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Stability of unsupported conical excavations in non-homogeneous clays

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ABSTRACT

New plasticity solutions for the undrained stability of unsupported conical excavations in homogeneous and non-homogeneous clays were solved by axisymmetric finite element limit analysis. Three parametric studies were performed on excavated height ratios, slope inclinations and dimensionless strength gradients. In all cases, the exact stability factors were accurately bracketed by computed bound solutions within 0.6%. An accurate closed-form equation of the stability factor was proposed from nonlinear regression analysis of lower bound solutions. New conical stability factors for soil cohesion, strength gradient, and coupling effect of these components were deduced to conveniently and accurately predict a safe solution in practice.

1. Introduction

In practice, unsupported excavations are commonly found in the construction of footings, piers, columns, water tanks, etc. For cohesive soils, an unsupported vertical cut can be achieved by excavating from the ground surface to the final depth of these structures. To minimize the ground movement, a temporary retaining wall, such as a braced or cantilever sheet pile wall, can be employed for the open excavation of such constructions, but this requires the additional expense of installing a retaining wall. Thus, the unsupported open cut method is still one of the most practical methods for temporary excavations to prepare the foundations of the above structures.

A relatively simple open excavation corresponds to an infinitely long unsupported cut that can be represented by a two-dimensional (2D) plane strain problem. In general, an unsupported vertical cut appears in rectangular or square shapes, which represents a relatively complicated problem in three-dimensional (3D) analysis, but it may be idealized by an axisymmetric or circular excavation as a first approximation suggested by Britto and Kusakabe [1]. Conical excavations can also be found in various practical applications. For example, an unsupported square excavation with all-around side slope may be approximated as this problem. In addition, conical excavations can be employed to construct underground conical pits for energy storage applications [2,3] known as pit thermal energy storages [4,5]. Furthermore, they can be encountered in a construction of an underground structure such as a conical concrete storage tank for molten salt in a storage solar power plant [6]. Thus, the determination of a safety factor of conical excavations for these practical applications is the most important aspect to ensure an adequate safety during the excavation, which is the subject of this study note.

The problem definition of an unsupported conical excavation that consists of a height (H), a radius at the bottom of excavation (b), and a slope inclination (β) is shown in Fig. 1. The clay obeys the rigid-perfectly plastic Tresca material with the associated flow rule. The soil profile is non-homogeneous clay, where the undrained shear strength increases linearly with the depth from the ground surface (s_{u0}) and has the strength gradient (ρ). The clay is assumed to have a constant unit weight (γ). Based on the dimensionless analysis [7] of this problem, it can be shown that the undrained stability of unsupported conical excavation in non-homogeneous clay can be represented by three dimensionless groups, as shown in Eq. (1).

$$N = \frac{\gamma H}{s_{u0}} = f\left(\frac{H}{b}, \frac{2\rho b}{s_{u0}}, \beta\right) \quad (1)$$

where $\gamma H/s_{u0}$ = undrained stability factor, H/b = excavated height ratio, $2b\rho/s_{u0}$ = dimensionless strength gradient and β = slope inclination of conical excavation.

A large number of studies on the undrained stability of vertical cuts in the plane strain condition have been conducted in the past [e.g., 8–14], and the exact solution of an unsupported vertical cut in the plane strain condition was numerically solved by employing finite element limit analysis (FELA) with the adaptive mesh refine-

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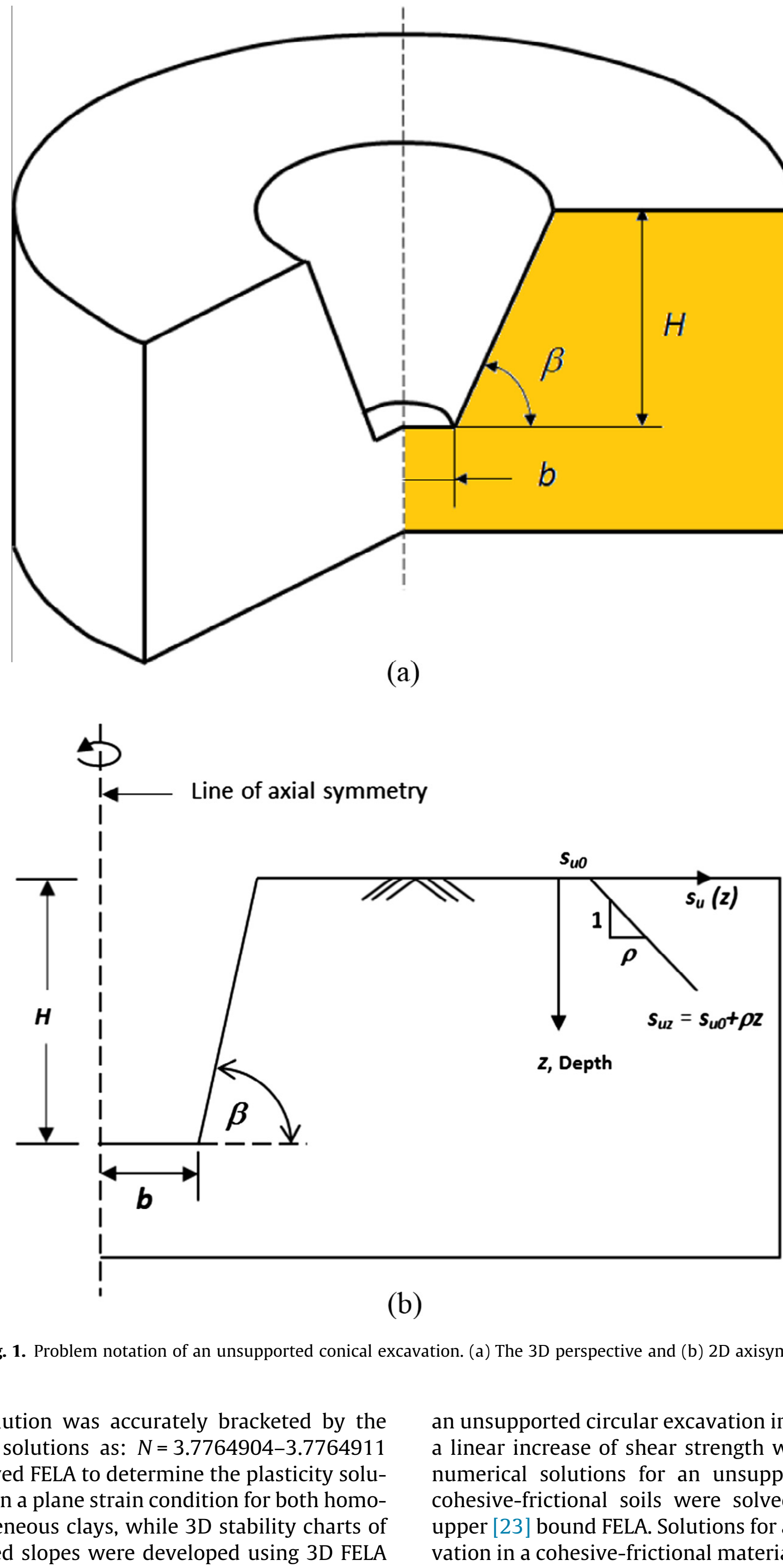

Fig. 1. Problem notation of an unsupported conical excavation. (a) The 3D perspective and (b) 2D axisymmetry.

ment [14]. The exact solution was accurately bracketed by the lower and upper bound solutions as: $N = 3.7764904–3.7764911$ [14]. Yu et al. [15] employed FELA to determine the plasticity solutions of an inclined slope in a plane strain condition for both homogeneous and non-homogeneous clays, while 3D stability charts of the drained and undrained slopes were developed using 3D FELA [16,17].

An undrained stability problem for an unsupported circular excavation, which represents the special case of the proposed study (where $\beta = 90°$), has been numerically investigated in the past [1,18–20]. Khatri and Kumar [21] employed an axisymmetric lower bound FELA to determine the undrained stability factors for an unsupported circular excavation in non-homogeneous clay with a linear increase of shear strength with depth. Subsequently, the numerical solutions for an unsupported circular excavation in cohesive-frictional soils were solved using the lower [22] and upper [23] bound FELA. Solutions for an unsupported circular excavation in a cohesive-frictional material have also been presented in the state-of-the-art paper, geotechnical stability analysis by Sloan [24] who employed 3D FELA, where the exact solution of this problem was accurately bracketed by computed lower and upper bound solutions. Unsupported conical excavations in a cohesive-frictional soil were solved as benchmark solutions to check the performance of new formulations in 3D FELA [25,26], but they were