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Evaluation of Scour Risk at Foundations of River Bridges †

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ABSTRACT

River bridges experience more inconvenient conditions due to the structure-flow interaction compared to bridges having no contact with flow. Therefore, one of the most important components of the bridge failure risk is the risk induced by soil-flow interaction. In this study, the uncertainties of the hydrological and hydraulic parameters affecting the scouring around bridge piers are examined using appropriate probability density functions. In the analyses, the uncertainties involved in the temporal variation of clear water scouring mechanism are considered. Influences of general bed degradation of the main channel and the contraction scour are ignored. The risk associated with the scouring around piers is estimated using Monte Carlo simulations. In the model, the scouring risk of the bridge pier is determined for the given flow, pier geometry and bed material characteristics. The developed model is presented with an example.

Keywords: *Bridge, scour, uncertainty, risk, safety factor.*

1. INTRODUCTION

Many bridges fail every year leading to loss of lives and properties as well as some inconvenient situations for transportation systems. That is why flow-soil-structure interaction has been evaluated with an increasing trend by bridge designers. The most important point to be considered in this stage is to accomplish the safest design with respect to local and regional characteristics. This is normally based on determination of the maximum possible depth of scour at bridge infrastructural elements and geometrical characteristics of the scour hole around them. Conventional bridge design approaches do not account for uncertainties involved in many aspects, which may cause an unknown level of risk. Depending on the degree of risk, a bridge may be severely damaged or may even collapse during its physical life. Therefore, conventional design approach is based on selection of a high safety factor to compensate risk. This may cause an unnecessarily high cost of the structure. On the contrary, safety level of the structure can be evaluated more precisely by using a risk estimation approach incorporating all possible uncertainties.

Reliability of the bridge design can be computed mathematically if the probability distributions of relevant variables are known. Moreover, various adverse effects that can be

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anticipated during the physical life of a bridge can be incorporated easily. Therefore, it is also intended to decrease the annual cost of operation, repair and maintenance. That is why there is a growing tendency to apply the reliability theory to structural systems in the recent years. Johnson [1] is probably the first researcher who incorporated scour induced risk concept into bridge design. In that study, a relationship was developed between probability of failure and safety factor. In a different study, Johnson [2] conducted a fault tree analysis for the probability of failure using several scouring and bridge instability variables. Johnson and Ayyub [3] investigated the relationship between probability of failure and safety factor under various flow return periods. Other studies dealing with bridge performance uncertainty and reliability analyses have been conducted by Johnson and Ayyub [4], Johnson and Simon [5], Johnson and Ayyub [6] and Yanmaz [7]. Yanmaz and Çiçekdağ [8] developed a scouring reliability model for circular piers using resistance-loading interference. This model was generalized for different pier shapes by Yanmaz and Üstün [9]. A dynamic reliability model was developed by Yanmaz [10] to account for the physical life effect and flow return period on the concept. The number of reliability models developed for abutments are less than those developed for piers. The models developed by Yanmaz and Çelebi [11] and Köse and Yanmaz [12] are valid for various abutment types.

In this study, a reliability model is developed for clear water scouring at bridge piers. It accounts for uncertainties involved in hydrologic/hydraulic parameters and bed material characteristics. Independent scouring variables are represented by suitable PDFs. Since this approach yields more precise results than those of a conventional deterministic approach, it enables safer design. The model is demonstrated with an application.

2. INTERPRETATION OF UNCERTAINTIES

Uncertainty may be present in every aspect out of the control of the designer. The accuracy of the reliability model is related to the type and magnitude of the uncertainties involved in modeling. Common types of uncertainties encountered in water resources systems originate mainly from hydrologic, hydraulic, and structural aspects [13]. Hydrologic uncertainties include natural, parameter, and model uncertainties. In addition to parameter and model uncertainties, hydraulic uncertainties comprise also uncertainties arising from dimensioning of the structural components, material properties, and operational policies. Structural uncertainties in view of bridges reflect bearing capacity problems of the foundation and increased scouring potential at bed level induced by many sources. Besides the aforementioned uncertainties, there exist also some human induced uncertainties arising from the construction technique, deficiencies in maintenance, operation, repair, measurement errors and design mistakes.

Natural uncertainty originates from random characteristics of hydrologic events, such as precipitation, runoff, seepage, and evaporation and is normally out of control. Model uncertainty is based on the ability of the model employed to represent any physical event. Therefore, it may change according to the model used. That is why it is important to include all relevant variables characterizing the event in the model concerned. Model uncertainties involved in scour prediction equations can be evaluated in detail. Many mathematical models in empirical and semi-empirical nature have been developed for bridge scour determination up until now. These models are normally valid for their derivational conditions tested in the laboratory medium. That is why no universal model dealing with wide ranges of flow, bed material characteristics, pier geometry and orientation have been developed. Furthermore, laboratory data may be subject to scale effects, especially for sediment size. Therefore, calibration of the model is needed with reference to field data. However, the problem of the quality of the field data may arise at this stage. The collection of scour data from a river bridge either in the flow section or from the banks of the river is both difficult and dangerous during a flood. Moreover, the determination of the maximum scour depth with respect to time is almost impossible since the river bed severely interacts with the flow. Therefore, the measurement of the scour depth in the field after the flood does not reflect a realistic maximum depth for the scour, because, during the recession period of the flood, suspended coarse materials in the flow may start to accumulate in the scour holes. In this case, a robust mathematical model that considers the local conditions in detail may yield more realistic results.

The parameter uncertainty arises from the uncertainties of the parameters of the model used. The uncertainties associated with surface runoff coefficient of a basin, the roughness coefficient of a river, the flow depth and the flow velocity can be considered as examples to parameter uncertainty. Since the hydraulic design depends on the results of the hydrologic model, the uncertainty in flow parameters dependently increases. The uncertainty of the parameters can be decreased by the use of sensitive models. The uncertainty of a variable can be expressed with coefficient of variation, $COV=\sigma/\mu$, in which σ is the standard deviation and μ is the mean of the variable. The total parameter uncertainty of a problem can be obtained from the linear combination of the coefficient of variation values of the variables involved in the problem. However, for most of the times, statistical information about the design parameters may not be available. The deviation of a variable from its mean can be determined by the engineering judgment and experience, observations and the available information provided in the literature [14].

The uncertainties resulting from the construction techniques and the material used (such as the surface roughness of the bridge piers and abutments) may affect the hydraulic parameters and the boundary conditions of the flow. Other uncertainties may arise from the operation of the bridge and human-based factors. The removal of the accumulated material from the river bed to increase the flow accommodation ability of the bridge opening may increase the safety level of the bridge concerned. Besides, specifically in Black Sea Region of Turkey, the elevation of the riverbed has decreased because of the extraction of the riverbed material, which is named channel mining. Due to this intervention, the decrease in the riverbed elevation may reach to a couple of meters. Even the caps of pier piles may become visible above the water surface.

3. COMPUTATION OF PROBABILITY OF FAILURE

The safety level of a structure can be precisely estimated by considering all uncertainties in the parameters affecting its design. This can be explained from the example provided in Figure 1. In this figure, the probability density function of a load acting on a structure is shown with $f_S(s)$ whereas the probability density function of the resistance of the structure is presented with $f_R(r)$. The load and the resistance are independent variables and represented by s and r, respectively. The intersection area of the distributions of load and resistance is defined as risk. In other words, the probability of the load being greater than resistance is defined as the probability of failure. The probability of failure is affected by the positions of the load and resistance distributions. For instance, when the distributions of the load (R_1) and resistance (S_1) are dispersed, the intersection area of both distributions will be greater and this will result in a greater risk. When the distributions are narrower the risk becomes smaller (see Figure 1). In a hydraulic structure the loading depends on natural conditions and cannot be controlled; however, the resistance of the structure can be increased. For example, the resistance distribution of a river bridge can be shifted towards the positive side if its foundation depth is increased or when piles are used at the foundation or when its abutments are protected. These will result in a reduction in the risk since the position of the load distribution will not change.

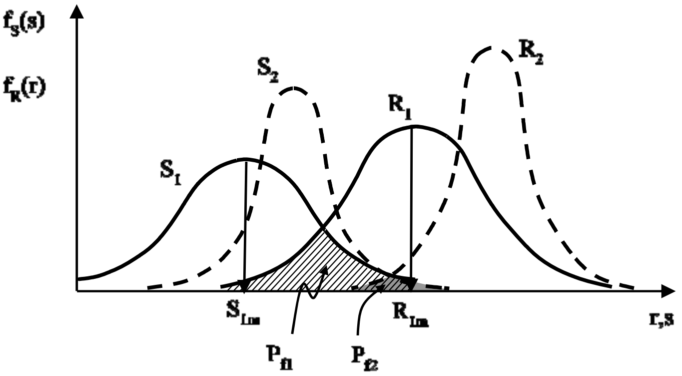

Figure 1. Probability density functions of loading and resistance

The difference between probability-based risk assessment and deterministic approaches can be understood by investigating the safety factor obtained from the mean values. When the distributions of the load and the resistance are considered, in the deterministic approach, the safety factor can be computed by dividing the mean of the resistance (R_{1m}) by the mean of the load (S_{1m}), (i.e. R_{1m}/S_{1m}) (see Figure 1). In this approach, when the safety factor is greater than 1.0, the design can be considered as a safe design. However, for the same conditions if the distributions of load and resistance are intersecting, there exists a certain probability of failure (P_f) for the design. The acceptability of the risk depends on the importance level and the location of the structure. For example, in the application practice of United States of America, for bridges that pass over small rivers, the limit P_f value can be taken as 10^{-3}, whereas larger bridges that are exposed to high traffic loads, the limit P_f value can be taken as 10^{-5} [15]. It is clear that structures may be exposed to such loads that make them fail during their lifetime. However, the probability of failure can be decreased by regular inspection and maintenance. For instance, if the foundation and the scour hole around the pier of a river bridge are not repaired after a heavy flood, it is clear that the resistance of the structure will be decreased. Therefore, it is important to take precautions at the piers against scouring not only for the design of new bridges, but also for the existing ones. The implementation of riprap or partially grouted riprap can be suggested as a protective measure at the bridge piers. Many design applications were developed in Turkey for the protection of bridge piers [16, 17, 18]. Also, by regular observations and inspections, the vulnerability and the risk of a bridge can be assessed [18, 19, 20]. This will help to control the resistance of the structure and take precautions with additional repairs when the safety level decreases.

4. APPLICATION

In the application of this study, the risk of a river bridge due to scouring around its circular pier is evaluated. The flow depth, the flow velocity, the bed slope of the river and the median particle size of the bed material are taken as 1.4 m, 0.7 m/s, 0.0002 and 4 mm, respectively. The diameter of the circular pier is 1.6 m. In the computation of the risk, the general bed degradation and contraction scour mechanisms are neglected. Also, it is assumed that the bridge is not under the influence of the interference region of the main channel and the flood plain. When the data given are used, the velocity that initiates the bed material motion in the riverbed can be computed as 1.1 m/s. This velocity is greater than the flow velocity. Therefore, it can be assumed that clear water scour conditions prevail at the bed, during which the scour depth rapidly changes at the beginning of the flood. Then, the rate of scour decreases and the scour depth reaches an equilibrium depth asymptotically [14]. When the expressions giving the scour depth around piers for clear water scour conditions are investigated, it can be seen that too much time is needed to observe the equilibrium depth. There are some criteria for the time required to reach the equilibrium flow depth [21, 22, 23]. Commonly, if the increase in depth of the scour is less than a limiting value during a 24-hour experiment, it is assumed that the equilibrium depth condition occurs. According to Melville and Chiew [21] this limit is defined as 5% of the pier diameter, whereas Grimaldi et al. [24] defined it as 1.7% of the pier diameter. Also, Fael et al. [25] introduced this limit as two times the median particle size of the riverbed material. In the study by Setia [26] it was stated that the equilibrium scour depth cannot be observed even in 100 hours in a laboratory medium. An estimation can be made using this value for the time required to reach the equilibrium scour depth in the nature. For an experiment conducted for 100 hours on a model having a length scale of 1/50, the corresponding time in the nature becomes $100*(50)^{0.5}=707$ hours according to Froude model. A flood having this much time to peak value is not observed in Turkey and in regions having similar hydrometeorological conditions. Therefore, the selection of the foundation depth of a bridge pier according to the equilibrium scour depth is not economical. The determination of the scour depth corresponding to the peak discharge of the flood is acceptable instead of estimation of its variation with time [15, 27, 28, 29].

In the application, the duration of the flood is assumed to be 4 hours and the depth of the pier foundation is taken as 2.0 m. The reliability of this foundation depth is investigated under various scenarios. The ratio of the pier foundation depth to the maximum scour depth at the end of the flow duration is defined as the safety factor.

In this study, a new expression obtained from the data of Yanmaz [30] by multiple regression analysis having a correlation coefficient of 0.96 is used. The data were obtained for clear water scour around circular piers. This expression is given in Eqn. (1).

$$\frac{d_s}{b} = 0.085 F_d^{1.868} \left(\frac{b}{y}\right)^{0.171} T_s^{0.205} \tag{1}$$

In the above equation d_s represents the maximum scour depth for a certain duration, b is the pier diameter, y is the approach flow depth, F_d is the densimetric particle Froude number, D_{50} is the median particle size and T_s is a dimensionless time parameter. The densimetric Froude number and the dimensionless time parameter are provided below.

$$F_d = \frac{u}{\sqrt{g\Delta D_{50}}} \tag{2}$$

$$T_s = \frac{tD_{50}\left(\Delta g D_{50}\right)^{0.5}}{b^2} \tag{3}$$

in which u is the mean velocity of the approach flow, t is the time, Δ is the relative submerged density and g is the gravitational acceleration. The parameters governing the scour mechanism are shown in Figure 2.

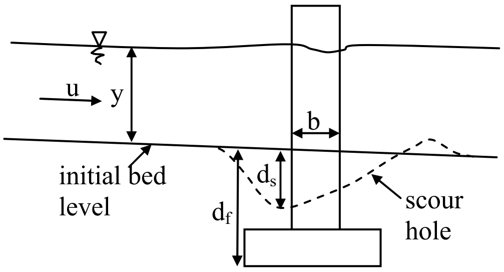

Figure 2. Governing variables involved in pier scouring

Inserting Equations (2) and (3) into Equation (1) and expressing the scour depth one obtains:

$$d_s = 0.0084\, u^{1.868} D_{50}^{-0.627} b^{1.3} y^{-0.171} t^{0.205} \tag{4}$$

As defined by Johnson [1], the probability of failure (P_f) can be computed as the probability of the safety margin (EA= d_f - d_s) being smaller than zero:

$$P_f = P(EA < 0) \tag{5}$$

where d_f is the depth of pier footing. Using Equation (4), the probability of failure can be expressed as:

$$P_f = P(EA < 0) = P\left(d_f - 0.0084u^{1.868}D_{50}^{-0.6265}b^{1.3}y^{-0.171}t^{0.205}\right) < 0 \quad (6)$$

in which d_f, b, and t can be accepted as deterministic variables. Therefore, the remaining variables, i.e. u, D_{50} and y are considered as independent probabilistic variables. In this study, probability density functions (PDF) and coefficient of variation (COV) recommended for various variables in the related literature are used. Some of the previous studies [2, 8, 12, 31, 32, 33] are considered and the recommended PDFs and COV values are used as presented in Combination A of Table 1. Furthermore, additional sensitivity analyses were conducted to account for the possible effects of alterations of this information on the results of probability of failure computations (see Table 1). The reason why such sensitivity analyses are made can be explained as follows. The recommended information is based on the analysis of available statistical data. With the inclusion of additional data reflecting the effect of different flow, pier size and shape, and bed material characteristics than considered in the previous data would increase the sample size of the data. Therefore, some alterations may be expected in the previously recommended PDFs and COV values.

Table 1. PDF and COV information assigned to probabilistic variables

Variable	Mean value (μ)	Combination	COV	PDF
y	1.4 m	A	0.10	Normal
		B	0.15	Normal
		C	0.20	Normal
		D	0.15	Normal
		E	0.15	Normal
u	0.70 m/s	A	0.010	Normal
		B	0.015	Normal
		C	0.020	Normal
		D	0.015	Uniform
		E	0.010	Triangle
D_{50}	4 mm	A	0.050	Normal
		B	0.075	Normal
		C	0.100	Normal
		D	0.075	Uniform
		E	0.075	Uniform

In the computation of probability of failure using Eqn. (6), random numbers are generated using Monte Carlo simulation. The determination of the number of the simulations in Monte Carlo method is very important. The standard deviation of the generated random variables become greater if fewer number of simulations are conducted. When the number of simulations increases, the standard deviation of the random variables decreases, and they approach to the mean value. The change of the coefficient of variation of the probability of failure with respect to number of simulations is obtained and presented in Figure 3 for the combinations provided in Table 1. As it can be seen from the figure, when the number of simulations increases, the coefficient of variation decreases. The number of simulations are stated to be adequate when the coefficient of variation is less than 0.1 [1]. This criterion is satisfied when the number of simulations are greater than 10000. Therefore, in the study, the number of simulations are selected as 15000 for all combinations.

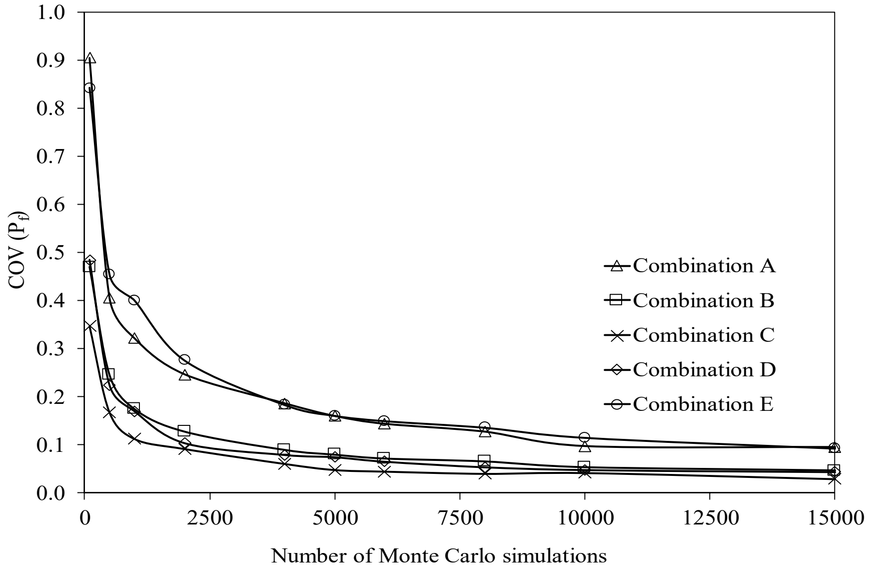

Figure 3. The variation of the coefficient of variation of the probability of failure with respect to time

The probability of failure values are computed for all combinations presented as scenarios in Table 1. The variation of probabilities with respect to safety factors are presented in Figure 4. For a constant foundation depth, when the depth of scour increases, the safety factor decreases for combinations. Besides, when the coefficient of variation of the parameters increases, the stochastic analyses are conducted with parameter values away from the median value of the parameter concerned. This results in smaller scour depths if the parameter values are sampled from the left hand side of its probability distribution. Conversely, greater scour depths are obtained if the parameter values are sampled from the right hand side of the distribution. The values are randomly sampled from both left and right hand sides of the median of the distribution and they are not equally sampled in number. Therefore, the most observed probability of failure value in 15000 Monte Carlo simulations is considered as the target P_f value. As a result of these, when the coefficient of variation of the parameters increases, the probability of having a larger scour depth increases (see Figure 4). In Combination A, the coefficient of variation values are chosen as relatively smaller values and the parameters are represented with normal distribution. In Combination C, the parameters are represented with normal distribution; however, the coefficient of variation values are doubled. This combination yielded the greatest probability of failure values. The results obtained from Combinations B and D are found to be very close. The shape of the distribution obtained for Combination E can be said to be close to those of Combinations B and D. For these combinations, the coefficient of variation of all parameters are considered as the same, except the flow velocity. The flow depth is represented with normal distribution, the flow velocity is characterized with normal, uniform and triangle distributions, whereas the particle diameter is considered to have normal and uniform probability distributions. The results showed that the probability of failure is less sensitive to the variation of the probability distributions than the variation of coefficient of variation. It is seen from the application study that, in order to have a reasonable probability of failure, e.g. P_f<0.001, the safety factor should be greater than 1.2.

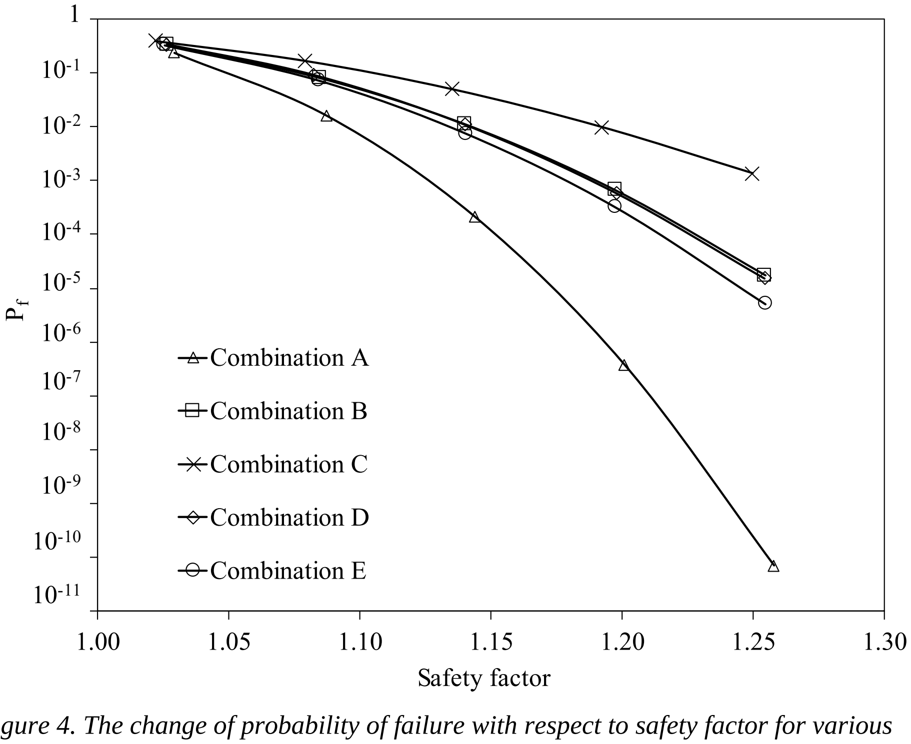

Figure 4. The change of probability of failure with respect to safety factor for various combinations.

The frequency histograms of the scour depths obtained from Monte Carlo simulations are presented in Figures 5 to 9 for all combinations. In these figures, the frequency values are given to show how many times each class interval are observed in the simulation. The total value of the frequency is 15000. The probability density functions that represents the frequency histograms are determined by goodness of fit tests. To this end, the most common probability distributions used in hydraulic engineering, which are normal (N), log-normal (LN), 3 parameter log-normal (LN-3P), Gamma (G), log-Pearson type 3 (LPT3), and generalized extreme value (GEV) distributions are tested for goodness of fit. In the tests, Chi-square and Kolmogorov-Smirnov tests are applied at α=5% and α=10% significance levels. The results of the goodness of fit tests are shown in Table 2. In this table, A stands for the acceptance of the test whereas R is for the rejection. If one of the test results is accepted and the other one is rejected for the same significance level, the test is assumed to be accepted as the overall decision. If both tests are rejected, the overall decision becomes rejected. It is seen that all probability distributions tested can be fitted to the scour depths obtained for Combination A (see Table 2). The frequency histogram and the fitted probability distributions for this combination are given Figure 5. Similar analyses were performed for other combinations (Figure 6 to 9). It is understood that for the scour depths obtained for Combination B, LN, LN-3P, LPT3 and GEV distributions; for the scour depths obtained for Combination C, LN-3P, LPT3 and GEV distributions can be used. For combination D and E, no distribution is recommended.

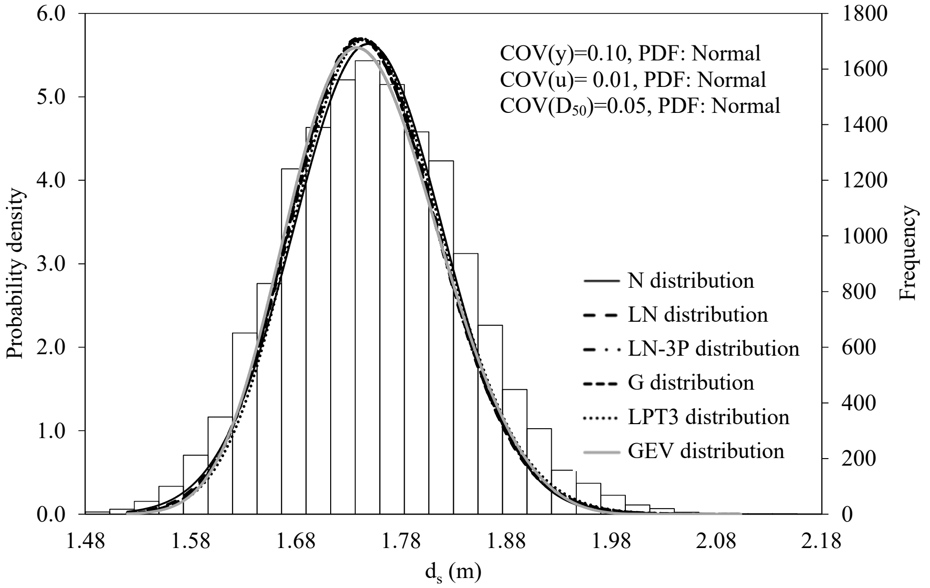

Figure 5. Frequency histogram for Combination A

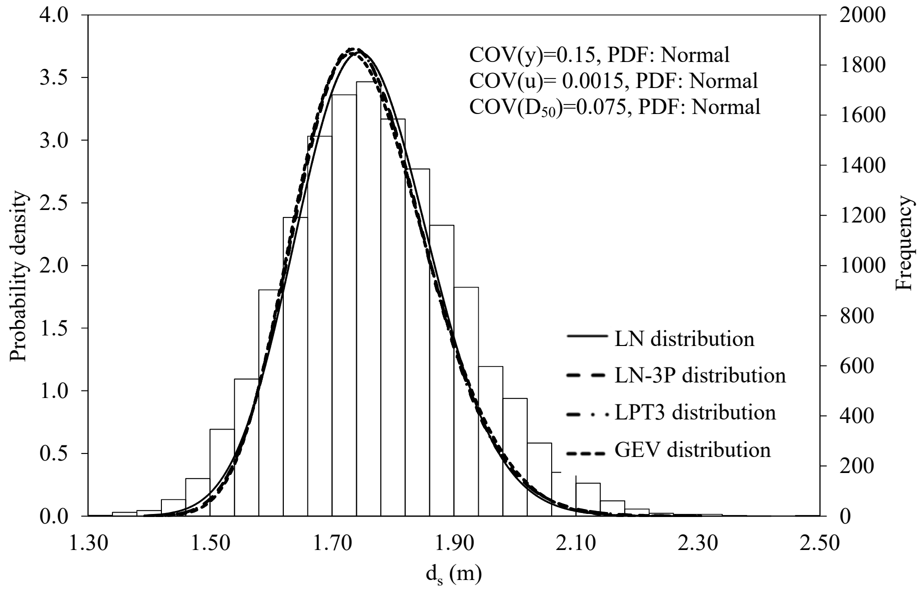

Figure 6. Frequency histogram for Combination B

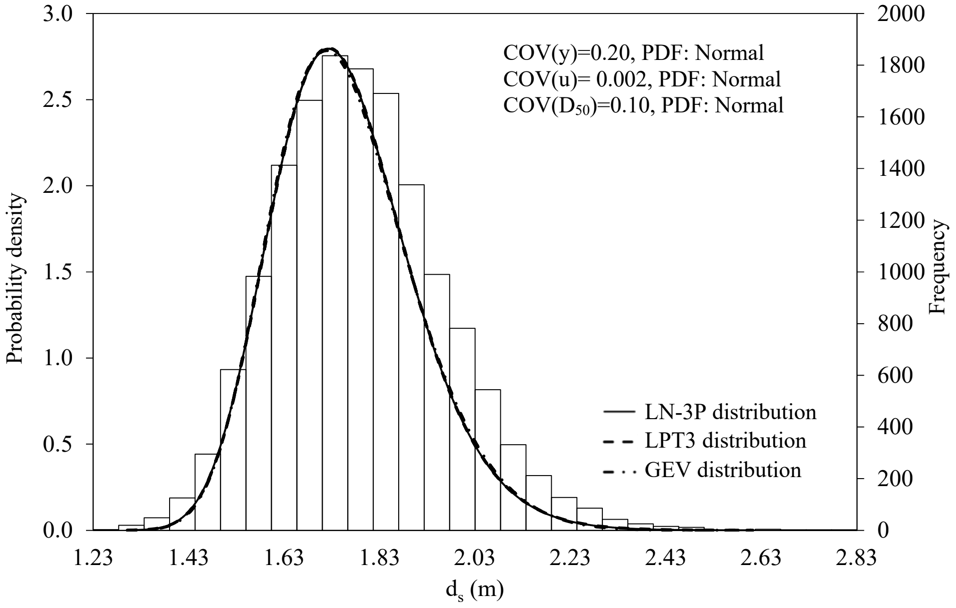

Figure 7. Frequency histogram for Combination C

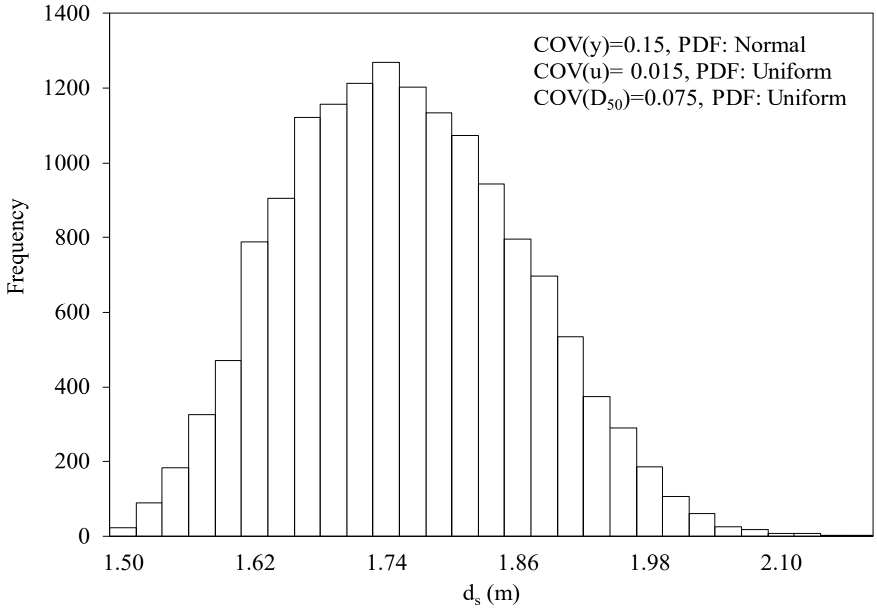

Figure 8. Frequency histogram for Combination D

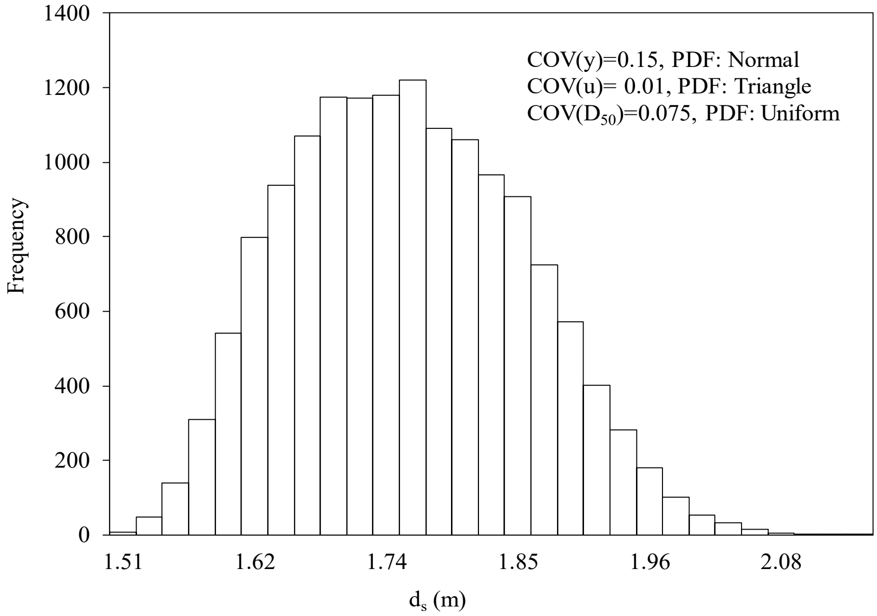

Figure 9. Frequency histogram for Combination E

Table 2. Goodness of fit test results for the probability density functions

Comb.	PDF	Chi-square test		Kolmogorov-Smirnov test		Overall decision	
		α=0.10	α=0.05	α=0.10	α=0.05	α=0.10	α=0.05
A	N	A	A	R	A	A	A
	LN	A	A	A	A	A	A
	LN-3P	A	A	A	A	A	A
	G	A	A	A	A	A	A
	LPT3	A	A	A	A	A	A
	GEV	-	-	A	A	A	A
B	N	R	R	R	R	R	R
	LN	A	A	R	A	A	A
	LN-3P	A	A	A	A	A	A
	G	R	R	R	R	R	R
	LPT3	A	A	A	A	A	A
	GEV	A	A	A	A	A	A
C	N	R	R	R	R	R	R
	LN	R	R	R	R	R	R
	LN-3P	A	A	A	A	A	A
	G	R	R	R	R	R	R
	LPT3	A	A	A	A	A	A
	GEV	A	A	A	A	A	A
D	LN	R	R	R	R	R	R
	LN-3P	R	R	R	R	R	R
	G	R	R	R	R	R	R
	LPT3	R	R	R	R	R	R
	GEV	R	R	R	R	R	R
E	N	R	R	R	R	R	R
	LN	R	R	R	R	R	R
	LN-3P	R	R	R	R	R	R
	G	R	R	R	R	R	R
	LPT3	R	R	R	R	R	R
	GEV	R	R	R	R	R	R

5. CONCLUSIONS

Probability of failure computations including the uncertainties associated with the random scouring variables give more realistic results than conventional approaches. According to the desired safety factor that corresponds to the possible adverse scenarios that the structure can be subjected to during its economical life, the depth of the pier foundation can be realistically determined. In this study, the variation of the probability of failure with respect to the safety factor was investigated. According to the results, it was determined that the probability of failure increases with the increase of the coefficient of variation assigned to the variables included in the scouring mechanism. Therefore, the design of river bridges can be conducted in a more robust manner by using the coefficient of variation values that correspond to the local flow conditions and bed regimes of the region concerned. In the related analyses, the statistical information given for Combination A can be used as the first approximation. However, a sensitivity analysis should also be conducted considering the effects of PDF and COV values since their properties can change with the increase of the existing statistical data. Then, the conditions giving the safest design should be determined according to the local conditions.

Symbols

b : Pier diameter
COV : Coefficient of variation
d_f : Pier footing depth
d_s : Maximum depth of scour
D_{50} : Median sediment size
EA : Safety margin
$f_S(s)$: Probability density function of loading
$f_R(r)$: Probability density function of resistance
F_d : Sediment Froude number
g : Gravitational acceleration
G : Gamma distribution
GEV : General extreme value distribution
LN : Log-normal distribution
LN-3P : 3 parameter log-normal distribution
LPT3 : Log-Pearson type 3 distribution
N : Normal distribution
OYF : Probability density function
R : Resistance
S : Loading
t : Time
T_s : Dimensionless time parameter
u : Mean approach flow velocity

y : Mean approach flow depth

α : Significance level

Δ : Relative submerged density

σ_g : Geometric standard deviation of particle size distribution

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