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Time-frequency analysis of instantaneous seismic safety of bedding rock slopes

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ABSTRACT

An earthquake wave has many non-linear and non-stationary components. In current methods for seismic slope stability analysis, the time-frequency-amplitude characteristics of the earthquake waves, which can significantly affect the computation results, are not taken into account. In this paper, formulas for computing the seismic safety factor of bedding rock slopes are derived based on the elastic wave mechanics. The Hilbert-Huang transform (HHT) signal processing technique is employed to identify the time-frequency-amplitude characteristics of the earthquake waves in the time-frequency domain. Then a time-frequency method for computing the instantaneous seismic safety factor of bedding rock slopes, which considers the time-frequency-amplitude characteristics of the earthquake waves simultaneously, is proposed. A shaking table test example is worked out to illustrate the application of the proposed time-frequency analysis method to a bedding rock slope. The instantaneous seismic safety factors of all bedding planes are calculated based on the time-frequency analysis method proposed in this research. The seismic safety factor changes significantly over time, and the seismic safety factor of the upper part of the bedding rock slope is smaller than that of the lower part of the bedding rock slope. Hence the upper part of the bedding rock slope is more vulnerable to seismic damage.

1. Introduction

Earthquake-induced landslides can be catastrophic, both in the loss of human lives and to the economy [1–3]. The 2008 Wenchuan earthquake (M_L 7.9) triggered more than 56,000 landslides in steep mountainous terrains covering an area of about 41,750 km^2 [4], and the landslides directly caused more than 20,000 fatalities [5]. An earthquake wave is a complex random signal with time-frequency-amplitude characteristics. The seismic slope stability is significantly affected by the time-frequency-amplitude characteristics of the earthquake waves. Neglecting any one of these three factors, i.e. time, frequency and amplitude of the earthquake wave, will have a significant impact on the evaluation of seismic slope stability. In recent decades, Newmark's method, numerical simulation methods and quasi-static methods have been widely utilized to evaluate the seismic slope stability. Newmark's method [6] is based on the assumption that the sliding mass is rigid-plastic. The permanent displacement of the sliding mass can be obtained by double integration of the acceleration exceeding the yield acceleration, then the slope stability can be evaluated in reference to the permanent displacement. The research of Nova-Roessig and Sitar [7] showed that the Newmark analysis was conservative at low intensity shaking and unconservative at high intensity shaking. In 1966, Clough and Chopra [8] analysed the dynamic response of an earth dam by finite element method for the first time; henceforth the finite element method was widely used in the dynamic response analysis of slopes [9,10]. After the development in the last several decades, advancements have been made in the finite element method, particularly in constitutive models and computing methods. The quasi-static method, which is an experiential method and recommended for seismic stability analysis in Code for Seismic Design of Building (GB50011-2010) in China [11], simplifies the seismic load induced by an earthquake as a static-equivalent force, hence the quasi-static method cannot accurately reflect the dynamic characteristics of earthquake waves and the dynamic performance of slopes. It is conceptually simple, but the process of selecting a seismic influence coefficient lacks a rational basis, and the analysis tends to be conservative [12,13].

The Newmark method and quasi-static methods do not take into account the time-frequency-amplitude characteristics of the earthquake waves simultaneously, and also the dynamic slope behaviour. Although the numerical simulation methods can consider the time-frequency-amplitude characteristics of the earthquake waves compre-

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hensively, the operation of numerical simulations is often complex. If lacking the verification with other methods, the accuracy of numerical analysis results could be suspicious. In order to overcome some of the disadvantages of the exiting methods for slope stability evaluation, a new time-frequency analysis method, which takes into account the time-frequency-amplitude characteristics of the earthquake waves simultaneously, is proposed in this paper.

Time-frequency analysis of signals is an intensively studied area, especially in the last decades [14–17]. Here time denotes the time domain and frequency denotes the frequency domain. It is inappropriate to use the Fourier Transform to analyse the non-stationary signals and construct a non-stationary signal using a stationary sinusoidal signal. Some of the limitations related to the classical Fourier Transform can be overcome by using the Short Time Fourier Transform (STFT). However, the width of the moving window adopted for the STFT analysis must be fixed as a function of the minimum frequency of interest. It is clear that this limitation can significantly affect the results. For this reason, over the last decades, several other techniques for time-frequency analysis of seismic signals have been proposed [18]. In 1998, Huang et al. [19] proposed a new method for analysing non-linear and non-stationary data, namely Hilbert-Huang transform (HHT), which has been widely used for several applications [20–26]. A key part of HHT is the Empirical Mode Decomposition (EMD) with which any complicated data set can be decomposed into a finite and often small number of Intrinsic Mode Functions (IMF) that admit well-behaved Hilbert transform. Each IMF can be either a stationary or non-stationary signal. With the Hilbert transform, the IMF yields instantaneous frequencies as functions of time t. Hence the time-frequency-amplitude characteristics of the seismic signal can be separated with HHT. The final presentation of the HHT results is a time-frequency-amplitude three-dimensional distribution of the original signal, designated as the Hilbert spectrum. The existing studies indicate that this new decomposition technique is adaptive and highly efficient, and most importantly the HHT is very suitable for processing non-stationary and non-linear signals, e.g. earthquake waves. As a new signal processing technique, HHT offers an available method to separate the time-frequency-amplitude characteristics of the earthquake waves.

Based on elastic wave mechanics and the HHT signal processing technique, a time-frequency analysis method for evaluating the instantaneous seismic safety of bedding rock slopes is proposed in this paper. Then a large-scale shaking table test example is utilized to illustrate the application of the proposed method to a bedding rock slope.

2. Time-frequency analysis method for safety factor

2.1. Assumptions and conceptual model

As rocks and soils are extremely complex media for the propagation of seismic waves, and the seismic waves exhibit strong characteristics in time and frequency domains, the analysis method in this paper is established based on several assumptions:

(1) The material of the slope mass is homogeneous and isotropic.
(2) After repeated reflections and refractions, the seismic wave is assumed to propagate to the bedding plane vertically; i.e. the slope is impacted by a far-field earthquake.
(3) The influences of surface waves, which are derived by the slope surface, are ignored.
(4) The damage of the slope mass satisfies the Mohr-Coulomb failure criterion.
(5) According to the field investigation in the Wenchuan earthquake area, the dynamic damage to the slopes in the earthquake stricken area was mainly caused by the shear vertical wave (*SV* wave); moreover, the duration of the compression wave (*P* wave) is short and the energy of the *P* wave is low, hence the seismic stability of the slope is assumed to be controlled mainly by the *SV* wave. Only the influence of the *SV* wave is taken into account in the formulations; namely the conceptual model is solely subjected to the *SV* wave.

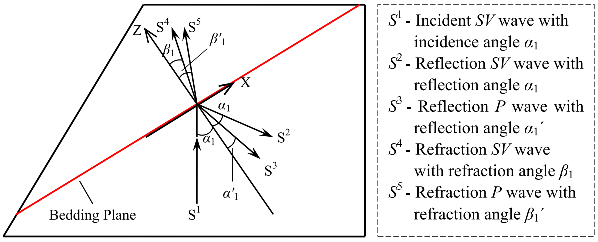

Fig. 1. Illustration of the two-dimensional conceptual model. Here the X axis coincides with the bedding plane, and the Z axis is perpendicular to the bedding plane.

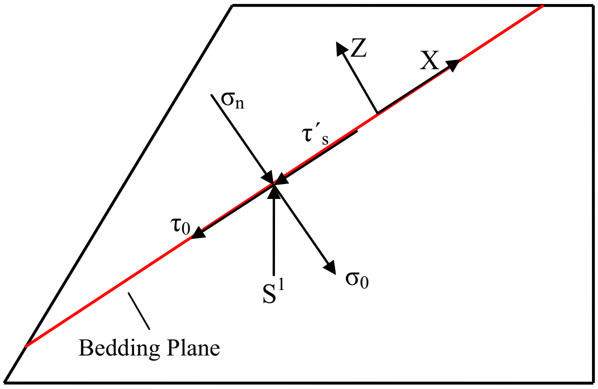

Fig. 2. Stress conditions on the bedding plane.

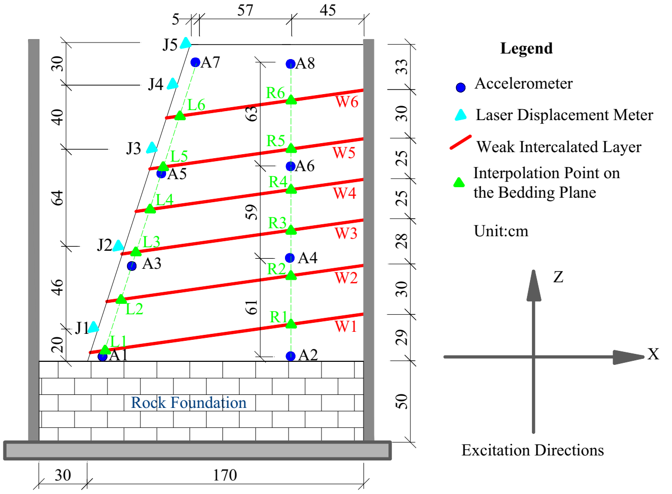

Fig. 3. Cross section of the test model and layout of monitoring points and interpolation points.

In the two-dimensional conceptual model, as shown in Fig. 1, the local morphological changes and the thickness of the bedding plane are ignored. In reference to the dynamics of seismic waves, complex reflections and refractions of the incident *SV* wave will appear on the bedding plane along with wave type conversion; namely not only the reflection *SV* wave and the refraction *SV* wave, but also the reflection *P* wave and the refraction *P* wave will appear on the bedding plane.

2.2. Dynamics of seismic waves

In the conceptual model, the elastic displacement is employed to

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