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Stochastic seismic response and dynamic reliability analysis of slopes: A review

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ABSTRACT

This study analyzes the factors that influence the seismic stability of slopes and summarizes the variability and uncertainties in the various components. It also shows why the variability should be considered in stability analyses of slopes. Furthermore, stochastic seismic performance evaluations corresponding to the different sources of variability are summarized and reviewed. In particular, new random vibration methods are applied to seismic response studies. Finally, by characterizing the intrinsic factors and understanding the variability in dynamic slope systems, future development of the stochastic seismic response analysis method is elaborated.

1. Introduction

Because of their large capacity to cause disasters, seismic landslide hazards have received worldwide attention. In the 20th century, tens of thousands of people have been killed and billions of dollars have been lost as a result of seismic landslides. However, when an earthquake occurs, the landslide and collapse hazards induced by the earthquake are much larger than the direct seismic hazard, especially in mountainous areas [1–8]. Therefore, seismic response analyses and dynamic stability assessments of slopes under earthquake loading have practical significance for earthquake-induced landslide disaster reduction, and it has become an important research theme. From the seismic design and evaluation perspective for engineering structures, accurate and reasonable calculations and external load excitation are key factors that are required to precisely obtain the seismic response of slopes under earthquake loading. However, the material property parameters and the seismic excitation are often uncertain owing to their intrinsic variability. While our real world may be causal and continuous, we have only to establish a basic model that reflects the inherent relation of things to discover the essential law among them based on the observation and abstraction of objective phenomena. As a part of this process, the stochastic system concept was introduced to extend the traditional deterministic system and more comprehensively and objectively reflect the physical world. The deterministic system, described by the deterministic differential equations, has been widely applied to physics, engineering, biology, and economic systems and other fields. However, with the development of science and technology, the requirement for precise description of the practical problem has increased sharply. Therefore, the influence of the stochastic factors cannot be easily ignored. As a result, analyses of real practical problems are also necessary to take into account the uncertainties affecting the accuracy of decision from stochastic viewpoint. However, to emphasize an important point, the stochastic analysis methods do not deflect from objective physics principles, and these methods are built upon the foundation of deterministic analysis skeleton [9]. The deterministic method is also an important and indispensable part in aseismic analysis of slopes. Namely, the progress of deterministic analytical theory also stimulates the development of the stochastic probability methods. Therefore, the newly developed deterministic numerical calculation methods such as the finite element method (FEM), smoothed particle hydrodynamics (SPH) algorithm and discontinuous deformation analysis (DDA) method can also be applied in stochastic seismic analysis of slopes [10,11]. Meanwhile, the differential equations for description of these actual systems should also be transferred naturally from deterministic to stochastic, so the deterministic system is transferred into a stochastic system. This evolutionary process is also applicable for dynamic slope systems with seismic activity. The seismic responses of slopes are also influenced by random factors. For instance, the variabilities in seismic ground motion and rock and soil parameters have great impact on the seismic responses of slopes.

In recent years, there has been an increase in the study of seismic response and dynamic stability of slopes from a stochastic perspective; in particular, the seismic stability reliability of slopes has been extensively studied by more and more researchers [12–19]. Meanwhile, considerable developments in relevant disciplines have also encouraged innovation in the stochastic seismic response and dynamic stability

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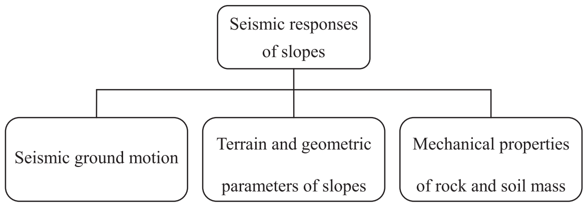

Fig. 1. Decision tree for the seismic performance of slopes under earthquake loading.

reliability theory. In this context, this paper attempts to systemically scrutinize and review the progress and development of slope stochastic seismic response and dynamic reliability analyses.

2. Theory: stochastic sources and mechanisms

With the gradual improvement and development of structural deformation, stress, and stability analyses, the randomness in these analyses has been appreciably revealed. Because the physical relations are interlocking in the objective world, the causal relationship tree can be applied in the investigation of objective physical phenomena. For instance, for slopes under seismic loading, the seismic ground motion and the geometric and physical parameters of the slopes are variables in the physical solution of slopes as determined by Newton's second law. Therefore, the stability of the slopes is controlled by many complicated factors, for instance, the material properties of rock and soil, geological structure, rock mass structure, distribution characteristics of groundwater, earthquakes, and so on. An evaluation of these factors using a decision tree for the seismic performance of slopes is shown in Fig. 1. The seismic responses and dynamic stability are mainly related to three categories of factors: seismic ground motions, terrain and geometric parameters of slopes, and mechanical properties of rock and soil masses [20,21].

For these controlling factors, some have significant random variability to various degrees. For instance, prediction of future earthquakes has been always a challenge [22–26], and so the uncertainties and randomness of seismic ground motions present great difficulties in the analysis of the seismic responses of slopes. Generally, the randomness and uncertainties include the following several aspects for the seismic responses of slopes:

2.1. The variability in the soil and rock material properties of the slope

The core research issues for slope activity under earthquake loading are the deformation characteristics and dynamic stability assessment. The dynamic constitutive model (e.g., Hardin-Drnevich model, Ramberg-Osgood model and Iwan model, etc.) and determination of corresponding parameters are two problematic areas that can seriously trouble geotechnical engineers [27–31]. There are three main reasons: First, because soil and rock are the products of nature, their various properties have significant variability in both space and time. The spatial variability concept for soil was first proposed by Lumb, when he noted that the geotechnical parameters in different locations in the same layer had remarkable variability and correlation [32]. In Vanmarcke's research on the variability of soil, diverse trends and locally varied characteristics were distinguished, and the stochastic field model of the soil profile was introduced [33]. Some researchers also noted that the functions of geotechnical structures are determined by the spatially averaged properties of soil [34]. Thereafter, many researchers carried out studies on the seismic responses of slopes, and many research results on the variability of rock and soil parameters were obtained [19,35–40]. The variability of soil properties not only reflects in space, but also in time. This is because the soil characteristics are seriously affected by the environment, climate and construction factors. Accordingly, there are differences of soil properties during engineering investigation and construction, and the mechanical performance of soil material will degrade with increase of serving time. In addition, the mechanical properties of soil are also strongly controlled by the water table. Obviously, the season temporal variability in groundwater is decided by rainfall and drought in rainy summer and arid winter [41]. Therefore, affected by the aforementioned factors, the variability in mechanical properties of slope materials is related with time. In general, it's a challenge to consider the variability of soil in time by limited geotechnical investigation tests. Hence, this variability is identified by geotechnical engineers based on their experience and test data [42].

The second aspect is that the scale and size of slopes are much larger than other engineered structures in general, and so the variability of rock and soil must be considered in the seismic response analyses of slopes.

Last, rock and soil masses are highly nonlinear materials; under earthquake loading, they show different deformation characteristics under different stress levels. These variabilities will result in a strong randomness in the seismic responses of slopes [43]. It should be noted that the variability in rock is not exactly same as that in soft soil. The essential differences between the rock mass and other engineering material lie in inhomogeneity of properties and structures. Theoretically, the inherent heterogeneity problem of rock can be solved by sufficient measuring points. However, due to the limitation of conditions known to all, it's difficult or impossible for us to deterministically describe the properties and geometry parameters of rock mass. Hence, the uncertainties of rock mainly embody in following two aspects: (1) the uncertainty of joints and faults distribution in rock mass, (2) the non-determinism in mechanical properties of rock mass [44]. Generally, the variability and uncertainty of joints and faults can be considered by Monte Carlo simulation in the discontinuous medium mechanics (e.g., DDA) [10,45]. Therefore, we mainly discuss the variability in property parameters in this paper.

Without loss of generality, the general dynamic system of slopes with seismic activity can be written as follows [46]

$$M\ddot{\mathbf{X}} + C\dot{\mathbf{X}} + f(\dot{\mathbf{X}}, \mathbf{X}) = -\mathbf{MI}\ddot{x}_g(t) \tag{1}$$

where $\mathbf{M}$ and $\mathbf{C}$ are the mass matrix and damping matrix respectively; $f(\dot{\mathbf{X}}, \mathbf{X})$ is the restoring force vector, which expressed into the nonlinear dynamic behavior of the slope rock and soil material under seismic excitation; $\ddot{\mathbf{X}}$, $\dot{\mathbf{X}}$, and $\mathbf{X}$ are the seismic acceleration, velocity, and displacement vectors of the slope, respectively; $\mathbf{I}$ is a unit vector, and $\ddot{x}_g$ is the temporal evolution of the earthquake acceleration. When the aforementioned variability in the material of slope is considered in the general dynamic equation, the deterministic dynamic Eq., Eq. (1), is converted to a dynamic stochastic equation:

$$\mathbf{M}(\mathbf{\Theta})\ddot{\mathbf{X}} + \mathbf{C}(\mathbf{\Theta})\dot{\mathbf{X}} + f(\mathbf{\Theta}, \dot{\mathbf{X}}, \mathbf{X}) = -\mathbf{MI}\ddot{x}_g(t) \tag{2}$$

in which $\mathbf{\Theta}$ is the stochastic vector that describes the random variability of the rock and soil mass. According to Eq. (2), even with the same seismic ground motion, the solution for the dynamic seismic system for the slope has significant variability due to the randomness in the geotechnical parameters. Meanwhile, the nonlinear dynamic component is sensitive to the seismic ground motion. Even with the same seismic activity, the seismic dynamic responses of slopes are variable. Supposing that the nonlinear component from Fig. 2 is selected in Eq. (2), then the solution to Eq. (2) will be fully different from the same constitutive model using different parameter calibrations; namely, the seismic responses of slopes are varied for different geotechnical parameters.

2.2. The randomness of seismic ground motions

There are certain commonalities in earthquake occurrences; for example, most earthquakes happen at the boundaries of Earth's plates. About 70% of global earthquakes are distributed in the circum-Pacific seismic belt, 15% of earthquakes are in the Euro-Asia seismic zone, 5% earthquakes occur along mid-ocean ridges, and the other 10% are