Soil Dynamics and Earthquake Engineering 99 (2017) 74–85

Contents lists available at ScienceDirect

Soil Dynamics and Earthquake Engineering

journal homepage: www.elsevier.com/locate/soildyn

Seismic displacement along a log-spiral failure surface with crack using rock Hoek–Brown failure criterion

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ARTICLE INFO

Keywords:
Seismic displacement
Rock slopes with cracks
Hoek–Brown failure criterion
Sliding rigid block model
Upper bound limit analysis

ABSTRACT

Earthquakes can trigger slope instability, especially in the case of slopes with cracks. The most commonly used method for analyzing seismic slope stability is the pseudo-static analysis technique. However, information about slope displacements is difficult to obtain. The purpose of this paper is to present a model for calculating the seismic displacements of rock slopes with cracks using the upper bound limit analysis and the rigid block displacement technique. The Hoek–Brown (H–B) failure criterion is employed in this model, and actual horizontal and vertical earthquake ground motion records are utilized. The equivalent Mohr–Coulomb (M–C) parameters including friction angle and cohesive strength are determined by fitting an average linear relationship to the curve of relationship between major and minor principle stresses for H–B failure criterion. A comparison of the seismic displacements obtained by using the equivalent M–C parameters and the H–B failure criterion is performed. The difference of the seismic displacements obtained by using the two methods is significantly larger than the difference of factor of safety for rock slopes with cracks under seismic action. The results indicate that the equivalent M–C parameters method may cause an overestimation of the stability of a slope. To understand the influence of rock strength parameters and crack depth, a detailed parametric study is carried out. These parameters can significantly influence seismic displacement, especially for large crack depths. For the numerical example considered in this study, the ratio of crack depth to slope height varied from 0 to 0.2, and the increase in seismic displacement can exceed 23%.

1. Introduction

Seismic slope stability is often evaluated by the factor of safety and the seismic slope displacement. The factor of safety can be obtained from the pseudo-static analysis method, which is commonly applied in seismic slope stability analysis. The method is also referred to the seismic coefficient analysis of the horizontal and vertical coefficients, which are assumed to calculate the earthquake inertia force. Although the pseudo-static analysis is simple and extensively applied [1–3], the seismic process is neglected and information about the displacements of slopes is difficult to obtain. Newmark [4] presented a method to estimate the seismic-induced sliding movement by adopting a rigid-plastic sliding block model proposed by Ambraseys [5] and recommended the use of slope sliding movement instead of the factor of safety for evaluating seismic slope performance. As revealed by Marcuson [6] and recently reported by Reitherman [7] and Garini et al. [8], Newmark's method was inspired by a previous unpublished study by R. V. Whitman in connection with a study on the displacements of the Panama Canal slopes. Many researchers have discussed the seismic displacement of a slope based on geotechnical experiments and actual earthquake damage information using the Newmark block model [9–13]. However, few researchers considered the nonlinear characteristics of geomaterials and the actual horizontal and vertical accelerations to evaluate the slope stability by seismic slope displacement.

Cracks often can be found in soil and rock slopes due to tensile stress, desiccation, or cycles of drying and wetting [14]. The effect of cracks on slope stability have been investigated by many scholars [14–19]. Utili and Abd [15] examined the influence of cracks on displacement considering the horizontal and vertical seismic effect. Yang [20] calculated slope seismic displacement with a modified Hoek-brown failure criterion by deriving the expression for the yield seismic coefficient. Calculation of the seismic displacement by the yield seismic

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http://dx.doi.org/10.1016/j.soildyn.2017.04.019
Received 17 April 2016; Received in revised form 14 February 2017; Accepted 30 April 2017

coefficient is infeasible when both the actual horizontal and vertical earthquake ground motion records are considered.

The experimental results indicate that the strength envelopes of virtually all geomaterials are characteristically nonlinear in the σ_n–τ stress space, particularly in the range of small normal stresses [21,22]. Nonlinearity is closer to the nature of the geomaterials than linearity, and many researchers [22–26] have shown that nonlinear failure criterion serves a significant role in slope stability. The Hoek–Brown (H–B) failure criterion is considered to model the nonlinear destruction of rock mass reasonably well. However, the majority of the calculation methods and numerical software in geotechnical engineering are built based on the Mohr–Coulomb (M–C) failure criterion. Hoek et al. [27–30] specifically proposed a calculation method for transforming different periods of the H–B failure criterion to the parameters of the linear M–C failure criterion. Li et al. [31,32] compared the probability of failure and the factor of safety between the H–B failure criterion and equivalent M–C parameters and concluded that use of equivalent M–C parameters can cause overestimation of the stability of a slope. Zhang et al. [33] investigated the effect of vertical seismic force on slope stability using the equivalent friction angle and cohesive strength according to the experience values of the input index for the H–B failure criterion. However, the accuracy of using the equivalent M–C shear strength parameters (cohesion and internal frictional angle) to estimate the seismic displacement should be further studied.

There are many methods to analyze the stability of rock slopes, such as limit equilibrium method, limit analysis (e.g. upper or lower bound limit analysis and limit analysis finite element method) and numerical analysis method (e.g. finite element method and discrete element method). Generally, the failure surface must be assumed when limit equilibrium method and limit analysis is used to investigate the stability of rock slopes. For homogeneous and isotropic rock slopes, the curve failure surface including circular arc and log-spiral are always used [20,34]. Yang [20] analyzed the seismic stability of rocks slopes and Qin et al. [34] evaluated the stability of the rock slope reinforced by piles based on the log-spiral failure mechanism. For rock slopes with weak interlayer or joint, the translational failure surface is always assumed [35,36]. Meanwhile, the log-spiral failure mechanism is also commonly used in soil slope stability [11,14,17,39,40]. According to the above analysis, the log-spiral failure mechanism is a conventional collapse mechanism used for stability analysis of soil slopes and homogeneous rock slopes when the upper bound limit analysis is used.

In this study, a calculation model is developed for rock slopes with cracks based on an upper bound limit analysis and a rigid block displacement technique that the H–B failure criterion is considered. A comparison of the seismic displacement obtained by using equivalent M–C parameters and the H–B failure criterion is performed using actual vertical and horizontal earthquake ground motion records. A detail parametric study is carried out to investigate the effect of rock strength parameters (e.g., geological strength index *GSI*, material constant m_i, disturbance coefficient *D* and uniaxial compressive stress σ_c) and crack depths on the seismic displacement of rock slopes. The research results are significant in the seismic design and engineering application of rock slopes with cracks.

2. Generalized H–B failure criterion

H–B failure criterion can reflect the inherent nonlinear characteristics of a rock mass and is highly accepted and extensively applied. Its latest revised form [30] is expressed as

$$\sigma_1 = \sigma_3 + \sigma_c(m\sigma_3/\sigma_c + s)^n \tag{1}$$

where σ_1 is the maximum principal stress; σ_3 is the minimum principal stress; σ_c is the rock uniaxial compressive strength; and *m*, *s* and *n* are material constants given by

$$m = \exp(\frac{GSI - 100}{28 - 14D})m_i \tag{2}$$

$$s = \exp(\frac{GSI - 100}{9 - 3D}) \tag{3}$$

$$n = \frac{1}{2} + \frac{1}{6}\left[\exp(-\frac{GSI}{15}) - \exp(-\frac{20}{3})\right] \tag{4}$$

The geological strength index (*GSI*) describes the quality of the rock mass. The results indicated that the value of *GSI* varies from 5 for extremely poor rock mass to 100 for intact rock. *D* is the disturbance coefficient that varies from 0 for undisturbed rock mass to 1 for very disturbed rock mass. Hoek et al. [30] presented the suggested value of *D* for typical rock mass. m_i is the material constant; its value can be obtained by compression tests.

The “external tangent method” [3,20,37–40] is applied in this paper for establishing the relation between c_t (the intercept of the tangential line with the τ-axis) and φ_t (the tangential friction angle). The envelope of shear failure can be determined by the following types:

$$\frac{\tau}{\sigma_c} = \frac{\cos\varphi_t}{2}\left[\frac{mn(1 - \sin\varphi_t)}{2\sin\varphi_t}\right]^{\frac{n}{1-n}} \tag{5}$$

$$\frac{\sigma_n}{\sigma_c} = \left(\frac{1}{m} + \frac{\sin\varphi_t}{mn}\right)\left[\frac{mn(1 - \sin\varphi_t)}{2\sin\varphi_t}\right]^{\frac{1}{1-n}} - \frac{s}{m} \tag{6}$$

where τ is the shear stress of the H–B failure criterion nonlinear curve (shown in Fig. 1), which can be determined by

$$\tau = c_t + \sigma_n\tan\varphi_t \tag{7}$$

Then, c_t can be expressed as the function of φ_t

$$\frac{c_t}{\sigma_c} = \frac{\cos\varphi_t}{2}\left[\frac{mn(1 - \sin\varphi_t)}{2\sin\varphi_t}\right]^{\frac{n}{1-n}} - \frac{\tan\varphi_t}{m}\left(1 + \frac{\sin\varphi_t}{n}\right)\left[\frac{mn(1 - \sin\varphi_t)}{2\sin\varphi_t}\right]^{\frac{1}{1-n}} + \frac{s}{m}\tan\varphi_t \tag{8}$$

The instantaneous internal friction angle φ_t is introduced as an intermediate variable in searching for the critical sliding surface of slopes by the optimization program.

3. Slope stability assessment based on H-B failure criterion

3.1. Failure mechanism

The log-spiral failure mechanism of rock slopes with cracks is illustrated in Fig. 2. In the figure, the rotational failure surface is defined by the log-spiral equation, which can be expressed as

$$r = r_0 \cdot e^{(\theta-\theta_0)\cdot\tan\varphi_t} \tag{9}$$

where θ_0 is the angle parameter that describes the log-spiral failure mechanism, *r* is the radius that corresponds to θ, r_0 is the radius when

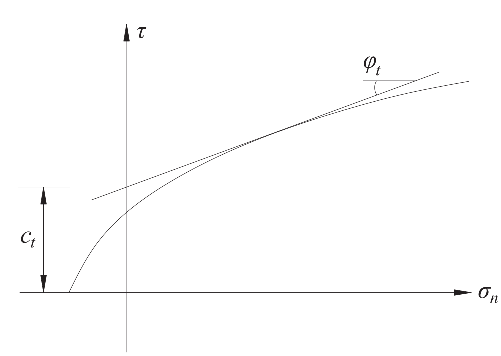

Fig. 1. Tangent line of H–B failure criterion nonlinear curve.