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Research Paper

Stability analysis of seismic slopes with cracks

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ABSTRACT

Earthquakes can trigger slope instability, especially in the case of slopes with cracks. Studies of slope stability rarely account for the presence of cracks. In this study, the upper bound limit analysis technique and the pseudo-static method were used to examine the stability of homogeneous slopes with cracks subjected to seismic loading. A series of stability charts for slope inclinations of 2:1 ($\beta = 63.4°$), 1:1 ($\beta = 45°$), 2:3 ($\beta = 33.7°$), and 1:2 ($\beta = 26.6°$) (vertical to horizontal) and internal friction angles, φ, of 10°, 20°, 30°, and 40° are presented. These charts should be useful for readily determining the stability number (critical slope height), the critical crack depth, and the region affected by cracks for cracks of known depth but unknown location, cracks of known location but unspecified depth, and cracks of unspecified depth and location.

1. Introduction

A significant number of studies on earthquake-induced landslides have shown that cracks appear on slopes that experience seismic activity [1–3]. However, there have been very few analyses of slopes with cracks subjected to seismic effects, as either the crack or the seismic force is ignored in most studies on slope stability. Various methods, such as limit equilibrium methods, numerical approaches (e.g., finite element method and finite difference method), and limit analysis, have previously been used to investigate the stability of earth structures (e.g., embankments and slopes) with cracks [4–9]. Some scholars have assumed that the crack depth is known and prescribed a fixed crack position when evaluating slope stability, ignoring the effect of crack position [10,11]. However, there can be multiple cracks in a slope. Thus, there is no guarantee that the crack analyzed is the one most critical to the stability of the slope. Chen et al. [12] proposed a simple failure mechanism involving a rigid rotation for intact slopes (no cracks); subsequent numerical studies have shown this method to be effective in providing an upper bound very close to the true collapse load. Since then, numerous researchers have studied slope stability under complex conditions using upper bound limit analysis. Recently, Utili [7] and Michalowski [8,9] independently developed a method for assessing the effect of cracks on slope stability while taking into account both depth and location of the crack using the upper bound limit analysis technique suggested by Chen [13]; their discussions [14,15] inspired other researchers to further develop the analytical technique for cracked slopes. In most previous studies, cracks are considered as preexisting formations of the failure mechanism; however, Michalowski [8,9] considered crack formation as a part of the failure mechanism by calculating the energy dissipated during the crack formation process. However, the effects of the seismic forces have not yet been considered.

The most commonly used method for analyzing seismic slope stability is the so-called pseudo-static analysis technique, which was first employed by Terzaghi [16] in the analysis of slopes subjected to seismic effects; in this method, the seismic action on a slope is accounted for by applying horizontal and vertical seismic forces. There is no consensus on how to select the values of the pseudo-static factors (vertical and horizontal), yet a widely accepted practice is to take the peak acceleration for the region where the slope is located [17–21]. Numerical methods, such as the finite element method, can be used to determine the failure mechanism without assuming a particular failure shape; however, these methods are complicated, as they depend significantly on the model and calculation process used. Newmark's sliding block analysis technique is mainly used for permanent seismic displacement analysis [22,23]. Nevertheless, stability charts for seismic slopes based on the aforementioned methods that account for cracks are hard to find.

Michalowski [8,9] concluded that the reduction in the critical height of a slope due to cracks could be as high as 10%. It is well

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known that seismic forces have a significant effect on the stability of slopes [17–21]. Ignoring the existence of cracks in a slope may lead to overestimate the stability of a slope, especially when the slope is subjected to a strong earthquake [11,24]. Zhang et al. [11,24] analyzed the seismic slope stability based on a tension-shear failure mechanism; however, only a specified slope was studied in this case.

The main purpose of the present study was to extend the work of Utili [7] to the seismic condition. In this study, the vertical and horizontal seismic forces, as well as the cases in which cracks have known depth but unknown location, known location but unknown depth, and unknown depth and location were taken into account. A series of stability charts were obtained using the upper bound limit analysis technique and the pseudo-static method. These charts should be useful for preliminary slope design, allowing the designer to determine—without having to use an iterative process—the stability number (critical slope height), critical crack depth, and the region where the presence of cracks does not affect the stability of the slope.

2. Stability analysis

2.1. Basic assumptions

The upper bound limit analysis technique is based on the principle of virtual work. The objective function is determined by equating the rate of external work to the rate of internal dissipation in the soil mass sliding away, and the lowest limit load can be obtained based on the principle of minimum energy dissipation. When the upper bound limit analysis technique is used to analyze slope stability, the following basic assumptions are made: (1) the soil mass of the slope is an ideal rigid, perfectly plastic body; (2) the soil mass obeys the associated flow rule; (3) plane strain conditions apply; and (4) the principal stress and principal strain are coaxial.

2.2. Failure mechanism

The log-spiral failure mechanism adopted in previous slope studies can be of the following three types: shallow toe log-spiral mechanism, deep toe log-spiral mechanism, and below toe log-spiral mechanism [25,26] (see Fig. 1(a)). The stability number formulae corresponding to the shallow toe and deep toe log-spiral mechanisms are identical special cases of the stability number formula corresponding to the below toe log-spiral mechanism when $\beta = \beta'$. Therefore, in this study, the failure of a slope passing below a slope toe was used as the general case for analysis. Cracks can be divided into two types based on their location: cracks through the upper surface of a slope (the failure mode is illustrated in Fig. 1(b)) and cracks through the slope face (the failure mode is illustrated in Fig. 1(c)).

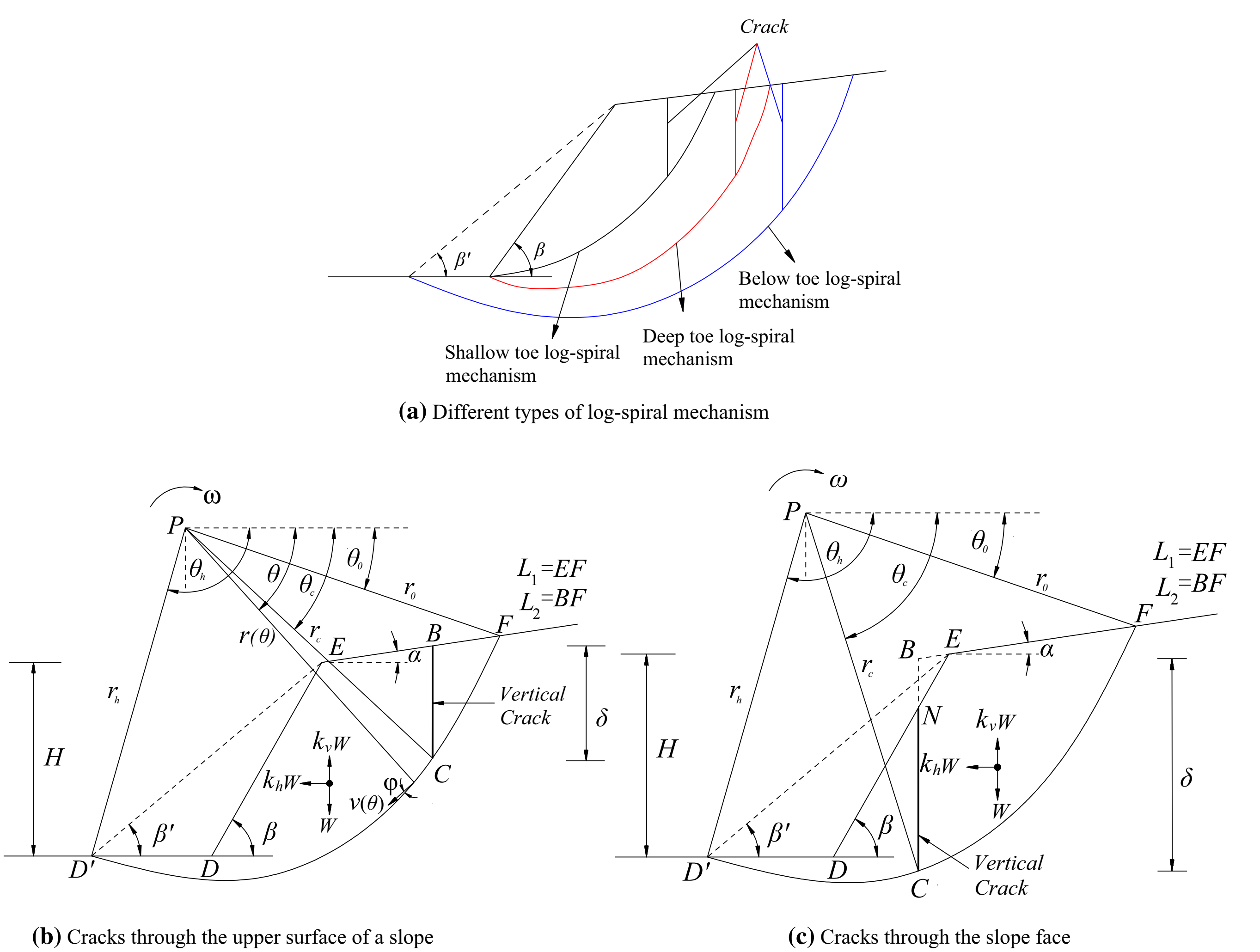

Fig. 1. Failure mechanism.