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On the role of topographic amplification in seismic slope instabilities

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ABSTRACT

Surface wave generation due to body wave propagation near ground surface has been discussed in the literature. This phenomenon, typically occurring in topographic changing areas, along with its interaction with body waves (SV), decreases precision of formulas for evaluation of slope displacement. This significant fact caused the researchers not only to investigate the combined surface and SV waves motion pattern, but also to consider its effect on structures built on the slopes. In order to reveal the phenomenon, several finite element numerical studies have been performed by ABAQUS programme. Besides, two physical model slopes simulating the landslide occurrence have been constructed and tested by shaking table device. The results of induced and calculated accelerations obtained by two approaches have been compared and Rayleigh wave generation has been proved. Furthermore, the slope displacements have been calculated by various empirical methods and the results were compared with numerical ones. The results proved that in order to increase the precision of empirical formulas for displacement prediction, surface wave effect should be taken into account. Finally, a concept of "effective depth of surficial amplification" is introduced and its effect on dynamic slope stability is analysed.

1. Introduction

Slope failure, as a result of inertial instability mechanism, is one of the most destructive seismic hazards. Pseudostatic and sliding blocks are the two most famous state-of-the-art procedures used for evaluation of seismic slope failures. Although pseudostatic approach is simple and straightforward, it only determines the potential for initiation of movement along a predefined slip surface by giving a safety factor (Kramer, 1996).

As permanent deformation analysis (Newmark, 1965; Makdisi and Seed, 1978) is placed between overly simplified pseudostatic and overly complex stress-deformation approaches (Clough, 1960), it has been widely used by engineers in practice (Jibson, 2011). The concept and applications of this method, which is based on the analogy of the sliding mass with a moving block on an inclined plane, were comprehensively discussed by many researchers (Lin and Whiteman, 1986; Jibson, 1993; Kramer and Smith, 1997; Rathje and Antonakos, 2011).

Though convenient for engineering purposes, permanent deformation procedure for dynamic slope stability evaluation only considers the effect of shear body waves (SV). However, Rayleigh wave is typically generated near soil slopes due to topographic effects on seismic wave propagation.

Uncommon damages have been reported and attributed to topographic amplification of earthquake motions in the 1971 San Fernando earthquake (Boore, 1972), 1982 Coalinga earthquake (Stewart and Sholtis, 2005), 1985 Chile earthquake (Celebi, 1987) and 1999 Athens earthquake (Gazetas et al., 2002). Irregular geometry of the slope surface and its effect on Rayleigh wave propagation have been the subjects of considerable researches and discussions (Assimaki and Gazetas, 2004; Bouckovalas and Papadimitriou, 2005). The generated surface waves can significantly affect the response of soil slopes subjected to seismic waves (Uenishi, 2010).

By verifying the Rayleigh wave generation in horizontally excited slopes, this paper tries to investigate the effect of surface Rayleigh waves combined with SV body waves generated by earthquake event on soil slopes. Although consequential, this phenomenon has gained less attention by scientists and there are relatively few reported studies in the literature. Herein, finite element analysis along with shaking table model tests is used to discover the fact.

Accordingly, topographic amplification effect on inertial forces acting on a sliding mass during seismic slope instability has been studied. Finally, the calculated slope displacements are compared with empirically predicted ones, and frequency dependent nature of dynamic slope deformations is recognised.

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2. Topography effects and Rayleigh wave generation

Seismic body waves are modified as they reach the earth's surface due to topographic irregularities. High peak accelerations have been measured at different points along the surface and near the top of ridges, hills and step-like slopes in many earthquakes, such as a ridge in Matsuzaki, Japan (Jibson, 1987) in which the average crest peak acceleration was 2.5 times the base acceleration near the toe of the ridge. Reflection and diffraction are considered to be the main causes of seismic wave amplification near soil slopes. Incident SH waves do not usually generate other wave types (e.g. P, SV and Rayleigh). In fact, SH waves can result in formation of Love waves under site-specific conditions which help trapping these waves inside a shallow near-surface layer (e.g. a soft layer upon a dense layer). On the contrary, propagating SV waves near slopes are reflected in the form of other wave types, especially Rayleigh surface waves. It has also been shown that amplification of SV waves can be much higher than that of SH waves (Assimaki and Gazetas, 2004).

As reported by Ohtsuki and Harumi (1983), Rayleigh waves are generated by incident SV waves near the toe of the slope and then propagate along the surface towards the crest of the slope. It has also been stated that the generated Rayleigh waves behind the slope crest can have an amplitude of up to 35%–40% compared to that of the incident waves. However, based on the interaction of various reflected and diffracted waves, analysis of topographic amplification and deamplification is a complicated issue. In fact, patterns of topographic effects rely upon the geometry of the irregularity and upon the types, frequencies, and angles of incident waves (Sanchez-Sesma and Campillo, 1993). Consequently, there are a few systematic studies in that context which gave a clear insight to consider the effect of each wave separately.

In any case, it is accepted that Rayleigh surface waves are generated in the vicinity of soil slopes due to diffraction of incident SV waves. Horizontal and vertical displacement amplitudes of Rayleigh waves clearly show that there is an effective depth, approximately equal to the wavelength (λ_R), to which these waves produce considerable motions. Keeping in mind the fact that the generated Rayleigh waves impose inertial forces on the sliding mass in addition to those by the incident body waves, the significance of the above mentioned surface wave characteristic is magnified. Hereafter, the depth beneath a slope surface to which the diffracted Rayleigh waves generated by the incident SV waves result in additional accelerations and inertial forces, is referred to as the "effective depth of surficial amplification".

Within the rigid block theory proposed by Newmark (1965) for evaluation of seismic slope displacements, it was originally assumed that the "failure mass" is rigid; however the materials that comprise most slopes are rather compliant. The extent to which the assumption of rigid "failure mass" remains accurate depends on the wavelength of the input motion compared to the size of the potential sliding mass (Kramer and Smith, 1997). For thin failure masses and/or long wavelengths (low input frequencies), motions within the sliding mass are in phase and the effects of failure mass compliance are small. In a different manner, for thick failure masses and/or short wavelengths (high input frequencies), the effect may be significant and the fact that the resulting driving force acting on the potential failure mass is not proportional to the acceleration of each individual point within the mass, clearly shows the importance of frequency-dependent nature of seismic response of slopes. To account for the effect of frequency content of the input motion, Yegian et al. (1991) proposed the following normalised expression for the permanent deformation of slopes by using Newmark's sliding block analysis and recorded acceleration time histories:

$$\begin{aligned}\log_{10}u^* &= \log_{10}\left(\frac{u}{a_{\max}N_{\mathrm{eq}}T^2}\right)\\ &= 0.22 - 10.12\frac{a_y}{a_{\max}} + 16.38\left(\frac{a_y}{a_{\max}}\right)^2\\ &\quad - 11.48\left(\frac{a_y}{a_{\max}}\right)^3 \end{aligned} \tag{1}$$

where u^* is the normalized permanent deformation, u is the total relative deformation, a_y is the yield acceleration, $a_{\max}$ is the peak acceleration, N_{eq} is an equivalent number of cycles, and T is the predominant period of the input motion.

Within the concept of the effective depth of surficial amplification, another critical aspect of frequency-dependent nature of seismic slope failure can be developed. As discussed before, the generated Rayleigh waves increase induced accelerations to a specific depth beneath the surface of the slope directly proportional to the predominant wavelength of the input motion (inversely proportional to the predominant frequency). Hence, it can be summarised that the smaller the predominant frequency of the input motion, the larger the area (mass) affected by the generated Rayleigh waves near the slope (Fig. 1). This phenomenon leads to greater inertial forces acting on the sliding mass; thus larger induced displacements occur. In fact, this assertion is consistent with the above equation proposed by Yegian et al. (1991). Both of them suggest that the lower predominant period of input motion causes larger displacements.

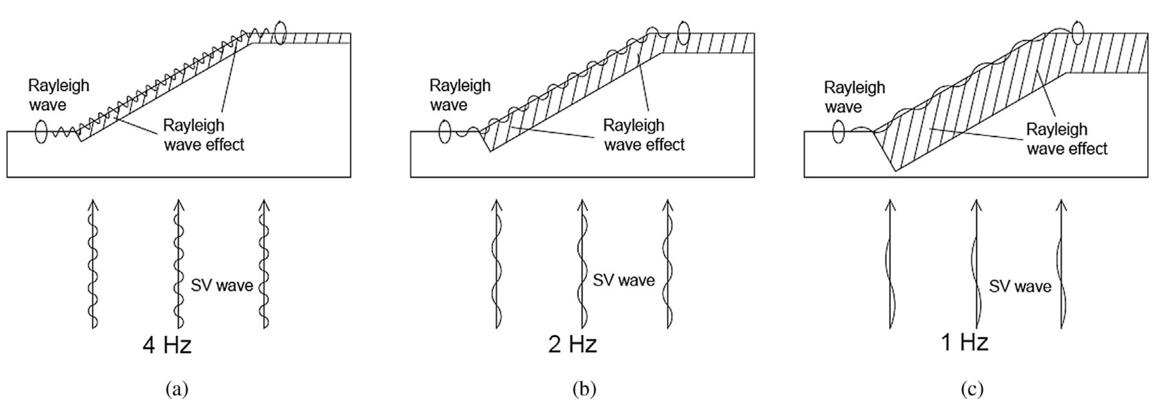

Fig. 1. Effective depth of surficial amplification for (a) 4 Hz, (b) 2 Hz, (c) 1 Hz incident SV waves.