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Generalized Reliability Model for Local Scour around Bridge Piers of Various Shapes

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Abstract

Excessive local scour around piers and abutments is known as a major cause of bridge failure induced by hydraulic deficiencies. Complexity of the scouring phenomenon and high degrees of uncertainties in governing parameters lead to an unavoidable risk in bridge pier design. In this paper, a generalized reliability model based on static resistance-loading interference is developed for the assessment of reliability of bridge scour for various pier shapes. In the model, the relative maximum scour depth and the linear combination of the relative approach flow depth and flow Froude number are defined as the system resistance and external loading, respectively. By examining sets of data, a two-parameter bivariate lognormal distribution is found to represent the joint probability density function of the resistance and loading. Reliability expressions are developed for various pier shapes. To obtain relevant information for decision-making, the model is applied to a case study in which a relationship is obtained between the reliability and safety factors for cylindrical and non-cylindrical piers under various return periods.

Key Words: Reliability, bridge pier, scour, pier shape, resistance, loading, safety factor, return period.

Değişik Şekilli Köprü Ayakları Etrafındaki Oyulma Güvenilirliği için Genelleştirilmiş Model

Özet

Köprü ayakları ve yanal mesnetleri etrafındaki aşırı oyulma, hidrolik zaafiyet nedeniyle yıkılan köprülerin ana etkenidir. Oyulma mekanizmasının karmaşıklığı ve olayı etkileyen parametrelerdeki belirsizlik nedeniyle köprü tasarımında kaçınılmaz bir risk mevcuttur. Bu çalışmada, statik direnç-yükleme bağıntısına dayanarak değişik şekillerdeki köprü ayakları etrafındaki oyulma güvenilirliğini tahmin eden genelleştirilmiş bir model geliştirilmiştir. Modelde, göreli maksimum oyulma derinliği direnç; göreli akım derinliği ve Froude sayısının doğrusal kombinasyonu ise yükleme parametresi olarak kabul edilmiştir. Bir dizi verinin incelenmesiyle bağımlı direnç ve yüklemenin değişiminin çift değişkenli bileşik lognormal olasılık yoğunluk fonksiyonuyla temsil edilebileceği görülmüştür. Değişik köprü ayağı şekilleri için güvenilirlik bağıntıları geliştirilmiştir. Tasarımda karar verme aşamasında modelin uygulanmasını göstermek amacıyla sunulan bir örnek çalışmada farklı dönüş aralıklarında dairesel ve dairesel olmayan köprü ayakları etrafındaki oyulma güvenilirliğinin emniyet faktörüyle değişimi araştırılmıştır.

Anahtar Sözcükler: Güvenilirlik, köprü ayağı, ayak şekli, direnç, yükleme, emniyet faktörü, dönüş aralığı

Introduction

In the traditional bridge design approach, the safety margin is usually made large enough to compensate for uncertainties in the phenomenon. This may lead to a conservative design. Decision making for bridge pier design should be based on the assessment of dimensions of pier width and footing depth under various risk levels. As the local conditions exhibit considerable variations among possible feasible bridge sites even on the same river, no general guidelines which are valid under universal conditions can be proposed for the design return period. Instead, the variation of risk should be assessed with respect to the annual total cost of the bridge and its possible appurtenant training facilities in terms of safety and economy under various return periods. Hydraulic, structural and geotechnical interactions should be interpreted in the short and long terms in such an integrated manner that the bridge would be safe under the worst possible conditions likely to occur during the physical life of the structure.

Local scour around bridge piers and abutments has remained a major cause of bridge failures induced by hydraulic deficiencies. Combined effects of turbulent boundary layer, time-dependent flow pattern, and sediment transport mechanism in and around the scour hole make the phenomenon extremely complex, so that experimental studies can be conducted by considering only certain aspects of the problem and accepting the other parameters as constants. In addition, field data are limited due to observational difficulties (Yanmaz and Altınbilek, 1991; Yanmaz and Coşkun, 1995). Lack of relevant information may lead to pronounced model and parameter uncertainties in the scouring phenomenon (Yanmaz, 2001). That is why the literature is not rich in models assessing the risk of bridge pier scour. Some of the previous studies have been carried out by Johnson and Ayyub (1992), Johnson (1992), Johnson and Ayyub (1996), Johnson (1998), and Yanmaz and Çiçekdağ (2001).

In a composite reliability analysis based on resistance-loading interference, the relevant resistance and loading terms need to be identified. The overall loading, x, on a system is the measure of the impact of external events, which can be taken as a linear combination of n independent loads, $x = x_1 + x_2 + \cdots x_n$ (Yen et al., 1986). The resistance, y, is the measure of the ability of the system to withstand the loading. Therefore, the reliability, α, of a system can be expressed as the probability that the resistance of the system exceeds or equals the loading. If the loading and resistance are dependent variables, the system reliability can be expressed as follows (Mays and Tung 1992):

$$\alpha = \int_0^{\infty} \int_0^{y} f_{x,y}(x,y)\,dx\,dy \qquad (1)$$

where $f_{x,y}(x,y)$ is the joint probability density function of the resistance and loading. In a static reliability model, the system performance should be checked under a single worst loading. The aim of this study is to extend the capability of the reliability-based model, which was proposed by Yanmaz and Çiçekdağ (2001) for assessment of risk levels of scour around cylindrical piers. The present study is based on the generalization of this model such that it is applicable to various shapes of piers. The model gives valuable information in terms of the relationship between the reliability and safety factors for various return periods and pier shapes that will be required for decision making in the design.

The Scouring Mechanism

The following functional relationship can be derived for the live-bed bridge pier scour under the conditions of non-cohesive bed material, single pier, long flow duration, wide and straight prismatic channel, and flow velocities at or above the threshold conditions:

$$y = f\left(\frac{d_0}{b}, F_r, shape, \theta, \sigma_g, \frac{b}{D_{50}}\right) \qquad (2)$$

where $y = d_s/b$ is the relative scour depth; d_s=maximum depth of local scour around a bridge pier; b=width of the bridge pier perpendicular to the flow direction; d_0=depth of approach flow; F_r=flow Froude number given by $u/\sqrt{gd_0}$, where u is the mean flow velocity; θ=angle between the approach flow and pier axis; σ_g=standard deviation of grain size distribution, and D_{50}=median sediment size. Effects of pier shape, pier alignment with respect to the flow direction, sediment grading, and the relative effect of pier width to sediment size can be incorporated by some adjustment factors, K_1, K_2, K_3 and K_4, respectively, which can be found in Raudkivi and Ettema (1983), Raudkivi (1986), Melville and Sutherland (1988), Breusers and Raudkivi (1991), and Melville (1997). 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 data having $b/D_{50} \geq 50$ will be considered throughout this study. For a single pier mounted in a non-cohesive uniform bed material under $b/D_{50} > 50$, the adjustment factors K_3 and K_4 are equal to unity (Melville and Sutherland, 1988). The form of Equation (2) can then be expressed by a new functional relationship:

$$y = K_1 K_2 f_1 \left(\frac{d_0}{b}, F_r \right) \tag{3}$$

which forms the basis of most of the scour prediction equations (Inglis et al., 1939; Izzard and Bradley, 1958; Liu et al., 1961; Chitale, 1962 (See Günyaktı, 1988); Shen et al., 1969; Richardson, 1987; Jain and Fischer, 1980; and Yanmaz, 2001). The relative effects of independent parameters on y need to be studied.

For shallow flows, the surface roller that forms ahead of the bridge pier interferes with the scour action of the horseshoe vortex. With increasing flow depth, the interference decreases and eventually becomes insignificant (Ettema, 1980). According to Melville and Sutherland (1988), the relative approach flow depth, d_0/b, has almost no influence on the relative scour depth for $d_0/b > 2.6$. The effects of flow intensity on the relative scour depth under highly turbulent flow conditions with $u > 4u_c$, where u_c is the mean threshold velocity, is negligible (Breusers and Raudkivi, 1991). The values of K_1 are 1.0 and 1.1 for cylindrical or round-nosed rectangular piers and blunt-nosed rectangular piers, respectively. The values of K_2 are given in Table 1, in which L is the length of the pier in the direction parallel to the flow.

Table 1. Adjustment factors for flow alignment, K_2, (Melville, 1997)

L/b (1)	$\theta = 0°$ (2)	$\theta = 15°$ (3)	$\theta = 30°$ (4)	$\theta = 45°$ (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

Framework for Model Development

The first step in the development of the model is the identification of the relevant resistance and loading terms. The preliminary step in the development of the reliability model based on resistance-loading interference is the identification of appropriate loading and resistance terms that reflect the physics of the scouring phenomenon. In this study, a linear combination of $x = d_0/b + F_r$ is considered by assuming that this sum reflects the effects of external loads imposed on the system. The justification for this selection is given in the following discussion. The physical significance of the loading term, x, is based on the fact that the parameters comprising x should be involved in the scouring process. They are also the basic variables in the forces acting on bridge piers. The approach flow depth is an important variable involved in pressure, body and inertia forces. The pier width b is required in the computation of dynamic drag and lift forces acting on the pier and is also used in the momentum equation in the close vicinity of the bridge opening. The Froude number indicates the relative effects of inertia and body forces. Since the total loading composed of n independent loads, x_1, x_2, x_n, is considered a linear combination of them as $x_1 + x_2 + ... + x_n$ (see Yen et al., 1986), the linear combination of the aforementioned parameters, $d_0/b + F_r$, is assumed to reflect the combined effects of external loads acting on bridge piers. The maximum relative depth of local scour around a single pier, d_s/b, which is assumed to be the minimum required relative depth of the bottom of the pier footing, d_f/b, is considered as the resistance of the system.

As previously stated in Equations (2) and (3), the shape of the pier has a direct influence on the development of local scour depth around bridge piers. Selection of a particular shape for a bridge pier is normally dictated by constructional and structural requirements. While a streamlined pier geometry contributes a well hydraulic conformity as it weakens the strength of the horseshoe vortices, it may not be practical because of constructional limitations. Therefore, other shapes, which are of practical importance, should be investigated. Piers may have uniform or non-uniform shapes. Uniform piers have a constant cross-sectional shape throughout their length. Non-uniform piers consist of tapered piers, slab footings, and caisson and piled foundations (Melville and Coleman, 2000). This paper is focused on the development of a reliability model for uniform piers since there is limited information on the scouring mechanism around non-uniform piers. To this end, cylindrical piers, square piers, and long rectangular piers having rounded or blunt noses will be considered in this study. Although rectangular piers with blunt noses are not considered feasible since they contribute a pronounced scouring, this shape also needs to be analysed because the rectangular caissons having blunt noses may sometimes be located above the mean bed level and act as rectangular piers at the mean bed level. The system reliability should then be developed with reference to the analysis of the statistical randomness of the local scour data around bridge piers of various shapes.

To examine the relationship between x and y, two sets of data covering maximum live-bed scour measurements around single cylindrical and non-cylindrical piers, respectively, over non-cohesive uniform bed materials with $b/D_{50} > 50$ were studied. The types of piers and the ranges of relevant variables considered in this study are presented in Table 2. The statistical information concerning the mean, μ, and coefficient of variation, C_v, of the calibration data is presented in Table 3. The best-fit curve of the form of Equation (3) for cylindrical pier data is shown in Figure 1 for which the correlation coefficient is 0.783. In a previous study carried out by Yanmaz and Çiçekdağ (2001), it was observed that Equation (3) was in good agreement with the Equation proposed by Richardson (1987), which is commonly used in the USA and also termed HEC-18 or the Colorado State University (CSU) equation. The functional form of this curve can be multiplied by K_1 and K_2 coefficients to consider the effects of shape and flow alignment for piers different from cylindrical cross-sections. Hence one obtains the following equation for arbitrary pier shapes:

$$y = K_1 K_2(-0.1331x^2 + 0.9249x + 0.1371) \quad \text{for } 0.69 \leq x \leq 3.30 \tag{4}$$

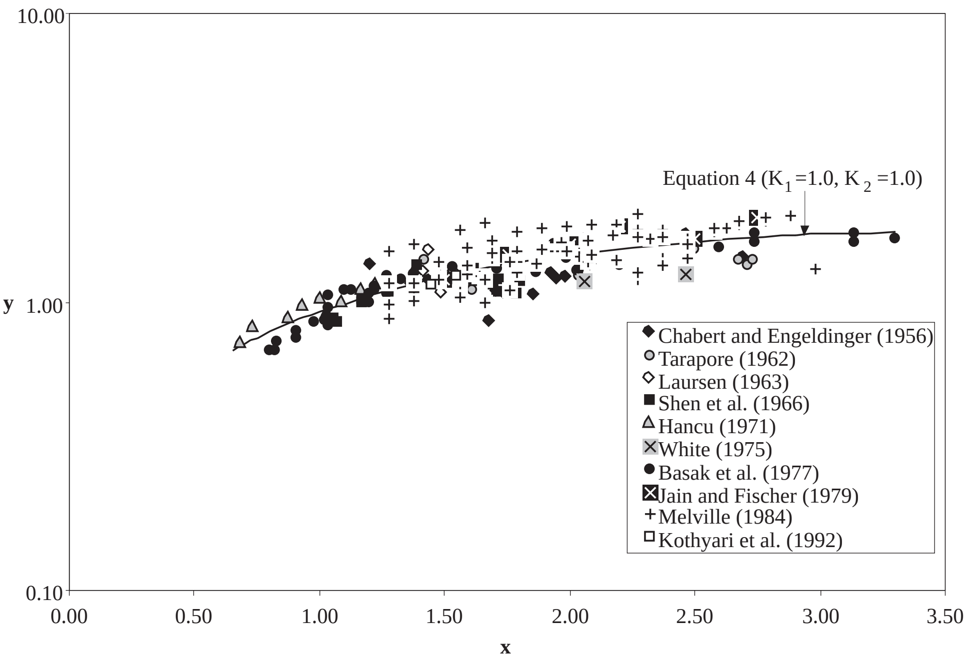

Figure 1. Relationship between y and x for cylindrical piers

The variation of y with respect to x for non-cylindrical piers under zero angle of attack, $\theta = 0°$, ($K_2 = 1.0$) is shown in Figure 2. As can be observed in this figure, the field data compiled from Froehlich (1988) exhibit a high degree of scattering with smaller resistance values as compared to the experimental measurements. 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 the in-situ particle gradation that has a retarding effect on the scouring due to the armouring at the riverbed. To assign a probability distribution under a reasonable confidence interval, the field data for non-cylindrical piers have been excluded from the analysis. In the case of cylindrical piers, two field measurements compiled from Kothyari et al., (1988) were included in the analysis (see Figure 1). Inspection of Figure 2 indicates that Equation (4) gives a good fit for the experimental local scour data around non-cylindrical piers.

Table 2. 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)	10.0-15.0	10.0-35.0	0.52-3.0	11.5-21.14	0.35-0.77
	Tarapore (1962)	5.0	3.7-11.8	0.15-0.5	6.1-7.6	0.37-0.98
	Laursen (1963)	17.4	17.9-21.5	0.16-0.51	18.5-23.1	0.33-0.46
	Shen et al. (1966)	15.0-17.4	11.37-21.31	0.24-1.51	12.75-23.1	0.30-1.02
	Hancu (1971)	13.0	5.0	0.5	9.36-14.89	0.31-0.85
	White (1975)	8.0	10.0	0.9	9.33-10.0	0.81-1.21
	Basak et al. (1977)	4.0-39.50	3.26-16.7	0.7	4.5-27.0	0.37-0.55
	Jain and Fischer (1979)	5.08-10.16	10.16	0.25	8.38-18.49	0.50-1.2
	Melville (1984)	5.08-10.16	10.0	0.24-1.4	6.1-18.9	0.3-1.21
	Kothyari et al. (1963)	305-488	303-253	0.44-0.72	348-602	0.46-1.03
Rectangular	Chabert and Engeldinger (1956)	10-15	10-35	0.52-3	11.5-20.3	0.23-0.77
	Shen et al. (1969)	15.2-91.4	11.6-61.0	0.24-0.46	13.4-54.9	0.2-0.31
	Basak et al. (1977)	4.0-24.0	3.85-14.3	0.7	6.0-23.0	0.44-0.53
Square	Basak et al. (1975)	4.0-40.0	3.85-14.3	0.7	5.8-28.5	0.44-0.53
Round-nosed rectangular	Laursen and Toch (1956)	6.1	6.1-18.3	0.46-0.58	10.7-13.7	0.29-0.64
	Basak et al. (1977)	15.0-40.0	10.7-14.3	0.7	15.5-31.0	0.44-0.46

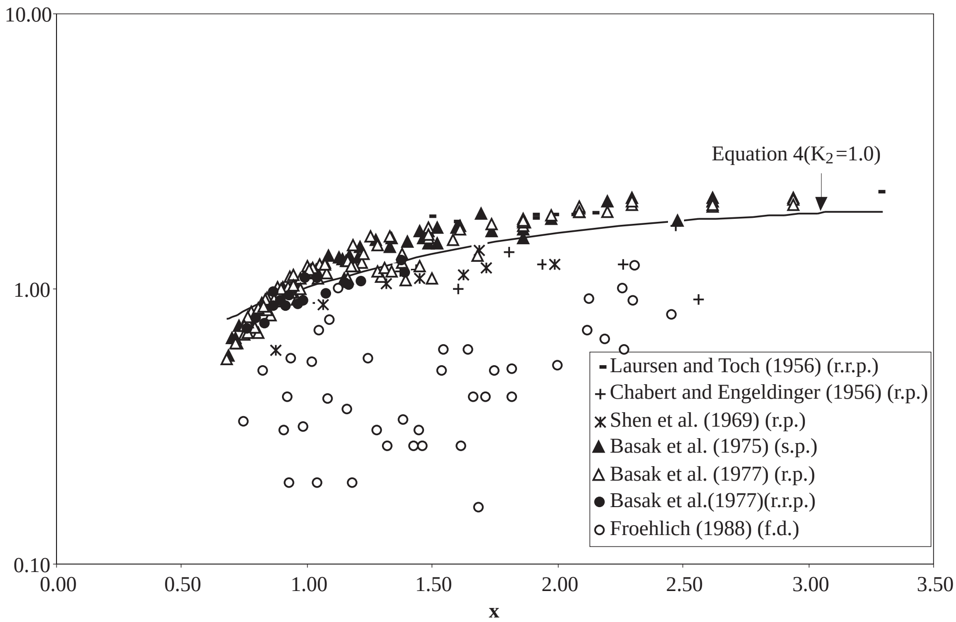

Figure 2. Relationship between y and x for non-cylindrical piers

Table 3. Statistical Information on the calibration data

Type of pier (1)	Parameter (2)	μ (3)	C_v (4)
Cylindrical	d_0/b	1.2204	0.2121
	y	1.3437	0.0645
	F_r	0.6054	0.0946
Non-cylindrical	d_0/b	0.9024	0.6342
	y	1.2652	0.3251
	F_r	0.4703	0.1427

Probability distributions of the resistance and loading should be determined through frequency analysis. To examine the uncertainty of the statistical randomness of scouring variables, the data presented in Figures 1 and 2 need to be interpreted. As the lognormal probability distribution has been widely used in hydraulic reliability analyses, e.g., Tang and Yen (1972), Mays (1979), Tung and Mays (1980), and Yanmaz and Çiçekdağ (2001), it is also assumed to reflect the probability distributions of the resistance and loading in this study. Tests of goodness of fit were then applied for the lognormal probability distributions of x and y for both cylindrical and non-cylindrical piers under a 95% confidence interval using Chi-square and Kolmogorov-Smirnov tests (see Table 4). The results of these tests indicate that lognormal distribution can be fitted to the probability distributions of x and y.

Table 4. Tests of goodness of the lognormal probability distribution for x and y

Type of pier (1)	Parameter (2)	χ^2 (3)	Critical χ^2 (4)	D_n (5)	Critical D_n (6)
Cylindrical	x	7.5652	15.50	0.043	0.095
	y	2.9565	15.50	0.019	0.095
Non-cylindrical	x	14.4246	15.50	0.058	0.102
	y	12.5140	15.50	0.051	0.102

The parameters of the lognormal distribution, i.e., mean (μ_{ln}), standard deviation (σ_{ln}), and coefficient of skewness (G_{ln}), were obtained using the method of maximum likelihood (see Table 5). The variables x and y were considered to be dependent due to high correlation coefficients, i.e., 0.8047 for cylindrical piers and 0.8876 for non-cylindrical piers. Since lognormal distribution is a commonly accepted function for the dependent variables x and y, then the joint probability density function of the dependent variables for cylindrical and non-cylindrical piers can be expressed by a bivariate lognormal distribution function according to the central limit theorem (Yevjevich, 1972). The reliability of system using Equation (1) is then computed from

Table 5. Parameters of lognormal distribution for x and y

Type of pier (1)	Parameter (2)	μ_{ln} (3)	σ_{ln} (4)	G_{ln} (5)
Cylindrical	x	0.5561	0.0971	-0.4666
	y	0.2704	0.0520	-0.4373
Non-cylindrical	x	0.2429	0.1422	0.4065
	y	0.1824	0.1090	-0.0966

$$\begin{aligned}\alpha \; = \; & \int_0^{\infty}\int_0^{y} \frac{1}{2\pi x y \sigma_{\ln x}\sigma_{\ln y}\sqrt{1-\rho^2}} \exp(-\frac{1}{2(1-\rho^2)}((\frac{\ln x-\mu_{\ln x}}{\sigma_{\ln x}})^2 - 2\rho(\frac{\ln x-\mu_{\ln x}}{\sigma_{\ln x}})(\frac{\ln y-\mu_{\ln y}}{\sigma_{\ln y}}) \\ & +(\frac{\ln y-\mu_{\ln y}}{\sigma_{\ln y}})^2))dxdy\end{aligned} \tag{5}$$

where ρ is the correlation coefficient. The double integral in Equation (5) cannot be evaluated analytically. The Simpson one-third rule of numerical integration can be used for the solution of Equation (5) (Wylie and Barrett, 1985):

$$\int_{y_o}^{y_2}\int_{x_o}^{x_2} f_{x,y}(x,y)\,dxdy = \frac{hk}{9}\left[(f_{00}+f_{02}+f_{20}+f_{22})+4(f_{01}+f_{10}+f_{12}+f_{21})+16f_{11}\right]+E_t \tag{6}$$

where h and k are the intervals at which x and y are tabulated, respectively, E_t is the error term and $f_{ij} = f(x_o + ih, y_o + jk)$ for $0 \leq i$ and $j \leq 2$. By applying the expression given in Equation (6) successively, Yanmaz and Çiçekdağ (2001) developed the following solution algorithm:

$$\int_{y_o}^{y_{2m}}\int_{x_o}^{x_{2n}} f_x, y(x,y)\,dxdy = \frac{hk}{9}\left(\begin{array}{l} 4\left(\sum\limits_{i=2}^{2n-2,2}\sum\limits_{j=2}^{2m-2,2} f_{ij} + \sum\limits_{i=1}^{2n-1,2}\sum\limits_{j=0}^{2m,2m} f_{ij} + \sum\limits_{i=0}^{2n,2n}\sum\limits_{j=1}^{2m-1,2} f_{ij}\right) + \sum\limits_{i=0}^{2n,2n}\sum\limits_{j=1}^{2m,2m} f_{ij} + \\ 16\sum\limits_{i=1}^{2n-1,2}\sum\limits_{j=1}^{2m-1,2} f_{ij} + 8\left(\sum\limits_{i=1}^{2n-1,2}\sum\limits_{j=2}^{2m-2,2} f_{ij} + \sum\limits_{i=2}^{2n-2,2}\sum\limits_{j=1}^{2m-1,2} f_{ij}\right) + \\ 2\left(\sum\limits_{i=0}^{2n,2n}\sum\limits_{j=2}^{2m-2,2} f_{ij} + \sum\limits_{i=2}^{2n-2,2}\sum\limits_{j=1}^{2m,2m} f_{ij}\right) \end{array}\right) + E_t \tag{7}$$

where $2n$ and $2m$ are the number of segments for x and y-axes, respectively. The expression given in Equation (7) is limited to cases with an even number of segments and an odd number of points. To obtain a relation for the reliability, Equation (7) is applied to the range considered in the calibration data, i.e., $0.69 \leq x \leq 3.30$. As the bivariate lognormal function is used in the analysis, the lower bounds x_0 and y_0 must be greater than zero and can be taken as 0.1. In this range, the computations were initiated from the lower bound and y values were incremented with intervals of 0.1. The range of y values was taken from the information presented in Figure 1. Therefore, a set of y versus α values was obtained. To develop a relationship between α and y, the best-fit equations of this data set has been obtained through regression analysis. The results of this analysis can be expressed by the following piece-wise functions for cylindrical piers having correlation coefficients of unity:

$$\begin{array}{l}\alpha = 3.1829y^3 - 7.3196y^2 + 5.8042y - 1.5700 \\ \text{for } 0.71 \leq y \leq 1.17\end{array} \tag{8}$$

$$\begin{array}{l}\alpha = -1.1466y^3 + 3.5248y^2 - 1.6511y - 0.7584 \\ \text{for } 1.17 < y < 1.74\end{array} \tag{9}$$

According to the information provided in Table 1, $K_1 = 1.0$, $K_2 = 1.0$ for a long rectangular pier having rounded noses under $\theta = 0°$. Therefore, the reliability expressions given by Equations (8) and (9) can also be used for this type of piers when they are aligned with θ=0°. Using Equation (7) with the relevant statistical information, the following expressions are obtained for square and rectangular piers aligned with θ=0°:

$$\begin{array}{l}\alpha = 1.1368y^2 - 1.8029y + 0.71 \\ \text{for } \ 0.78 \leq y \leq 1.35\end{array} \tag{10}$$

$$\begin{array}{l}\alpha = -0.9062y^3 + 4.1899y^2 - 5.2016y + 1.9608 \\ \text{for } \ 1.35 < y \leq 1.91\end{array} \tag{11}$$

Variation of reliability with respect to resistance is shown in Figure 3 for cylindrical and round-nosed rectangular piers under θ=0° (curve A) and rectangular piers under θ=0° (curve B). As can be observed in Figure 3, greater resistance, i.e., greater pier footing depths, are required for the rectangular piers relative to the cylindrical and round-nosed rectangular piers aligned with θ=0° under the same reliability level. The model could not be extended to cover the effect of attacking angle, θ, mainly because of lack of data. It is a known fact that the depth of scour increases with increasing θ and length to width ratio, L/b, of non-cylindrical piers. Therefore, appurtenant training facilities like guiding walls, series of spur dikes, etc., should be implemented in the close vicinity of bridges to facilitate approaching of the flow by zero angle of attack with the pier axis.

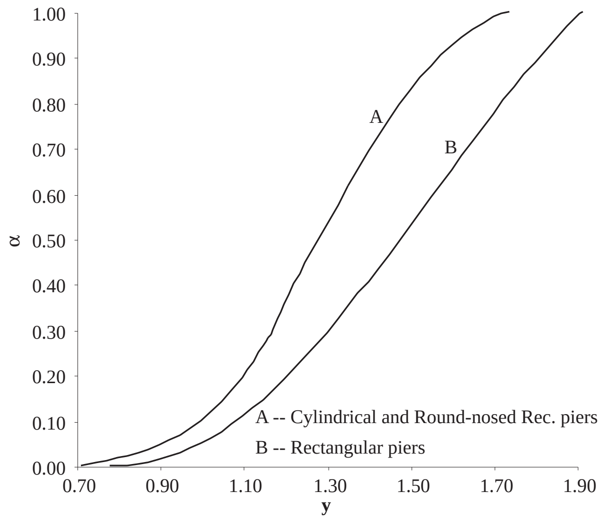

Figure 3. Variation of reliability with respect to resistance under $\theta = 0°$

Application

Decision-making is needed for the pier design of a bridge to be constructed at a hypothetical site. Hydraulic, structural and geotechnical interactions under various alternatives need to be interpreted. At a nearby stream gauging station the following long-term averaged rating curve relation is available: $Q = 75d_0^{1.7}$, where d_0 is in m and Q is the discharge in m^3/s. The straight and prismatic river is wide and its bed is composed of poorly graded quartz sand having $D_{50} = 1.7$ mm and a mean bed slope of $S_0 = 0.001$. The annual series of the flows is considered to follow a lognormal distribution function with a mean of $\mu_{lnQ} = 4.5\ m^3/s$ and a standard deviation of $\sigma_{lnQ} = 0.6\ m^3/s$.

Information is required concerning the interrelation among the reliability and safety factors, and the return period for various pier shapes. In the analysis, a single cylindrical pier and long rectangular piers having round and blunt noses will be considered separately. The hydraulic computations are presented in Table 6 for various return periods, T_r. The critical shear velocity, u_{*c}, is determined to be 0.0284 m/s using Shield's criterion. The discharges given in column (2) of Table 6 are obtained from the frequency analysis of lognormal distribution. The corresponding approach flow depths presented in column (3) are obtained from the rating curve relation. Column (4) of Table 6 presents the shear velocities that can be determined approximately from $(gd_0S_0)^{0.5}$, where g is the gravitational acceleration. With this information, live-bed conditions prevail in the bed level. The average velocity is determined using Engelund's method (see Breusers and Raudkivi, 1991) (column (5) of Table 6). The corresponding Froude numbers are presented in column (6). The pier width b is defined as a decision variable and the corresponding maximum depth of local scour and reliability are determined using Equations (4), and (8) to (11), respectively.

Table 6. Hydraulic computations for the practical application

T_r (yr) (1)	Q (m^3/s) (2)	d_0 (m) (3)	u_* (m/s) (4)	u (m/s) (5)	F_r (6)
5	149.2	1.499	0.121	1.276	0.333
10	195.0	1.754	0.131	1.464	0.353
25	257.2	2.065	0.142	1.709	0.380
50	308.9	2.299	0.150	1.904	0.401
100	363.2	2.529	0.157	2.102	0.422
150	392.7	2.648	0.161	2.207	0.433

Level of reliability may be assessed by a safety factor (Ang, 1973; Mays, 1979; Tung and Mays, 1980; Tung and Mays, 1981; Lee and Mays, 1983; Yen et al., 1986; Chow et al., 1988; Mays and Tung, 1992; Johnson, 1992; Johnson and Ayyub, 1992; Lewis, 1996; Yanmaz, 2000; Yanmaz and Çiçekdağ, 2001); etc.). In the analysis, it is assumed that a maximum value of 4.0 m can be taken for the depth of pier footing, d_f. The safety factor, SF, is then defined as the ratio of d_f to the maximum value of the scour depth, d_s, for a particular return period.

With the application of the model, a set of information can be gathered for decision-making. Some of the results are outlined graphically. The relationship between the reliability and safety factors under various return periods is presented in Figure 4 for rectangular piers. In the analysis, it is observed that $b/D_{50} > 50$ and x is in the range between 0.69 and 3.30 for all cases. For any return period, the reliability increases with the increasing safety factor (see Figure 4). The results of the analysis are consistent with similar studies performed earlier for different applications, e.g., for culvert design by Tung and Mays (1980). The relationship between pier width and the safety factor under a high reliability level of α=0.999 is shown in Figure 5, which shows that greater safety factors are attained for the cylindrical piers and round-nosed rectangular piers with θ=0° compared to the rectangular piers with θ=0°. The final decision for the pier design is based on the consideration of hydraulic, structural and geotechnical interactions jointly. As the slab thickness, width and length of piers and spacing between two successive piers are dictated by structural requirements according to the magnitude of dead and live loads, the corresponding hydraulic conditions concerning the type and state of flow and contraction ratio through the bridge opening should be investigated. The required depth and type of pier footing should be assessed in terms of local geotechnical conditions. Further information for the integrated assessment of hydraulic and structural aspects involved in bridge design can be obtained from Yanmaz and Kürkçüoğlu (2000) and Yanmaz and Bulut (2001). Implementation of a set of scour countermeasures around bridge piers, such as the use of riprap, gabions, caissons, and Iowa vanes would further increase the system stability.

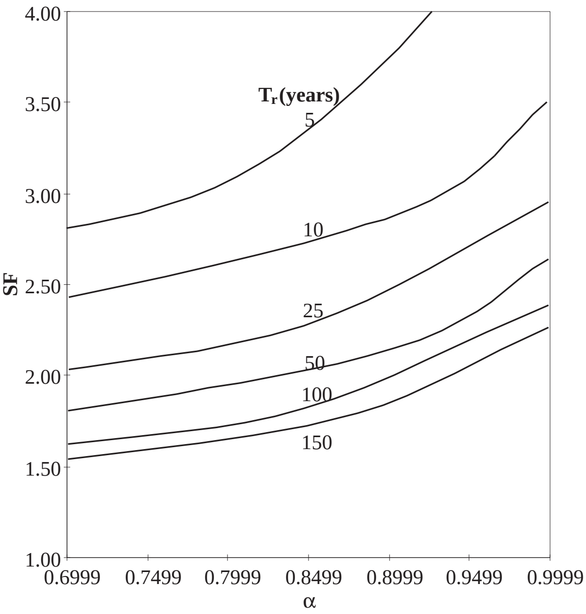

Figure 4. Relationship between reliability and safety factor under various return periods for rectangular piers

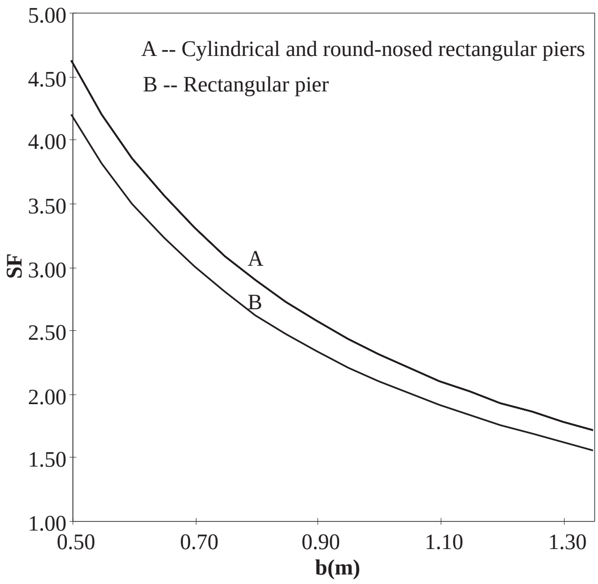

Figure 5. Variation of pier width with respect to safety factor under α=0.999 level

Conclusions

A generalized reliability model is developed for the assessment of the reliability of live bed scour around various shapes of bridge piers using static resistance-loading interference. The method is based on the reliability assessment considering only the local scour mode of failure around bridge piers. The overall reliability of a bridge in terms of the other failure modes, such as structural and material deficiency, abutment failure and localized scour due to contraction, may be assessed by means of fault tree analysis, which may be a subject of a future study. Based on physical reasoning and the analysis of the data presented in Figures 1 and 2, the linear combination of the relative approach flow depth and the flow Froude number is taken as the external loading, x. The relative scour depth (the minimum relative bottom elevation of pier footing) around a single pier, y, is defined as the system resistance. The relationship between the resistance and loading is given by Equation (4) for arbitrary pier shapes. This is valid in the range of $0.69 \leq x \leq 3.30$ under live bed conditions with non-cohesive uniform bed material having $b/D_{50} > 50$.

The statistical analysis of the data indicate that x and y are dependent and their joint probability distribution function for cylindrical and non-cylindrical piers can be represented by a two-parameter bivariate lognormal distribution. Composite reliability analysis of the dependent variables over the range of $0.69 \leq x \leq 3.30$ using Equation (7) yields reliability relations (Equations (8) to (11)), which enable a designer to assess various levels of reliability in terms of safety factors and return periods. By using Equations (8) to (11), a designer can easily compare various alternatives for the pier size and shape, and depth of pier footing in terms of economy and safety. With the application of the model, it is observed that the reliability for an arbitrary pier shape increases with the increasing safety factor under a particular return period. Furthermore, the pier size increases with the increasing return period under a particular reliability level. For the same pier width under a constant reliability level, the safety factor for rectangular piers is smaller than that of the cylindrical and round-nosed rectangular piers aligned with the flow direction. The final decision for the design pier size and depth of pier footing may be made by considering the interaction between hydraulic, structural and geotechnical conditions. Local topographic, geologic and hydrologic factors in addition to the navigational and economic requirements should also be taken into account to improve the design. Implementation of various scour countermeasures in the close vicinity of bridges should be considered in order to increase safety.

Nomenclature

b	=	pier width;
C_v	=	coefficient of variation;
D_n	=	Kolmogorov-Smirnov statistic;
D_{50}	=	median sediment size;
d_f	=	elevation of the bottom of pier footing;
d_s	=	maximum depth of scour around a single pier;
d_0	=	approach flow depth;
F_r	=	Froude number of approach flow;
f.d	=	field data;
$f_{x,y}(x, y)$	=	joint probability density function of loading and resistance;
G_{lnx}	=	logarithmic coefficient of skewness for dimensionless loading;
G_{lny}	=	logarithmic coefficient of skewness for dimensionless resistance;
g	=	gravitational acceleration;
h	=	interval;
K_1	=	adjustment factor for pier shape;
K_2	=	adjustment factor for pier alignment;
K_3	=	adjustment factor for sediment grading;
K_4	=	adjustment factor for sediment to pier size;
k	=	interval;
L	=	length of the pier in the direction of the flow;
M	=	sample size;
m	=	number of segments;
n	=	number of segments;
P	=	probability;
r.p	=	rectangular pier
r.r.p	=	round-nosed rectangular pier
Q	=	discharge;
SF	=	safety factor;
s.p	=	square pier;
T_r	=	return period;
u_*	=	shear velocity;
u_{*c}	=	critical shear velocity;
x	=	loading;
y	=	resistance;
α	=	reliability;
θ	=	angle between approach flow and pier axis;
ρ	=	correlation coefficient;
μ	=	mean value;
μ_{lnx}	=	logarithmic mean of dimensionless loading;
μ_{lny}	=	logarithmic mean of dimensionless resistance;
σ	=	standard deviation;
σ_g	=	standard deviation of grain size distribution;
σ_{lnx}	=	logarithmic standard deviation of dimensionless loading;
σ_{lny}	=	logarithmic standard deviation of dimensionless resistance; and
χ^2	=	Chi-square statistic.

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