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Stability charts of slopes under typical conditions developed by upper bound limit analysis

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ABSTRACT

This paper presents stability charts of homogeneous isotropic slopes developed by the upper bound limit analysis theory and strength reduction technique. The objective function of the homogeneous isotropic slope safety factor is optimized by nonlinear sequential quadratic programming. The stability charts of homogeneous isotropic slopes under simple conditions are developed by the analysis of substantial data and those of slopes under different conditions, by considering the effects of typical factors such as surcharge load, pore water pressure, and horizontal seismic forces. These charts can be quickly and easily used to determine the safety factor and corresponding slope failure mechanism under different typical conditions. The failure mechanisms of sample slopes under different conditions are provided to illustrate the uses of these stability charts.

1. Introduction

Stability charts are convenient for the preliminary assessment of slope safety, and therefore, several studies have aimed to develop such charts for use in engineering practice.

Taylor [1] used the friction circle method to construct stability charts for undrained clay slopes (cohesion force $c \neq 0$, internal friction angle $\varphi = 0$) and general clay slopes (cohesion force $c \neq 0$, internal friction angle $\varphi > 0$). These charts can be used to evaluate slope stability based on certain parameters. The stability factor N of an undrained clay slope is obtained without iterations as $N = c/\gamma HF$, where γ is the unit weight of the soil; F, the safety factor of the slope; and H, the height of the slope. However, iterations are required to evaluate the safety factor of a homogeneous slope.

Many studies have been revised and improved available stability charts to avoid iterative calculations when the stability factor N was introduced to define slope stability. Bishop and Morgenstern [2], Bell [3], Singh [4], Hoek and Bray [5], Cousins [6], Baker and Tanaka [7], Baker et al. [8] proposed different stability factor ($N = c/\gamma HF$) calculation methods based on the limit equilibrium or limit analysis theory. The stability factor N defined by Bell [3] and Hoek and Bray [5] was convenient because it did not require an interpolation calculation process. Michalowski [9–11] used the limit analysis theory to plot a series of stability charts according to the stability number ($N^* = c/\gamma H\tan\varphi$) defined by Bell [3] without iterative calculations.

Based on the work of Sun and Zhao [12], Klar et al. [13] used the limit equilibrium method to develop a new set of stability charts. The use of these charts in estimating the safety factor and determining the failure mechanism of homogeneous soil slopes is quite simple and straightforward. By using compound circles comprising two circular arcs separated by a straight line at the interface with a stiff stratum, Steward et al. [14] proposed five types of failure mechanisms of homogeneous soil slopes and updated the stability charts ($N = c/\gamma HF$) developed by Taylor [1]. They used the SLOPE/W software to obtain the stability factor and determine the type of critical failure circles, eventually developing a stability chart that could be used to quickly determine the stability factor without iterative calculations. Their chart also enables the mutual authentication of calculation results and therefore has good application potential.

The main purpose of the present study was to extend the work of Steward et al. [14] to typical conditions. The stability charts presented in this paper are an extension of those obtained by Michalowski. Furthermore, they consider the effects of pore water pressure and seismic forces on the slope as well as the effect of surcharge load on slope stability. For given values of c, φ, γ, H, and β (β is the slope angle), the safety factor F be obtained reading $\tan\varphi/F$ or $c/\gamma HF$ from these stability charts under different conditions. These stability charts could be used for the quick evaluation of the safety status of a homogeneous slope under typical conditions

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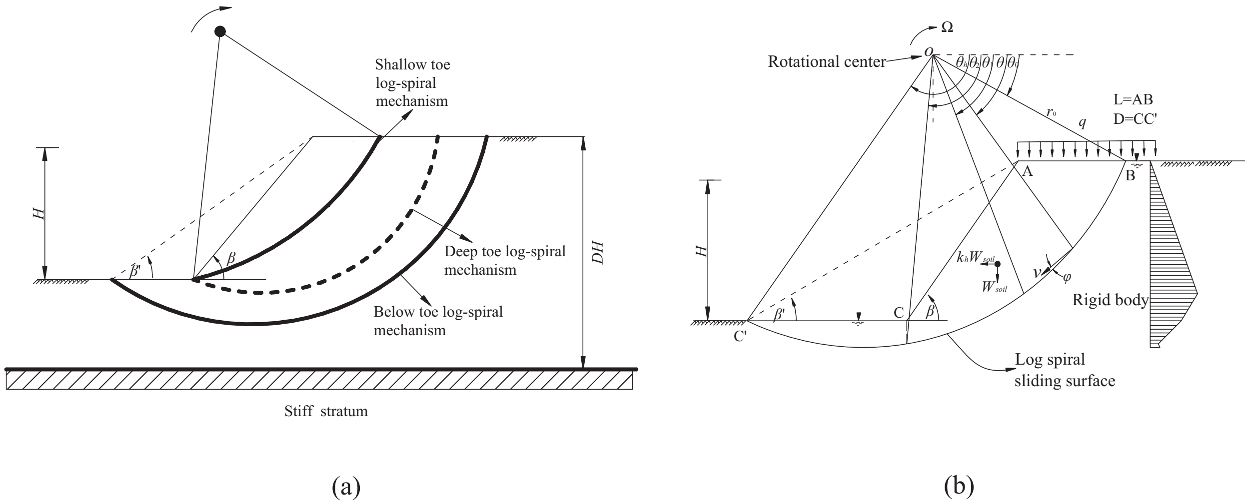

Fig. 1. Stability analysis: (a) three types of slope failure mechanisms; (b) rotational failure mechanism of slope under different typical conditions; for shallow and deep toe failure mechanisms, $\beta' = \beta$.

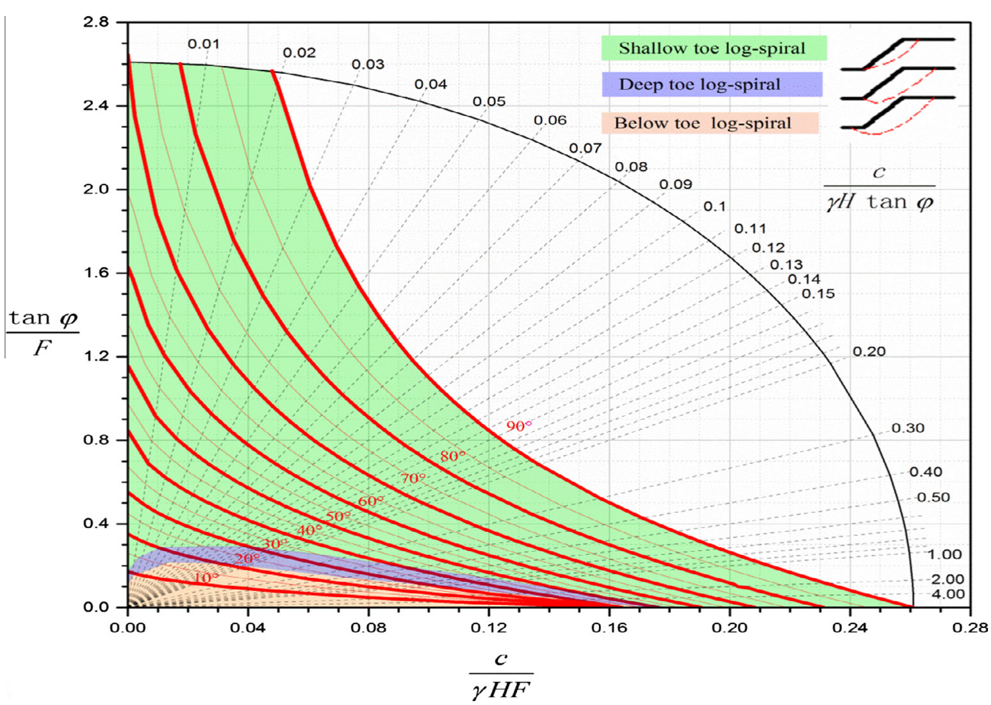

Fig. 2. Stability charts for simple homogeneous slope.

and to identify the types of rotational failure mechanisms associated with the stability factor. The upper bound limit analysis was used for this purpose. The work reported in this paper involved thousands of runs to analyze the stability of various slopes with different geometries and soil parameters under different conditions. Approximately 4000 solutions were obtained and used to develop a single design chart by nonlinear sequential quadratic programming.

2. Strength reduction technique and homogeneous slope stability analysis

In engineering practice, the natural or artificial slope of a geotechnical structure has a certain safety reserve, but changes in the external and internal conditions may destroy it. In the evaluation of the safety reserve of a slope, researchers have often combined the limit analysis method with the strength reduction technique to determine the slope safety factor. The strength reduction technique was first proposed by Bishop [15], and it is widely used in the analysis of the stability safety factor based on the linear Mohr–Coulomb (M-C) failure criterion (Zienkiewicz et al. [16], Duncan [17], Griffiths and Lane [18], Das [19], Steward et al. [14]). The principle of the strength reduction technique is roughly consistent with engineering practice considering that the failure of geotechnical slopes is often caused by external factors that decrease the strength of the rock mass.

The use of the strength reduction technique to determine the safety factor of a slope based on the upper bound limit analysis