Research Paper

Reliability analysis of stability against piping and sliding in diversion dams, considering four cutoff wall configurations

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1. Introduction

Diversion dams are important hydraulic structures that are usually built on the cross-section of alluvial rivers to raise the level of water in the river [1]. These hydraulic structures are usually of low height and therefore have small reservoirs. The essential criteria governing the design of diversion dams are the concerns of stability against internal erosion and sliding [1–5].

Internal erosion in the soil foundation of dams may be initiated by backward erosion. As a result, a continuous tunnel, also called a pipe, is formed between the upstream and downstream sides of the dam, causing dam failure [6–10]. To decrease the risk of piping, an upstream impervious blanket and cutoff wall are usually designed to increase the creep length of seepage flow [11]. More importantly, sliding due to active forces, including the earthquake and hydraulic forces, is possibly the predominant reason for the failure of diversion dams [1,3]. The prevailing stability analysis of diversion dams is usually based on the deterministic methods, mainly reported in the United States Bureau of Reclamation (USBR) criteria and the other design books [1,3,12]. However, there is uncertainty associated with the soil properties [13,14], earthquake components, and active forces exerted on dams [5,15], leading to uncertainty in the safety factor. This leads to a question of how safe the newly designed or existing diversion dam is. Therefore, the probabilistic analysis of the safety factor is essential to estimate the possibility of dam failure under different operating conditions.

Recently, probabilistic analysis using the random field theory has been employed in different fields of engineering, including geotechnical, structural, and water engineering. Several types of stochastic slope stability analyses have been conducted by Griffiths et al. [16], Lo and Leung [17] and Ji et al. [18,19]. Do et al. [20] considered random field for the Young’s modulus and body force in the analysis of structures.

Concerning seepage analysis, Griffiths and Fenton [21] considered the effect of spatial variability of hydraulic conductivity to examine seepage flow underneath a retaining structure. The finite element method in conjunction with the random field theory was applied in their study. Cho [22] performed probabilistic seepage analyses beneath an embankment dam using the random finite element method. Two types of soil layer were assumed for the dam foundation in that study, in which the permeability followed lognormal distributions. More studies can be found in Tan et al. [23], Srivastava et al. [24], Ahmed

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https://doi.org/10.1016/j.compgeo.2018.02.019
Received 15 October 2017; Received in revised form 16 February 2018; Accepted 20 February 2018
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Nomenclature

- $K_x$: hydraulic conductivity along x direction
- $K_z$: hydraulic conductivity along z direction
- $h$: total head
- $\mu_K$: mean of hydraulic conductivity
- $\sigma_K$: standard deviation of hydraulic conductivity
- $\mu_{\ln K}$: mean of logarithmic hydraulic conductivity
- $\sigma_{\ln K}$: standard deviation of logarithmic hydraulic conductivity
- COV: coefficient of variation of hydraulic conductivity
- $\tau_{xij}$: distance between the centroid of the ith and jth elements in the horizontal direction
- $\tau_{zij}$: distance between the centroid of the ith and jth elements in the vertical direction
- $\delta_h$: horizontal autocorrelation distance of the hydraulic conductivity
- $\delta_v$: vertical autocorrelation distance of the hydraulic conductivity
- $\rho(\tau_{xij}, \tau_{zij})$: auto-correlation coefficient between the centroids of elements
- $C$: auto-correlation matrix
- $n_e$: number of random field elements
- $L$: lower triangular matrix
- $G_i$: standard Gaussian random field
- $Z_i$: an indicator of standard normal distribution
- $K_{xi}$: hydraulic conductivity assigned to the ith element in the x direction
- $K_{zi}$: hydraulic conductivity assigned to the ith element in the z direction
- $\text{SF}$: safety factor
- $g(s)$: performance function
- $E$: expected value
- $\bar{g}$: reliability function
- $F_{\text{failure}}$: probability of failure
- $\Phi$: standard normal cumulative distribution function
- $F_{\text{piping}}$: safety factor against piping
- $F_{\text{sliding}}$: safety factor against sliding
- $i_{cr}$: critical hydraulic gradient
- $i_{exit}$: exit hydraulic gradient
- $\gamma'$: submerged unit weight of soil particles
- $\gamma_w$: unit weight of water
- $\gamma_s$: submerged unit weight of sediment
- $\phi_i$: angle of shearing resistance
- $\lambda_i$: area of the plane of sliding
- $W_i$: weight of the dam
- $\rho_h$: horizontal seismic coefficient
- $\rho_v$: vertical seismic coefficient
- $H$: dam height
- $C_e$: dimensionless hydrodynamic factor
- $R^2$: correlation coefficient
- $\mu$: skewness
- $\omega$: constant of skew normal distribution
- $\xi$: constant of skew normal distribution
- $\mu_{sk}$: mean of skew normal distribution
- $\sigma_{sk}$: standard deviation of skew normal distribution
- $S$: skewness
- $\lambda$: a constant

In terms of dam sliding, the effect of uncertainty in the cohesive strength of the interface between a concrete dam and a rock foundation was examined by Krounis et al. [5].

To the best of the author’s knowledge, no article has been found that is focused on the probabilistic stability analysis of diversion dams. In the deterministic design procedure, the provision of an adequate creep length of water beneath the dam is a key parameter for decreasing the exit hydraulic gradient. Therefore, there is no difference between the implication of a single cutoff wall or the construction of two cutoff walls at different locations, where the height of each wall is equal to half of the height of the single wall [1–4]. Although several articles have been found concerning probabilistic seepage analysis, the probabilistic assessment of different cutoff wall configurations has not yet been investigated [21–26].

Moreover, the anisotropy of soil hydraulic conductivity throughout history may stem from alluvial sedimentation. Little attention has been paid to the anisotropy of soil permeability in the literature [21,22,27–29]. In addition, few studies have explored the influence of several Auto-Correlation Functions (ACFs) in the random field generation [30,31]. Regarding sliding stability, a small number of investigations have concentrated on the probabilistic analysis of the safety factor against sliding [5]. The probabilistic approach has not yet been completely applied to dam safety guidelines, which is crucial to decision makers.

The main motivation of this study is to perform a probabilistic analysis of the stability of a diversion dam against piping and sliding. For this purpose, the random finite element method has been employed to perform probabilistic seepage analysis in two dimensions. The Cholesky decomposition technique is used to generate random hydraulic conductivity, considering exponential, second-order Markov, and binary noise two-dimensional auto-correlation functions. Moreover, four configurations of cutoff walls are considered in the probabilistic analyses. By the implementation of stochastic analysis on the exit hydraulic gradient, the best configuration of the cutoff wall has been determined. In addition, the stability of the dam against sliding is also examined stochastically using the MCS in combination with random field discretization. The ordinary and earthquake load combinations are considered in the stochastic analysis of sliding stability. Fig. 1 shows the flowchart of the procedure used in this study.

2. Seepage analysis

The seepage flow beneath a diversion dam can be modeled using the mass balance relationship. Assuming Darcy’s law, the governing equation of seepage flow is written as follows:

$$\frac{\partial}{\partial x}(K_x \frac{\partial h}{\partial x}) + \frac{\partial}{\partial z}(K_z \frac{\partial h}{\partial z}) = 0$$  \hspace{1cm} (1)

where $K_x$ and $K_z$ stand for the hydraulic conductivity of the soil along the x and z directions, respectively, and $h$ is the water head [22]. This equation can be solved numerically using the Finite Element Method (FEM). The detailed formulation of relevant algebraic equations obtained by FEM can be found in Reddy [32].

3. Random field theory

The properties of natural soil such as hydraulic conductivity have spatial variability because of the geological formation of the soil [31,33,34]. The spatial variability of hydraulic conductivity can be described by means of random field theory. Therefore, an appropriate Probability Density Function (PDF) and a correlation structure or ACF are required. The lognormal distribution is an appropriate tool to model the variability of soil properties, including the hydraulic conductivity [21,24]. The mean and standard deviation ($\mu_{\ln K}$ and $\sigma_{\ln K}$) of this distribution are stated as Eqs. (2) and (3), respectively.
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