determine their combined effect on water retention infrastructure despite the fact that the intensity of these hazards has a significant impact to the failure of such infrastructure. It should be noted that many researchers have conducted studies considering individual hazards, but there has been very limited work toward a uniform reliability model of infrastructure considering multiple hazards (Kaynia 2013). Therefore, there is an urgent necessity to expand the failure prediction methodologies developed to include multi-hazard effects, including flooding and heavy rain (Robinson et al. 2016).

Using the concept of fragility functions for flood risk assessment of was first introduced in a 1991 USACE Policy Guidance Memorandum (DePoto and Gindi, 1991). The method was further explained in a 1993 USACE Engineer Technical Letter (DePoto and Gindi, 1993). The goal of the proposed method was to evaluate the reliability of levees, which were no longer in full compliance with the design requirements at that time. After hurricane Katrina, fragility curves for flooding risk assessment were developed for the New Orleans area. The procedure was developed using an analytical approach for region down the crest of the levee and an empirical approach for the region over the crest of the levee. The analytical part of the fragility function was developed by performing probabilistic slope stability analysis with the first-order reliability method (FORM). (Schultz et al. 2010). The empirical portion of the fragility function was based on observed failure rates during Hurricane Katrina. These fragility curves have been incorporated into a flood risk assessment tool for the City of New Orleans, described in Schultz et al. (2010).

The current study aims to use fragility curves to evaluate the probability of failure of an earthen levee in Sacramento, CA under extreme precipitations. For this purpose, a fully coupled 2D stress-variably saturated flow finite element model is developed to simulate the levee behavior under combined effects of water level fluctuation and extreme precipitations. Probabilities of failure are calculated for normal and flooding conditions under various rain intensities/durations for different return periods obtained from the IDF curves.

FRAGILITY FUNCTIONS

A fragility function specifies the probability of damage state, or some other limit state of interest, of a structure as a function of some load intensity measure. The intensity is often quantified based on a specified return period. Collapse fragility functions obtained from structural analysis results are increasingly being used in structural assessment procedures (Porter 2015). In advanced applications, established geotechnical fragility functions use hydraulics and hydrologic modeling to conduct the probability of levee's failure (Simm et al. 2012).

A common nontechnical definition of fragility is "the quality of being easily broken or damaged." The concept of a fragility function in civil engineering dates at least to Kennedy et al. (1980), who defines a fragility function as a probabilistic relationship between frequency of failure of a component and any event may affect the structure. More broadly, one can define a fragility function as a mathematical function that expresses the probability of failure due to some undesirable event occurrence (typically that an asset—a facility or a component—reaches or exceeds some clearly defined limit state) as a function of some measure of environmental excitation (typically a measure of acceleration, deformation, or force in an earthquake, hurricane, or other extreme loading condition).

There is an alternative and equivalent way to conceive a fragility function. A fragility function represents the cumulative distribution function of the capacity of an asset to resist an undesirable limit state. Capacity is measured in terms of the degree of environment excitation at which the asset exceeds the undesirable limit state. For example, a fragility function could express the uncertain level of shaking that a building can tolerate before it collapses. The chance that it collapses at a given level of shaking is the same as the probability that its strength is less than that level of shaking.

Here, "cumulative distribution function" describes the probability that an uncertain quantity will be less than or equal to a given value. Proper application of fragility functions requires knowledge of all definitions and the ability to distinguish between them. For most cases, the framework of lognormal cumulative distribution function (CDF) is usually used to express the form of a fragility function (Kaynia 2013):

$$F_d(x) = P\{D \geq d|X = x\} \quad d \in \{1,2, \dots \dots .. N_D\} \tag{1}$$

$$F_d = \varphi\left(\frac{\ln x/\theta_d}{\beta_d}\right) \tag{2}$$

where:

P{}= represents the probability of failure.

$F_d(x)$ = a fragility function for damage state *d* evaluated at x.

D = the response threshold or uncertain damage state of a particular component. It can take on a value in {0,1,... N_D}, where D = 0 denotes the undamaged state, D = 1 denotes the 1st damage state, etc.

d = the response of the ith random variable that can be either a displacement quantity or a factor of safety or any other measure of safety for which adequate capacity exists.

N_D = number of possible damage states, N_D {1, 2, …}

X = an intensity measurement of loading conditions, which is it precipitation in this study.

X = a given loading intensity value.

φ = standard normal cumulative distribution function.

θ_d = median capacity of the asset to resist damage state *d* measured in the same units as X.

β_d = the standard deviation of the natural logarithm of the capacity of the asset to resist damage state *d*.

INTENSITY-DURATION-FREQUENCY (IDF) CURVES

The variability in rain intensity and its changes during seasons are expected to have important impacts on the hydrologic structures at different temporal and spatial scales. In order to process a successful design and/or analyze systems, civil engineers should take these potential events into account in their modeling and all simulations. Rainstorms occur with various intensities, durations, and frequencies (Ma et al. 2015). Therefore, the hydro-mechanical behavior of any earthen structures to extreme precipitation events is commonly analyzed using Intensity-Duration-Frequency (IDF) curves, which are graphical representations of the eventuality of precipitation that a given average rainfall intensity may occur (Robinson et al. 2016). Furthermore, proper analysis of hydrologic structures requires the use of IDF curves, which are derived by considering a stationary climate of the Generalized Extreme Value (GEV) distribution using historic rainfall data. For instance, this methodology relies the ground-based monitoring of rainfall intense from maximum precipitation quantity for different rainfall periods (e.g., 1- and 7-day) (Bonnin et al. 2006). In brief, the IDF curve gives the foreseeable precipitation intensity of a given storm period having desired frequency of occurrence or curves provide rainfall intensity, rainfall duration (how long it may rain at that intensity), and rainfall frequency, or return period (the likelihood of the storms occurrence) (DePoto and Gindi 1991).

STUDY AREA AND LEVEE MODEL

The Elkhorn levee is used for modeling purposes in this study. Khalilzad et al. (2014) used the same levee was used for numerical modeling by. The levee is located within Reclamation District No. 1000 in Sacramento County, California. This levee protects the area from flooding by the Sacramento River. Figure. 1 presents the geometry, and soil layers of the Elkhorn levee site. The model geometry and soil properties are adopted from those reported by Khalilzad et al. (2014). The soil profile consists of a four-layer system whereby the levee is constructed from silty sand (SM-ML) over a thin layer of sandy clay (CL) with low hydraulic conductivity. Under the CL layer is 2.1 m of SM-ML soil with properties similar to those of the top layer. Beneath this layer, the soil is mostly silty sand (Brizendine 1997).

METHODOLOGY

The Elkhorn levee section was numerically modeled using the finite-element program RS2 9.0 to examine the behavior of the levee under extreme precipitations. A series of fully coupled 2D stress- variably saturated flow finite element simulations were performed with various rain intensity-duration-frequency as well as water levels. The coupled model can properly represent the behavior of variably saturated zones of the levee by taking into consideration the time-dependent nature of extreme rainfall events with normal and flood water levels, as well as the interaction between solid particles and fluid flow. Tables 1 and 2 show soil properties as well as the hydraulic properties which were used in the model. The parameters are used form those reported in Khalilzad et al. (2014). For modeling the unsaturated region, van Genuchten's Soil Water Characteristic Curve (SWCC) model was used which includes two fitting parameters of n and α.

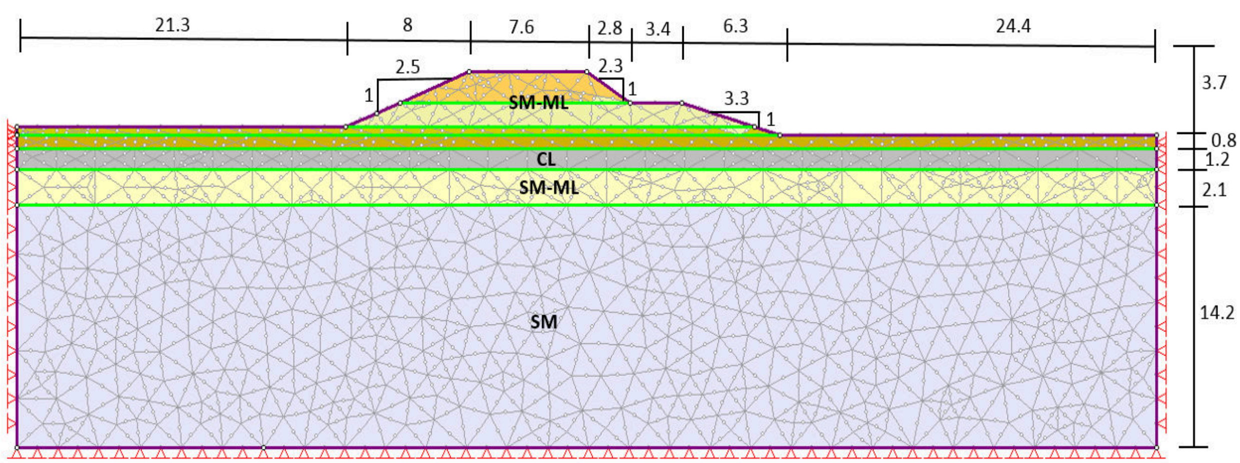


Figure 1. Geometry of Elkhorn levee used in numerical modeling (Khalilzad et al. 2014).

The IDF curves for the study area, shown in Figure 2, were employed to represent intensity, duration, and return period of extreme precipitations in the finite element model. Further, two water levels are considered in the simulation: the normal condition at 19.6 m and flood condition at 22 m. Eight-node quadrilateral elements are employed to create the finite element mesh. The bottom boundary is fixed in both directions, whereas the left and right boundaries are fixed only in the horizontal direction. To specify the flow boundary conditions, the bottom boundary is set as closed boundary against flow whereas the boundaries left and right boundaries are taken as seepage boundaries. The simulation for each model consists of two stages: stage 1: steady-state seepage using normal or flood water level to generate initial hydraulic conditions (t = 0); stage 2: transient seepage using the same water level in stage 1 with imposing the corresponding (t = 1 day to t = 7 days) extreme precipitations. The infiltration was simulated by assigning the precipitation boundary condition to the outer part of the levee. Rainfall data with 25, 50, and 100 yr return period were used in the simulations.

Table 1. Soil properties of Elkhorn levee.

Soil type	γ (kN/m^3)	K_m (m/s)	C (kPa)	Φ (degrees)	E_{ur} (kPa)
SM-ML	18.0	7.6×10^{-7}	3.8	32	2.6×10^4
CL	18.4	1.9×10^{-7}	3.8	30	2.1×10^4
SM	17.9	1.7×10^{-6}	1	34	5.0×10^6

Table 2. SWCCs for SM-ML layers with various k_{sat} values

Soil	k_{sat} (m/s)	n	α (1/m)	θ_{res}
Soil I	5.0×10^{-5}	2.28	3.78	0.139
Soil II	5.0×10^{-6}	1.48	1.80	0.256
Soil III	5.0×10^{-7}	1.23	0.3	0.207
Soil IV	5.0×10^{-8}	1.09	0.15	0.194

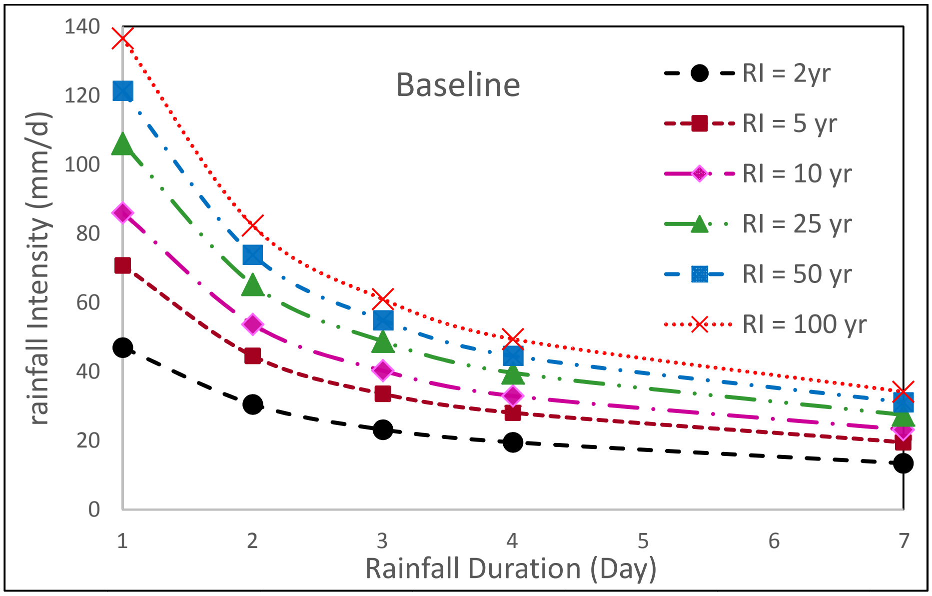


Figure 2. IDF curves of Sacramento, CA region, obtained from the National Oceanic and Atmospheric Administration (NOAA).

RESULTS

Figures 3 to 5 show the strength reduction factors to demonstrate the behavior of the levee for a 7-day rain event, which will cause maximum intensity over all. As shown, it is clear that the factor of safety decreases with increases in the return period due to increase of the intensity. Also, the factor of safety for the up-stream slope increases with increasing of the sea level.

a) **b)**

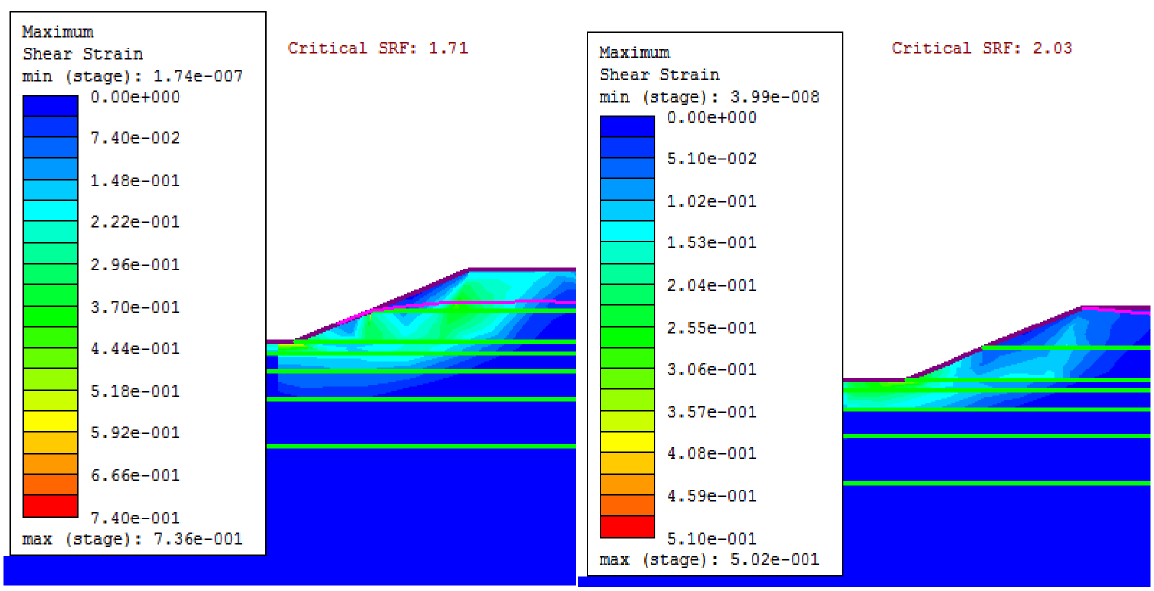


Figure 3. Strength reduction factor for 7-day rain intensity with 25 yrs. return period at a) 19.6 m water level, and b) 22 m water level.

a) b)

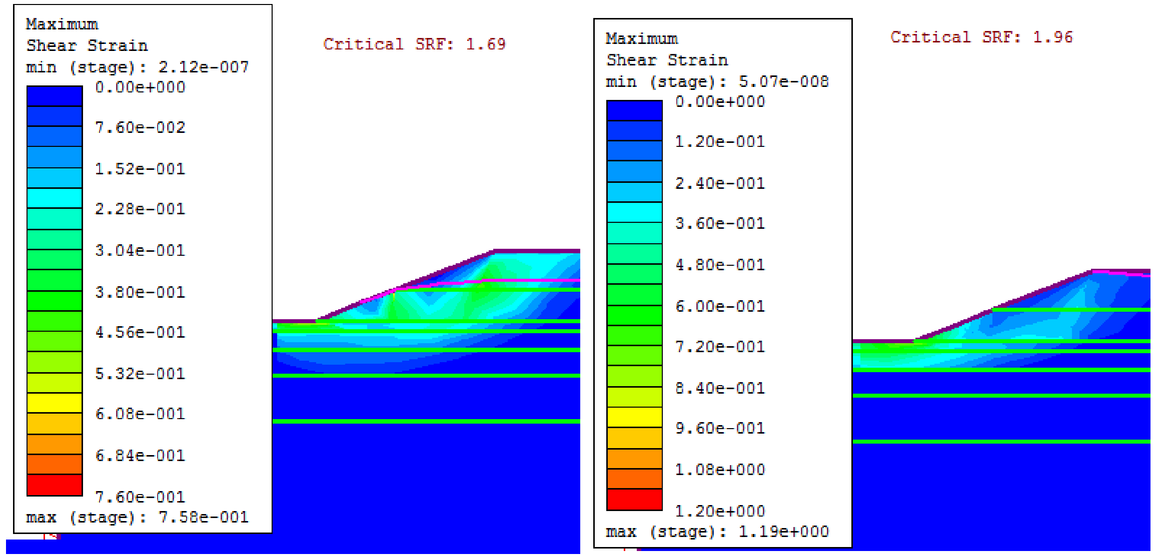
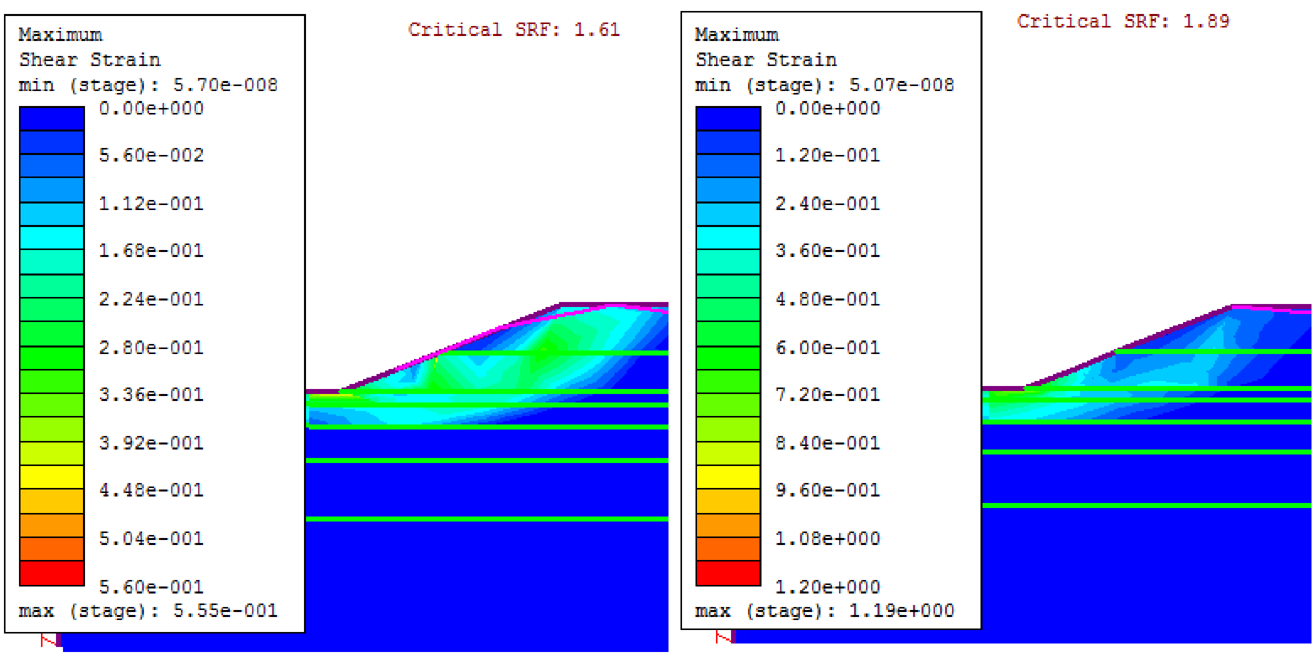


Figure 4 Strength reduction factor for 7-day rain intensity with 50 yrs. return period at a) 19.6 m water level, and b) 22 m water level.



a) b)

Figure 5. Strength reduction factor for 7-day rain intensity with 25 yrs. return period at a) 19.6 m water level, and b) 22 m water level.

For each model, the strength reduction factor was obtained and then was used in Equation 2 to develop the corresponding fragility function. Figure 6a shows the probability of failure versus intensity at the normal condition, while Figure 6b displays the same information for the flood condition. These two figures illustrate that the probability of failure increases slightly for durations less than three days. For rain durations longer than three days, the probability of failure increases faster for both normal and flood conditions. In addition, the low intensity rain lasting for long time will threaten the long term stability of the earthen levees. These increases in the rate of failure probability are due to the duration. In fact, and as shown in the IDF curves in Figure 2, long duration events have lower intensities, but these longer events have a greater effect on the factor of safety. It is clear in Figure 3 that the 100 yr return period has a duration with significant impact on the stability of the levee. Lower return periods provide lower risk to the stability of earthen levees. On the other hand, the results show a decrease in the probability of failure of the upstream side of the embankment with an increase of water level. The additional water on the upstream face will serve as a stabilizing factor against failure on this side. In this study, only the upstream lope was analyzed. However, the increased water level is expected to have a destabilizing impact on the downstream slope and can also reduce the factor of safety against internal erosion/piping.

CONCLUSION

Extreme precipitation can threaten the structural integrity of an earthen levee or any earthen structure and subsequently, can increase the probability of failure. This study aimed to quantify how changes in extreme precipitations may affect the performance of an earthen levee under normal and flooding water levels. For this purpose, a fully coupled 2D stress- variably saturated flow finite element model was built to simulate the behavior of the Elkhorn levee in Sacramento, CA under combined effects of water level fluctuation and extreme precipitation. Intensity-Duration-Frequency (IDF) curves of extreme precipitations were used in the numerical simulation. Based on the results, a set of fragility curves were presented showing the probability of failure versus rain intensity for various rain duration and return periods. The modeling framework presented in the present study can be used for other earthen structures, other areas and extreme events as well, to study the direct effects of extreme climatic events on geotechnical infrastructure.

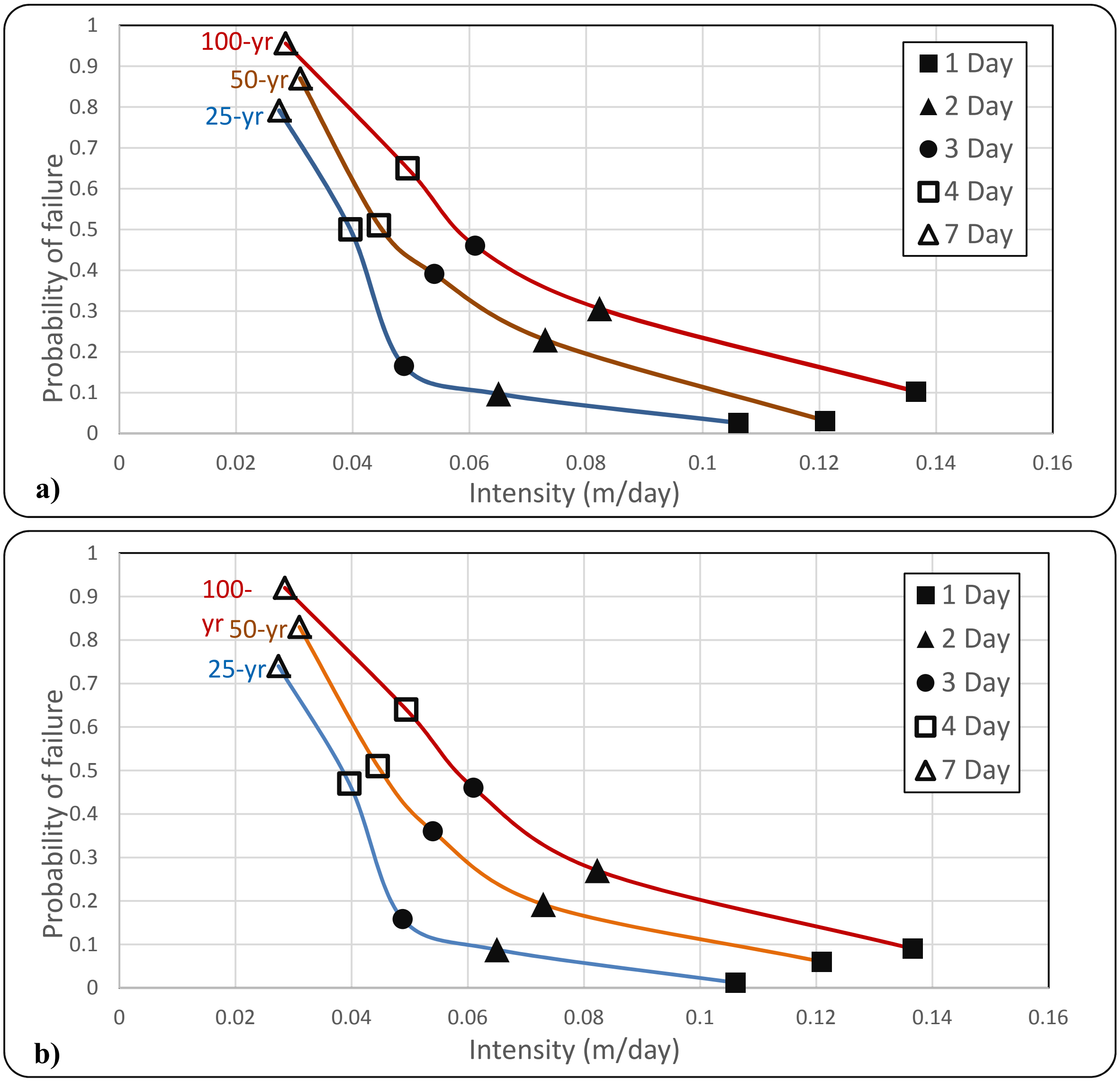


Figure 6. Probability of failure versus intensity for various rain duration and return period at a) 19.6 m water level, and b) 22 m water level

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Probabilistic Slope Stability Analyses: Effects of the Coefficient of Variation and the Cross-Correlation of Shear Strength Parameters

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Abstract

The assessment of the safety level of natural slopes, road cuts, embankments and levees require consideration of uncertainties and variability in material properties. In this study, for a number of slope geometries, including a real-life landslide case, probability of failure (PF) and the most critical failure surface are investigated with and without cross-correlation of shear strength properties. Slopes having different traditionally-defined factor of safety (FS) levels are studied. The uncertainty of soil properties are considered by different levels of coefficient of variation (COV). Limit equilibrium method is used for slope stability analyses and geotechnical material properties are considered to have normal statistical distribution. The results of this analyses show that the PF and the critical failure surface is significantly influenced by the COV level, the consideration of cross correlation of shear strength parameters, and by the traditional FS level of the slopes. The inverse relation between FS and PF is demonstrated to be nonlinear and the COV level has significant effect on this relationship. Results indicate that the deterministic slope stability analyses resulting in a single FS value is no longer sufficient to evaluate the safety of a slope in geotechnical engineering, and that the deterministic critical failure surface with minimum FS value is not always the most critical slip surface. The results presented in this study could be useful for further understanding of probabilistic slope stability and the effects of soil variability/uncertainty, with the aim of better geotechnical risk evaluation and communication.

INTRODUCTION

In the practice of geotechnical engineering, it is common to use deterministic analyses methods to assess the safety of slopes. In deterministic analyses, soil layers are assumed to be homogeneous and soil properties are selected to be representative values of the natural soil. This would be an ideal analysis type provided that a thorough site investigation and high quality extensive laboratory testing is available and they are well-interpreted to select the representative values. However, this is seldom the case in geotechnical engineering, especially in some countries where there is lack of strict regulations and quality control. In addition, there is inherent variability in soils, whereas in practice, based on only a limited number of borehole data interpolations/extrapolations have to be made to define soil layers at the site. Furthermore, a fair portion of soil idealization process is carried out based on empirical correlations which adds to the uncertainties in soil properties. In such circumstances, it would be more suitable to utilize probabilistic approach which considers the variability of soil properties in terms of a statistical distribution having mean values and standard deviation.