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Prediction of seismic displacement of dry mountain slopes composed of a soft thin uniform layer

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ABSTRACT

In this paper, the earthquake-induced permanent seismic displacement of dry mountain slopes is calculated from a series of two-dimensional dynamic nonlinear finite difference analyses. The mountain slopes considered are composed of a thin, soft, uniform soil layer underlain by an inclined bedrock parallel to the slope. The material properties of the soil, thickness of the soil layer, and slope inclination angles are varied. Equivalent acceleration time histories are calculated at potential sliding surfaces to derive amplification factors, and a Newmark sliding block analysis is used to calculate the seismic displacements. The calculated seismic displacements of the mountain slopes are compared with those predicted by empirical displacement models. The results show that mountain slopes composed of soft soil layers with a shear wave velocity less than or equal to 200 m/s cannot be modeled as a rigid block because the displacement under strong ground motions will be greatly overestimated. The displacement prediction is significantly enhanced if the slope is modeled as a flexible sliding mass and the amplification characteristics are accounted for. A new flexible sliding block model, which uses multiple ground motion parameters, is shown to provide a reliable estimate of the sliding displacement. The success rate of the model to predict the landslide hazard category ranges from 52 to 88.3%.

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1. Introduction

Permanent seismic displacement is most often used to assess the performance of slopes subjected to a broadband seismic motion. A simple method to calculate the magnitude of the seismic displacement was first introduced by Newmark [1]. The method approximates the sliding mass as a rigid frictional block that slides along an inclined plane, which represents a potential failure surface. The permanent downward displacement is determined by double integrating acceleration pulses that exceed the yield acceleration (k_y), where k_y is the acceleration that causes the factor of safety of the slope to reduce to 1.0 (Fig. 1). The pioneering concept of Newmark [1] is still widely used; however, the predictive equation to calculate the seismic displacement has continuously evolved to reduce the uncertainties in the estimated displacements [2–6].

Newmark-type displacement model can be classified by whether the sliding mass is modeled as a rigid block or as a flexible sliding mass [7]. If the sliding mass is shallow and stiff, the rigid block assumption was shown to be appropriate [4]. For a deep or soft sliding mass, the dynamic response of the sliding block needs to be accounted for. For natural slopes, it has been reported that the predominant mode of failure under seismic loading is shallow sliding [4,5,8,9] and thus, is most often modeled as a rigid block, whereas engineered slopes, such as landfills and embankments, are modeled as flexible masses [7,10–13]. Jibson [14] presented a period range within which a rigid block analysis provides reliable displacement estimates. However, the effect of the intensity of the motion was not considered. There is a need to perform detailed numerical simulations to account for the nonlinear soil behavior and intensity of the ground motion in estimation of the seismically induced permanent deformation.

In this study, the seismic displacements of mountain slopes composed of a thin, uniform layer of soil underlain by an inclined bedrock parallel to the slope angle were calculated. The focus of the paper is dry soft soil where earthquake induced loss of strength due to build-up of residual excess pore pressure is not expected. Landslides in saturated sands that induce large seismic displacements and cause changes in slope geometry, as documented in Stamatopoulos and Di [15], were not simulated. A series of nonlinear dynamic analyses were performed using commercial finite difference analysis (FD) software to investigate the amplification characteristics of mountain slopes and to calculate seismic displacements. The applicability of the rigid block assumption and various predictive equations were evaluated through comparisons with the computed responses.

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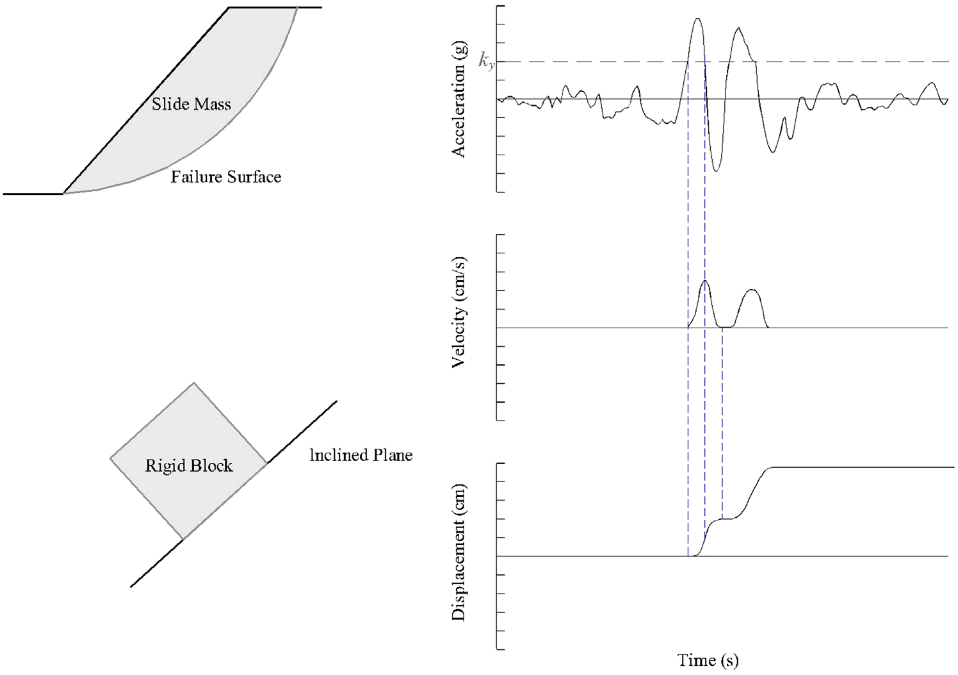

Fig. 1. Calculation of permanent displacement in the Newmark sliding block analysis [1].

2. Previous studies on seismic displacement of slopes

Since the introduction of the rigid sliding block concept by Newmark in 1965, the estimation of the permanent down-slope deformation of slopes has been a research topic of continued interest for practicing engineers. A large body of literature has been published on this topic, including empirical predictive equations, new numerical procedures, implementation of a probabilistic framework to assess hazards associated with seismic slope failure, and case studies. In this section, selected studies that provide the underpinnings of our work are presented.

As explained in the previous section, shallow slope failures are commonly predicted by empirical equations developed from a rigid block analysis. Based on 50 recordings, Ambraseys and Menu [2] proposed the following best fit empirical equation:

$$\log_{10} D = 0.9 + \log_{10}\left[\left(1-\frac{k_y}{PGA}\right)^{2.53}\left(\frac{k_y}{PGA}\right)^{-1.09}\right] \pm S\sigma_{\log D} \tag{1}$$

where D is the seismic displacement (cm), k_y is the yield acceleration (g), PGA is the maximum acceleration of the input ground motion (g), S is the standardized normal variate and $\sigma_{\log D}$ is the standard deviation of the seismic displacement.

Various forms of equations that use the Arias intensity (I_a) instead of PGA have been proposed [16–18]. It has been reported that the equations compare well for slopes with low values of k_y; however, the predictions were shown to be not as satisfactory for higher k_y values [4]. Chousianitis et al. [19] used I_a to predict the Newmark displacement for evaluation of seismic landslide hazard in Greece. The regression analysis showed an improved fit compared to other equations derived from world wide data, demonstrating the importance of using region-specific motion dataset. Stamatopoulos et al. [20] proposed a correction factor for Newmark displacement to account for changes in the geometry of the slope with seismically induced displacement. The correction has been shown to be important for slides with small slip length and large seismic displacement.

A revised equation of the Ambraseys and Menu [2] model was proposed by Jibson [4]:

$$\log D = 0.215 + \log\left[\left(1-\frac{k_y}{PGA}\right)^{2.341}\left(\frac{k_y}{PGA}\right)^{-1.438}\right] \pm 0.510 \tag{2}$$

The equation has been successfully used to predict the seismic landslide hazards in Anchorage, Alaska [8]. More recent models include works of Watson-Lamprey and Abrahamson [21] and Bray and Travasarou [22].

Saygili and Rathje [5] reported that Jibson's [4] model has significant aleatory variability. Various forms of empirical equations that use multiple ground motion parameters have been proposed to reduce the variability and uncertainties of the model. The following model, which uses two ground motion parameters, was shown to be extremely effective in predicting the seismic displacement

$$\begin{aligned}\ln D = & -1.56 - 4.58\left(\frac{k_y}{PGA}\right) - 20.84\left(\frac{k_y}{PGA}\right)^2 + 44.75\left(\frac{k_y}{PGA}\right)^3 \\ & - 30.50\left(\frac{k_y}{PGA}\right)^4 \\ & - 0.64\ln(PGA) + 1.55\ln(PGV)\end{aligned} \tag{3}$$

$$\sigma_{\ln D} = 0.41 + 0.52\left(\frac{k_y}{PGA}\right) \tag{4}$$

where PGV is the peak ground velocity (cm/s) of the input ground motion.

For deep slope failures, the assumption of a rigid block slippage is not applicable due to the dynamic amplification or deamplification effects of the sliding mass and therefore, should be modeled as a flexible sliding mass. Makdisi and Seed [23] proposed a procedure to account for the dynamic response of a deformable sliding mass to determine the seismic displacement. Using the concept of equivalent acceleration [24], which is defined as the averaged acceleration time history of a potential sliding mass calculated by integrating stresses that act along a predetermined failure surface, design charts that relate seismic displacement with k_y, PGA, and the depth of the failure surface were developed. The

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