



## Research Paper

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

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## ABSTRACT

The stability against piping and sliding, which is subject to numerous sources of uncertainty, is of great importance in the design of diversion dams. In this study, the performance of four cutoff wall configurations, including a single wall and two walls with half the length of the single wall, was evaluated stochastically using the random finite element method. The Cholesky decomposition technique in conjunction with three types of Auto-Correlation Function (ACF) was employed to generate numerous random fields. The results indicate that the probabilities of failure related to different cutoff wall configurations are similar, considering isotropic hydraulic conductivity. However, there are noticeable differences between the probabilities of failure of these configurations in anisotropic situations. Moreover, the use of a single cutoff wall on the upstream face of an impervious blanket provides the lowest probability of failure for piping. In addition, the exponential ACF ends up with greater exit hydraulic gradients than the second-order Markov and binary noise ACFs. In addition, the sliding stability of the ordinary and earthquake load combinations was examined stochastically using random field theory and Monte Carlo Simulation (MCS). The probability of failure appears to increase with an increase in the autocorrelation distance.

## 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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**Nomenclature**

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

[25,26], and Griffiths and Fenton [27–29]. 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:

$$\frac{\partial}{\partial x} \left( K_x \frac{\partial h}{\partial x} \right) + \frac{\partial}{\partial z} \left( K_z \frac{\partial h}{\partial z} \right) = 0 \quad (1)$$

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 followed 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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