Probabilistic Stability Assessment of Earthen Levees Subjected to Earthquake Loads

Lei Wang, M.ASCE[1]; Sandae Tait, S.M.ASCE[2]; Sara Khoshnevisan, M.ASCE[3]; Farhad Barati, S.M.ASCE[4]; C. Hsein Juang, F.ASCE[5]

[1]Assistant Professor, Department of Civil Engineering, University of the District of Columbia, Washington DC 20008. Email: lei.wang@udc.edu
[2]Research Assistant, Department of Civil Engineering, University of the District of Columbia, Washington DC 20008. Email: sandae.tait@udc.edu
[3]Assistant Professor, Department of Civil and Architectural Engineering and Construction Management, University of Cincinnati, Cincinnati OH 45221. Email: sara.khoshnevisan@uc.edu
[4]Research Assistant, Department of Civil Engineering, University of the District of Columbia, Washington DC 20008. Email: farhad.barati@udc.edu
[5]Chair Professor, Department of Civil Engineering and Graduate Institute of Applied Geology, National Central University, Taoyuan City 32001, Taiwan. Email: hsein@ncu.edu.tw

ABSTRACT

Earthen levees are critical flood protection infrastructure consisting primarily of earthen masses to retain water and secure the landside area against flooding. However, many earthen levees are located in the active seismic zone. Thus, it is critical to evaluate the reliability of earthen levees in the face of earthquake hazards since the failure of such structures can be catastrophic and cause loss of lives, damages to properties, and significant adverse economic and societal impacts. This paper presents a simplified probabilistic assessment framework for earthen levees under earthquake loads. In this framework, the pseudo-static method with the finite element analyses is used for the stability analyses of earthen levees under earthquake loads. The pseudo-static method uses a static horizontally applied load to simulate the effect of an earthquake on the earthen structure. Then the probabilistic assessment is conducted using an efficient reliability method that accounts for propagation of uncertainties from the input random variables through the finite element modeling. The effects of acceleration level on the probability of failure of earthen levees are quantified. The developed framework provides an efficient tool for probabilistic evaluation of earthen levees that is easy-to-use by practicing engineers. The results can help engineers make a risk-informed decision in the face of earthquake hazards. A case study is utilized to demonstrate the effectiveness of the proposed framework for the reliability assessment of earthen levees under earthquake loads.

INTRODUCTION

Earth levees are critical infrastructure throughout the United States for a multitude of purposes. Evaluating the safety and reliability of earthen levees has become imperative because many of these structures are reaching the end of their designed life span and require some form of risk-based mitigation, especially considering potential hazards they may endure. Also, the effect of possible earthquake loads on the stability of earthen levees is an important aspect in the risk analyses of levees. Due to uncertainties in design parameters, engineers have used conservative estimates for their design parameters, which are implemented into a deterministic model. Although deterministic models have been used for decades, they do not explicitly account for the nature of uncertainties in geotechnical parameters. Uncertain geotechnical parameters include geomaterial's strength and permeability parameters. Traditionally, the deterministic method was used to calculate a factor of safety to cope with these uncertain parameters. Because geotechnical conditions are site-specific, however, the factor of safety method cannot explicitly account for all the scenarios for stability analysis of earthen levees under earthquake hazards. To account for these uncertainties, most investigators preferred using probabilistic methods (Duncan 2000; Dodagoudar and Venkatachalam 2000; Xu and Low 2006; Cheng et al. 2007; Gong et al. 2014; Li et al. 2015; Wang et al. 2017; Gong et al. 2020; Wang et al. 2020). Unlike the deterministic analysis, which often requires conservative estimates of input parameters, the probabilistic methods allow for the seismic evaluation of the probability of failure of an earthen levee considering all the uncertainties.

The probability of failure can provide valuable information for risk-based assessment and making risk-informed decisions. Probabilistic seismic analyses, however, may require a large number of simulations to determine the probability of failure, it is difficult and time-consuming to perform such analyses combined with numerical methods such as finite element modeling. A simplified approach is proposed in this paper to provide an effective tool for evaluating the stability of earthen levees under earthquake loads, which can offer useful references for decision making concerning seismic designs of earthen levees.

FINITE ELEMENT MODELING SUBJECTED TO EARTHQUAKE LOADS

Finite element analysis is a widely used approach for evaluating large and complex geo-structures (Brinkgreve and Engin 2013). The complexity of geo-structures is incorporated into their geometry and material makeup. Finite element analysis takes a large model body and divides it into smaller bodies connected at nodes. It then solves deformation and/or shear strength at these nodes and combines them to produce an effective solution for the entire problem. The finite element program used to perform this analysis was PLAXIS 2D (*referred to as FEM code afterward*). It is widely used in industry practice for geotechnical design related to the earthen levees. The FEM code combines the finite element method with the strength reduction technique to produce results for many different modeled scenarios (Brinkgreve et al. 2015). The strength reduction method is adopted for evaluating the factor of safety for the earthen levees, which artificially weakens the properties of modeled soils by a factor until the soil slope fails. The factor at which the soil fails is the factor of safety of the slope (Dawson et al. 1999; Cheng et al. 2007). The factor of safety can also be calculated by taking the strength parameters of the geotechnical materials and dividing it by the strength parameters at which the materials fail. The FEM code runs a series of analyses to produce a factor of safety for the slope under the given loading and geotechnical parameters.

The earthen levee stability analyses under earthquake loads can be rigorously studied using the dynamic analysis; however, it involves the input of the ground acceleration history and can be computationally intensive. In this paper, the pseudo-static method is employed in the analyses, which is a widely accepted method in geotechnical practice (e.g., FHWA 1997; Wang and Rathje 2015). Within the pseudo-static method, the earthquake load is represented by a pseudo-static force in terms of a constant horizontal acceleration coefficient applied on the earthen levee slope. The vertical acceleration coefficient of the pseudo-static force is usually negligible (Sarma 1975). The horizontal acceleration coefficient can be related to the peak ground acceleration using the relationship described in Xiao et al. (2016). Here, the horizontal acceleration coefficient is adopted to represent the level of the earthquake load, and the effects of the earthquake loads on the probability of failure are analyzed with the proposed probabilistic approach.

PROBABILISTIC METHOD FOR EARTHEN LEVEE STABILITY ANALYSES

For the reliability assessment of earthen levees under earthquake loads, it is essential to evaluate the effects of uncertain geotechnical parameters on the seismic stability of earthen levees in terms of factor of safety. Here, the factor of safety calculated using the pseudo-static method with the FEM code is treated as the response of the geotechnical system (represented as FS). There is also uncertainty in the input parameters assigned to each soil layer. This applies to the effective cohesion, effective friction angle, and permeability, which are represented as x_1, x_2, x_3. Symbolically, the FS is obtained using the FEM code and related to the input parameters x_1, x_2, x_3 using the following equation:

$$FS = FEM\ Solution = f(x_1, x_2, x_3) \tag{1}$$

According to the first-order second-moment principles, the mean and variance of the system response can be determined as (Ang and Tang 2007):

$$\mu_{FS} = f(\mu_{x_1}, \mu_{x_2}, \mu_{x_3}) \tag{2}$$

$$\sigma_{FS} = \left(\frac{\partial FS}{\partial x_1}\right)^2 \sigma_{x_1}^2 + \left(\frac{\partial FS}{\partial x_2}\right)^2 \sigma_{x_2}^2 + \left(\frac{\partial FS}{\partial x_3}\right)^2 \sigma_{x_3}^2 + \left(\frac{\partial FS}{\partial x_1}\right)\left(\frac{\partial FS}{\partial x_2}\right)\left(\rho_{x_1,x_2}\sigma_{x_1}\sigma_{x_2}\right) + \left(\frac{\partial FS}{\partial x_2}\right)\left(\frac{\partial FS}{\partial x_3}\right)\left(\rho_{x_2,x_3}\sigma_{x_2}\sigma_{x_3}\right) + \left(\frac{\partial FS}{\partial x_1}\right)\left(\frac{\partial FS}{\partial x_3}\right)\left(\rho_{x_1,x_3}\sigma_{x_1}\sigma_{x_3}\right) \quad (3)$$

where μ_{x1}, μ_{x2}, μ_{x3} are the mean values of each of the input parameters (e.g., effective cohesion, effective friction angle, and permeability). σ_{x1}, σ_{x2}, σ_{x3} are the standard deviation of each of the input parameters. $\rho_{x1,x2}$ are the correlation coefficient between x_1 and x_2. $\rho_{x1,x3}$ and $\rho_{x2,x3}$ are defined similarly as the correlation coefficients between x_1 and x_3 and between x_2 and x_3, respectively. It has been indicated in other investigations that cohesion and friction angle are negatively corelated (e.g., Low 2017).

From the above equations, the mean value of the system response (FS of earthen levee) is determined by evaluating the factor of safety based on the mean values of each input parameter, and the variance of the system response can be determined using the following equation (Dang et al. 2012):

$$\sigma_{FS} = (\Delta FS_1)^2 + (\Delta FS_2)^2 + (\Delta FS_3)^2 + 2\rho_{x_1,x_2}(\Delta FS_1)(\Delta FS_2) + +2\rho_{x_2,x_3}(\Delta FS_2)(\Delta FS_3) + 2\rho_{x_1,x_3}(\Delta FS_1)(\Delta FS_3) \quad (4)$$

where ΔFS_1 is the difference between the FS value evaluated at $f(\mu_{x_1} + \sigma_{x_1}, \mu_{x_2}, \mu_{x_3})$ and $f(\mu_{x_1} - \sigma_{x_1}, \mu_{x_2}, \mu_{x_3})$, and then divided by 2. Similarly, ΔFS_2 and ΔFS_3 can be calculated by changing the second and the third variable with one standard deviation from the mean value in the evaluation of the FEM code. One advantage of this framework is that it can quantitively evaluate the contribution of each random input parameter (e.g., effective cohesion, effective friction angle, and permeability for each geotechnical material) on the system response analyses (resulting FS). With the mean and variance of FS obtained from the above procedures, the probability of failure for the earthen levee slope can be determined assuming the factor of safety follows the lognormal distribution.

EXAMPLE FOR EARTHEN LEVEE STUDY

A case study was conducted using the proposed probabilistic method combined with the FEM code to demonstrate its efficiency in the earthen levee stability analyses. The example levee consists of three types of geotechnical materials (embankment soil, rockfill zone, and No. 57 stones), and the foundation soil underneath the levee is manly residual soil (Wang et al. 2017). The slope of the levee is 2H: 1V. Figure 1 shows the layout of the earthen levee in the finite element mesh.

The field investigation and laboratory testing were conducted for evaluating the soil parameters used in the design. However, there are significant uncertainties involved in evaluating these parameters. Here, the strength and permeability parameters of each geotechnical material are treated as uncertain soil parameters in evaluating the stability of the levee. The mean values of these parameters are estimated based on the correlations with N_{60} values from field Standard Penetration Test (SPT) results, limited laboratory testing results, and the coefficient of variation for these parameters are estimated based on the published literature (Phoon and Kulhawy 1999; Wang et al. 2018). The statistics for the key geotechnical parameters, including effective cohesion, effective friction angle, and permeability coefficient, are shown in Table 1. The coefficient of variation (COV) of the permeability coefficient in Table 1 represents the COV of the soil parameter in its logarithmic form. It should be noted that the uncertainty in the unit weight of soil is not considered since the COV of unit weight is typically small (e.g., 5%) and its effect of unit weight on the stability analyses is typically not significant compared with strength and permeability parameters (Phoon and Kulhawy 1999; Wolff 1999; Wolff et al. 2004; Xiao et al. 2016). However, if deemed appropriate, the uncertainty of the unit weight can be easily integrated into the probabilistic framework.

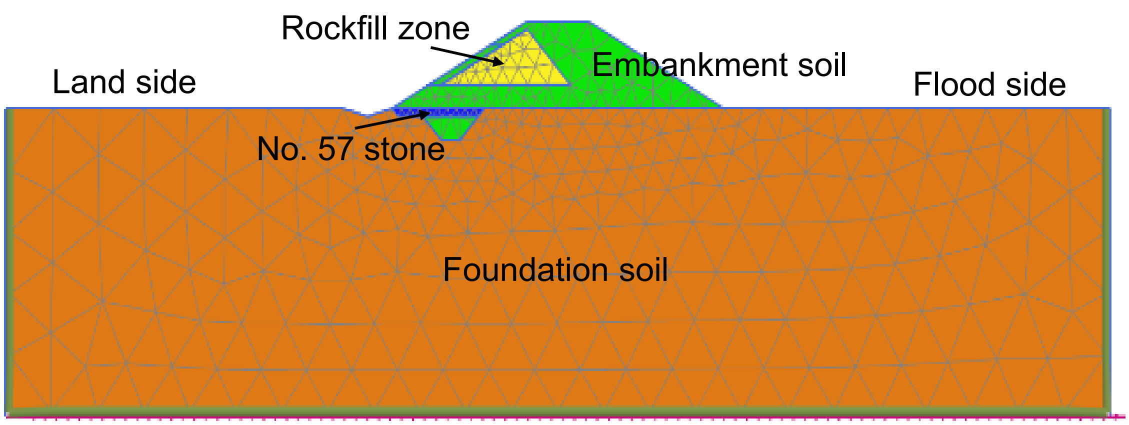

Figure 1. FEM mesh of the earthen levee used in this study

Table 1. Statistics of uncertain geotechnical parameters used in this study (after Wang et al. 2018)

Uncertain Soil Parameter	Embankment Soil		Rockfill Zone		No. 57 Stone		Foundation Soil	
	Mean	COV	Mean	COV	Mean	COV	Mean	COV
Effective Cohesion, c' (lb/ft^2)	25	10%	25	10%	0	-	25	10%
Effective Friction Angle, φ' (°)	30	15%	30	10%	36	10%	32	15%
Permeability coefficient, k (ft/sec)	3.28×10^{-6}	25%	3.28×10^{-5}	25%	3.28×10^{-3}	25%	3.28×10^{-6}	25%

Furthermore, the correlation coefficient between effective cohesion and effective friction angle for each soil layer is assumed to be − 0.5 (Juang et al. 2013). The water level on the flood side is modeled at an elevation of 446 ft (the crest elevation is 450 ft). The groundwater level on the land side of the levee is modeled at an elevation of 437 ft (the land side elevation is 440 ft). The slope stability of the land side is the main focus in the seismic evaluation.

First, the deterministic analyses are performed using the pseudo-static method within the FEM code. Figure 1 depicts the FEM mesh for the earthen levee in this study. The factor of safety for the seismic stability of earthen levee is determined using strength reduction method by fixing all the uncertain soil parameters at their mean values in Table 1. The factor of safety is then evaluated at various earthquake levels represented by different acceleration coefficients. Figure 2 shows the influence of increasing seismic demand on the deterministic design safety of the slope stability. The factor of safety without considering the earthquake effects is about 1.43. With the increase of the horizontal acceleration coefficient, the resulting factor of safety decreases following a general linear trend, and the factor of safety is about 1.09 when the acceleration coefficient increases to 0.1 (corresponding to a horizontal acceleration as 10% of the acceleration due to gravity.).

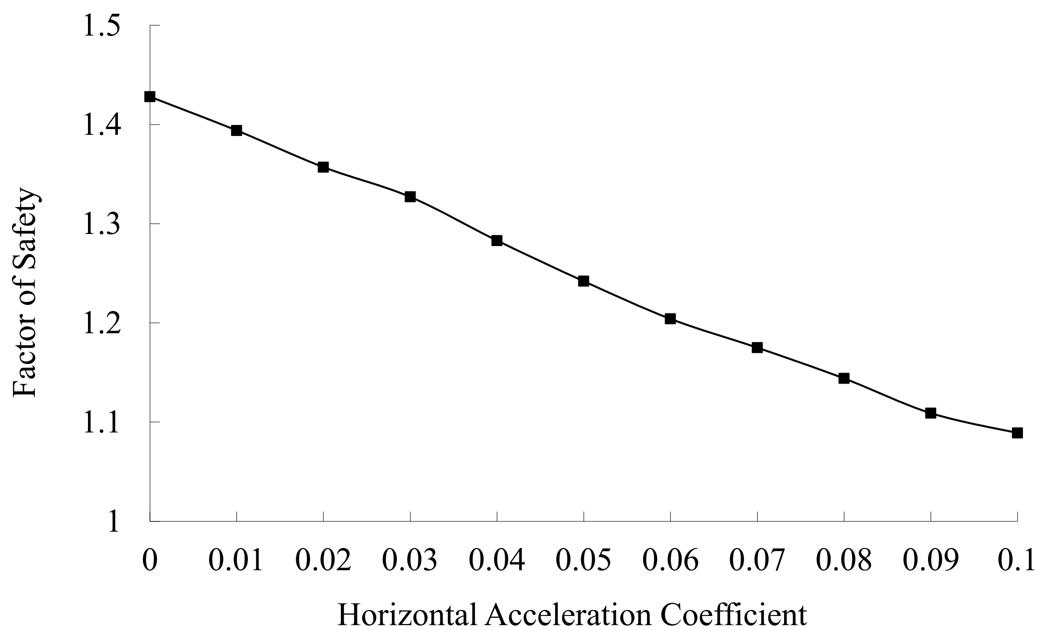

Figure 2. Resulting factor of safety with the horizontal acceleration coefficient from deterministic analyses.

Next, the probabilistic analyses are conducted using the simplified probabilistic procedure that combines the reliability analyses with the finite element method to determine the reliability index and probability of failure. The statistical values in Table 1 are put into the framework for uncertainty propagation. Using Eq. (2) and Eq. (4), the mean and standard deviation of the resulting factor of safety can be calculated. The probability of failure is then determined based on the mean and standard deviation of the factor of safety for a given acceleration level.

The process is repeated for each acceleration level (for acceleration coefficient from 0 to 0.1 with 0.01 increment); the probability of failure for each acceleration level can then be evaluated, and the curve for the change of probability of failure is shown in Figure 3. It is observed that the probability of failure for the earthen levee significantly increases with the increase of the horizontal acceleration level. It can be found that the probability of failure for the levee is very sensitive to the input earthquake load in terms of the acceleration coefficient. Also, it is interesting to compare the factor of safety and the probability of failure at each given acceleration coefficient. Without considering the earthquake effects, the factor of safety is about 1.43, which corresponds to a negligible probability of failure (in the magnitude of 10^{-5}). Typically, a safety factor of 1.4 is required for the stability analyses for most levee design. However, when the acceleration coefficient increases to 0.1, the factor of safety is decreased to 1.09, and the probability of failure is increased to more than 20%, which is considered as a very high probability of failure for a levee design. The derived probability of failure from the probabilistic assessment combined with the deterministic analyses can provide valuable references for engineers to make a risk-informed decision for seismic analyses and design of the earthen levees.

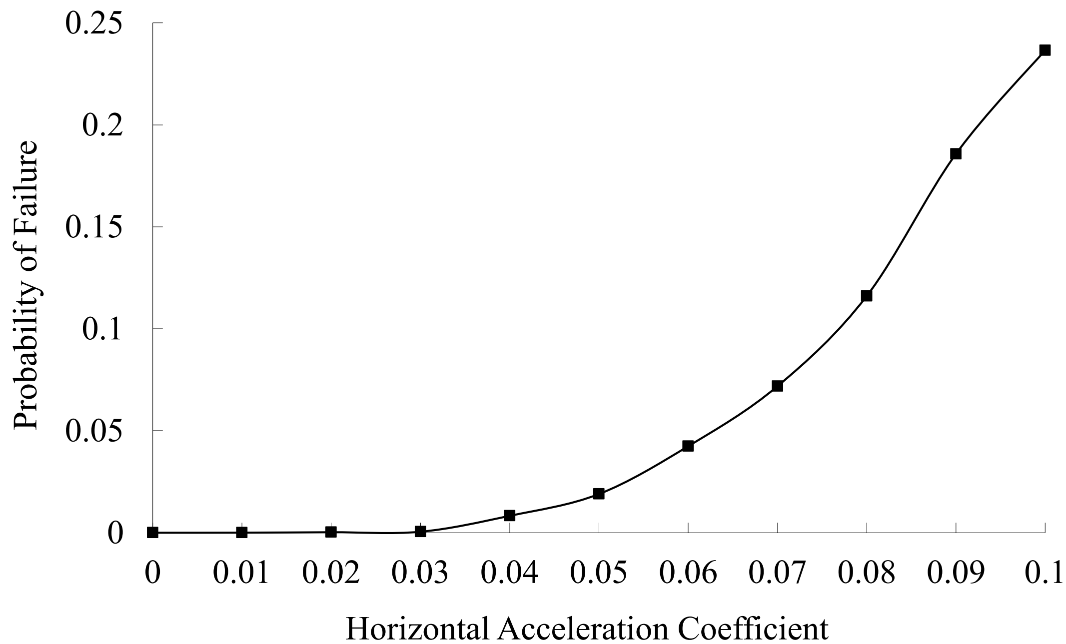

Figure 3. Resulting probability of failure with the horizontal acceleration coefficient from probabilistic analyses.

CONCLUSION

This paper presents a simplified method for probabilistic seismic assessment of earthen levees in the face of uncertainties. Within this framework, the uncertainties are propagated by considering the uncertain geotechnical parameters as the input and the resulting factor of safety as the system response. The pseudo-static method is adopted to evaluate the stability of earthen levee under earthquake loads. The factor of safety for a given level of horizontal acceleration coefficient is determined using the strength reduction method and finite element analyses. A case study for earthen levee safety evaluation is employed to demonstrate the effectiveness and efficiency of the proposed framework. Both the deterministic and probabilistic analyses are carried out to determine the factor of safety and probability of failure at various acceleration levels. The results showed that the factor of safety decreases approximately linearly with the earthquake hazards. For the same horizontal acceleration coefficient levels, the corresponding probability of failure is also obtained, which can be used to evaluate the fragility of levee with respect to earthquake loads. The results can provide useful references that allow engineers to make more informed decisions in the face of earthquake loads.

ACKNOWLEDGEMENTS

The study on which this paper is based was supported by National Science Foundation through Grant #1900445 and NASA-MIRO Grant awarded to University of the District of Columbia. The results and opinions expressed in this paper do not necessarily reflect the views and policies of the National Science Foundation and National Aeronautics and Space Administration.

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