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Probabilistic seismic stability analysis of slope at a given site in a specified exposure time

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ABSTRACT

This paper presents a probabilistic approach for seismic stability analysis of a slope at a given site in a specified exposure time. For a probabilistic seismic stability analysis, the ground motion parameter, in terms of the peak ground acceleration (PGA), at a given site in a specified exposure time of interest (say, 30 years) is treated as a random variable, and the PGA distribution at the given site is derived based on the USGS National Seismic Hazard Maps data. Further, the spatial variability of the soil property is simulated herein by a random field, and the fluctuation of the groundwater level is simulated by a random variable. Within the probabilistic framework, a deterministic model for evaluating the slope stability is required; here, a pseudo-static analysis is adopted and implemented through 2D finite difference program FLAC version 7.0. In the face of the uncertainties in the input parameters, the performance or safety of the slope is expressed as a failure probability; within the proposed probabilistic analysis framework, a recently developed sampling method is adopted for the uncertainties propagation through the deterministic solution model. This probabilistic analysis framework is demonstrated with an illustrative example of a two-layer earth slope. Finally, a parametric study is undertaken to investigate how the failure probability of the slope (at a given site in a specified exposure time) is affected by the uncertain factors such as the earthquake-induced ground motion and the spatial variability of soil property. The study results demonstrate the versatility and effectiveness of the proposed framework for probabilistic seismic stability analysis of slope at a given site in a specified exposure time.

1. Introduction

In a traditional stability analysis of a slope subjected to static or dynamic loads using a deterministic approach, the level of stability is generally expressed as a factor of safety (FS). Because of the uncertainties in the input parameters, it is rarely possible to capture the stability of a slope with a single FS. To this end, use of the probabilistic approach that explicitly considers parameter and model uncertainties has long been reported (e.g., Griffiths and Fenton, 2004; Cho, 2007; Silva et al., 2008; Ching et al., 2009; Juang et al., 2015), and the level of stability is expressed accordingly as a probability of failure (P_f). It has been demonstrated that slopes with the same FS might exhibit different failure probabilities due to various levels of uncertainty in the input parameters and the adopted solution model (e.g., Li and Lumb, 1987; El-Ramly et al., 2002; Gong et al., 2014b). Therefore, it is considered more appropriate to evaluate the stability level of a slope in terms of the failure probability, especially when the slope is subjected to future seismic loads in a specified exposure time (say, 30 years), which exhibits a large uncertainty. The knowledge of the failure probability of a slope plays a vital role in the risk-based assessment or engineering treatment of the slope (e.g., Dai et al., 2002; Faber and Stewart, 2003; Silva et al., 2008).

This paper presents a probabilistic approach for seismic stability analysis of a slope at a given site in a specified exposure time. The uncertain factors considered in this study include the earthquake-induced ground motion, the spatial variability of the shear strength parameters and the fluctuation of the groundwater level. Among them, the earthquake-induced ground motion at a site in a specified exposure time is characterized as a random variable (Jalayer and Beck, 2008; Juang et al., 2008; Juang et al., 2010), the spatial variability of the shear strength parameters is characterized as a random field (Fenton, 1999; Griffiths and Fenton, 2004; Wang and Cao, 2013; Gong et al., 2014a; Feng and Jimenez, 2014), and the fluctuated groundwater level is treated as a random variable (Kim et al., 2004; Rahardjo et al., 2010; Zhang et al., 2014). The stability analysis within the proposed probabilistic framework is carried out using a finite difference program FLAC version 7.0 (2011). The propagation of the uncertainties in the input parameters through

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the FLAC model is performed through an efficient sampling method by Gong et al. (2016b).

The structure of this paper is organized as follows. First, the deterministic model for evaluating the slope stability using FLAC is presented to set the stage. Second, the uncertainties in the input parameters for the slope stability analysis, including the earthquake-induced ground motion, the spatial variability of the shear strength, and the fluctuation of the groundwater level, are discussed. Third, the probabilistic analysis of slope stability using the sampling method by Gong et al. (2016b) is outlined. Fourth, an example of a two-layer earth slope is studied to illustrate the probabilistic analysis framework. Finally, a parametric analysis is conducted to investigate how the performance of the slope, in terms of the failure probability over an exposure time, is influenced by the uncertain factors such as the earthquake-induced ground motion and the spatial variability of the soil property.

2. Deterministic stability analysis of slope subjected to dynamic load

The stability of a slope can be evaluated using either numerical methods (Duncan, 1996; Griffiths and Lane, 1999; Cheng et al., 2007) or limit equilibrium methods (Bishop, 1955; Spencer, 1967; Gong et al., 2014b). In this study, the 2D explicit finite difference program FLAC version 7.0 (2011) is adopted as the deterministic model for evaluating the slope stability. Within FLAC version 7.0, the strength reduction method (Dawson et al., 1999; Cheng et al., 2007) is adopted for calculating FS, in which the shear strength of the soil is progressively reduced to bring the slope to a state of limiting equilibrium. It is noted that the strength reduction method is often applied with the Mohr-Coulomb failure criterion. With the strength reduction method, the shear strength of the soil, in terms of the cohesion (c) and internal friction (φ), is reduced by a trial value of FS, denoted as *fs*, which is often >1.0.

$$c_r = \frac{c}{fs} \tag{1}$$

$$\varphi_r = \arctan\left(\frac{\tan\varphi}{fs}\right) \tag{2}$$

where c_r and φ_r represent the reduced cohesion and reduced internal friction, respectively. Then, a series of FLAC simulations are made using different trial values of *fs* until the occurrence of the slope failure. A bracketing approach similar to that proposed by Dawson et al. (1999) is used in FLAC version 7 for deriving FS. Note that if the slope is initially unstable, the shear strength of the soil will be progressively *increased* (i.e., $fs \le 1.0$) until the limiting condition is reached.

The stability of a slope under earthquake can be rigorously studied with the fully coupled dynamic analysis, which may be implemented using FLAC built-in dynamic option (Cetin et al., 2004; Bouckovalas and Papadimitriou, 2005; Bourdeau and Havenith, 2008). However, the fully coupled dynamic analysis requires the input of the ground acceleration (or velocity) history and it is often computationally prohibitive, especially within a probabilistic analysis framework. Thus, the pseudo-static method, which is widely adopted and recommended in design guidelines and codes (e.g., Eurocode 8, 1993; BSI, 1995; FHWA, 1997; Shukha and Baker, 2008; Loáiciga, 2015; Wang and Rathje, 2015), is employed herein. In the context of the pseudo-static method, the influence of an earthquake on a slope is represented by a pseudo-static force, which could be captured by a constant horizontal acceleration (a_h) and a constant vertical acceleration (a_v); and, in order to prevent tensile failure of the slope, the tensile strength of the soil is usually set to a high value in FLAC analysis. The study by Sarma (1975) showed that the vertical component of the pseudo-static force might be neglected in a typical slope stability analysis; and thus, only the earthquake-induced horizontal acceleration (a_h), which may be approximated as follows (Shukha and Baker, 2008), is considered in this study for simplicity.

$$a_h = \frac{1}{3}\mathrm{PGA}^{\frac{1}{3}} \ \ (\mathrm{g}) \tag{3}$$

where PGA represents the peak ground acceleration at the level of slope toe (unit: g). Here, the peak ground acceleration at the rock outcrop is taken as the PGA in Eq. (3) for simplicity. That is to say, the amplification at the site is not considered in this study.

In the context of numerical modelling with FLAC, the geometrical domain of the slope is discretized into a set of elements, as shown in Fig. 1; in which, different soil properties can be assigned to different elements utilizing FLAC built-in *fis* languages. Thus, the spatial variability of the soil property can be easily modeled through assigning different soil properties to different elements; and similarly, the groundwater level, in an uncoupled flow-mechanical analysis, can be modeled by assigning different soil properties to the zones above and below the groundwater level.

3. Characterization of parameters uncertainties for slope stability analysis

In this section, the uncertain input parameters in the slope stability analysis, including the earthquake-induced ground motion, shear strength, and groundwater level, are discussed.

3.1. Probability distribution of PGA at a given site in a specified exposure time

The procedure outlined by Juang et al. (2008) is employed here to derive the probability distribution of PGA at a given site in a specified exposure time. At a given site of known latitude and longitude, the rock outcrop PGAs for various levels of probability of exceedance can be obtained from the USGS website (USGS, 2012). A seismic hazard curve at this site can then be established using the discrete data points provided in the USGS website, in terms of the annual rate of exceedance λ versus the corresponding PGA. Fig. 2 depicts an example of a seismic hazard curve at an example site (longitude = −122.30° and latitude = 47.53°) in Seattle.

The hazard curve, shown in Fig. 2, is readily adopted to calculate the probability of exceedance of PGA in a specified exposure time (say, T years).

$$P_{Ei} = 1-(1-\lambda_i)^T \tag{4}$$

where P_{Ei} is the probability that PGA would exceed PGA_i in an exposure time of T years, and λ_i is the annual rate of exceedance corresponding to PGA_i.

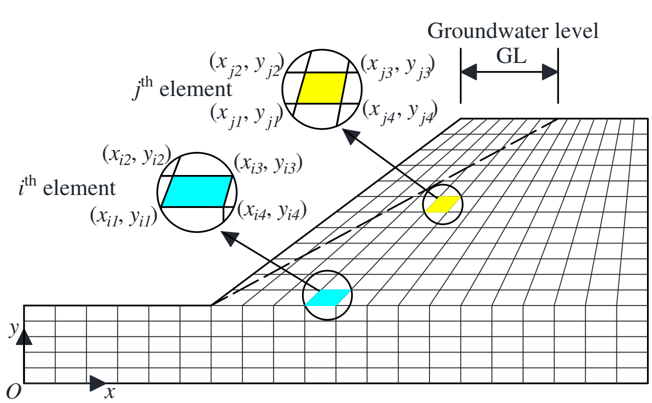

Fig. 1. Schematic diagram of the mesh of a slope in FLAC analysis.