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# Seismic stability analysis of a layered rock slope

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ABSTRACT

In general, the determination of the factor of safety and the location of the critical slip surface are two major challenges in seismic slope stability analysis. In this paper, a new approach for determining the factor of safety and the corresponding critical slip surface of a layered rock slope subjected to seismic excitations is presented, through a case study based on the combination of the shear strength reduction technique and distinct element method. According to this proposed method, the seismic factor of safety and the critical slip surface of the slope are estimated and compared with those obtained by the pseudo-static approach, combined with the limit equilibrium method. It is found that the factor of safety obtained from the proposed method is slightly greater than that computed by the pseudo-static analysis, with a difference of 4.2%, and that the critical slip surface obtained from the two methods is identical, which confirms the reasonability and feasibility of the proposed method.



## 1. Introduction

Seismically induced failure of rock slopes in mountainous regions is one of the most common geological hazards. In most cases, the landslide may cause severe traffic interruption, structural destruction and the loss of human life. Layered rock slopes are especially prone to collapse under seismic excitations, due to the relatively weak strength characteristics of discontinuities, such as joints, bedding planes and foliations. Therefore, the seismic stability evaluation of layered rock slopes becomes more important when the slope is located in an earthquake-prone area. In addition, it is also essential for the purpose of the safe design and the implementation of mitigation measures for both natural and artificial slopes.

At present, the conventional pseudo-static method is still widely used in seismic slope stability analysis, and has even been incorporated into specifications in some regions, due to its simplicity and feasibility [1–5]. Although the pseudo-static approach is simple and practical, it has some inherited limitations, mainly due to some of the assumptions it makes, including: (1) the slope is an absolutely rigid body, and the accelerations for both the slope body and ground are the same; (2) the pseudo-static force remains constant; and (3) the failure of the slope will only occur when the factor of safety is less than one. However, it is well known that the slope is a deformable body rather than a rigid one. Seed [6] made detailed discussion about the deficiencies of this method, and pointed out that: (1) the inertial force is not constant, but has fast fluctuations, either in terms of the magnitude or the direction; and (2) even if the factor of safety of a slope is temporarily less than one, it does not necessarily indicate the overall collapse of the slope, though it may lead to a certain permanent deformation.

Due to these limitations of the pseudo-static method, other approaches must be sought and used to study the behavior of rock slopes subjected to dynamic loads. In the past several decades, more and more researchers have paid much attention to numerical continuum and discontinuum modeling of dynamic slope stability analysis, due to the fact that it has many particular advantages over pseudo-static analysis. Among the continuum methods, the finite element method (FEM) has been widely used in dynamic slope stability analysis. For example, Xu et al. [7] developed a rock mass damage evolutional model based on microseismic data and then established a 3D finite element model to quantitatively evaluate the stability of a rock slope. They also analyzed the relationship between microseismicity, degradation of the rock mass strength, and dynamic instability of the slope. Li [8] conducted the finite element analysis of slope stability with the consideration of earthquake effects using a nonlinear shear strength criterion of power-law type. He concluded that compared with the limit analyses, the finite element formulation is shown to be more accurate and efficient to compute stability numbers and that failure mechanisms can be reasonable defined without priori assumptions. Similar works were done by Mousavi et al. [9] and Guo et al. [10], etc.

In addition, other continuum methods, such as the finite difference method (FDM), and the boundary element method (BEM)

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have also been employed to study the site response, amplification and attenuation of slopes subjected seismic excitations. For example, Latha et al. [11] carried out seismic stability analysis of a Himalayan rock slope using both the pseudo-static approach and the finite difference code of FLAC. Their results confirm the global stability of the slope as the factor of safety obtained from the pseudo-static analysis is above one and the displacements observed from the FLAC analysis are within the permissible limits. Gatmiri et al. [12] used an improved boundary element approach to study the seismic response of slopes subjected to incident SV waves, and found that large amplifications take place on the upper surface close to the slope, while attenuations are produced on the lower surface.

Compared with the continuum methods mentioned above, the discrete element method (DEM) has been more commonly used in dynamic stability evaluation of rock slopes. The most popular representation of DEM is the commercial distinct element code of UDEC [13]. Liu et al. [14] simulated the dynamic response of a jointed rock slope in China subjected to explosions using UDEC, and found that the simulated results agreed well with site measurements, which demonstrates the feasibility of using UDEC to simulate the dynamic response of jointed rock slopes. Bhasin and Kaynia [15] conducted static and dynamic stability analysis of a 700-m-high Norwegian rock slope using UDEC, and provided some useful insights into the deformation mechanisms of the rock slope. Pal et al. [16] performed earthquake stability analysis of a Surabhi landslide in India using UDEC, focusing on the weak zones, and concluded that most of the total displacement observed in the slide model was due to the zone of detachment.

In addition, other discontinuum methods such as the discontinuous deformation analysis (DDA) and the Particle Flow Code (PFC) have also shown their capability to reproduce the dynamic failure process of slopes [17,18].

Due to the fact that the factor of safety is still a very important and useful index for determining whether a slope will suffer from collapse under seismic loads, it is usually preferable to offer both the factor of safety and the corresponding critical slip surface for the purpose of the safety design and the implementations of mitigation measures for man-made or natural slopes if they are situated in earthquake-prone areas. However, none of the numerical methods described above fulfills these objectives. In the present study, a comprehensive numerical simulation focusing on seismic stability analysis of a typical layered rock slope is conducted, based on the combination of the shear strength reduction technique and two-dimensional (2D) discrete element program UDEC, and a new approach to estimate the limit equilibrium state of the slope subjected to seismic loads is proposed according to the velocity and displacement features of the monitoring points in the slope. In addition, the procedure for calculating the factor of safety and for locating the corresponding critical slip surface of the slope based on the suggested approach is presented. Finally, the results are compared with those obtained by the pseudo-static approach combined with the limit equilibrium method, to verify the feasibility of the proposed method.

## 2. Geological features of the case slope

The Shanghai–Chengdu Expressway is one of the most important traffic arteries stretching from eastern to western China. Along this line there are about 46 layered rock slopes in the section between Yichang City and Enshi City. Among these slopes, the Zhongjiawan layered rock slope is a typical representative, and is located in the segment of K55+261–581 m on the line from Yichang to Enshi. The strike of the expressway line at this location is N103°E. Fig. 1 shows the location map of the rock slope, and the cross-section of the slope at K55+500 m is illustrated in Fig. 2 [19].

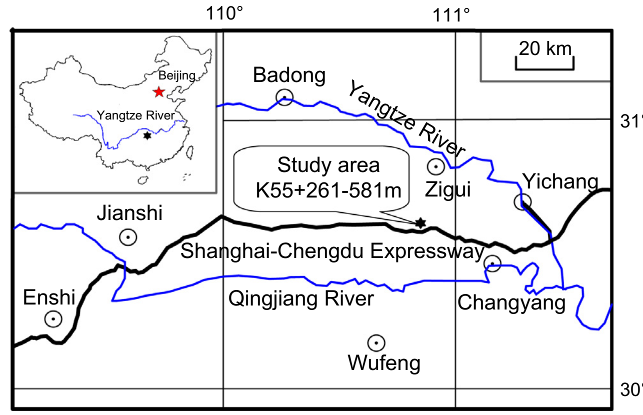


**Fig. 1.** Location map of the case slope.

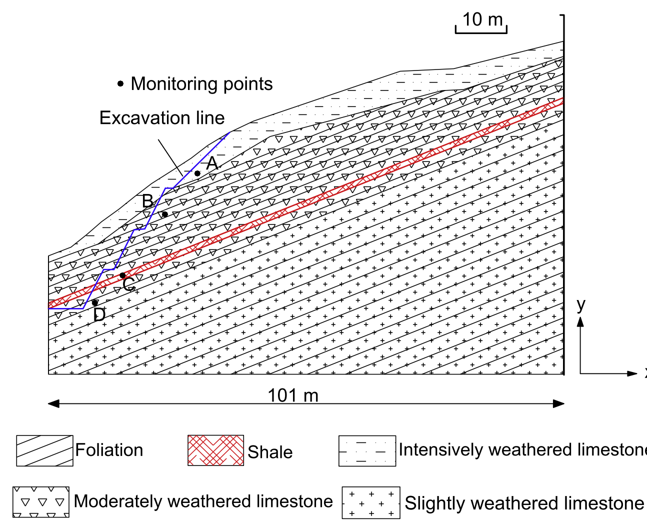


**Fig. 2.** Cross-section of the layered slope at K55+500 m.

There are no faults in the study area. The fault closest to the site is Xiannv fault, which is not active and 3 km away from the site. History records have shown that there is no distribution of epicenter and seismic activities are rare at the site and its vicinities. According to the report on seismic safety evaluation of engineering site proposed by the Institute of Seismology, China Earthquake Administration, the regional tectonic stability for the site is classified as a stable condition [19].

The rocks in the slope area consist of Ordovician thick limestone with different degrees of weathering mixed with the shale. The limestone in upper part of the slope is intensively weathered. The rocks in the central section of the slope including limestone and shale are moderately weathered and the limestone in the lower section of the slope is slightly weathered. The rocks are well foliated, with a strike of N30°E and dip of 22° in the northwest (NW) direction. Most of the foliation joints are persistent in nature. In addition to joints along the foliation, there are also two sets of non-consecutive sub-vertical joints dipping in the NW direction at the site. The spacing of the sub-vertical joints is very small, varying between 8 and 25 cm, and thus it is difficult to model these joints in a dynamic numerical model. An alternative is to consider the effects of the discontinuities by reducing the strength of the intact rock to those of the rock masses. Therefore, the shear