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Seismic stability of earth-rock dams using finite element limit analysis

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ABSTRACT

In this study, a finite element limit analysis method is developed to assess the seismic stability of earth-rock dams. A pseudo-static approach is employed within the limit analysis framework to determine the lower and upper bounds on the critical seismic coefficients of dams. The interlocking force in the soil is considered, and the rockfill material is assumed to follow the Mohr–Coulomb failure criterion and an associated flow rule. Based on the native form of the failure criterion, the lower and upper bound theorems are formulated as second-order cone programming problems. The nonlinear shear strength properties of rockfill materials are also considered. The developed finite element limit analysis is applied to two different types of earth-rock dams. The results indicate that the rigorous lower and upper bounds are very close even for rockfill materials with large internal friction angles. The failure surfaces are easily predicted using the contour of the yield function and the displacement field obtained by the limit analysis method. In addition, the pore water pressures are modelled as external forces in the limit analysis to assess the seismic stability of earth-rock dams in the reservoir filling stage.

1. Introduction

Numbers of earth-rock dams have been constructed in the southwest area of China, which poses a high seismic risk. Thus, the risk assessment of the behaviour of earth-rock dams during earthquakes has become increasingly significant and has attracted considerable attention in geotechnical engineering [1–4]. After the Wenchuan earthquake (2008, M_s=8.0), the seismic design of hydropower projects in China was strengthened.

According to seismic damage statistics, slope failure is a common failure mode for earth-rock dams. In the Wenchuan earthquake, 69 dams were severely damaged. Among them, 16 had landslides including the Fengshou, Minle and Yuejing dams [5,6]. Therefore, the analysis of the seismic stability of dam slopes is extremely important. Many researchers are developing new calculation methods to analyse seismic stability problems. However, the conventional pseudo-static approach is still widely used in engineering design because of its simplicity. In a pseudo-static analysis, the seismic loading is modelled as statically applied inertial forces. The pseudo-static approach has traditionally been implemented with limit equilibrium methods to assess the seismic stability of slopes [7–11]. However, neither static nor kinematic admissibility is necessarily satisfied in limit equilibrium.

Limit analysis, as an alternative approach, has been a powerful tool that provides rigorous lower and upper bounds on the exact collapse load in recent years. Many researchers have made significant progress in developing finite element (FE) limit analysis for stability and bearing capacity problems [12–20]. In FE limit analysis, the problem is transformed into a numerical optimisation problem. To robustly and efficiently solve the optimisation problem, a linear programming (LP) problem of lower or upper bound limit analysis was formulated by linearising the yield function, as shown by Sloan [12,13], Sloan and Kleeman [16], Yu et al. [17], and Kim et al. [18]. Loukidis et al. [19] used a numerical limit analysis based on the previously mentioned studies to determine the lower and upper bounds on solutions to pseudo-static slope stability problems. However, linearization of the yield surface causes the difference of the lower and upper bounds to increase with the internal friction angle ϕ [16,19]; thus, the LP formulation of the limit analysis is suitable for $\phi=0$ or small ϕ values. Over the last decade, the emergence of efficient algorithms for large-scale nonlinear programming (NLP) has resulted in a gradual shift from LP-based methods for limit analysis. By smoothing the Mohr–Coulomb yield surface, Lyamin and Sloan [21,22] employed a general NLP algorithm to solve various problems in geomechanics using limit analysis. Li et al. [23] calculated seismic stability charts of rock slopes using a pseudo-static approach to develop upper and lower bound techniques based on studies by Lyamin and Sloan [21,22] and Krabbenhoft et al. [24]. Yang et al. [25] and Li and Yu

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[26] have also adopted NLP-based approaches to limit analysis. Recently, Makrodimopoulos and Martin [27–29] concentrated on FE limit analysis using second-order cone programming (SOCP) to solve stability or bearing capacity problems.

The study by Makrodimopoulos and Martin[27,28] is followed in this paper to develop both upper and lower bound techniques using a pseudo-static approach to investigate the seismic stability of earth-rock dams in plane strain conditions. Considering the shear strength parameter c as the interlocking force, the rockfill material is assumed to follow the Mohr–Coulomb criterion. A substantial number of experiments [30–32] have shown that rockfill materials have very large internal friction angles. To obtain much tighter bounds than achieved by LP-based limit analysis, the numerical limit analysis is formulated as an SOCP problem using the native form of the Mohr–Coulomb criterion and high-order element type (six-node element) in upper bound limit analysis. By iteratively determining the internal friction angle, the nonlinear shear strength properties of the rockfill materials are also considered in this study. The pore water pressure also affects slope failure in earth-rock dams. Based on the seepage analysis, the seismic stability of a typical rockfill dam with a core wall in the reservoir filling stage, in which pore water pressures are modelled as external forces, is also analysed using FE limit analysis.

2. Shear strength properties of rockfill materials

According to a series of tests, a linear function of the shear strength τ_f and normal (effective) stress σ_n was originally expressed by Coulomb in 1776 as

$$\tau_f = c + \sigma_n \tan\phi \tag{1}$$

where c and ϕ denote the shear strength parameters, described as the cohesion and angle of internal friction, respectively. When an effective stress analysis is conducted, the effective shear strength parameters, which are frequently denoted as c' and ϕ', should be adopted. Cohesion does not exist in rockfill material, which is a type of coarse-grained soil. However, previous studies proved the existence of a new force in the coarse-grained soil, namely interlocking force, which is manifested as cohesion in cohesive soils [31]. Therefore, c in Eq. (1) denotes the interlocking force for rockfill material.

A substantial number of triaxial tests [30,32] have demonstrated that rockfill materials are susceptible to particle breakage under high confining pressure, which causes a redistribution in the intergranular stress and a reduction in the internal friction angle. Consequently, the Mohr–Coulomb envelopes for rockfill materials, as given by Duncan [33], are typically curved

$$\phi = \phi_0 - \Delta\phi \lg(\sigma_3/P_a) \tag{2}$$

where ϕ_0 is the friction angle at the unit atmospheric pressure P_a of confining pressure σ_3 and $\Delta\phi$ is the reduction in ϕ for a 10-fold increase in σ_3. Eq. (2) shows that the shear strength in rockfill materials exhibit nonlinear behaviour.

In this study, both the linear and nonlinear properties of the shear strength of rockfill materials are considered. According to the *Design code for rolled earth-rock fill dams* (SL274-2001) [34] (China), the minimum average values of the shear strength parameters should be adopted.

3. The pseudo-static approach

The *Specifications for seismic design of hydraulic structures* (DL5073-2000) [35] (China) recommends the use of a pseudo-static approach for the seismic stability analysis of earth-rock dams. The concept of the pseudo-static approach relies on the representation of the earthquake-induced loading by statically applied inertial forces. To assess the distribution of the response acceleration along the height of dams, the pseudo-static loads are calculated in terms of the dynamic distribution coefficient α_i, which is also recommended by the specifications mentioned above. For a seismic design intensity of degrees VII, VIII, and IX, the maximum dynamic distribution coefficients α_m at the top of the dam are 3.0, 2.5, and 2.0, respectively, as shown in Fig. 1. In this paper, we assume a design intensity of degree IX (α_m=2.0) and only consider the horizontal seismic loads. Thus, the horizontal seismic loads acting on each element can be calculated as follows:

$$Q = k_h \xi \alpha_i W \tag{3}$$

where ξ denotes the seismic reduction coefficient (generally ξ=0.25) [35]; W denotes the weight of each element; and k_h denotes the horizontal seismic coefficient, which is the ratio of the horizontal peak ground acceleration (PGA) at free-field a_h to the acceleration of gravity g (=9.81 m/s^2), i.e., $k_h = a_h/g$. In this study, the seismic stability of the dam slope is expressed in terms of a single parameter, the critical (or yield) seismic coefficient, k_c, which is equivalent to k_h for a critically unstable dam slope.

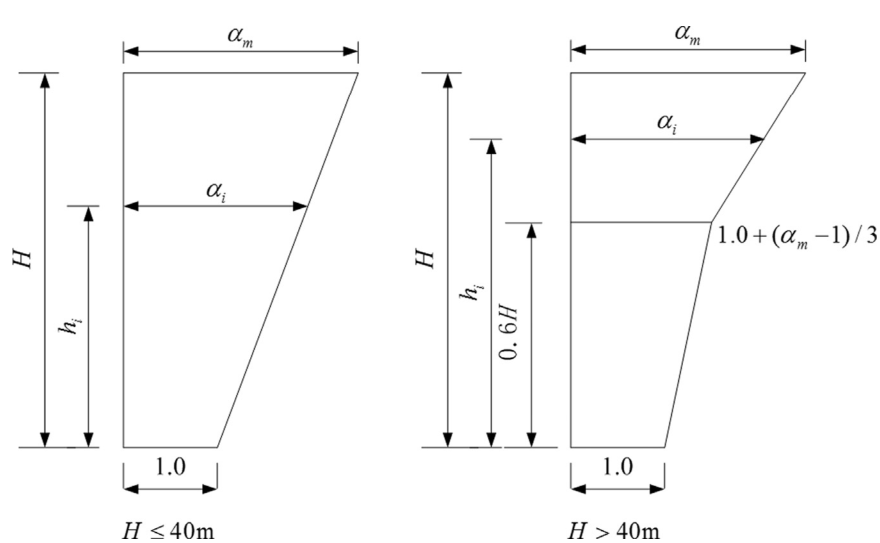

Fig. 1. Dynamic distribution coefficient α_i for rockfill dams.