 594 bed materials by grain size classification is shown in figure 4. While the field data include observations in all 10 grain size classifications, the laboratory data from CSU and FHWA include observations in five of the classifications: medium sand, coarse sand, very coarse sand, very fine gravel, and coarse gravel. Among all grain size classes, coarse sand is the most frequently represented with more than 35 percent of the observations. The least represented is very fine gravel, with only six observations, including five from the laboratory data and one from the field.

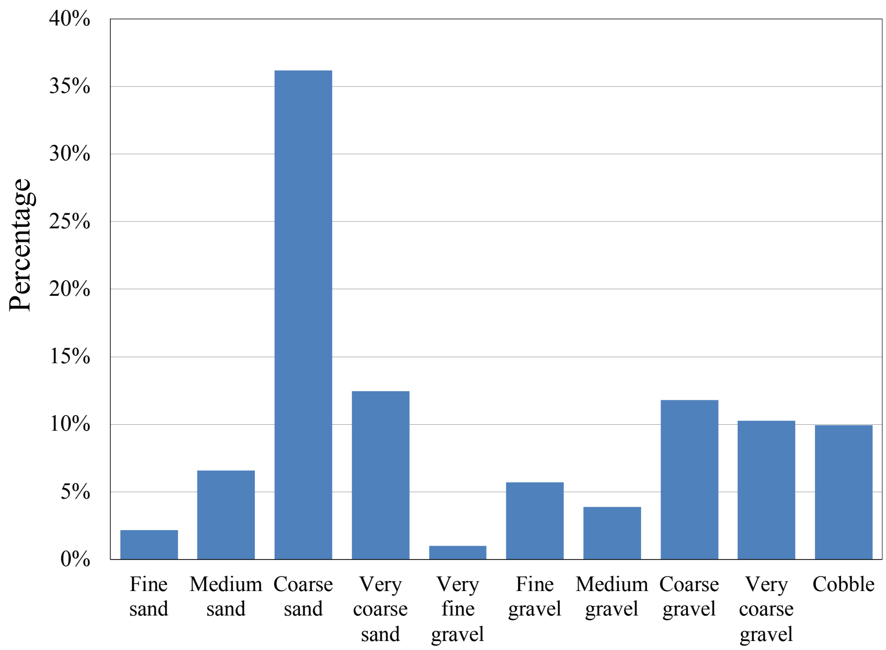

Figure 4. Graph. Distribution of grain size classification.

The dataset includes observations of both clear water and live bed scour. If the approach velocity is greater than the critical velocity, live bed conditions exist; if not, clear water conditions govern. The critical velocity is calculated by Laursen's critical velocity equation, as shown in figure 5.(1)

$$V_{c,50} = K_u y_1^{1/6} D_{50}^{1/3}$$

Figure 5. Equation. Laursen's critical velocity equation.

Where:
$V_{c,50}$ = Critical velocity based on D_{50}, ft/s (m/s).
K_u = Unit conversion constant, 11.17 for U.S. customary units (6.19 for SI units).

Table 3 summarizes the ratio of $V/V_{c,50}$ for determining clear water versus live bed conditions for the dataset. The maximum ratio of the average velocity to the critical velocity is 5.13 in the medium sand classification. The ratios range from 0.29 to 2.61 for the other grain size classifications.

Table 3. Ratio of velocity to critical velocity.

D_{50} Range (mm)	Grain Size Classification	Observation	$V/V_{c,50}$				
			Minimum	Maximum	Median	Mean	Standard Deviation
0.125–0.25	Fine sand	13	0.49	1.54	0.78	0.84	0.28
0.25–0.5	Medium sand	39	0.45	5.13	1.51	2.21	1.53
0.5–1	Coarse sand	215	0.34	2.31	0.83	0.97	0.45
1–2	Very coarse sand	74	0.29	2.58	0.83	1.04	0.60
2–4	Very fine gravel	6	0.82	1.32	0.82	0.91	0.20
4–8	Fine gravel	34	0.36	2.61	1.22	1.18	0.40
8–16	Medium gravel	23	0.61	1.56	1.15	1.07	0.29
16–32	Coarse gravel	70	0.38	2.02	0.90	0.95	0.30
32–64	Very coarse gravel	61	0.43	1.46	0.79	0.82	0.21
64–256	Cobble	59	0.37	1.35	0.74	0.74	0.17

1 inch = 25.4 mm.

CHAPTER 3. ANALYSIS OF PIER SCOUR

As previously stated, the objective of this research is to determine if the equation described in figure 1 can be used for conditions beyond those for which it is currently limited. The pier scour equations are evaluated using the scour observations from the field and laboratory datasets. The evaluation will compare the performance of the equations on data within the ranges specified in HEC-18 as well as beyond those ranges.

Performance is assessed by visual inspection of graphs of predicted and measured scour and by quantitative measures of reliability and accuracy. Reliability is defined by the reliability index (RI), which measures the risk of underpredicting the actual value of some property, which, in this case, is scour depth. A higher RI indicates a lower risk of underpredicting scour depth. RI is defined in general terms in figure 6.

$$RI = \frac{1 - M_x}{S_x}$$

Figure 6. Equation. RI.

Where:
M_x = Mean of a set of x values (dimension is that of the x values).
S_x = Standard deviation of a set of x values (dimension is that of the x values).

For this analysis, x is defined as shown in figure 7.

$$x = \frac{y_{s,m}}{y_{s,p}}$$

Figure 7. Equation. Ratio of measured to predicted scour depth.

Where:
x = Ratio of measured to predicted scour depth, dimensionless.
$y_{s,m}$ = Measured scour depth, ft (m).
$y_{s,p}$ = Predicted scour depth, ft (m).

To facilitate direct comparison between the laboratory and field data, accuracy is characterized by the relative error (RE) and the relative root mean square error (RRMSE). RE is defined in figure 8, and RRMSE is defined in figure 9.

$$RE = \frac{y_{s,p} - y_{s,m}}{y_{s,m}}$$

Figure 8. Equation. RE.

$$RRMSE = \sqrt{\left[\sum\left(\frac{y_{s,p} - y_{s,m}}{y_{s,m}}\right)^2\right]/(n-1)}$$

Figure 9. Equation. RRMSE.

Where:
n = Number of observations.

HEC-18 EQUATIONS

The equations for general pier scour (figure 3) and pier scour for coarse bed materials (figure 1) both employ the following adjustments described by HEC-18:

- K_1.
- K_2.
- The correction factor (K_w) for wide piers in shallow water.
- The rules of thumb for maximum scour depth for round nose piers.

In addition, the general pier scour equation employs K_3 as described in HEC-18.

Comparison between measured and predicted scour estimates will employ dimensionless scour depths so that field and laboratory data may be directly compared. The dimensionless scour depth is defined in figure 10.

$$dimensionless\ scour = \frac{y_s}{a}$$

Figure 10. Equation. Dimensionless scour depth.

Application of the HEC-18 Equations to the Data

Application of the HEC-18 general pier scour equation to the full dataset resulted in predicted scour estimates that were compared to measured scour estimates in figure 11. Because the HEC-18 equation is intended for design, it is not surprising that predicted scour is predominately greater than measured scour. A limited number of data points are not shown in the figure because the dimensionless predicted scour goes as high as 8.5.

Using the HEC-18 coarse bed material equation in the same manner results in the comparison summarized in figure 12. As a design equation, it also generally estimates scour depths exceeding measured values, though the patterns are not identical. For example, this equation results in a larger number of underpredicted scour values. As before, a limited number of data points are not shown in the figure because the dimensionless predicted scour for this equation goes as high as 10.2.

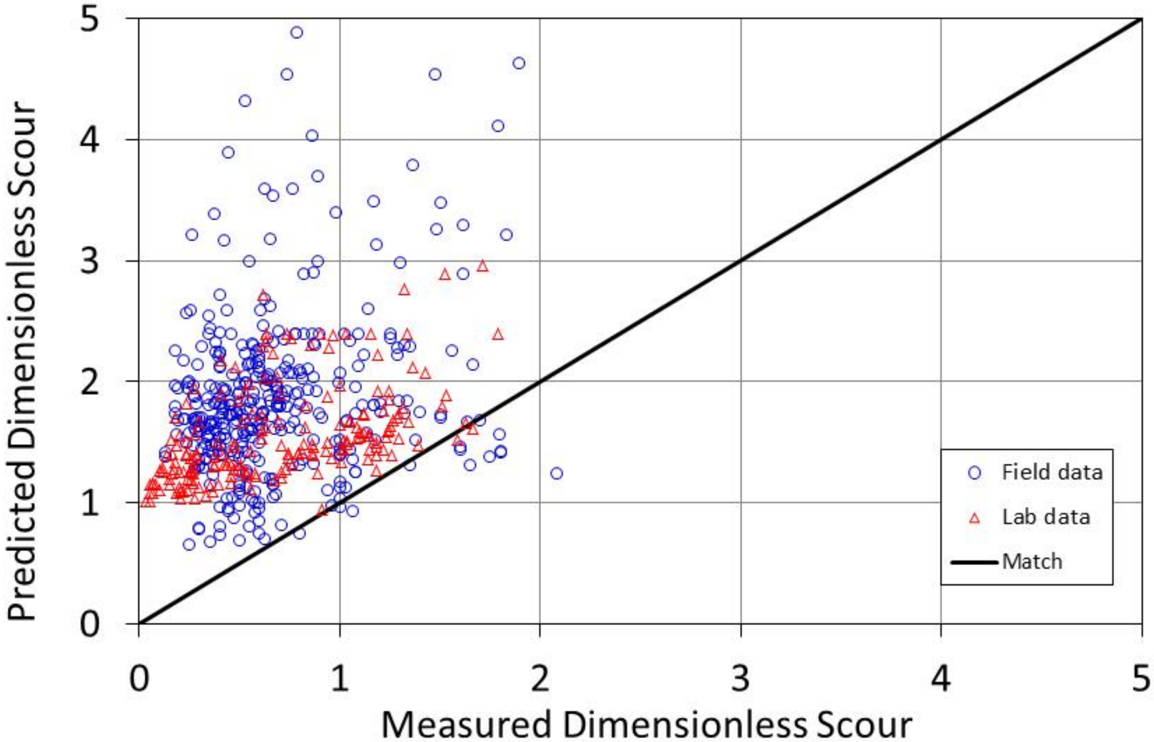

Figure 11. Graph. Predicted versus measured scour: HEC-18 general pier scour equation.

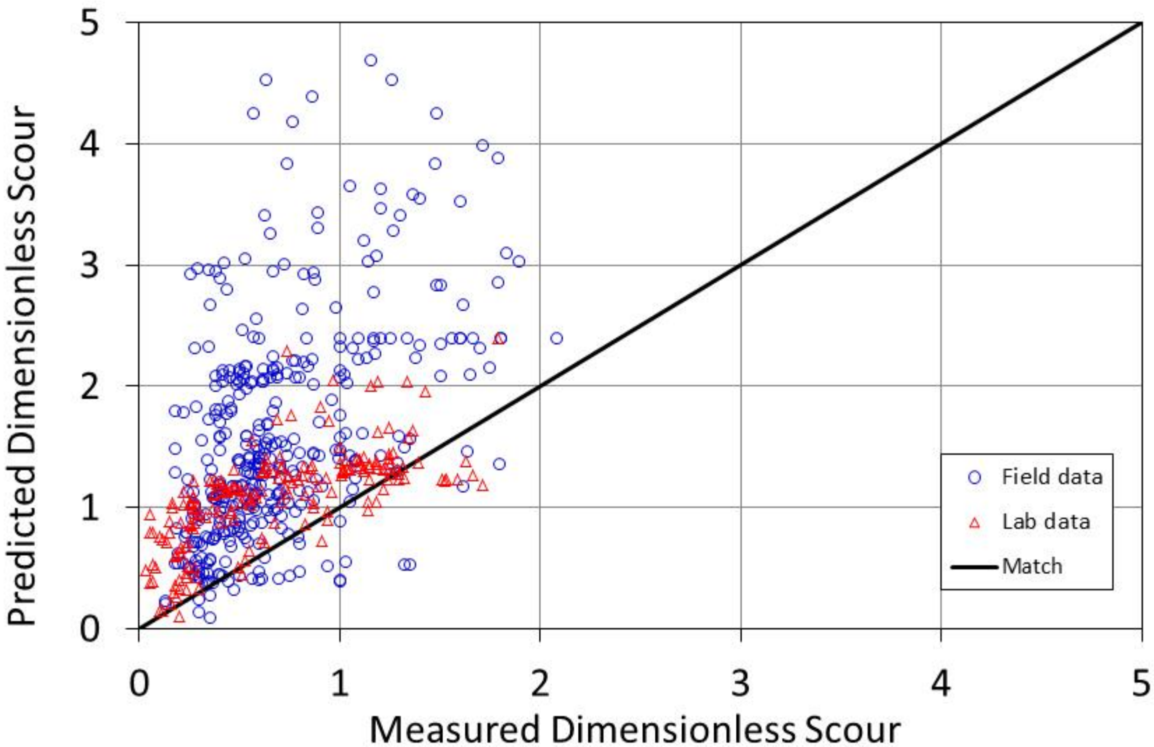

Figure 12. Graph. Predicted versus measured scour: HEC-18 coarse bed pier scour equation.

Table 4 provides detailed information on the performance of the HEC-18 general pier scour equation. The reliability of the equation reflected in the RI and the accuracy of the equation reflected in the RRMSE are provided for the data as a whole and partitioned into various groups. Results for the field and laboratory data are also differentiated.

Table 4. Performance of HEC-18 general pier scour equation.

Data Description			HEC-18 Coarse Bed Criteria		Bed Load Transport		Gradation		$D_{50} \geq$ 0.79 Inches	
Source	**Parameter**	**All**	**Yes**	**No**	**Clear Water**	**Live Bed**	**Uniform**	**Nonuniform**	**Yes**	**No**
Field	*n*	402	120	282	218	184	31	371	168	234
	RI	2.56	6.22	2.16	2.42	2.75	2.29	2.58	1.10	1.24
	RRMSE	3.42	4.28	2.98	3.56	3.25	2.95	3.46	1.92	3.02
Lab	*n*	192	0	192	163	29	52	140	0	192
	RI	2.25	0.00	2.25	2.40	2.12	1.72	2.56	0.00	2.25
	RRMSE	5.10	0.00	5.10	5.52	1.18	3.80	5.51	0.00	5.10
Total	*n*	594	120	474	381	213	83	511	168	426
	RI	2.46	6.22	2.20	2.41	2.68	1.93	2.58	1.10	1.54
	RRMSE	4.04	4.28	3.98	4.50	3.05	3.51	4.12	1.92	4.09

1 inch = 25.4 mm.

The RI and RRMSE measures for the combined dataset of 594 scour observations are 2.46 and 4.04, respectively. In the columns labeled HEC-18 Coarse Bed Criteria, the data are partitioned as follows based on the criteria described in HEC-18 for use of the coarse bed equation:

- $D_{50} \geq 0.79$ inches (20.1 mm).
- $\sigma \geq 1.5$ (nonuniform gradation).
- Clear water scour: $V_1/V_{c,50} < 1$.

When all three criteria are met, HEC-18 recommends that the coarse bed pier scour equation be used rather than the general pier scour equation. For the field data, the RI of the general pier scour equation is 6.22 for the 120 observations meeting the criteria as coarse bed materials, while it is only 2.16 for the 282 observations not meeting the criteria. These results show that the HEC-18 general pier scour is more reliable when applied to data meeting the coarse bed material criteria than it is for data not meeting the criteria. However, the reverse is true in terms of accuracy where the equation is more accurate for data not meeting the criteria (RRMSE = 2.98) compared with data meeting the criteria (RRMSE = 4.28).

Table 4 also summarizes the data partitioned by nonuniform ($\sigma \geq 1.5$) versus uniform gradations as well as by median grain size greater than or equal to 0.79 inches (20.1 mm). None of the laboratory observations included data with D_{50} greater than 0.79 inches (20.1 mm).

Table 5 provides the performance information for the HEC-18 coarse bed material equation. The RI and RRMSE measures for the combined dataset of 594 scour observations are 1.19 and 2.66, respectively. Compared to the general pier scour equation, the coarse bed material scour equation is less reliable (more prone to underpredicting) but more accurate (lower RRMSE). Both of these observations are apparent when comparing figure 11 with figure 12.

With respect to the HEC-18 coarse bed criteria, the HEC-18 coarse bed equation is significantly more accurate for the field data meeting the criteria (RRMSE = 1.60) than for those data not meeting the criteria (RRMSE = 2.94). However, it is also less reliable (RI = 0.88 versus RI = 1.34) when considering the field data only.

Table 5. Performance of HEC-18 coarse bed equation.

Data Description			HEC-18 Coarse Bed Criteria		Bed Load Transport		Gradation		$D_{50} \geq$ 0.79 Inches	
Source	**Parameter**	**All**	**Yes**	**No**	**Clear Water**	**Live Bed**	**Uniform**	**Nonuniform**	**Yes**	**No**
Field	*n*	402	120	282	218	184	31	371	168	234
	RI	1.18	0.88	1.34	0.91	1.70	1.61	1.16	1.10	1.24
	RRMSE	2.61	1.60	2.94	2.05	3.16	2.59	2.62	1.92	3.02
Lab	*n*	192	0	192	163	29	52	140	0	192
	RI	1.23	0.00	1.23	1.38	0.66	0.75	1.51	0.00	1.23
	RRMSE	2.75	0.00	2.75	2.97	0.59	2.79	2.74	0.00	2.75
Total	*n*	594	120	474	381	213	83	511	168	426
	RI	1.19	0.88	1.30	1.06	1.58	1.03	1.22	1.10	1.23
	RRMSE	2.66	1.60	2.87	2.49	2.94	2.72	2.65	1.92	2.90

1 inch = 25.4 mm.

Error Analysis

Prediction errors for both equations were evaluated against a variety of variables to expose trends that might exist. Figure 13 and figure 14 display the RE versus the ratio of the approach velocity to the critical velocity for the general and coarse bed equations, respectively. For ratios less than 1, clear water conditions exist, while for ratios greater than 1, live bed conditions exist. There is no apparent trend in RE with increasing bed transport capacity for either equation. In fact, it appears that for both equations, the distinction between live bed and clear water is not meaningful. A few observations (6 for the general pier scour equation and 2 for the coarse bed pier scour equation) exhibited REs exceeding 14 and are not shown on the figures.

Figure 15 and figure 16 present the REs versus the ratio of approach depth to median grain size for the general and coarse bed equations, respectively. For the general equation, a trend of decreasing error with increases in the ratio seems apparent, especially if the observations with the greatest errors are removed. Conversely, for the coarse bed equation, a trend of increasing error with increases in the ratio seems apparent.

Figure 17 and figure 18 show RE versus the gradation coefficient. Again, there is no discernable pattern in the error distributions for either equation between uniform versus nonuniform gradations.

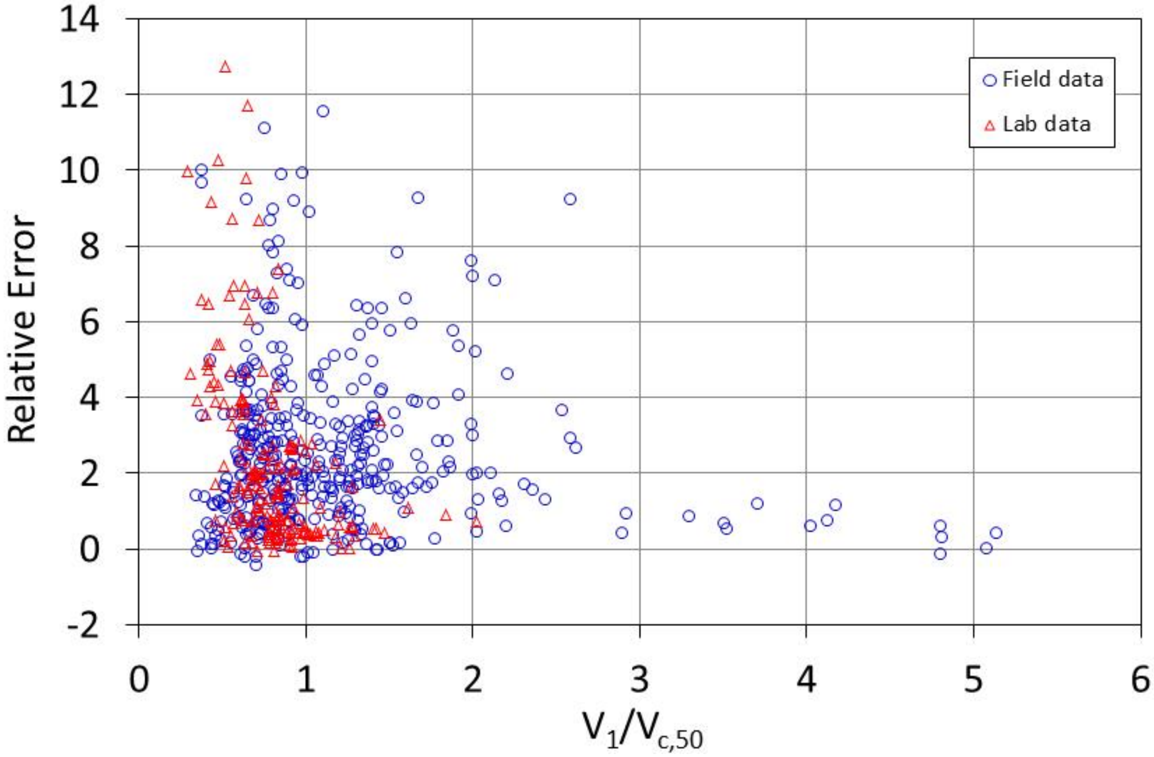

Figure 13. Graph. Error versus bed load transport: general equation.

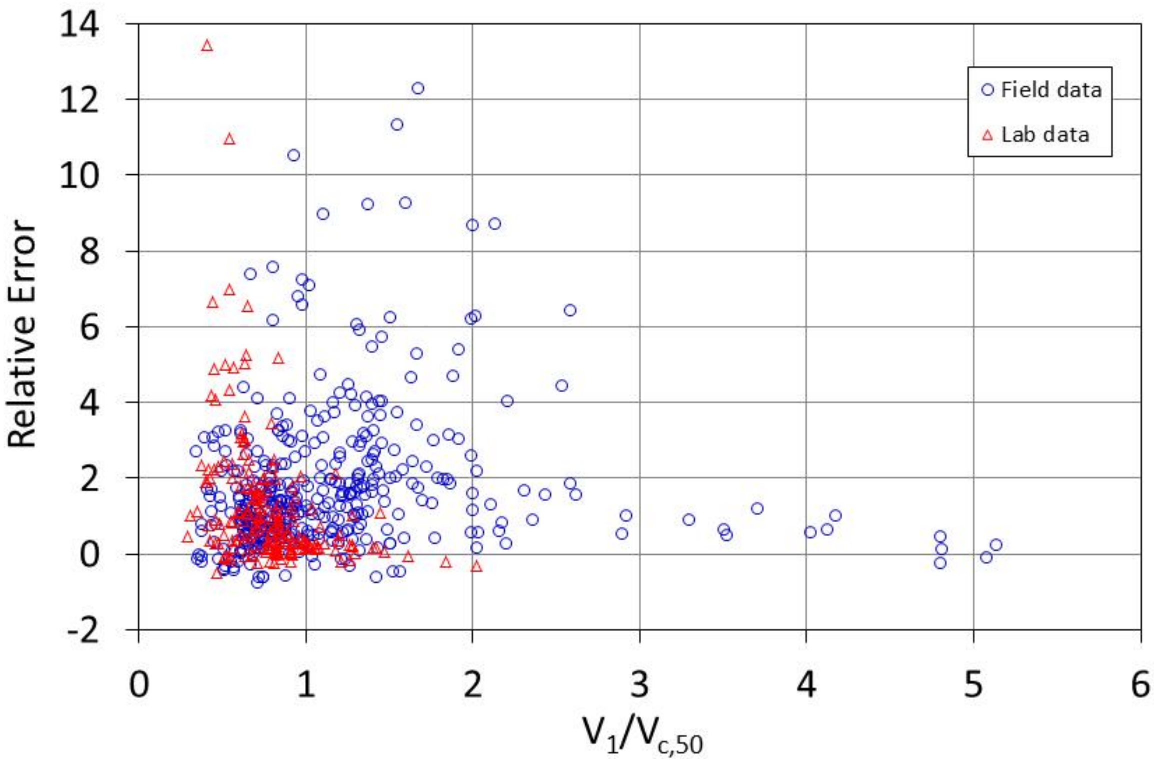

Figure 14. Graph. Error versus bed load transport: coarse bed equation.

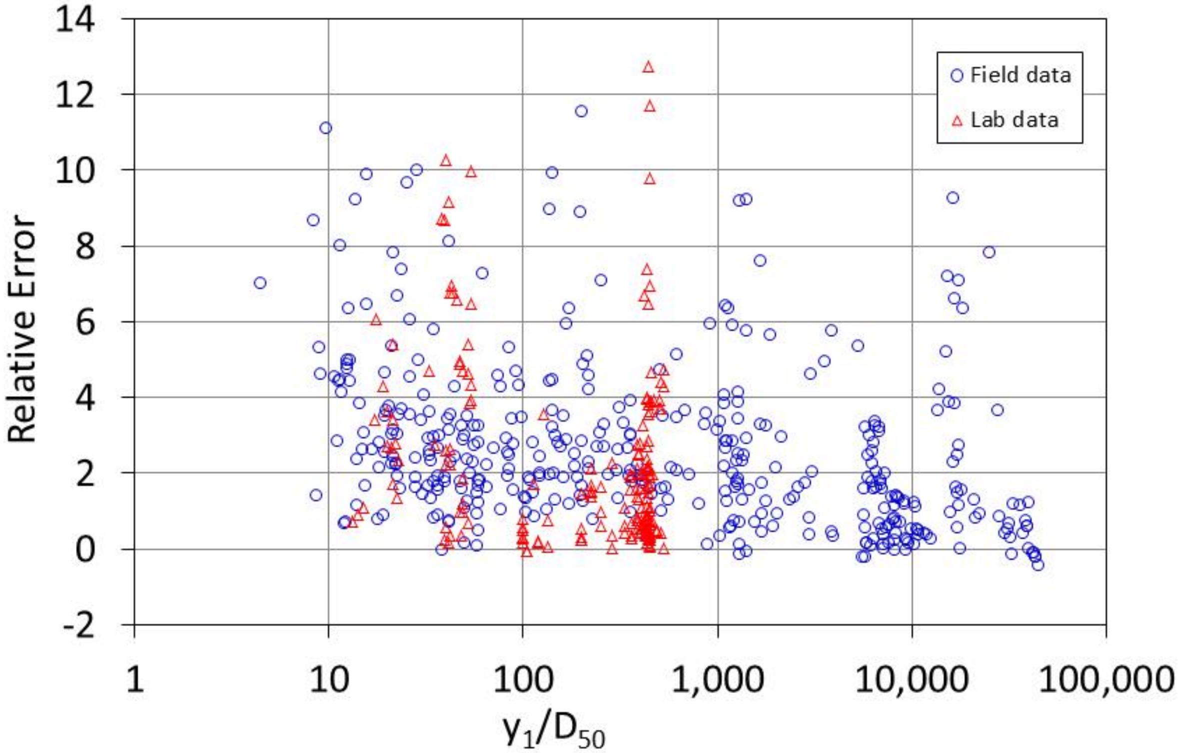

Figure 15. Graph. Error versus y_1/D_{50}: general equation.

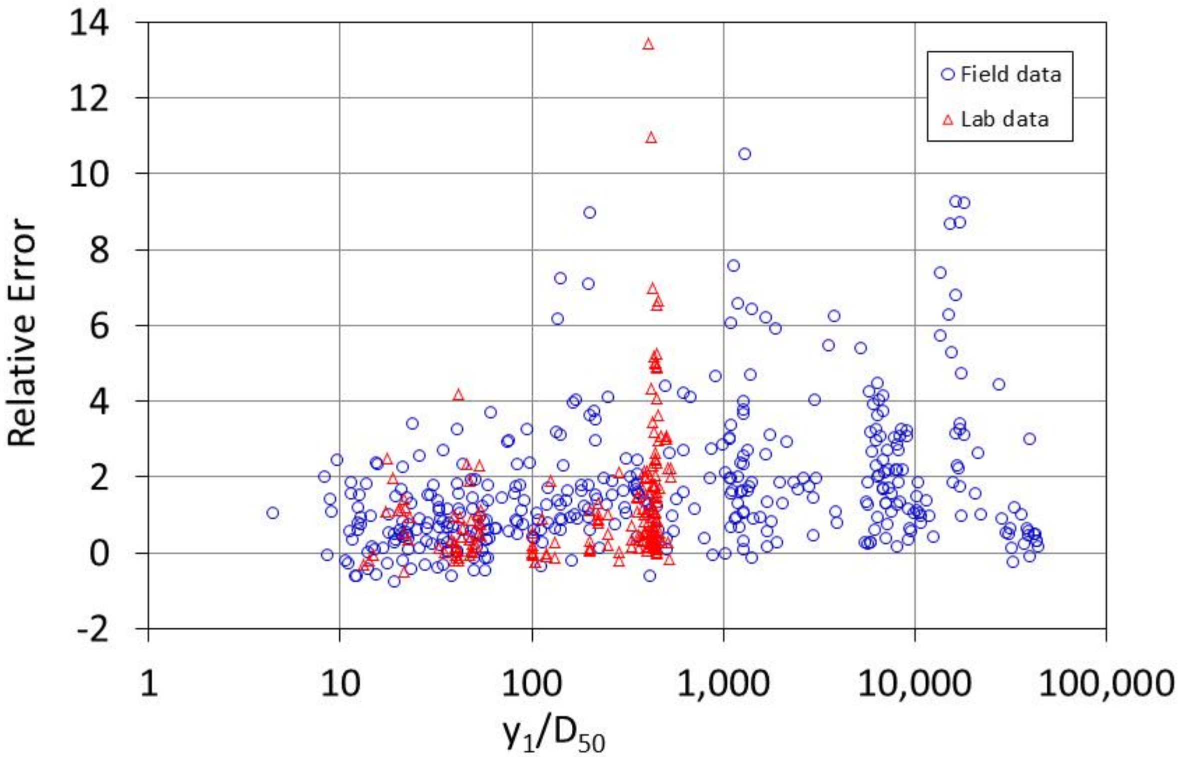

Figure 16. Graph. Error versus y_1/D_{50}: coarse bed equation.

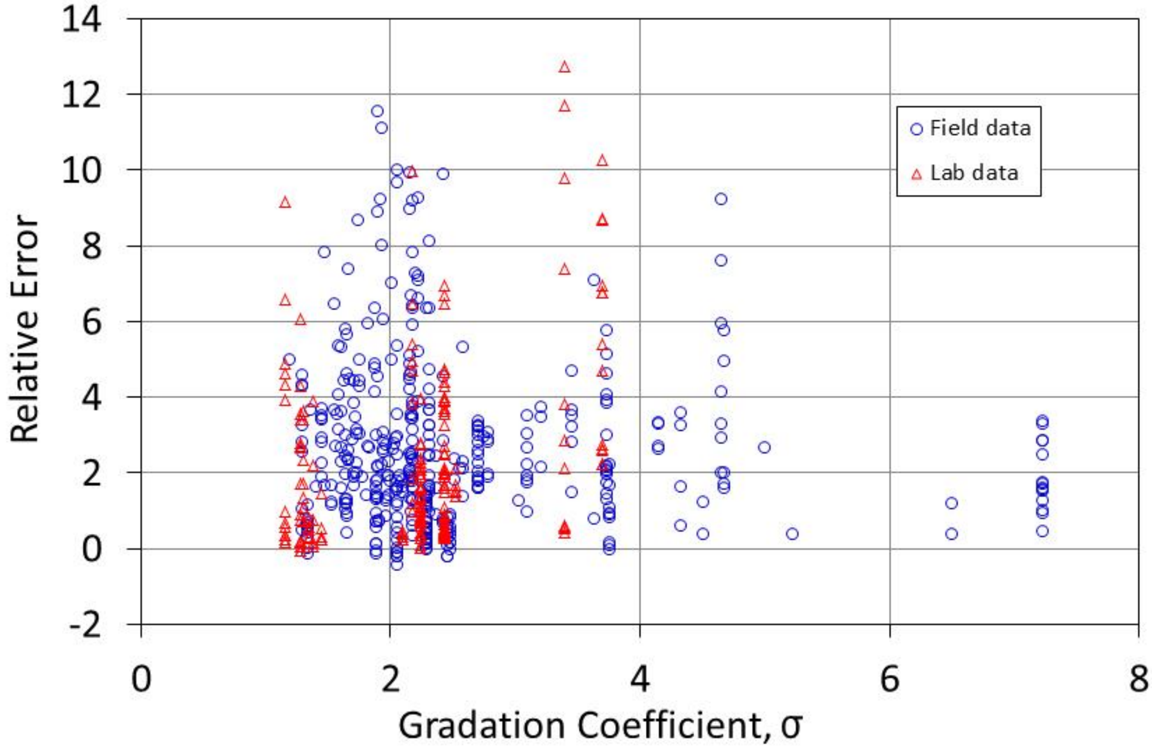

Figure 17. Graph. Error versus gradation coefficient: general equation.

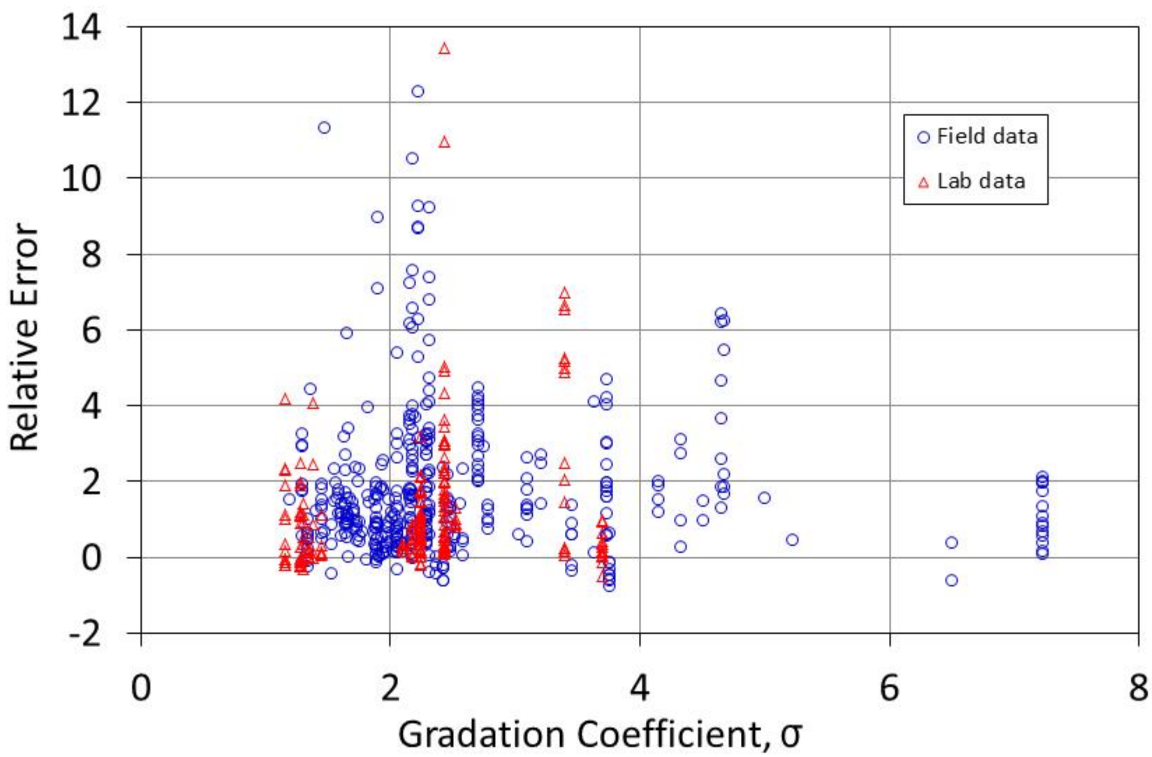

Figure 18. Graph. Error versus gradation coefficient: coarse bed equation.

Limiting Predicted Scour

For round nose piers aligned with the flow direction, HEC-18 recommends that predicted scour be limited to 2.4 times the pier width when the Fr is less than 0.8 and limited to 3.0 times the pier width when the Fr is greater than 0.8. These limits governed for 22 observations when using the general equation and for 20 observations when using the coarse bed equation. (Nine additional predicted scour estimates were limited by the wide pier adjustment when using both equations.)

The maximum measured dimensionless pier scour values were 2.6 in the field data and 1.8 in the laboratory data. Limiting the dimensionless predicted scour to 3.0 was evaluated relative to its effect on the RI and RRMSE. Such a limit only affects the field data because all predicted dimensionless scour values from both equations are less than 3.0 in the laboratory data. The results of this evaluation were mild increases in the accuracy and mild decreases in the reliability of both equations. Because development of such an adjustment was not an objective of this research, no further consideration was given. However, additional research into such a limit may be useful.

CALIBRATING EQUATION COEFFICIENTS

Bridge designers seek reliable (low risk of underdesign) and cost-effective (accurate) estimates of pier scour. Because a higher reliability generally means a lower accuracy, finding the most appropriate balance is a challenge. The trade-off is further complicated because although the study dataset is large and includes a wide variety of situations, it may not be representative for specific bridge design situations.

To address these challenges and to achieve the study objective, the coefficient from the HEC-18 coarse bed material equation (figure 1) was adjusted to a target RI. The selection of an appropriate target RI is best accomplished within the context of a larger risk analysis. For this study, it is noted that, for the general pier scour equation (figure 3) applied to the current dataset for the data not meeting the coarse bed criteria, the RI is 2.20 for 474 field and laboratory observations. For the coarse bed pier scour equation (figure 1), the RI is 0.88 for 120 field observations. Therefore, a target reliability of 2.0 is used that roughly reflects the composite reliability for pier scour estimates under current HEC-18 guidance.

To achieve an RI of 2.0 for the Hager number/gradation coefficient (HN/GC) based pier scour equation (figure 1), the coefficient required is 1.32. The resulting equation is shown in figure 19. Note that the adjustment for bed condition, K_3, has been reintroduced to the HN/GC equation to evaluate its use for clear water ($K_3 = 1.1$) and live bed ($1.1 \leq K_3 \leq 1.3$) conditions. Because the previous analyses showed equivalent performance under a wide range of conditions, the equation is referred to as the HN/GC equation rather than as a coarse bed pier scour equation.

$$\frac{y_s}{a^{0.62} y_1^{0.38}} = 1.32 K_1 K_2 K_3 \left[tanh\left(\frac{H^2}{1.97\sigma^{1.5}} \right) \right]$$

Figure 19. Equation. HN/GC equation for pier scour with RI = 2.0.

Application of the HN/GC pier scour equation to the full dataset results in predicted dimensionless scour estimates that are compared to measured dimensionless scour estimates in figure 20. Because the coefficient was increased, the predicted scour estimates also increased.

The maximum scour predictions using the equation were limited by the following:

- Wide pier adjustment using K_w.
- $y_s/a \leq 2.4$ for round nose piers aligned with the flow and Fr ≤ 0.8.
- $y_s/a \leq 3.0$ for round nose piers aligned with the flow and Fr > 0.8.

For the HN/GC equation, the limits were enforced for 76 field observations and 9 laboratory observations.

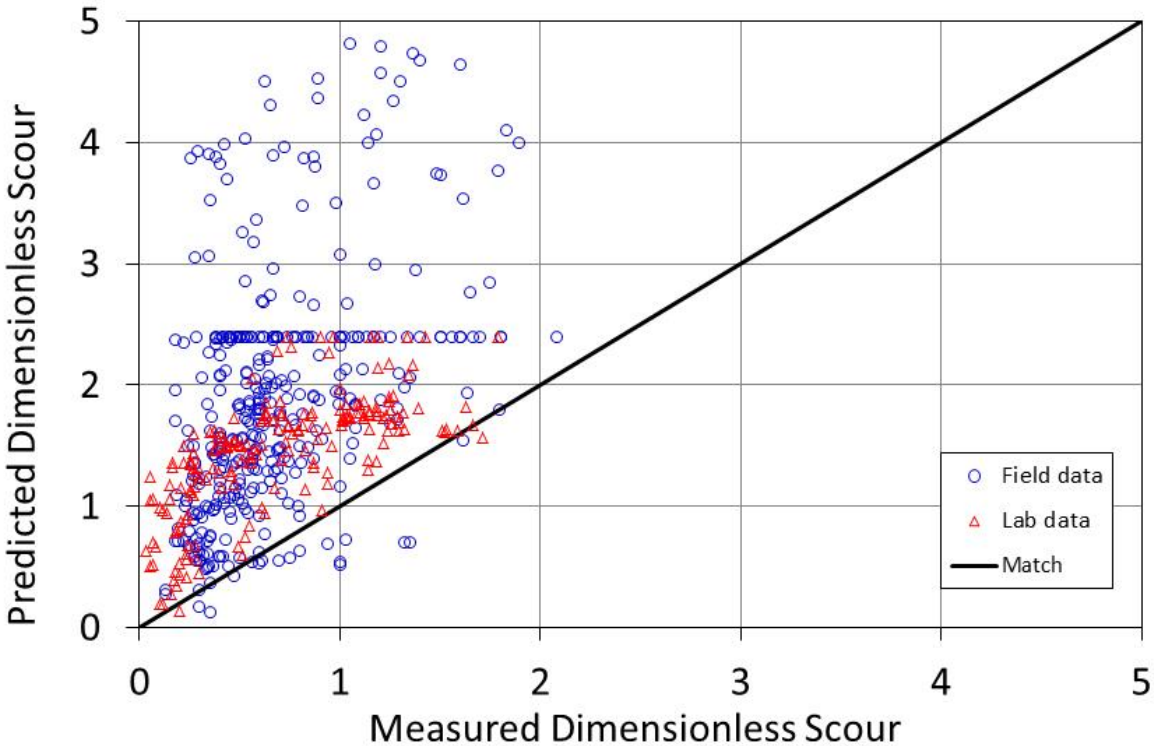

Figure 20. Graph. Predicted versus measured scour: HN/GC equation with RI = 2.0.

Table 6 provides the performance information for the HN/GC equation. The RI and RRMSE measures for the combined dataset of 594 scour observations are 2.0 (by design) and 3.67, respectively. The original development of the HN/GC equation was accomplished on a subset of the current dataset that generally (though not exclusively) met the requirements for application as the HEC-18 coarse bed equation. Therefore, when partitioning the data between those that meet the criteria and those that do not, it is not surprising that the equation is more accurate (lower RRMSE) for those data that meet the criteria. As shown in table 6, the RRMSE for data meeting the criteria is 2.34 while for the remaining data it is a much higher 3.94. However, because of the typical trade-off between accuracy and reliability, the equation is less reliable for the data meeting the criteria (RI = 1.68) than for the data not meeting the criteria (RI = 2.12).

For the bed load partitioning, the same ambiguity between accuracy and reliability exists. The equation is more accurate in estimating clear water scour but more reliable in estimating live bed scour.

The gradation partition reveals virtually no distinction between uniform and nonuniform gradation. For the uniform and nonuniform partitions, the RIs are 2.01 and 2.02, respectively, and the RRMSEs are 3.75 and 3.66, respectively.

For D_{50}, the picture is slightly different. The reliability is virtually identical between the two partitions: 1.96 for $D_{50} \geq 0.79$ inches (20.1 mm) and 2.03 for $D_{50} < 0.79$ inches (20.1 mm). However, for the same level of reliability, the equation is more accurate for the larger D_{50} (RRMSE = 2.75) compared with the smaller D_{50} (RRMSE = 3.97).

Table 6. Performance of the HN/GC equation with RI = 2.0.

Data Description			HEC-18 Coarse Bed Criteria		Bed Load Transport		Gradation		$D_{50} \geq$ 0.79 Inches	
Source	Parameter	All	Yes	No	Clear Water	Live Bed	Uniform	Nonuniform	Yes	No
Field	*n*	402	120	282	218	184	31	371	168	234
	RI	1.93	1.68	2.08	1.61	2.55	2.74	1.89	1.96	1.93
	RRMSE	3.61	2.34	4.03	2.87	4.32	3.62	3.60	2.75	4.11
Lab	*n*	192	0	192	163	29	52	140	0	192
	RI	2.24	0.00	2.24	2.40	2.00	1.65	2.60	0.00	2.24
	RRMSE	3.80	0.00	3.80	4.11	0.89	3.82	3.79	0.00	3.80
Total	*n*	594	120	474	381	213	83	511	168	426
	RI	2.00	1.68	2.12	1.85	2.49	2.01	2.02	1.96	2.03
	RRMSE	3.67	2.34	3.94	3.46	4.02	3.75	3.66	2.75	3.97

1 inch = 25.4 mm.

Recall that the objective of this study is to determine if the equation described in figure 1 can be used for conditions beyond those to which it is currently limited. The previous observations suggest that the equation, modified with a revised coefficient to achieve a RI of 2.0, can be used for a broader range of conditions. These conditions are summarized as follows:

- Clear water or live bed conditions ($V_1/V_{c,50} < 5.2$).
- Sands, gravels, and cobbles (0.0079 inches (0.21 mm) < D_{50} < 5.0 inches (127 mm)).
- Gradation coefficients (σ) less than 7.5.
- Fr less than 1.7.

PIER GROUPS

The HEC-18 pier scour methodology includes guidance to estimate scour for piers that are composed of groups of cylinders. Of the 402 field scour data observations, 60 involve pier groups. None of the laboratory observations include pier groups.

Table 7 provides the performance metrics for pier groups with the HN/GC equation from figure 19. The pier group observations show a significantly higher RI than for the single pier observations but with significantly lower accuracy. The HN/GC equation overpredicts all 60 scour observations.

Table 7. Performance of the HN/GC equation on pier type with RI = 2.0.

Data Description			Pier Type	
Source	**Parameter**	**All**	**Group**	**Single**
Field	*n*	402	60	342
	RI	1.93	3.36	1.81
	RRMSE	3.61	5.79	3.07

Although the HN/GC could be used for pier groups, the addition of an adjustment factor reflecting pier groups might be appropriate. For the HN/GC equation, the factor would be less than one. It is recommended that this be investigated further for both this equation and the equation in figure 3. The 60 data observations in the current dataset could be used as a basis for further evaluation.

CHAPTER 4. CONCLUSIONS AND RECOMMENDATIONS

A dataset of 594 pier scour observations from 2 laboratory and 3 field studies was compiled. The dataset served as the testing ground for evaluating potential enhancements to the pier scour tools for noncohesive soils in HEC-18. In the current (fifth) edition of HEC-18, there are two primary equations for pier scour in noncohesive soils. The first is the general equation applicable to most situations including clear water and live bed conditions. The second is a coarse bed material equation recommended only for use under clear water conditions with coarse bed materials. Coarse bed materials are defined as those where the D_{50} is greater than or equal to 0.79 inches (20.1 mm) and the gradation coefficient, σ, is greater than or equal to 1.5.

The original objective of this research was to determine if the coarse bed materials equation described in figure 1 could be used for conditions beyond those under which it is currently limited. A framework for evaluating the pier scour equations was developed using qualitative and quantitative tools. Qualitative tools included visual inspection of comparative graphs. Quantitative tools included the RI as a measure of equation reliability and the RRMSE as a measure of equation accuracy.

The HN/GC equation was adjusted to a target RI of 2.0. It was evaluated by partitioning the dataset into two groups based on the key conditions, including the HEC-18 coarse bed criteria, clear water versus live bed transport conditions, gradation, and median grain size. The equation performed reasonably consistently in all partitioned datasets; this result leads to the conclusion that it can be used for a broader set of conditions.

A subset of the dataset included pier group scour observations. The equation performed better for single piers but offered a basis for predicting local scour at pier groups. The HN/GC equation tended to provide predictions higher than desired for pier groups and could be adjusted downward.

Considering all of these findings, the HN/GC equation in figure 19 is recommended for a broad range of conditions. It is further recommended that the application be generally limited to the following conditions:

- Clear water or live bed conditions ($V_1/V_{c,50} < 5.2$).
- Sands, gravels, and cobbles (0.0079 inches (0.21 mm) < D_{50} < 5.0 inches (127 mm)).
- Gradation coefficients (σ) less than 7.5.
- Fr less than 1.7.
- Single piers.

Designers may choose to extend these limits after site-specific evaluation of the risks and alternatives. The evaluation of pier groups in the previous chapter may be a starting point for considering the application of the equation to pier groups.

In addition to these primary conclusions and recommendations, this study of pier scour equations revealed the following issues, which warrant further investigation:

- Trends in errors did not exist for most variables involved with scour prediction. The one exception was that for both equations (HEC-18 general scour and HN/GC), trends in error were observed with increases in the ratio of approach depth to median grain size (y_1/D_{50}). These trends should be further investigated and possibly eliminated.

- Refinements either to the HEC-18 method for analyzing pier groups or an adjustment to the recommended equation should be provided to improve scour predictions for pier groups.

- The RI was employed as a quantitative measure of reliability indicating the likelihood of overpredicting actual scour. A target value of 2.0 was selected for this study based on an assessment of the reliability of current practice. Further evaluation of the appropriate reliability level would inform trade-offs between conservativism and costs.

- Investigation of other quantitative means of estimating reliability and accuracy could improve the development and testing of scour estimation methods.

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