PROBABILISTIC EVALUATION OF SCOURING DOWNSTREAM OF DAMS

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Excessive scouring downstream of an outlet facility may cause serious foundation stability problems. Degree of scour depends on the characteristics of the jet leaving the outlet facility, available head, depth of tailwater, and properties of the bed material. Most of the previous studies reported in the literature are of deterministic character, which do not account for possible uncertainties in the governing variables. This paper concerns the investigation of a relationship between reliability of scouring induced by free inclined jets downstream of dams and safety factor. The scour equation proposed by Mason has been used in the simulation model based on the Monte Carlo analysis. An application is presented to illustrate the use of the model in which the effects of foundation depth, jet discharge, bed material size, and tailwater elevation on scouring reliability have been evaluated. Additional relationship has also been obtained to present the variation of required size of armoring bed material against reliability under a constant foundation depth. Sensitivity analyses were carried out to observe the effects of statistical parameters.

1 Introduction

Dams may be subject to extreme loading conditions. On the other hand the overall resistance may reduce due to aging and some external factors. The interference of resistance and loading would dictate the level of safety. The overall risk analysis is based on the availability of relevant information concerning various failure modes and their statistical properties. Because of lack of required information for most dam sites, only certain aspects of the overall failure have been studied while the modes of secondary importance were ignored. The present study is only based on the probabilistic evaluation of scour induced by free inclined jets, which can progressively undermine loose riverbed material downstream of dams. Upon entering the tailwater, the free jet disperses and the available energy at the riverbed is dissipated by excavating a large scour hole. The eroded particles forming the riverbed are carried by the flow and the scour process continues until the scour hole is stabilized. The literature is rich in drastic examples of this phenomenon some of which were introduced by Mason (1984). Due to complexity of modeling the problem, the scour-resistant foundation design of dams comprises one of the ambiguous fields of hydraulic engineering.

Modeling of scour mechanism is relatively complicated because of difficulties in investigation of sediment-laden flow in and around the scour hole. Simplified laboratory experiments may suffer from representing the prototype conditions, which may be entirely different from those of a laboratory medium Restrictions in modeling the actual scour phenomenon may pronounce the overall uncertainty of empirical models.

Scour prediction equations proposed up to date are deterministic such that their results are subject to an unknown level of risk of foundation scouring. This study concerns probabilistic assessment of scouring of foundations downstream of dams. Possible uncertainties associated with the phenomenon are discussed. The reliability computations are carried out by simulating the scouring safety margin using the Monte Carlo technique. The model is based on the scour equation proposed by Mason (1984). An example is presented to illustrate the use of the model. Effects of governing variables and their statistical parameters on reliability are examined.

2 Local Scour Downstream of Dams Induced by Free Jets

When a jet leaves a pressurized outlet facility, it impinges on the bed downstream of the dam and excavates the streambed to a considerable depth. Hydraulic characteristics of jet, particle properties and fall velocity of the bed material, height of the jet above the tailwater stage, depth of tailwater, and duration of scouring action are key parameters characterizing the scouring process. At the early stages of the erosion, the rate of scour development is extremely high. As the scour hole enlarges progressively, the local velocity in the scour hole reduces to low values such that the wall shear stresses are not capable of eroding the bed to further elevations. Hence the depth of scour converges to a terminal value asymptotically.

Although many scour equations have been proposed in the literature, the results of these equations may differ widely from each other because of variations in their derivational conditions. Therefore, it is of utmost importance to study the randomness of the phenomenon using a suitable equation, which is developed on the basis of physical interpretation of the mechanism and calibrated with extensive data. To this end Mason’s (1984) equation has been selected in probabilistic assessment of the problem. By reviewing the available equations and compiling 26 sets of scour data from prototypes and 47 from models, Mason (1984) proposed the following equation for the depth of scour downstream of dams induced by inclined free jets.

$$d_s = K \frac{q^x H^y h^w}{g^v D^z} \tag{1}$$

where d_s is the maximum scour depth measured from free water surface, q is the unit discharge issuing from the sluiceway, H is the elevation difference between the upstream and tailwater, h is the tailwater depth above unscoured bed level, g is the gravitational acceleration, D is the mean size of particle at riverbed, K is a coefficient and x, y, w, v, and z are exponents of q, H, h, g, and D, respectively. The ranges of data used by Mason (1984) are outlined in Table 1. Because of insufficient prototype information, Mason (1984) used D=0.25 m and 0.30 m throughout his analysis. Impact angles of jets varied from 25 to 85°, and 20 to 72° for model and prototype data, respectively. Based on minimization of coefficient of variation of model bias of Eq. (1), Mason (1984) proposed $K=6.42-3.10H^{0.10}$, v=0.30, w=0.15, x=0.60-H/300, y=0.15+H/200, and z=0.10.

Table 1. Ranges of data used in the derivation of Eq. (1).

Variable	Prototype data	Model data
H (m)	15.82 – 109.0	0.325 – 2.150
q (m^3/s/m)	2.36 – 220.0	0.015 – 0.420
d_s (m)	6.70 – 90.0	0.071 – 1.175
D (m)	Insufficient information	0.001 – 0.028

3 Sources of Uncertainties in Scouring

With the application of the reliability theory to local scour problems, probabilistic design approaches can be developed in which various reliability levels under different combinations of design parameters can be evaluated (Yanmaz, 2003). One of the advantages of a reliability based analysis is that the evaluation is site specific and may provide broad source of information. On the contrary, it should also be stated that the procedure of probabilistic evaluation is time-consuming since it requires detailed statistical information, which is mostly unavailable.

Identification of possible uncertainties and incorporating them in the process of reliability estimation would provide a realistic mean for probabilistic evaluation of scour. Uncertainties may originate from various sources. Natural or physical uncertainty arises from the inherent randomness of the phenomenon and cannot be controlled. Limited data would lead to a statistical uncertainty, which can be reduced with the availability of sufficient data. Model uncertainty stands from the approximations made in scour equations. It can be incorporated into the model by a model correction factor. Parameter uncertainty results from the randomness of the variables. Additional uncertainty may also arise from operational policies of sluiceways. The total uncertainty cannot be quantified precisely because most of dam sites have insufficient information on the aforementioned aspects.

The validity of the results of an uncertainty analysis is dependent on the correct choice of the coefficient of variation and probability distribution of the variables, which are key parameters in expressing the uncertainties. The coefficients of variation of available head and tailwater depth reflect possible errors in the measurement of these variables, which may attain somewhat larger values in prototype conditions depending on the operation practices of the reservoir, sediment transport regime of the river, precision of the gages, and human-induced errors. The uncertainty of jet discharge is based on variations of roughness and area of the conduit and friction slope. Foundation depth may also be considered as a random variable since the foundations are normally composed of key-trench formations. The riverbed materials may range from coarse armored beds to rocky formations whose probabilistic erosion nature is unknown.

There exists limited information on the order of magnitudes of coefficients of variation of geometric parameters. To offset this limitation, elaborate data measurements on the related variables are needed. By examining the available data on the variation of some hydraulic variables, Johnson (1996) presented limited information on the statistical parameters of some hydraulic variables. In a recent study, Yanmaz (2000) carried out an uncertainty analysis for a diversion canal. Furthermore, another uncertainty analysis has also been conducted by Yanmaz and Cicekdag (2001) for bridge pier scouring. Proper values can be assigned to the coefficients of variation of variables of Eq. (1) with reference to these studies.

4 Reliability Simulation

Simulation of the scouring reliability downstream of dams can be carried out using the Monte Carlo technique, which is based on generation of random numbers for the safety margin. Ignoring the other possible failure modes, the scouring safety margin, SM, can be defined as the difference between the depth of foundation, d_f, and the maximum depth of scour. The reliability, α, is then defined as the probability that the safety margin is greater than zero. Substituting Eq. (1) into the reliability expression yields the following nonlinear equation.

$$\alpha = P\left(d_f - \lambda_m \left[\left(6.42 - 3.10 H^{0.10}\right) \frac{q^{(0.60 - H/300)} H^{(0.15 + H/200)} h^{0.15}}{g^{0.30} D^{0.10}} - h \right] > 0 \right) \quad (2)$$

where P is probability and λ_m is the model correction factor whose mean value is assumed to be unity since Eq. (1) has been calibrated on the basis of the minimization of the coefficient of variation of model bias. In the Monte Carlo analysis, random numbers between 0 and 1 are generated for the variables having uniform distribution (Ang and Tang, 1984). These random numbers are then transformed to the desired distribution through an inverse transform method.

5 Application

The following information has been obtained for the design flow conditions of an upper surface sluiceway of a hypothetical gravity dam. The elevation difference between the upstream water level and tailwater stage is 40 m. The geometric mean size of the bed material is 20 mm. The tailwater depth is 3 m. As a preliminary approach, the depth of foundation below the thalweg level is assumed to be 10 m. A decision-making is required for the depth of foundation that can withstand erosive effects of flow due to jet action. Possible fluctuations in gross head and tailwater depth are tested using Eq. (2) in reliability computations. In this study the other governing factors that may be involved in structural and geotechnical aspects of the safety were not considered. In the literature, lognormal distribution was used to represent the randomness of discharge passing through conveyance structures (Mays, 1979; Tung and Mays, 1980; Yanmaz, 2000). Proper probability density functions (PDF) and coefficients of variation (Ω_i) are assigned to the remaining variables involved in Eq. (2) with reference to the aforementioned studies (See Table 2). Figure 1 shows the variation of reliability against unit discharge for two different heads. As can be observed from this figure, reliability increases with decreasing unit discharge and gross head. The effect of particle size on reliability is investigated for a particular case in which H=40 m, q=3 m^3/s/m, h=2 m, and d_f=9 m. Under these conditions, reliability increases with increasing particle size. The information presented in Figure 2 can be used to select appropriate size for riprap to be used as a countermeasure against downstream scour under a desired reliability level.

Table 2. Statistical information used in the application.

Variable	PDF	Ω
H	Normal	0.05
Q	Lognormal	0.10
h	Normal	0.05
D	Normal	0.20
d_f	Normal	0.05

The safety level of the foundation depth against scour can be assessed by a safety factor, SF, which is the ratio of the depth of foundation to the maximum depth of scour. Variation of reliability with respect to safety factor is shown in Figure 3 for H=40 m, q=3 m^3/s/m, h=2 m, and D=20 mm. Figure 3 implies that reliability increases with increasing safety factor. This information provides a mean to estimate the depth of foundation that can withstand erosive effects under desired reliability.

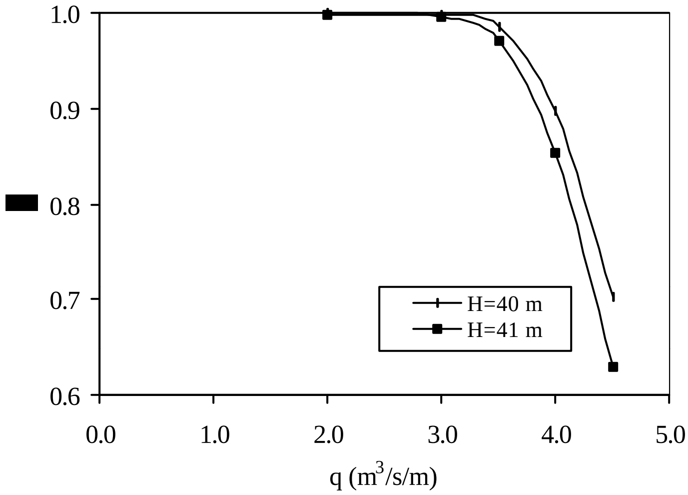

Figure 1. Variation of reliability with jet discharge.

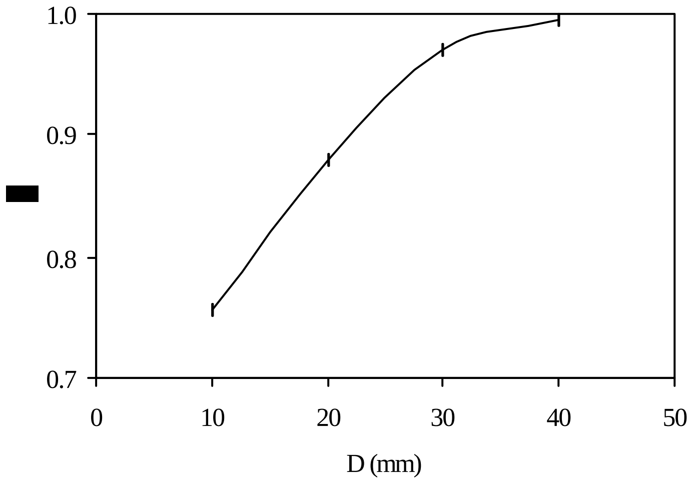

Figure 2. Variation of reliability with particle size of bed material.

A sensitivity analysis is also carried out to investigate the effect of coefficient of variation, Ω, which may change according to the size of data. Inclusion of new data may cause changes in Ω, which may alter reliability. To this end the initial coefficients of variation of the variables, Ω_i, stated in Table 2 have been incremented successively. Figure 4 shows variation of the percent change in reliability relative to the initial case against the ratio of incremental coefficient of variation to the initial coefficient of variation, Ω/Ω_i. Percent change of reliability is found to increase with increasing Ω/Ω_i value. However, even 20% increase of the coefficient of variation yields only 4% change in reliability. So, the reliability results are assumed to be insensitive to Ω_i values. However, change in reliability should be checked for different statistical information for every application.

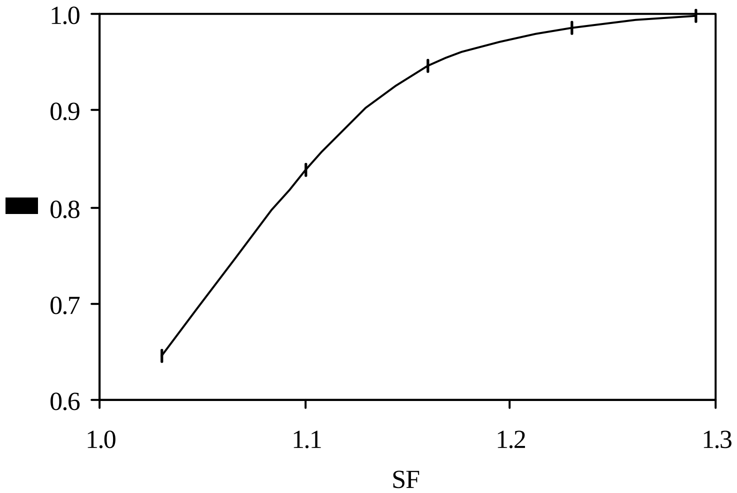

Figure 3. Variation of reliability with respect to safety factor.

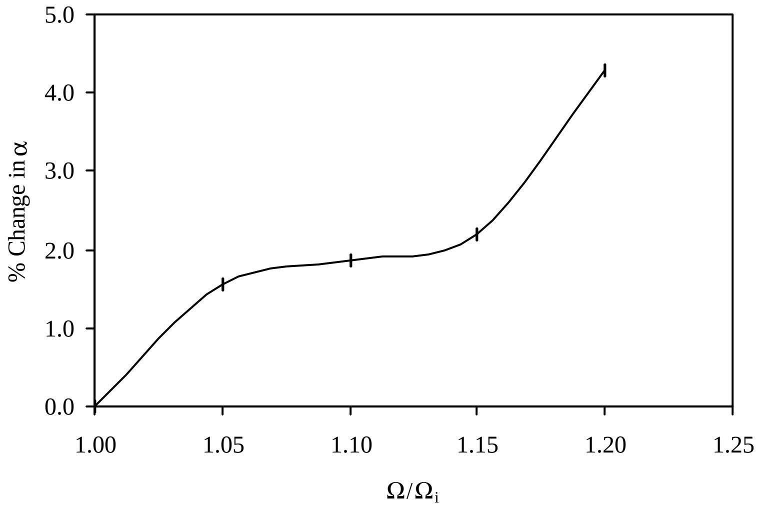

Figure 4. Sensitivity analysis for coefficients of variation.

Conclusions

Local scouring reliability downstream of dams is investigated using the Monte Carlo simulation technique. It is based on the generation of random numbers for the variables involved in the scouring safety margin by assigning proper coefficients of variation and probability density functions. In the model, Mason's scour equation was used. With the use of the model proposed herein, a reliability-based assessment of the safety level of foundation depths of dams against scouring action can be carried out. The model is demonstrated with an application. It is observed that the reliability increases with decreasing gross head and increasing tailwater depth. Reliability also increases with increasing safety factor and mean size of particle forming the downstream riverbed. A sensitivity analysis is carried out to observe the effect of coefficient of variation on reliability. Incremental values are assigned to the coefficients of variation and small changes in relative reliability are observed. The final decision on the required depth of foundation for the given bed material or the required size of armoring countermeasure under given hydraulic conditions and desired safety level should be given by further considering the structural requirements as well as the local geotechnical conditions.

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