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Uncertainty of Local Scouring Parameters Around Bridge Piers

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Abstract

Reliability-based assessment of local scouring mechanism around bridge piers provides information for decision-making regarding the pier footing design. Parameter uncertainties that may arise from various sources due to the inability to precisely quantify a parameter need to be estimated in order to quantify the level of risk of pier failure during the physical life of a bridge. By examining extensive experimental data from the literature on local scour depth around various shapes of bridge pier the functional dependence of relevant parameters is examined. The degree of uncertainty and the statistical randomness of these parameters are assessed in terms of coefficients of variation and probability distribution functions, respectively.

Key Words: local scour, bridge pier, reliability, uncertainty

Köprü Ayakları Etrafındaki Oyulma Parametrelerinin Belirsizliği

Özet

Köprü ayakları etrafındaki oyulma mekanizmasının güvenilirliğinin irdelenmesiyle ayak sömel tasarımı için gerekli bilgi edinilmektedir. Çeşitli nedenlerle oluşan parametre belirsizliğinin hesaplanması, köprü fiziksel ömrü boyunca oluşacak riskin tahmini için gereklidir. Literatürden elde edilen değişik şekillerdeki köprü ayakları etrafındaki oyulma derinliği verisinin değerlendirilmesiyle olayı etkileyen parametreler arasındaki fonksiyonel bağımlılık araştırılmıştır. Bu parametrelerdeki belirsizlik mertebesi ve istatistiksel rastgelelik değişim katsayıları ve olasılık dağılım fonksiyonları cinsinden ifade edilmektedir.

Anahtar Sözcükler: yerel oyulma, köprü ayağı, güvenilirlik, belirsizlik

Introduction

The major failure mode of a bridge results mainly from excessive local scour around bridge piers. Scour-induced bridge failure mode is relatively complex because of the combined effects of three dimensional river bed degradation, localized scour due to the channel constriction at the bridge opening, local scour around bridge piers and abutments due to the accelerated flow and generation of vortices at the bridge opening, and human interference, such as channel mining near a bridge site, upstream (Yanmaz and Çiçekdağ, 2000). Most of the parameters characterizing the overall phenomenon are of a stochastic nature. Although the aforementioned processes are normally interdependent to a certain extent, they are usually treated as independent events in order to simplify the modeling. Judgement and experience are also needed to estimate the level of overall scouring. Because of uncertainties that result from the lack of relevant information and the simplicity of the deterministic models, bridges are either underdesigned or overdesigned. An underdesigned bridge may be subject to a recoverable damage or complete failure during a severe flood (Yanmaz and Coşkun, 1995).

Available field data for local scour around bridge piers under severe flow conditions are limited. Moreover, data are normally not precise because of progressive changes in parameters of sediment laden flow and observational difficulties at bridge sites. The field data compiled from Froehlich (1988) exhibit a high degree of scattering with smaller relative scour depths compared to the available experimental data reflecting similar dimensionless hydraulic conditions. This may be due to the fact that the point measurements in the field may not comprise the equilibrium values, whereas laboratory measurements reflect the maximum terminal scour depths. Froehlich (1988) states that there is no information about in-situ particle gradation which has a retarding effect on the scouring due to armoring at the river bed. An uncertainty analysis based on the field data can, therefore, provide a very rough estimate for the risk due to the lack of relevant statistical information. On the other hand, the deterministic models calibrated using elaborate experimental data are relatively simplistic as they reflect only certain aspects of the phenomenon. This is mainly due to deficiency in modeling the actual prototype conditions, which normally reflect three-dimensional unsteady, non-uniform sediment-laden flow conditions.

In a previous study carried out by Yanmaz and Çiçekdağ (1997), the probability distributions of the governing scouring parameters around cylindrical piers are examined in various ranges of Froude numbers. In the present study, the scope of the previous analyses is extended by examining the functional dependence, coefficients of variation and probability distributions of the governing scouring parameters around various pier shapes using extensive experimental data. A first-order uncertainty analysis is carried out to examine the form of equations to express the uncertainties of the governing parameters for cylindrical and non-cylindrical piers.

Local Scouring Parameters

Estimation of the maximum local scour depth at a bridge pier in an alluvial river is required for the safe design of a bridge. The problem of local scour around bridge piers has been studied extensively by several investigators. However, this phenomenon still persists because of inadequacy in modeling due to the difficulties of the problem, such as the combined effects of complex turbulent boundary layer, time-dependent flow pattern, and sediment transport mechanism in and around the scour hole (Yanmaz and Altınbilek, 1991). A dimensional analysis can be performed to examine the interrelationship among the dimensionless terms which affect the development of the scour hole around bridge piers. Parameters influencing the scouring process can be expressed as:

$$\begin{aligned}&f(d_s, \rho, \nu, g, d_0, u, \alpha, u_*, S_0, B,\\&C_c, K_a, K_b, K_c, K_d, \rho_s, D_{50}, \sigma_g, C,\\&K_f, b, K_s, K_g, K_r, K_v, t) = 0\end{aligned} \tag{1}$$

where d_s=maximum depth of scour around a bridge pier; ρ=density of water; ν=kinematic viscosity of water; g=gravitational acceleration; d_0=depth of approach flow; u=mean velocity of approach flow; α=angle of approach flow with respect to the pier axis; u_*=shear velocity; S_0=bed slope; B=channel width; C_c=contraction coefficient; K_a=factor indicating the effect of flow alignment with respect to pier axis; K_b=roughness of the river bed upstream; K_c=roughness of the sidewalls of the channel; K_d=factor indicating the effect of the cross-sectional geometry of the channel; ρ_s=density of sediment; D_{50}=median sediment size; σ_g=standard deviation of particle size distribution; C=cohesion of bed material; K_f=factor indicating the effect of grain shape; b=characteristic size of pier; K_s=factor indicating the effect of pier shape; K_g=factor indicating the group effect of piers; K_r=roughness of pier surface; K_v=factor indicating the effect of angle between the vertical axis of pier and the plumb direction; and t=duration of flow. Dimensionless terms can be determined by using Buckingham's π theorem (Shames, 1992). After rearranging the dimensionless terms, the following expression is obtained under the assumption of a single, smooth, vertically mounded pier over a uniform non-cohesive bed material having a constant shape factor and density in a wide, prismatic, straight and smooth channel with no significant bed forms:

$$y = f_1(x, z, w, \eta, \epsilon, \psi, \beta, \alpha, K_s) \tag{2}$$

where $y = d_s/b$ (relative scour depth); $x = d_0/b$ (relative approach flow depth), $z = u/\sqrt{gd_0}$ is the Froude number; $w = ud_0/\nu$ is the Reynolds number; $\eta = u_*/u$; $\epsilon = ut/D_{50}$; $\psi = K_r/D_{50}$ and $\beta = b/D_{50}$. Experimental studies have been conducted by considering only certain aspects of the problem and accepting the other parameters to be constant (Yanmaz and Altınbilek, 1991). The number of dimensionless terms in Equation (2) can then be reduced by considering the relative importance of the terms. Experimental studies conducted by Chabert and Engeldinger (1956), Shen et al. (1969), etc., have shown that, for a pier with a given size, b, a sediment of a given size, D_{50}, and flow conditions at and above the threshold conditions (live bed conditions), the scour depth fluctuates around an equilibrium value. The Reynolds number has, therefore, no significant effect on the scour depth for this range, which corresponds to practical prototype conditions. For a case with a constant bed slope, the term $\eta = u_*/u$ is a function of d_0 only. So, its variation is treated in the term $x = d_0/b$. Time development of the scour hole can be ignored for a sufficiently long flow duration under live bed conditions. According to Raudkivi (1986) and Breusers and Raudkivi (1991), the local scour depth is independent of sediment size for $b/D_{50} \geq 50$. For grain sizes with $b/D_{50} < 50$, the grains are large enough relative to the width of the groove excavated by downflow which impedes the scouring process. Because the condition $b/D_{50} < 50$ is unlikely in practice (Melville, 1997), the effect of b/D_{50} term is neglected for practical purposes. The following relationship is then obtained for a single smooth pier having a particular shape which is aligned with the flow direction ($\alpha = 0°$):

$$y = f_2(x, z) \tag{3}$$

A statistical analysis can be carried out to examine the statistical randomness and the degree of uncertainty of the parameters given in Equation (3). This information can be used as a tool in a reliability-based analysis. To this end, a set of live bed scour data under $\alpha = 0°$ conditions around bridge piers of various shapes compiled from the literature are studied. The ranges of relevant parameters and the statistical information of the parameters, i.e. the mean, μ, and the coefficient of variation, Ω, are presented in Tables 1 and 2, respectively. It should be stated that the Ω values in Table 2 reflect the variations in the ranges of the parameters tested. So, they do not express the parameter uncertainty. To account for the effect of pier shape, the analyses are carried out for cylindrical piers and non-cylindrical piers. Based on a review of the literature, Melville (1997) proposes the shape and alignment adjustment factors in Table 3 in which l is the length of the pier. The values of K_s factors are 1.0 and 1.1 for cylindrical and round-nosed piers and blunt-nosed rectangular piers, respectively. The results of Günyaktı (1988) reveal that there is no significant shape effect among rectangular piers (r.p.), round nosed rectangular piers (r.r.p.) or square piers (s.p.) since the relative scour depths around these piers were observed to be almost in the same ranges. Therefore, two sets of analyses are carried out, for cylindrical piers and non-cylindrical piers separately. Using the calibration data, the functional relationship between the aforementioned parameters are determined through multiple regression analyses as follows:

$$y_c = 1.564x^{0.405}z^{0.413} \quad R = 0.90 \tag{4}$$

$$y_{nc} = 2.748x^{0.556}z^{0.859} \quad R = 0.93 \tag{5}$$

where y_c and y_{nc} are the relative scour depths for cylindrical and non-cylindrical piers, respectively, and R is the correlation coefficient.

Analysis of Uncertainties

In hydraulic and hydrologic problems, the statistical information available is often limited only to the first two moments of the variables. The values of the higher moments are normally either unreliable or unavailable. Therefore, the second order approximation is not only difficult to evaluate but also impractical. For this reason, the first order uncertainty analysis is usually carried out for the reliability evaluations of water resources systems (Yen et al. 1986). A function W of n random independent variables of $x_1, x_2, \ldots, x_n$ is expressed as:

$$W = f(x_1, x_2, \ldots, x_n) \tag{6}$$

The coefficient of variation of W for the first order analysis can be obtained from Taylor's expansion of Equation (6) about the expected value, $\overline{W}$, as follows (Tung and Mays, 1980):

$$\begin{aligned}\Omega_W^2 = & \left(\frac{\partial W}{\partial x_1}\right)^2_{W=\overline{W}} \left(\frac{\overline{x}_1}{\overline{\overline{W}}}\right)^2 \Omega_{x_1}^2 \\ & + \left(\frac{\partial W}{\partial x_2}\right)^2_{W=\overline{W}} \left(\frac{\overline{x}_2}{\overline{\overline{W}}}\right)^2 \Omega_{x_2}^2 \\ & + \cdots + \left(\frac{\partial W}{\partial x_n}\right)^2_{W=\overline{W}} \left(\frac{\overline{x}_n}{\overline{\overline{W}}}\right)^2 \Omega_{x_n}^2\end{aligned} \tag{7}$$

where Ω_i is the coefficient of variation of the parameter concerned.

Table 1. The Ranges of the calibration data

Pier type (1)	Researcher (2)	b (cm) (3)	d_0 (cm) (4)	D_{50} (mm) (5)	d_s (cm) (6)	F_r (7)
Cylindrical	Chabert and Engeldinger (1956)	10.00-15.00	10.00-35.00	0.52-3.00	11.50-21.14	0.35-0.77
	Tarapore (1962)	5.00	3.70-11.80	0.15-0.50	6.10-7.60	0.37-0.98
	Laursen(1963)	17.40	17.90-21.50	0.16-0.51	18.50-23.10	0.33-0.46
	Shen et al. (1966)	15.00-17.40	11.37-21.31	0.24-1.51	12.75-23.10	0.30-1.02
	Hancu (1971)	13.00	5.00	0.50	9.36-14.89	0.31-0.85
	Başak et al. (1977)	4.00-39.50	3.26-16.70	0.70	4.50-27.00	0.37-0.55
	Jain and Fischer (1979)	5.08-10.16	10.16	0.25	8.38-18.49	0.50-1.20
	Melville (1984)	5.08-10.16	10.00	0.24-1.40	6.10-18.9	0.30-1.21
Rectangular	Chabert and Engeldinger (1956)	10.00-15.00	10.00-35.00	0.52-3.00	11.50-20.30	0.23-0.77
	Shen et al. (1969)	15.20-91.40	11.60-61.00	0.24-0.46	13.40-54.90	0.20-0.31
	Başak et al. (1977)	4.00-24.00	3.85-14.30	0.70	6.00-23.00	0.44-0.53
Square	Başak et al. (1975)	4.00-40.00	3.85-14.30	0.70	5.80-28.50	0.44-0.53
Round-nosed Rectangular	Laursen and Toch (1956)	6.10	6.10-18.30	0.46-0.58	10.70-13.70	0.29-0.64
	Başak et al. (1977)	15.00-40.00	10.70-14.30	0.70	15.50-31.00	0.44-0.46

Table 2. Statistical Information on the calibration data

Type of pier (1)	Parameter (2)	μ (3)	Ω (4)
Cylindrical	x	1.2558	0.4795
	y	1.3436	0.2758
	z	0.6180	0.4055
Non-cylindrical	x	0.9716	0.8682
	y	1.2562	0.3979
	z	0.4667	0.1504

Table 3. Adjustment factors for flow alignment (Melville 1997)

	K_a			
l/b (1)	$\alpha = 0°$ (2)	$\alpha = 15°$ (3)	$\alpha = 30°$ (4)	$\alpha = 45°$ (5)
4	1.0	1.5	2.0	2.3
8	1.0	2.0	2.75	3.3
12	1.0	2.5	3.5	4.3

For the uncertainty analysis of the local scour mechanism around bridge piers, a model error term, λ_m, is incorporated to account for the effects of additional parameters which are ignored in the analysis. To express the uncertainty of Equations (4) and (5) in terms of measurable quantities, the scour depths around cylindrical and non-cylindrical piers, d_{sc} and d_{snc}, respectively, can be expressed in terms of b, d_0 and u. By performing a first-order analysis of Equations (4) and (5), the following equations are obtained:

$$\overline{d}_{sc} = 0.976\lambda_{mc}\overline{b}^{0.595}\overline{d}_0^{0.1985}\overline{u}^{0.413} \tag{8}$$

$$\overline{d}_{snc} = 1.03\lambda_{mnc}\overline{b}^{0.444}\overline{d}_0^{0.1265}\overline{u}^{0.859} \tag{9}$$

where the bar sign stands for the expected values of the parameters concerned. Using Equation (7), the total coefficients of variation of $\overline{d}_{sc}$ and $\overline{d}_{snc}$ are determined as follows:

$$\Omega^2_{d_{sc}} = \Omega^2_{\lambda_{mc}} + 0.354\Omega^2_b + 0.0394\Omega^2_{d_0} + 0.1706\Omega^2_u \tag{10}$$

$$\Omega^2_{d_{nsc}} = \Omega^2_{\lambda_{mnc}} + 0.197\Omega^2_b + 0.0160\Omega^2_{d_0} + 0.7379\Omega^2_u \quad (11)$$

Determination of the overall uncertainty using Equations (10) and (11) is based on the availability of the coefficients of variations of the model correction factors, λ_{mc} and λ_{mnc}, b, d_0 and u. The coefficients of variations in hydraulic parameters d_0 and u reflect the possible errors in the measurement of these variables which may be negligibly small in elaborate laboratory conditions under the control of an experienced hydraulician. However, these values may reach somewhat higher levels in the prototype conditions depending on the location of measurement, precision of the instrument and human-induced errors. The coefficient of variation of pier size b may arise due to a constructional error which is normally very small. In different applications carried out by Johnson (1996) and Yanmaz (2000), some guideline values are proposed for the coefficients of variations of some hydraulic and geometric variables. Determination of the coefficient of variation of model correction factor depends on the precision of the modeling of the scouring mechanism, which is so complex that no single method valid for universal conditions concerning flow, sediment, river and pier characteristics has been developed to date. All the methods proposed in the literature are then based on several simplifying assumptions, and hence valid under certain conditions. Although the forms of the equations proposed in the literature are similar, the results of these equations differ widely from each other due to the model and parameter uncertainties which reflect the variability of flow and bed material characteristics in the laboratory conditions. Jones (1983) compared a number of scour equations in terms of the relative scour depth, y, versus the relative approach flow depth, x, with a Froude number of 0.3. Günyaktı (1988) carried out a similar study for Froude numbers of 0.3 and 0.7. Their studies show considerable variations among the scour equations. To reinforce this, the agreement between the results of Equations (4) and (5), which are derived using extensive data, and those of the equation proposed by Richardson (1987), which is commonly used in the United States (Highways 1990) and also known as the Colorado State University equation (CSU equation), can be examined. The CSU equation is given as:

$$y = 2.0 K_s K_a x^{0.35} z^{0.43} \quad (12)$$

Although there is a fair correlation between the results of the present study based on Equations (4) and (5) and those of the CSU equation, this agreement is not good enough to ignore the effect of the model correction factor, λ_m (See Figures 1 and 2 for cylindrical and non-cylindrical piers, respectively). Similar tendencies can also be observed from the other equations, such as Jain and Fischers' (1980) equation. Hence, it can be concluded that the model correction factor cannot be estimated for a general case which is valid under universal conditions. This leads to the result that the uncertainties of the scour depths expressed by Equations (10) and (11) cannot be quantified. However, these equations reflect the form of the uncertainties of the relative scour depths around bridge piers.

A designer needs to estimate the level of risk which is required in decision making for the pier footing design. Determination of probability distributions of the governing parameters may provide a rational tool for a reliability-based analysis and would yield the frequencies of these parameters over their ranges of occurrences. To this end, the frequency histograms of the parameters are plotted as shown in Figures 3 and 4 for cylindrical and non-cylindrical piers, respectively. As can be observed from Figures 3 and 4, most of the experiments are performed under subcritical flow regime because of the limited capabilities of most of the laboratory conditions. In the analysis, the normal (N), two-parameter log-normal (LN2), three-parameter log-normal (LN3), extreme value type 1 (EV1), Pearson type 3 (PT3) and log-Pearson type 3 (LPT3) probability density functions (PDF) are tested for goodness of fit of x, y, and z using Chi-square and Kolmogorov-Smirnov techniques (Yevjevich, 1972) with 90% and 95% confidence intervals. The results of the goodness of fit tests are presented in Tables 4 and 5 for cylindrical and non-cylindrical piers, respectively. The overall decision for a fit is acceptable if any distribution is acceptable by the methods concerned under the confidence intervals used. For the ranges of the parameters for cylindrical piers, it is observed that LPT3 distribution can be fitted to x. All the PDFs can be fitted to y and all the PDFs, except for N distribution, are acceptable for z (See Table 4). For non-cylindrical piers, LN2, LN3, PT3 and LPT3 functions are fitted to x. All the PDFs tested can be fitted to y and no PDF is proposed for z.

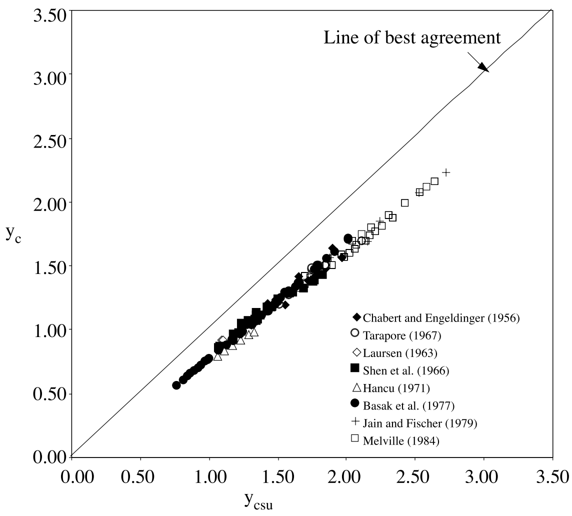

Figure 1. Correlation between Equation 4 and CSU Equation for cylindrical piers

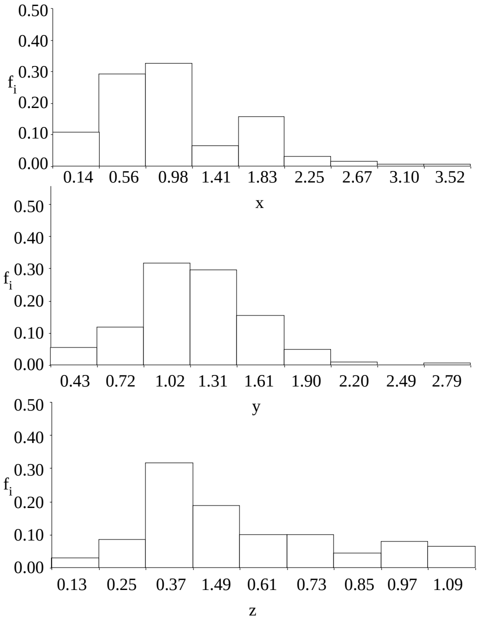

Figure 3. Frequency histograms of scouring parameters for cylindrical piers

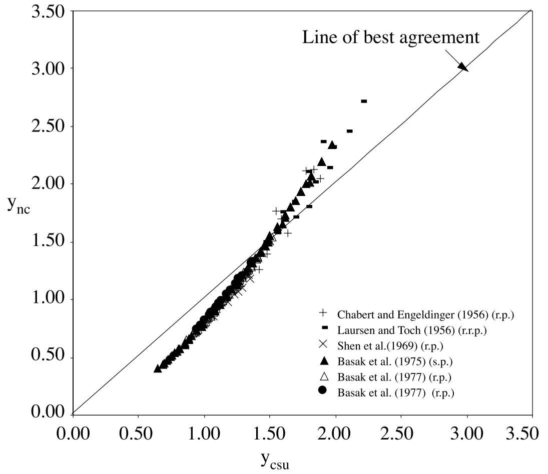

Figure 2. Correlation between Equation 5 and CSU Equation for non-cylindrical piers

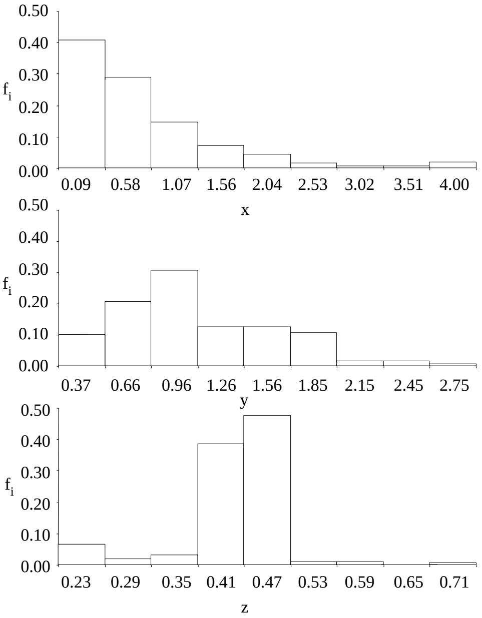

Figure 4. Frequency histograms of scouring parameters for non-cylindrical piers

Table 4. Tests of Goodness of Fit for PDFs for cylindrical piers

Parameter	PDF	χ^2					D_n					Overall decision
		Computed value	Critical value		Decision		Computed value	Critical value		Decision		
			CI=0.90	CI=0.95	CI=0.90	CI=0.95		CI=0.90	CI=0.95	CI=0.90	CI=0.95	
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)
x	N	48.9557	13.40	15.50	Reject	Reject	0.134	0.086	0.095	Reject	Reject	Reject
	LN2	117.4975	13.40	15.50	Reject	Reject	0.101	0.086	0.095	Reject	Reject	Reject
	LN3	99.3202	13.40	15.50	Reject	Reject	0.097	0.086	0.095	Reject	Reject	Reject
	EV1	98.3448	13.40	15.50	Reject	Reject	0.097	0.086	0.095	Reject	Reject	Reject
	PT3	98.3448	13.40	15.50	Reject	Reject	0.097	0.086	0.095	Reject	Reject	Reject
	LPT3	59.5074	13.40	15.50	Reject	Reject	0.092	0.086	0.095	Accept	Accept	Accept
y	N	7.9901	13.40	15.50	Accept	Accept	0.048	0.086	0.095	Accept	Accept	Accept
	LN2	7.9015	13.40	15.50	Accept	Accept	0.057	0.086	0.095	Accept	Accept	Accept
	LN3	6.7488	13.40	15.50	Accept	Accept	0.053	0.086	0.095	Accept	Accept	Accept
	EV1	11.2709	13.40	15.50	Accept	Accept	0.072	0.086	0.095	Accept	Accept	Accept
	PT3	6.7488	13.40	15.50	Accept	Accept	0.053	0.086	0.095	Accept	Accept	Accept
	LPT3	10.6502	13.40	15.50	Accept	Accept	0.048	0.086	0.095	Accept	Accept	Accept
z	N	113.0640	13.40	15.50	Reject	Reject	0.174	0.086	0.095	Reject	Reject	Reject
	LN2	25.9015	13.40	15.50	Reject	Reject	0.068	0.086	0.095	Accept	Accept	Accept
	LN3	49.4877	13.40	15.50	Reject	Reject	0.095	0.086	0.095	Reject	Accept	Accept
	EV1	24.7488	13.40	15.50	Reject	Reject	0.068	0.086	0.095	Accept	Accept	Accept
	PT3	33.6158	13.40	15.50	Reject	Reject	0.093	0.086	0.095	Reject	Accept	Accept
	LPT3	26.1675	13.40	15.50	Reject	Reject	0.068	0.086	0.095	Accept	Accept	Accept

Table 5. Tests of Goodness of Fit for PDFs for non-cylindrical piers

Parameter	PDF	χ^2					D_n					Overall decision
		Computed value	Critical value		Decision		Computed value	Critical value		Decision		
			CI=0.90	CI=0.95	CI=0.90	CI=0.95		CI=0.90	CI=0.95	CI=0.90	CI=0.95	
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)
x	N	79.1800	13.40	15.50	Reject	Reject	0.139	0.086	0.096	Reject	Reject	Reject
	LN2	11.6800	13.40	15.50	Accept	Accept	0.039	0.086	0.096	Accept	Accept	Accept
	LN3	8.3500	13.40	15.50	Accept	Accept	0.046	0.086	0.096	Accept	Accept	Accept
	EV1	47.5900	13.40	15.50	Reject	Reject	0.111	0.086	0.096	Reject	Reject	Reject
	PT3	5.9200	13.40	15.50	Accept	Accept	0.033	0.086	0.096	Accept	Accept	Accept
	LPT3	4.8400	13.40	15.50	Accept	Accept	0.023	0.086	0.096	Accept	Accept	Accept
y	N	17.8000	13.40	15.50	Reject	Reject	0.084	0.086	0.096	Accept	Accept	Accept
	LN2	11.9500	13.40	15.50	Accept	Accept	0.043	0.086	0.096	Accept	Accept	Accept
	LN3	14.5600	13.40	15.50	Reject	Accept	0.054	0.086	0.096	Accept	Accept	Accept
	EV1	14.0200	13.40	15.50	Reject	Accept	0.043	0.086	0.096	Accept	Accept	Accept
	PT3	14.2900	13.40	15.50	Reject	Accept	0.049	0.086	0.096	Accept	Accept	Accept
	LPT3	15.6400	13.40	15.50	Reject	Reject	0.049	0.086	0.096	Accept	Accept	Accept
z	N	104.5600	13.40	15.50	Reject	Reject	0.218	0.086	0.096	Reject	Reject	Reject
	LN2	104.5600	13.40	15.50	Reject	Reject	0.218	0.086	0.096	Reject	Reject	Reject
	LN3	2619.1250	13.40	15.50	Reject	Reject	0.875	0.086	0.096	Reject	Reject	Reject
	EV1	178.3600	13.40	15.50	Reject	Reject	0.249	0.086	0.096	Reject	Reject	Reject
	PT3	188.8000	13.40	15.50	Reject	Reject	0.138	0.086	0.096	Reject	Reject	Reject
	LPT3	104.5600	13.40	15.50	Reject	Reject	0.198	0.086	0.096	Reject	Reject	Reject

Conclusions

An uncertainty analysis is carried out for the local scour depth around bridge piers of various shapes with reference to extensive experimental data reported in the literature. By performing a dimensional analysis, the live bed relative scour depth, y, is assumed to depend mainly on the relative approach flow depth, x, and Froude number, z under the conditions of uniform bed material, long flow duration, wide and straight channel, and flow velocities at or above the threshold conditions. The analyses are carried out to examine the statistical randomness of x, y, and z. The form of uncertainties for maximum depths of local scour around cylindrical and non-cylindrical piers are given by Equations (10) and (11), which cannot be quantified for a general case due to the inability to precisely estimate the phenomenon mainly due to the variations of a number of local hydraulic, topographic and sedimentologic characteristics as well as human induced factors. A number of probability distributions are assigned to the governing parameters through frequency analyses. The results of these analyses may be used in determining the confidence limits of a specific PDF for a particular dimensionless prototype parameter that attains the same class interval range as those presented in Figures 3 and 4.

Nomenclature

B = channel width;
b = characteristic size of pier;
C = cohesion of bed material;
C_c = contraction coefficient;
CI = confidence interval;
D_{50} = median sediment size;
d_s = maximum depth of scour around a bridge pier;
d_0 = depth of approach flow;
EV1 = extreme value type 1 distribution;
f = relative frequency;
g = gravitational acceleration;
K_a = factor indicating the effect of flow alignment with respect to pier axis;
K_b = roughness of the river bed upstream;
K_c = roughness of channel sidewalls
K_d = factor indicating the effect of cross-sectional geometry of the channel;
K_f = factor indicating the effect of grain shape;
K_s = factor indicating the effect of pier shape;
K_g = factor indicating the group effect of piers;
K_r = roughness of pier surface;
K_v = factor indicating the effect vertical inclination of pier;
LN2 = 2-parameter lognormal distribution;
LN3 = 3-parameter lognormal distribution;
LPT3 = log-Pearson type 3 distribution;
l = length of bridge pier;
N = normal distribution;
PDF = probability density function;
PT3 = Pearson type 3 distribution;
S_0 = bed slope;
t = duration of flow
u = mean velocity of approach flow;
u_* = shear velocity;
w = ud_0/ν,
x = d_0/b;
y = d_s/b;
y_c = relative scour depth around cylindrical piers;
y_{nc} = relative scour depth around non-cylindrical piers;
$\overline{y}_c$ = mean value of relative scour depth around cylindrical piers;
$\overline{y}_{nc}$ = mean value of relative scour depth around non-cylindrical piers;
z = $u/\sqrt{gd_0}$;
α = angle of approach flow with respect to the pier axis;
β = b/D_{50};
η = u_*/u;
λ_{mc} = model correction factor for relative scour depth around cylindrical piers;
λ_{mnc} = model correction factor for relative scour depth around non-cylindrical piers;
Ω = coefficient of variation;
μ = mean value;
ϵ = ut/D_{50};
ν = kinematic viscosity of water;
ρ = density of water;
ρ_s = density of sediment;
σ_g = standard deviation of particle size distribution;
ψ = K_r/D_{50}

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