Scouring Reliability of Bridge Abutments[†]

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ABSTRACT

Failures of bridges crossing wide rivers may cause a number of inconveniences, such as loss of several lives, damages to public and private properties, and traffic disruption. That is why various modes of bridge failures should be accounted for in the planning and design phases to compensate for such negative impacts. Based on the experience gained from past events, it is known that excessive scouring at bridge piers and abutments has been the main cause of bridge failures. The scouring phenomenon is relatively complex and high degrees of uncertainties are associated with the parameters characterizing this event. Accurate determination of the maximum possible depth of scour at these elements is of importance in realistic decision-making for the safe design of footings. This study is based on the development of clear-water scouring models for bridge abutments having vertical-walls, by using empirical and semi-empirical approaches. The reliability of the abutment footing level is estimated using the empirical model employing Monte Carlo simulations. An application is also presented to illustrate the use of this approach.

Key words: *scour, abutment, reliability, Monte Carlo technique*

1. INTRODUCTION

Statistical surveys conducted to observe reasons of bridge failures imply that most of the failures have resulted from hydraulic based reasons. Wardhana and Hadipriono [1] investigated more than 500 bridge failures in the USA between 1989 and 2000. He observed that most of the bridges failed during floods. Main reason for damage or failure of bridges during floods is attributable to excessive scouring at bridge piers and abutments.

This topic has been studied intensively since the mid of the 20th century. To this end, the mechanism of bridge scouring and scour countermeasures, have been investigated. It is relatively difficult to develop a universally accepted method because of the complex nature of the scouring phenomenon. With the advances in experimental and analytical techniques, various aspects of this topic are still the concern of hydraulic engineers. This paper deals with temporal variation of clear water scour depth at vertical-wall abutments. Most of the previous empirical approaches are based on equilibrium time, which is achieved in a relatively long duration. That is why footing depths determined according to equilibrium time gives uneconomical results [2], [3].

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Determination of time-dependent development of scour hole around abutments during design flood not only leads to a realistic value of footing depth but also provides relevant information for determining appropriate scour countermeasures [4].

Time-dependent analysis of clear water scouring at bridge abutments has already been studied by Wong [5], Tey [6], Cardoso and Bettess [7], Ballio and Orsi [8], Oliveto and Hager [9], Coleman et al. [10], Dey and Barbhuiya [11], Oliveto and Hager [12], and Yanmaz and Köse [4], among which the approach of Dey and Barbhuiya [11] is semi-empirical. Empirical studies of Oliveto and Hager [9] and Coleman et al. [10] are based on extensive laboratory data. Complex nature of sediment-laden turbulent flow, showing temporal and spatial variation, makes the phenomenon relatively complicated such that no universally accepted single method is available to date. In spite of the aforementioned restrictions, there is still a need to perform additional experiments for different flow conditions, bed material characteristics, and abutment shapes. It is relatively difficult to model this problem in a laboratory medium because of scale effects and simplifying assumptions. Furthermore, there is a model calibration problem because of limited field data. In this paper, empirical and semi-empirical models giving temporal variation of clear water scouring at vertical-wall abutments will be presented. Empirical approach is based on dimensional analysis, whereas sediment continuity equation of the scour hole has been considered in the semi-empirical model. Scouring reliability has been obtained using the empirical model, which is accompanied with Monte Carlo simulations.

2. EXPERIMENTAL WORK

A number of experiments have been carried out to investigate time-dependent variation of clear water scour at vertical-wall abutments. The flume is 30 m long, 1.25 m wide and has a bottom slope of 0.001. The scope of the experiments is outlined in Table 1, in which L is the abutment length perpendicular to the flow direction, D_{50} is median sediment size, u is mean flow velocity, u_c is mean threshold velocity, y is mean flow depth, F_d is densimetric particle Froude number ($u/(\Delta g D_{50})^{0.5}$), Δ is relative density, $\Delta=(\rho_s - \rho)/\rho$, ρ_s is density of sediment grains, ρ is density of water, g is gravitational acceleration, and t_m is maximum duration of an experiment, which is 6 hours according to the physical conditions of the laboratory. Experiments C1-C5 and C6-C10 have been conducted for determining contour lines of the scour hole at different times i.e. 5, 20, 60, 100, and 150 minutes. Two different bed materials having median sizes 1.8 mm and 0.9 mm have been used in the experiments. The geometric standard deviation of particle size distributions of these materials is $\sigma=1.40$. Therefore, the bed material can be accepted as uniform.

In the experiments, plexiglas abutments having a width of 20 cm and lengths of 12.5 cm and 10 cm were tested separately. Incipient motion was investigated visually and critical velocities were found from the Shields criterion. Since clear water conditions were used in the experiments, the upper limit of approach flow velocity was selected such that no sediment threshold was observed at the bed level. Therefore, all u/u_c values are smaller than unity as shown in Table 1. In the experiments, the maximum scour depths around the vertical-wall abutments, d_s, were measured against time t, relative to the initial bed level using a number of vertical scales attached to the interior of the abutment with a stick having a small inclined mirror at its end. The maximum test duration of an experiment, t_m, was

limited by six hours during which the final equilibrium scour depths were not achieved. However, the rate of scour decreased to smaller values for all experiments. This duration is accepted to correspond to relatively long flood durations in the prototype. During the course of the experiments, it was observed that the maximum scour depths occurred around the upstream corner of the abutment due to development of strong primary vortices. The measured data to be used in the analysis are presented in Figure 1, which gives correlation between $S=d_s/L$ and t/t_m. Sediment accretion was observed at the rear face of the abutment.

Table 1. Experimental data

Experiment	L	D_{50}	u/u_c	y	F_d	L/y	t_m
	(cm)	(mm)		(cm)			(min)
1	12.5	1.8	0.777	8.9	2.370	1.40	360
2	12.5	1.8	0.751	8.3	2.259	1.51	360
3	12.5	1.8	0.741	7.5	2.187	1.67	360
4	12.5	1.8	0.713	6.8	2.068	1.84	360
5	12.5	1.8	0.682	6.1	1.921	2.05	360
C1	12.5	1.8	0.777	8.9	2.370	1.40	5
C2	12.5	1.8	0.777	8.9	2.370	1.40	20
C3	12.5	1.8	0.777	8.9	2.370	1.40	60
C4	12.5	1.8	0.777	8.9	2.370	1.40	100
C5	12.5	1.8	0.777	8.9	2.370	1.40	150
6	10	1.8	0.777	8.9	2.370	1.12	360
7	10	1.8	0.751	8.3	2.259	1.20	360
8	10	1.8	0.741	7.5	2.187	1.33	360
9	10	1.8	0.713	6.8	2.068	1.47	360
C6	10	1.8	0.777	8.9	2.370	1.12	5
C7	10	1.8	0.777	8.9	2.370	1.12	20
C8	10	1.8	0.777	8.9	2.370	1.12	60
C9	10	1.8	0.777	8.9	2.370	1.12	100
C10	10	1.8	0.777	8.9	2.370	1.12	150
10	12.5	0.9	0.985	5.2	2.549	2.40	360
11	12.5	0.9	0.899	4.4	2.260	2.84	360
12	10	0.9	0.985	5.2	2.549	1.92	360
13	10	0.9	0.899	4.4	2.260	2.27	360

3. EMPIRICAL APPROACH

This approach is based on dimensional analysis of variables involved in the scouring mechanism. The depth of scour around a bridge abutment, d_s, can be expressed by the following functional form [13]:

$$d_s = f(L, u, y, \rho, \rho_s, \nu, u_c, g, D_{50}, \sigma, K_s, K_G, t) \tag{1}$$

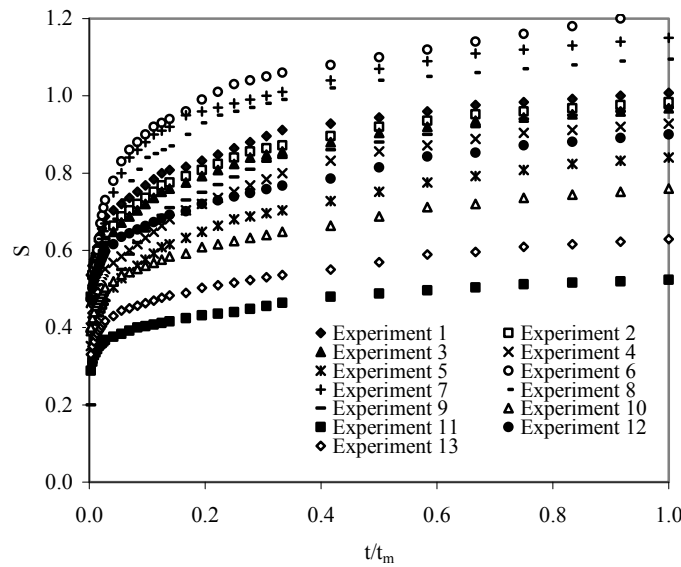where υ is kinematic viscosity, K_s is abutment shape factor, and K_G is an adjustment factor accounting for the geometric characteristics of the approach channel.

Figure 1. Variation of dimensionless scour depth with respect to dimensionless time

Detailed information on adjustment factors can be found in Yanmaz [13]. Dimensionless parameters are obtained from Equation (1) using Buckingum's π theorem. With simplification, the flowing relation is obtained:

$$\frac{d_s}{L} = f\left(R_e, F_d, \frac{u}{u_c}, \frac{L}{D_{50}}, \frac{L}{y}, \sigma, K_s, K_G, T_s\right) \tag{2}$$

in which R_e is Reynolds number (uy/υ), T_s is dimensionless time parameter as previously used by Yanmaz and Altınbilek [2] and Yanmaz [3] for piers, which can be defined for abutments as $tD_{50}(\Delta g D_{50})^{0.5}/L^2$. This parameter combines time, sediment size, and abutment length in a single parameter. Equation (2) can be further simplified with reference to

relative importance of parameters over each other. The effect of Reynolds number can be ignored for fully developed turbulent flow conditions. Moreover, for the condition, $L/D_{50}>25$, which reflects most prototype conditions, the effect of L/D_{50} term on scour development can be ignored [14]. Therefore, for a particular abutment shape in a prismatic channel composed of uniform sand bed with negligibly small floodplains ($\sigma \approx 1.0$, $K_s=1.0$, $K_G=1.0$), Equation (2) simplifies to:

$$\frac{d_s}{L} = f\left(F_d, \frac{u}{u_c}, \frac{L}{y}, T_s\right) \tag{3}$$

In Equation (3), the terms u/u_c and F_d reflect the effects of flow depth, bed slope, median sediment size, and bed resistance characteristics [4]. That is why L/y and T_s can be correlated to u/u_c and F_d separately to end up with a prediction equation having a high correlation coefficient. Therefore, using the information presented in Figure 1 and Table 1, the best combination having a correlation coefficient of 0.87 has been obtained as

$$\frac{d_s}{L} = 0.25 F_d^{0.85} \left(\frac{L}{y}\right)^{0.15} (\log T_s)^{0.60} \tag{4}$$

4. SEMI-EMPIRICAL APPROACH

As a second approach, a semi-empirical model is developed for determining temporal variation of clear water scour depth around vertical-wall abutments. This approach is based on continuity equation of the scour hole around the abutment, which is expressed for clear water conditions as follows:

$$\frac{dV}{dt} = Q_{so} \tag{5}$$

where V is volume of the scour hole and Q_{so} is the rate of sediment flux leaving the scour hole. As can be observed from Equation (5), this approach requires information on temporal variation of scour hole volume. That is why series of experiments have been conducted for determining this volume at different test durations. These experiments were performed with $F_d=2.370$ using $D_{50}=1.8$ mm. The experiments C1 – C5 and C6 – C10 have been conducted for L=12.5 cm and L=10 cm, respectively. These experiments have been performed in consecutive order using 5, 20, 60, 100, and 150 minutes of test duration. The scour contours at the end of these durations have been measured with point gage. The bed material of the flume was flattened before each run and the flume was filled up with water at a low rate without causing any disturbance to the bed material. After each run, the bed was flattened to run the experiment with the next duration. The surface area and volume of the scour hole have been obtained via a software with the measured scour contour lines.

Variation of dimensionless scour hole volume, $V^*=V/(d_s L^2)$, with respect to dimensionless time, T_s, is expressed by

$$V^* = 1.142 T_s^{0.281} \tag{6}$$

which has a correlation coefficient of 0.980. Equation (6) implies that scour hole volume decreases with respect to time. With the observation of the scour contour lines, it can be assumed that side slopes of the scour hole, except the rear face, can be approximately taken as the angle of repose of sediment, ϕ. One of the scour contour lines is shown in Figure 2. The second step in model development is determination of Q_{so}. The volumetric rate of sediment transport leaving the scour hole can be expressed as:

$$Q_{so} = f \frac{E A_p}{\Delta \rho_s} \tag{7}$$

in which f is an adjustment coefficient reflecting geometric characteristics of the scour hole, flow and bed material properties, E is sediment pickup rate, and A_p is a unit area over which sediment pickup takes place. Sediment pickup function developed by Dey and Debnath [15] for steep slopes can be used in this model. This function is

$$E = 0.0006 T D_*^{0.24} \sigma^{1.9} \rho_s \sqrt{\Delta g D_{50}} \tag{8}$$

where T is transport stage parameter, which is defined by Dey and Barbhuiya [11] as $(\tau_b - \tau_{bc})/\tau_{bc}$. Herein τ_b is bed shear stress in flat region of the scour hole, $\tau_{bc} = \psi \tau_{cr}$ is critical bed shear stress on inclined slope, τ_{cr} is critical bed shear stress on flat bed, ψ is a coefficient depending on turbulent fluctuations and primary vortex oscillations in front of the abutment, and D_* is dimensionless sediment size, $D_{50}(\Delta g/\upsilon^2)^{1/3}$. Temporal variation of τ_b has been determined according to the procedure given by Dey and Barbhuiya [11].

The mean value of τ_b during the first two minutes of the experiments is approximately $2\tau_0$, where τ_0 is bed shear stress of the approach flow. The value of τ_b decreases with time and approaches eventually to τ_0. For the sake of mathematical simplicity, time dependent value of bed shear stress at the flat bed region of the scour hole is assumed to be $\tau_b(t) \cong \tau_0$. Critical bed shear stress on the boundary of the scour hole is relatively difficult to obtain because of time effect and geometric characteristics of the scour hole. That is why an approximate value of $\psi=0.5$, which was proposed by Dey and Barbhuiya [11], has also been used in this analysis. Because of the aforementioned reasons, sediment pickup rate shows variations along the boundary of the scour hole. It is, therefore, necessary to make an approximation for a representative unit pickup area, A_p. Maximum scour develops at the upstream face of the abutment, whereas the rear face is subject to accretion. Flow accelerates because of contraction effect along the side of the abutment. A unit area defined at the upstream side of the abutment is assumed to represent pickup motion, which is

$$A_p = (d_s \cot\phi + L) D_{50} \tag{9}$$

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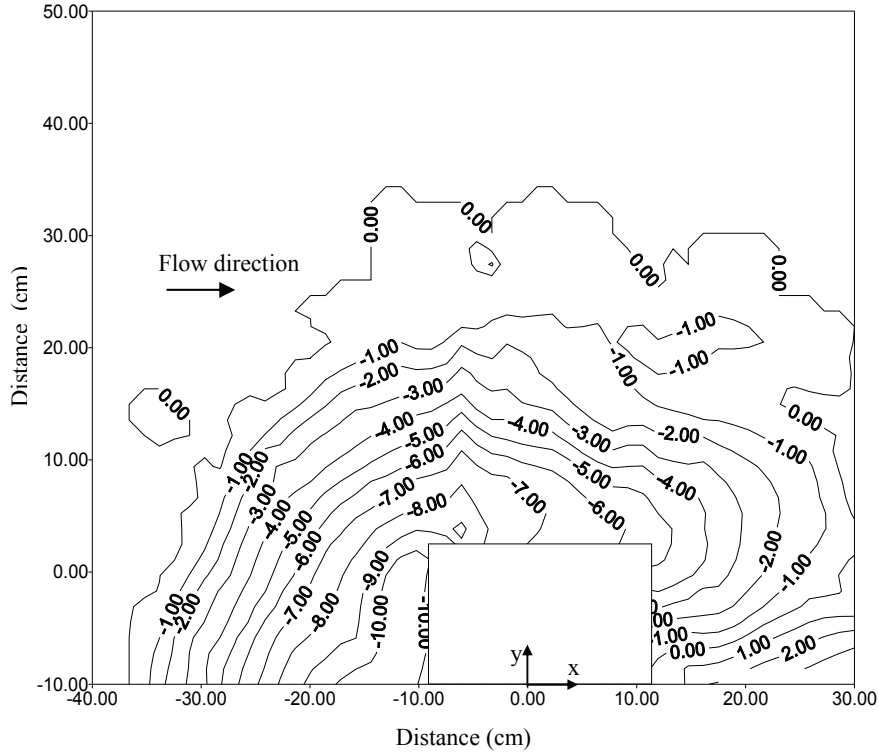*Figure 2. Scour contours in cm in the scour hole (L=12.5 cm, t=100 minutes)*

This area is the multiplication of the maximum surface width of the scour hole with the median size of the sediment. This definition was previously used by Yanmaz and Altınbilek [2] and Yanmaz [3] for piers. When the sediment pickup rate E is multiplied with the unit pickup area, it gives the rate of sediment transport out of the scour hole. By solving Equation (5) together with Equations (6), (7), and (8), a new equation, giving time-dependent variation of scour depth at an abutment is found. Inserting the values of V* and T_s, the derivative of Equation (6) with respect to time becomes

$$\frac{dV}{dt} = ct^{0.281} \frac{dd_s}{dt} + \frac{0.281cd_s}{t^{0.719}} \tag{10}$$

in which $c = 1.142L^{1.438}D_{50}^{0.281}(\Delta gD_{50})^{0.1405}$. Using Equation (8) and inserting necessary information in Equation (7), the functional relation, f, is obtained as:

$$f = \frac{\int\limits_{ds1}^{ds2} mct^{0.281}dd_s + \int\limits_{t_1}^{t_2} 0.281mcd_st^{-0.719}dt}{\int\limits_{t_1}^{t_2}(d_s \cot\phi + L)dt} \qquad (11)$$

where $m = \Delta\rho_s/(ED_{50})$. Taking successive integral limits of Equation (11) according to the data presented in Figure 1, a series of f-values, representing the whole experimental conditions can be found. Investigation of these values imply that sediment transport rate out of the scour hole decreases with respect to time. To obtain solution to this problem, the adjustment coefficient f needs to be expressed explicitly. This coefficient depends on geometric characteristics of the scour hole, abutment length, flow and bed material properties. To this end, various combinations of dimensionless parameters characterizing f have been formed and expressed using a multiple regression analysis. The combination, which gives the best correlation with the computed f-values, has been obtained as

$$f = 143\left(\frac{u_*t}{L}\right)^{-0.31}\left(\frac{d_s \cot\phi}{L}\right)^{-2.95} \qquad (12)$$

where u_* is shear velocity of approach flow. Combining Equations (7), (10), and (11) and solving for dd_s/dt, one obtains

$$\frac{dd_s}{dt} = 143\left(\frac{u_*t}{L}\right)^{-0.31}\left(\frac{d_s \cot\phi}{L}\right)^{-2.95}\frac{(d_s \cot\phi + L)}{mct^{0.281}} - \frac{0.281d_s}{t} \qquad (13)$$

Equation (13) is a first order nonlinear partial differential equation, which was solved using Euler's technique. In the computations, angle of repose values were taken as 31° and 30° for sediment sizes 1.8 mm and 0.9 mm, respectively. The relative density has been taken as 1.65. The results of solution of Equation (13) were compared with some experimental data (See Figures 3, 4, and 5). As can be seen from these figures both approaches agree well with the experimental data.

Semi-empirical model, based on the solution of Equation (13), is found to give slightly greater results than the empirical approach for the data sets presented in Figures 3 to 5. However, when the whole data sets are considered, it was observed that empirical models also give slightly greater results than the semi-empirical model for some experiments. Detailed results can be found in Köse [16]. Therefore, the general trend can be accepted as that both approaches are in good agreement. Since application of the empirical approach using Equation (4) is simple, it will be used in scour reliability computations.
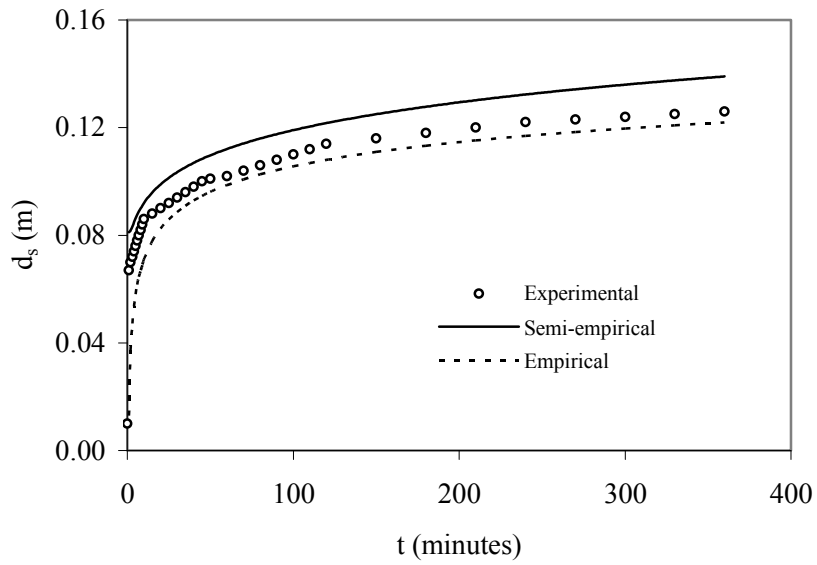
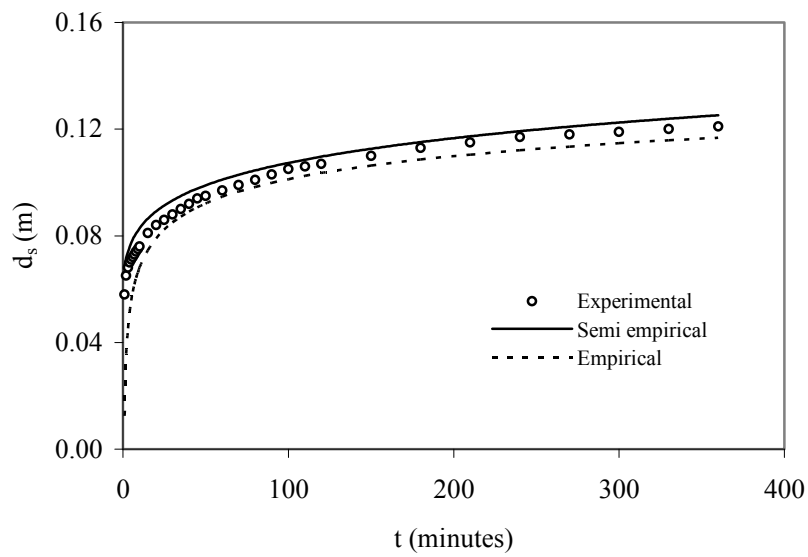*Figure 3. Comparison of empirical and semi-empirical model with experimental data (Experiment 1)*

Figure 4. Comparison of empirical and semi-empirical model with experimental data (Experiment 3)
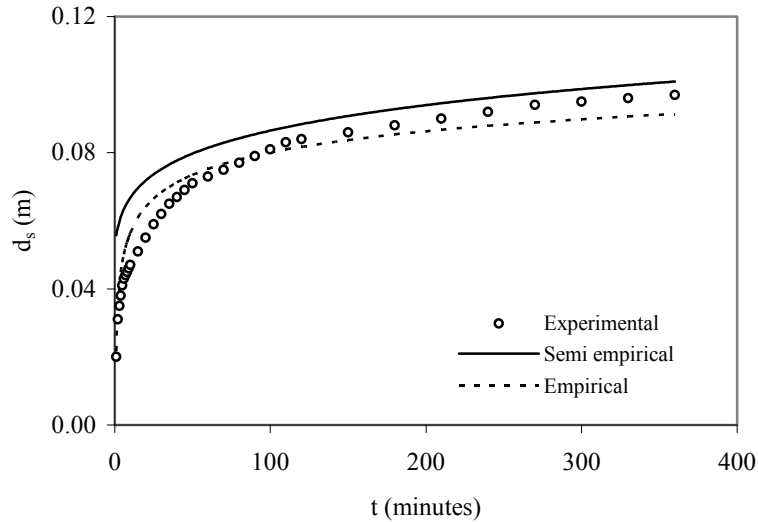
Figure 5. Comparison of empirical and semi-empirical model with experimental data (Experiment 9)

4. SCOURING RELIABILITY OF ABUTMENT FOOTING

Bridge safety should be assessed for various failure modes not only from structural view point but also from geotechnical and hydraulic aspects. Functionality of a bridge during its service life depends on joint consideration of these aspects and implementation of necessary countermeasures and repair works. Lack of such evaluations would lead to increase in uncertainties and risk levels during the physical life of the bridge. In fact, high safety levels and economical solutions can be attained with the identification and incorporation of uncertainties in the design. With periodical inspection and monitoring of bridges during their life spans, relevant data can be collected. Moreover, necessary repairs can be made at the right time so that the desired safety level can be maintained [17], [18].

This study ignores other possible failure modes and considers only time-dependent scouring mode at vertical-wall abutments. A realistic decision-making is possible for footing depth using reliability based calculations. In the analysis, the empirical model will be used. The safety margin of the footing depth, d_f below the mean bed level can be defined as SM = $d_f - d_s$, where d_s is the expected maximum depth of scour for a given design flood duration. Hence the reliability of footing can be defined as:

$$\alpha = P(SM > 0) \tag{14}$$

in which P is probability. In deterministic approach, the values of d_f and d_s are constant for given design conditions and the value of SM needs to be greater than zero. In fact, most of

the variables affecting scouring mechanism are of random character. Therefore, for the worst combination of scouring variables, the safety margin may attain a negative value. That is why a reliability-based assessment gives more realistic results than a deterministic model. Ignoring model uncertainty, Equation (14) is expressed using Equation (4) with SI unit system as:

$$\alpha = P(SM \geq 0) = P\left(d_f - 0.0766L^{1.15}y^{-0.15}u^{0.85}D_{50}^{-0.425}\left[\log\left(4.023tD_{50}^{1.5}L^{-2}\right)\right]^{0.60}\right) \qquad (15)$$

which is nonlinear. Monte Carlo simulation technique is used in the computation of reliability given in Equation (15), which is based on generation of random numbers for probability P between 0 and 1. This application is illustrated with an example.

5. APPLICATION

A bridge will be constructed on a river having a bed slope of 0.0006. Structural requirements imply a vertical-wall abutment with a length of 2.5 m. Footing depth will be determined according to the reliability level computed from Equation (15). The median size of the uniform bed material is 17 mm. The mean values of the scouring variables have been taken to satisfy the continuity principle as y=2.2 m, u=1.31 m/s, and t=4 hours. These values lead to u/u_c=0.79, L/y=1.14 and F_d=2.50, which are within the limits of applicability of Equation (4) with clear water conditions. Therefore, Equation (4) can be used for determining the maximum scour depth at the end of the design flood duration. In this analysis, the abutment length and footing depth were assumed as deterministic variables, whereas the remaining variables i.e. y, u, and D_{50} are treated as random variables. For reliability computation using Equation (15), relevant statistical information i.e. probability density function (PDF) and coefficient of variation (Ω) should be defined. However, sufficient data are needed to assign realistic statistical information, which can be obtained from the prototype and laboratory medium. Intuition of an experienced engineer is also worthy of attention. However, relevant information should be used for a particular bridge considering local conditions. That is why site-specific statistical information is needed, which is mostly unavailable. Coefficients of variation of hydraulic variables reflect measurement errors and changes in channel bed resistance. These coefficients may be relatively small under elaborate laboratory conditions; however they may have somewhat greater values in the prototype because of difficulty of using measuring instruments in the field, their low precision, location of the measurement, and human-induced errors. This study uses the statistical information presented by Johnson [19], Johnson [20], Yanmaz [21] and Yanmaz and Çiçekdağ [22].

A sensitivity analysis is also carried out to investigate the effects of PDF and Ω on reliability computations. To this end, 4 different cases were analyzed whose statistical information is presented in Table 2. To investigate the effect of footing depth on reliability, different footing depths were taken into account. In the design, the mean value of the footing depth is planned to be 1.50 m according to the local conditions. To this end, footing depths ranging from 1.42 m to 1.54 m were tested. In cases A, B, and C, the effect of coefficient of variation on reliability has been investigated. With the inclusion of additional

future data, the present statistical information i.e. PDFs and Ω-values may change. Therefore, the worst possible combination may be found to assess the reliability during the expected life of the structure.

Table 2. Statistical information used in the application

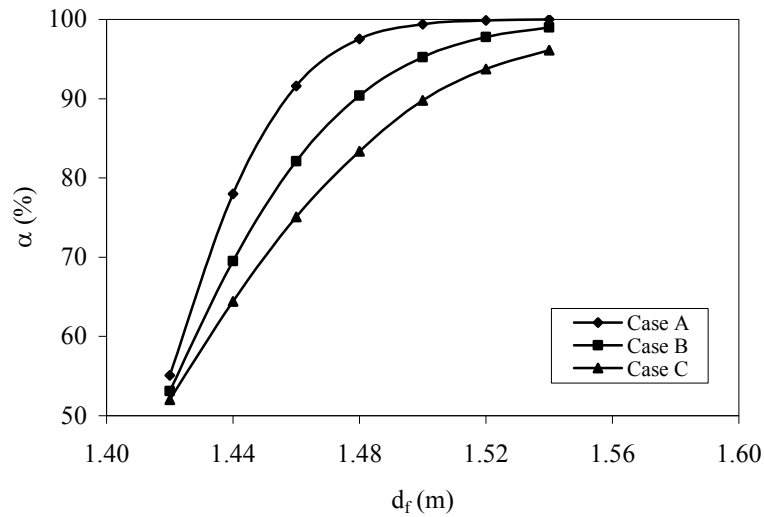| Variable	Case	Ω	PDF
y	A	0.10	Normal
	B	0.15	Normal
	C	0.20	Normal
	D	0.15	Normal
u	A	0.010	Normal
	B	0.015	Normal
	C	0.020	Normal
	D	0.015	Uniform
D_{50}	A	0.05	Normal
	B	0.075	Normal
	C	0.10	Normal
	D	0.075	Uniform

Figure 6. Variation of reliability with respect to footing depth

The results of the analyses are presented in Figure 6, which implies that reliability increases with increasing footing depth. Relatively high reliabilities were obtained for all cases when the footing depth is d_f=1.54 m. Therefore, further increase of footing depth does not lead to a significant increase in reliability but increases the cost. These analyses implied that the reliability was sensitive to the coefficient of variation. The effect of probability density function on reliability has also been investigated for Case D. To this end, uniform distribution was assigned to mean approach flow velocity and median sediment size by keeping Ω-values the same as the Case B. However, negligibly small variations were observed in the reliability values.

6. CONCLUSIONS

This paper deals with development of an empirical and semi-empirical model for determining temporal variation of clear water scour depth at vertical-wall bridge abutments. In the experiments, two different uniform bed materials having median sizes 1.8 mm and 0.9 mm and two abutments having lengths 12.5 cm and 10 cm were used with the ranges $0.682 \leq u/u_c \leq 0.985$, $1.12 \leq L/y \leq 2.84$, and $1.921 \leq F_d \leq 2.549$. Equation (6) is proposed for determining temporal variation of scour hole volume. Empirical model is based on dimensionless parameters characterizing scour mechanism, whereas sediment continuity equation was used in the development of the semi-empirical model. Sediment transport rate out of the scour hole was formulated using a sediment pickup function proposed by Dey and Debnath [15]. Using this approach Equation (13) was obtained for determining temporal variation of scour depth at vertical-wall abutments. Both empirical and semi-empirical models agree well with the experimental data. Empirical model has been used in scouring reliability modeling of abutments because of practical ease. According to an application, reliability was observed to increase with increasing footing depth, whereas reliability was found to decrease with increasing coefficient of variation of random variables involved in the scouring mechanism.

Symbols

A_p : unit pickup area

c : coefficient

D_{50} : median sediment size

D_* : dimensionless sediment size

d_s : instantaneous maximum depth of scour at abutment

E : sediment pickup rate

f	: adjustment coefficient for scour hole
F_d	: densimetric particle Froude number
g	: gravitational acceleration
L	: abutment length
m	: coefficient
Q_{so}	: sediment transport rate out of scour hole
S	: relative scour depth
T	: sediment transport stage parameter
T_s	: dimensionless time parameter
t	: time
t_m	: maximum duration of experiment
u	: mean approach flow velocity
u_c	: mean threshold velocity
u_*	: shear velocity
u_{*c}	: critical shear velocity
V	: volume of scour hole around abutment
V^*	: dimensionless scour hole volume
y	: mean approach flow depth
ρ	: density of water
ρ_s	: density of sediment
υ	: kinematic viscosity of water
Δ	: relative density
σ	: geometric standard deviation of particle size distribution
ψ	: coefficient for turbulent fluctuations and vortex oscillations
ϕ	: angle of repose of sediment
τ_b	: bed shear stress at flat region of scour hole
τ_{bc}	: critical bed shear stress in scour hole
τ_{cr}	: critical bed shear stress at flat bed.

References

[1] Wardhana, K., Hadipriono, F.C. Analysis of Recent Bridge Failures in the United States. J. Perf. of Const. Fac., ASCE, 17 (3), 144-150, 2003.

[2] Yanmaz A.M., Altinbilek HD. Study of Time-Dependent Local Scour Around Bridge Piers. J. Hydr. Eng., ASCE, 117(10), 1247-1268, 1991.

[3] Yanmaz A.M. Temporal Variation of Clear Water Scour at Cylindrical Bridge Piers. Canadian J. Civil Eng., 33(8): 1098-1102, 2006.

[4] Yanmaz A.M, Köse, Ö. Time-wise Variation of Scouring at Bridge Abutments. J. Sadhana, 32 (3), 199-213, 2007.

[5] Wong W.H. Scour at Bridge Abutments. Report No.275, School of Engineering, University of Auckland, Auckland, New Zealand, 1982.

[6] Tey C.B. Local Scour at Bridge Abutments. Report No.329, School of Engineering, University of Auckland, Auckland, New Zealand, 1984.

[7] Cardoso, A.H., Bettess, R. Effects of Time and Channel Geometry on Scour at Bridge Abutments. J. Hydr. Eng., ASCE, 125(4), 388-399, 1999.

[8] Ballio, F., Orsi, E. Time Evolution of Scour Around Bridge Abutments. Water Eng. Res. 2(4), 243-259, 2000.

[9] Oliveto, G., Hager, W.H. Temporal Evolution of Clear Water Pier and Abutment Scour, J. Hydr. Eng., ASCE, 128(9): 811-820, 2002.

[10] Coleman, S.E., Lauchlan, C.S., Melville, B.W. Clear Water Scour Development at Bridge Abutments., J. Hydr. Res., 41(5): 521-531, 2003.

[11] Dey, S., Barbhuiya, A.K. Time Variation of Scour at Abutments. J. Hydr. Eng., ASCE, 131(1), 11-23, 2005.

[12] Oliveto, G., Hager, W.H. Further Results to Time-dependent Local Scour at Bridge Elements., J. Hydr. Eng., ASCE, 131(2), 97-105, 2005.

[13] Yanmaz, A.M. Bridge Hydraulics, METU Press, Ankara, 2002 (in Turkish).

[14] Melville, B.W., Coleman, S.E. Bridge Scour, Water Resources Publications, LLC, Colorado, ABD, 2000.

[15] Dey, S., Debnath, K. Sediment Pickup on Stream wise Sloping Beds., J. Irrig. and Drain. Eng. ASCE, 127(1), 39-43, 2001.

[16] Köse, Ö. Analytical and Experimental Investigation of Temporal Variation of Clear Water Scour Depth at Bridge Abutments, Ph.D. Thesis, Civil Engineering Department, METU, 2007.

[17] Yanmaz, A.M., Caner, A., Berk, A. Renovation of a Safety-Inspection Methodology for River Bridges. J. Perf. Const. Facil., ASCE, 21 (5), 382-389, 2007.

[18] Caner, A., Yanmaz, A.M., Yakut, A., Avşar, Ö., Yılmaz, T. Service Life Assessment of Existing Highway Bridges with no Planned Regular Inspections, J. Perf. Const. Facil., ASCE, 22(2), 108-114, 2008.

[19] Johnson, P.A. Uncertainty of Hydraulic Parameters", J. Hydr. Eng., ASCE, 122 (2), 112-114, 1996.

[20] Johnson, P.A. Fault Tree Analysis of Bridge Failure due to Scour and Channel Instability", J. Infra. Sys. ASCE, 5(1),35-41, 1999.

[21] Yanmaz, A.M. Overtopping Risk Assessment in River Diversion Facility Design, Canadian J. Civil Eng., 27, 319-326, 2000.

[22] Yanmaz, A. M., and Çiçekdağ, Ö. "Composite Reliability Model for Local Scour Around Cylindrical Bridge Piers", Canadian Journal of Civil Engineering, 28, 3, 520-535, 2001.