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Seismic bearing capacity of non-uniform soil slopes using discretization-based kinematic analysis considering Rayleigh waves

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ABSTRACT

This study aims to present a procedure for predicting the bearing capacity of a soil slope under seismic loading. The emphasis is on the variations of soil strength parameters. In order to account for soil profile with varying friction angles in the generation of a potential collapse mechanism, the discretization technique is introduced. The kinematically admissible failure surface is gradually formed by 'point-to-point' method. The modified pseudo-dynamic approach is employed to represent seismic accelerations and forces, with considerations to the Rayleigh wave apart from the primary and shear waves. The upper bound solution of limiting surcharge is formulated from the work rate-based balance equation. The results obtained from the discretization-based kinematic analysis are compared with those computed with the conventional upper bound analysis using the pseudo-static approach. In order to better understand the implication of non-uniform strength parameters on the ultimate bearing capacity and the extent of critical failure surface, a parametric study is carried out to encompass a range of spatial variations of soil strength parameters.

1. Introduction

Slopes are more susceptible to fail in the event of an earthquake, when the additional external action exceeds the available resistance. Such occurrences of landslides threaten human lives and damage to properties. Therefore, its capacity to sustain additional surcharge due to earthquake shaking should be ensured under the limit state in the design of soil slopes.

The limit analysis theory has been widely adopted to evaluate slope stability. By constructing a kinematically admissible velocity field and statically allowable stress field, the upper and lower bound limits of the failure load can be computed. When both solutions converge to a common value, the actual failure load is obtained. Thereof, the upper bound is more commonly used in the design phase, indicating that the actual load at failure is no larger than the load obtained by equating the rate of internal energy dissipation to the rates of total external work [1]. Adopting this approach, the upper bound solutions for some common geotechnical problems were derived by researchers [2–10]. This approach provides a concise and rigorous way for predicting slope stability. In the application of upper bound theorem, there are however some limitations: 1) a pre-assumed rotational failure mechanism is usually suitable for a uniform soil condition, and therefore unable to account for variation in soil friction angle; 2) the seismic stability analyses are mainly investigated based on the pseudo-static approach with constant accelerations, which are unable to characterize the dynamic properties of seismic waves.

In the presence of an earthquake, a direct and accurate way to account for the seismic effect is to adopt the actual acceleration time-history as the input, which is principally feasible in numerical analysis due to the complexity. In contrast, the pseudo-static approach simplifies the seismic accelerations with constant values which may not represent the actual seismic effect on the slope. In order to account for the time- and space-dependent seismic waves in an analytical manner, the pseudo-dynamic approach was proposed to offer a compromise between the aforementioned methods. A pseudo-dynamic earth pressure theory was initially applied to account for the influence of phase difference over the height of a vertical retaining wall [11]. This approach recognizes that a base acceleration input will propagate up through the retained soils at a speed that corresponds to the shear velocity of the soil. This approach has been applied to retaining walls to estimate the active and passive forces acting on a wall [12]. For simplification, both the horizontal and vertical accelerations were expressed by sinusoidal functions without phase difference between the two waves [13–15]. However, an intrinsic limitation exists in this approach – the zero-stress boundary condition at the ground surface cannot be satisfied. In an effort to overcome this drawback, the modified pseudo-dynamic approach was applied to predict the seismic active/passive earth pressure [16,17], considering the Rayleigh wave displacement as derived in

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Kramer [18]. Note that, the limit equilibrium method was used in the above literatures, and related research with the limit analysis theory is limited at present. Although normally consolidated or deposited soils widely exist in site, the non-uniform soil properties are hardly able to be considered in the pseudo-dynamic analyses of earth pressure calculations as mentioned above. The above two aspects can be readily accounted for in this paper.

As mentioned earlier, the conventional kinematic analysis is mainly suited to a uniform soil layer when determining the failure mechanism. The variation of soil strength parameters on slope stability was often neglected. Based on the conventional upper bound analysis, it is hardly able to propose a kinematic velocity field considering the non-uniformity of the soil. A feasible way is to introduce the discretization technique to discretize the problem into components. In the kinematic analysis, this technique is applied to generate a potential collapse mechanism which follows an associated flow rule by the forward difference method. Through discretization, the non-uniform soil properties and external loading conditions can be accounted for within each infinitesimal element. Initially, the method was mainly used for analyzing face stability of pressurized tunnels [19,20]. Two-dimensional and three-dimensional failure mechanisms were generated separately for collapse and blow-out cases. Such a discretization technique was then applied to investigate the seismic stability of a non-uniform soil slope with the pseudo-dynamic approach [21].

In this study, the modified pseudo-dynamic approach will be used to characterize earthquakes in terms of horizontal and vertical accelerations. According to the normality condition, discretized points along the potential failure surface are generated with non-standard curves with considerations to the non-uniformity of friction angles. Resorting to this discretized mechanism, the variations of soil cohesion, friction angle and soil unit weight can be considered, as well as the modified pseudo-dynamic accelerations in different layers and time t in the kinematic analysis. This study aims to estimate the seismic slope stability in terms of limiting surcharge acting on a slope, using this proposed discretization-based kinematic-analysis method.

2. Methodology

2.1. Discretization technique

In conventional upper bound analysis, a potential failure mechanism meeting the kinematically admissible condition is assumed for calculation of rate of external work and internal energy dissipation. In this case, the assumed collapse mechanism plays a key role in deriving the actual ultimate load at failure. The common failure surface is either circular or logarithmic spiral for cohesive materials. However, the above simplified mechanisms are solely appropriate in a uniform soil. Variations of soil strength parameters cannot be accounted for.

In the field, non-uniform soil strength parameters are common in normally consolidated clay. Therefore for a natural slope, approximation of a failure mechanism based on the assumption of a uniform soil is no longer suitable and can potentially lead to errors in design. The requirement to consider seismic effect further adds to the importance of addressing the shortcoming of conventional uniform soil slope stability analysis. Therefore, a revised approach to encompass the variations in soil strength parameters such as friction angle and cohesion must be introduced in slope analysis. This is the objective of this study. In order to account for variations in both the friction angle and cohesion in the kinematic analyses, the discretization technique is introduced to provide a sound methodology to generate a potential failure mechanism.

In the generation of a failure mechanism, the normality condition should be satisfied, which implies that the generated infinitesimal sliding plane makes an angle of internal friction with the velocity vector. In this situation, the varying friction angles can be introduced into a two dimensional problem based on the discretization technique where the potential failure surface is obtained point by point with a given starting point along the contour of the velocity discontinuous line. The detailed procedure will be presented in the next section.

For simplicity, some assumptions are made: 1) the soils are $c-\varphi$ materials satisfying an associated flow rule; 2) a toe failure is expected for a steep slope with high friction angle soils; 3) each infinitesimal triangular failure block rotates as a rigid body around the same rotation center.

2.2. Modified pseudo-dynamic approach

In order to take into account of the dynamic effect induced by an earthquake, a time-dependent approach is necessitated. The pseudo-static method with constant accelerations is therefore unable to represent the inertia forces in this case. The modified pseudo-dynamic approach is superior to the pseudo-dynamic approach and hence adopted in this study as a compromise between the highly complex acceleration time-history and crude approximation of the pseudo-static method. The modified pseudo-dynamic approach considers not only finite primary and shear seismic waves but the Rayleigh wave proposed by Lord Rayleigh [22]. A V_p/V_s ratio of 1.87 is widely accepted for common geological materials given the Poisson's ratio $\upsilon = 0.3$. The introduction of the Rayleigh wave is to ensure the zero-stress boundary condition at the ground surface. Also, the majority of the seismic energy is occupied by the Rayleigh wave which can be significant within a few kilometers from the earthquake epicenter. The detailed derivation of the Rayleigh wave displacement and the application of the modified pseudo-dynamic approach can be found in Kramer [18] and Choudhury and Katdare [16], respectively.

For a two-dimensional problem considering Rayleigh waves, the displacement amplitude is derived as

$$\begin{cases} u = -A_1\left(-ik_R e^{-qz} + \frac{2iqsk_R}{s^2+k_R^2}e^{-sz}\right)e^{i(\varpi t - k_R x)} \\ w = A_1\left(\frac{2qk_R^2}{s^2+k_R^2}e^{-sz} - qe^{-qz}\right)e^{i(\varpi t - k_R x)} \end{cases} \tag{1}$$

where

$$q^2 = k_R^2 - \frac{\varpi^2}{V_p^2}\ ,\ \ s^2 = k_R^2 - \frac{\varpi^2}{V_s^2} \tag{2}$$

For a random earthquake input, its seismic signal can be expressed as a weighted sum of harmonic signals by the means of Fourier transform. Therefore, the harmonic waves are considered for the seismic waves in this study. Through differentiating the above displacement formulas twice with respect to time, the seismic horizontal (a_h) and vertical (a_v) accelerations are derived by considering the real parts only, namely,

$$\begin{cases} a_h = \frac{\partial^2 u}{\partial t^2} = -\varpi^2 A_1\left(-k_R e^{-qz} + \frac{2qsk_R}{s^2+k_R^2}e^{-sz}\right)\sin(\varpi t - k_R x) \\ a_v = \frac{\partial^2 w}{\partial t^2} = -\varpi^2 A_1\left(\frac{2qk_R^2}{s^2+k_R^2}e^{-sz} - qe^{-qz}\right)\cos(\varpi t - k_R x) \end{cases} \tag{3}$$

Since the above equations consider seismic horizontal and vertical accelerations separately, combinations of primary and shear waves can be achieved, which offers a more comprehensive seismic analysis and readily adaptable to the discretization technique to compass varying soil properties encountered in slope stability problems.

3. Pseudo-dynamic stability analysis

3.1. Generation of a potential collapse mechanism

The purpose of this study is to estimate the bearing capacity of a soil slope under seismic effect. As mentioned earlier, the discretization technique generates a discretized failure mechanism which allows for variation in soil strength parameters. The process of generating a