Bridge Scour Estimates Using the Probabilistic Method

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INTRODUCTION

Physics involved in local scour around bridge piers seems to be too complicated. Turbulent flow tends to accelerate when it has to circumvent the pier. So the scour hole develops specially around the pier, and the changed geometry affects the flow in turn. Thus, the flow responsible for the local scour is characterized by highly three-dimensional turbulent motion. Since this type of problems cannot be analyzed by a simplified mathematical model, hydraulic engineers have had two choices: using an empirical relationship obtained through experiments or solving the Navier-Stokes equations directly. Although the empirical formulas sometimes perform poor predictions, the former is good for the practical purposes because of its simplicity. However, recently, hydraulic engineers equipped with high-performance computers solve time-averaged Navier-Stokes equations directly with a turbulence model (Olsen and Melaaen, 1993; Ushijima, 1996; Richardson and Panchang, 1998; Tseng et al., 2000; Wang and Jia; 2000). Up to date, however, the simulation requires tremendous computing time even with the fixed bed assumption. Moreover, if they allow moving bed, the computing time will increase additionally without guaranteeing the convergence of the solution. Therefore, a use of the empirical approach is preferred rather than the expensive numerical modeling.

US Federal Highway Administration (FHWA) recommends HEC-18 by Richardson and Davis (1995) as a standard procedure for estimating the local scour. The CSU equation in HEC-18 is the relationship being used most widely, and it is known to yield moderate results compared to other formulas. However the relationship is deterministic, it does not consider the uncertainty.

Johnson and Dock (1998) indicated that three forms of uncertainty exist in the equations used to estimate local scour: (1) model, (2) hydrologic, and (3) parameter. Model uncertainty arises from that the mathematical model does not represent the physical process completely.

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Most formulas for local scour are developed through the laboratory experiments. Thus, when they are applied to a field case, the scale problem may occur. This is obviously related to the model uncertainty. Hydrologic uncertainty comes from the process of determining the design flood event at a particular location. This uncertainty is increased when there are limited data available such as at an ungauged stream cross section. Finally, parameter uncertainty results from an inability to assess parameters in the scour formulas accurately. For example, the parameters representing the bed form and the armoring of the channel bed, cannot be simply determined.

In the present study, we apply the probabilistic approach to a bridge across a middle range stream in Korea. We followed the procedure by Johnson and Dock (1998), which takes hydraulic and other parameters as probabilistic variables. As a result, the foundation depth of the bridge is determined for the design flood at a probability of bridge failure of 0.0001.

BRIDGE SCOUR ESTIMATES

HEC-18 recommends the following CSU equation for estimating local scour around bridge pier (Richardson and Davis, 1995):

$$\frac{d_s}{y} = 2.0K_1K_2K_3K_4\left(\frac{b}{y}\right)Fr^{0.43} \tag{1}$$

where d_s is the scour depth, y is the upstream flow depth, b is the effective pier width, Fr is the upstream Froude number ($Fr = V/(gy)^{0.5}$, where V is the approach velocity), and K_1, K_2, K_3, and K_4 are correction factors for the pier shape, angle of attack, bed form, and sediment gradation, respectively. The CSU equation is one of the relationships most preferred by hydraulic engineers (Jones, 1993).

PROBABILISTIC SCOUR ESTIMATES

The probabilistic study is performed on a bridge in Korea. Figure 1 depicts the substructure of the bridge, which consists of a cylindrical pier of 1.8 m diameter and a foundation of 4.0 m in diameter. The foundation is located along the deposited and the residual soil layers above the weathering rock, and the penetration depth is 3.76 m. Since the foundation does not reach the weathering rock, it can be indicated that the foundation of the bridge is not properly placed.

Table 1 provides the upper and lower values and the distributions of parameters in the CSU equation. The same distributions are used as in Johnson and Dock (1998), and the upper and lower values are determined accordingly. In the table, the mean values of the hydraulic parameter correspond to the 100-year design flood in the stream being considered. Since the foundation is exposed to the channel bed, the effective pier width estimated as a function of the flow depth. The factors of K_1, K_2, and K_4 in eq. (1) are assumed to be deterministic by setting of $K_1 = K_2 = K_4 = 1$. However, we take K_3 as a random variable ranging between 1.1 and 1.3 with a uniform distribution.

Number of simulation cycles

In this study, the Monte Carlo simulation is used to generate random samples of the parameters in eq.(1). Thus, it is necessary to determine the number of simulation cycles that is required for sufficient accuracy of the estimated scour depth. Figure 2 shows the mean scour depth and the coefficient of variation (COV) as a function of the number of simulation cycles. It is seen that the COV decreases as the number of simulation cycles increases. As a result, the estimated scour depths converge to a certain value. For the computation, we choose 10,000 as the number of computation 10,000 which is thought to be enough to get the converged estimate.

Scour depth

By using the data listed in Table 1, we performed 10,000 simulations, yielding a mean scour depth of 5.12 m, a COV of 0.035, and a standard deviation of 0.179 m. Figure 3 shows a frequency histogram of the simulated scour depths. The computed scour depths vary between 4.6 m and 5.7 m. We also do χ^2 goodness-of-fit test, and confirmed that the estimated scour depths are normally distributed at a level of significance of 0.01.

Based on this, the probability that a particular scour depth will occur is computed. Table 2 lists the probabilities of various scour depths at the bridge. For example, the probability that a scour depth of less than 5.15 will occur is 67 %. The scour depth that has a 83 % non-exceeding probability of occurrence is 5.25 m. Regarding the foundation depth of 3.76 m, the probability that the scour depth will exceed the foundation depth seems to be about 100 % for the 100 year flood.

Foundation depth

In the present paper, failure of the foundation due to scour is defined as the point at which the scour reaches the bottom of the foundation. This is the same definition made in Johnson and Dock (1998). If we assume that the annual occurrence of a flood can be described as a Poisson process, then the probability of failure of the bridge foundation is given by (Lewis, 1994)

$$P_f = 1 - e^{-\gamma p t} \qquad (2)$$

where P_f is the probability of failure of the bridge, γ is the frequency of the flood, p is the probability of failure of the bridge due to scour, and t is the life span of the bridge. If we use $P_f = 0.0001$ (AASHTO, 1991), then eq.(2) with $\gamma = 1/100$ and $t = 50$, yields $p = 2 \times 10^{-3}$. If we further assume that the foundation depth is normally distributed with the same coefficient of variation as the scour depth, then the probability of failure due to scour can be expressed as

$$p = 1 - p\left[Z < \frac{d_f - d_s}{\left(S_f^2 + S_s^2\right)^{0.5}} \right] \qquad (3)$$

where Z is the standard normal variate, S_f and S_s are standard deviation of the foundation and scour depth, respectively, and d_f is the foundation depth. By using eq.(3) with $d_s = 5.12$ m and $S_s = 0.179$ m estimated previously, the foundation depth is estimated to be 5.83 m, which is deeper than the current depth of 3.76 m.

CONCLUSIONS

We have estimated the scour depth around the bridge pier with three kinds of uncertainties, namely model, hydraulic, and parameter uncertainties. If we choose a particular formula, which means that we abandon the model uncertainty, we can reflect the hydraulic and parameter uncertainties in estimating the scour depth using the relationship. This is achieved by treating velocity, stage (or discharge), and other parameters (relevant to angle of approach velocity, bed forms, and sediment gradation) as probabilistic variables. We applied a procedure proposed by Johnson and Dock (1998) to a bridge crossing a middle-sized stream in Korea. The foundation depth was determined for the 100 year flood at a probability of bridge failure of 0.0001. It was shown that the current foundation of the bridge need to be deepened.

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Table 1. Parameter estimates and distributions for the bridge being considered

Variable	Upper bound	Lower bound	Mean	Probability distribution
b	3.19	2.48	2.0	Symmetrical triangular
V	3.07	1.82	2.45	Symmetrical triangular
y	8.17	4.02	6.01	Symmetrical triangular
K_1	1.0	1.0	1.0	-
K_2	1.0	1.0	1.0	-
K_3	1.2	1.1	1.15	Uniform
K_4	1.0	1.0	1.0	-

Table 2. Probabilities of local scour

Scour depth, d_s (m)	Probabilities that scour is less than d_s
5.40	0.97
5.25	0.83
5.15	0.67
5.05	0.46
4.95	0.27
4.85	0.12

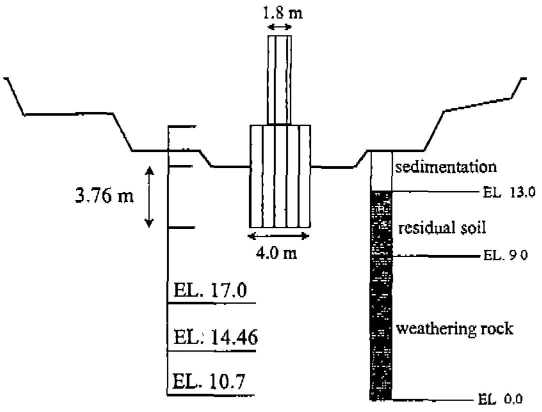

Figure 1. Substructure of the bridge being considered

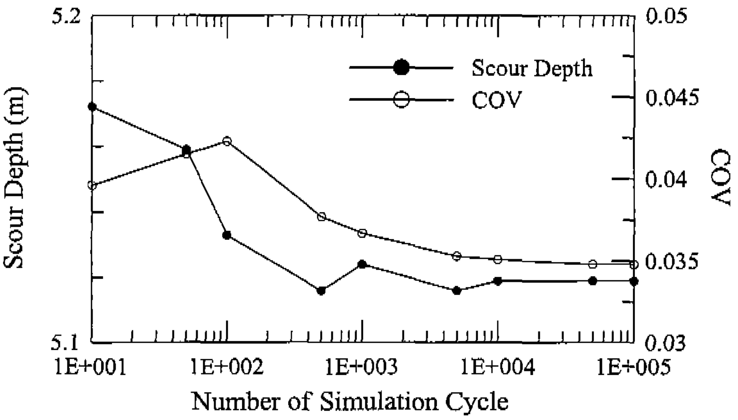

Figure 2. Scour depth and coefficient of variation versus number of simulation cycle

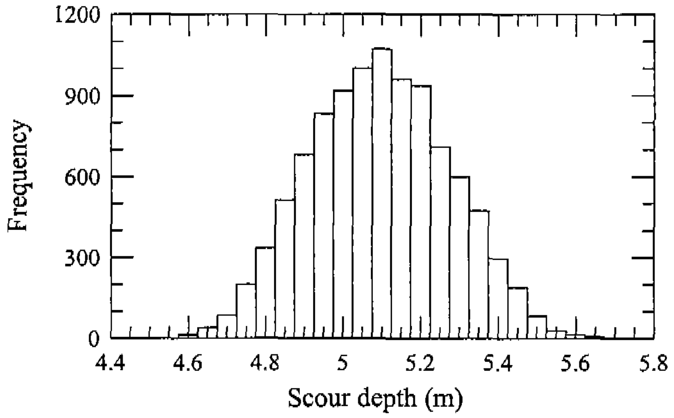

Figure 3. Frequency histogram for 10,000 simulated scour depths.