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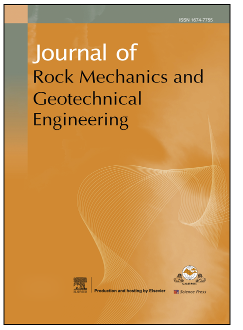

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A new design equation for drained stability of conical slopes in cohesive-frictional soils

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Abstract: New plasticity solutions to the drained stability of conical slopes in homogeneous cohesive-frictional soils were investigated by axisymmetric finite element limit analysis. Three parameters were studied, i.e. excavated height ratios, slope inclination angles, and soil friction angles. The influences of these parameters on the stability factor and predicted failure mechanism of conical slopes were discussed. A new design equation developed from a nonlinear regression of the lower bound solution was proposed for drained stability analyses of a conical slope in practice. Numerical examples were given to demonstrate a practical application of the proposed equation to stability evaluations of conical slopes with both associated and non-associated flow rules.
Keywords: limit analysis; slope stability; conical slope; unsupported excavation; cohesive-frictional soils

1. Introduction

Various civil construction projects involve slope stability problem, such as natural, filled and cut slopes. Determination of the factor of safety for these slopes is the most important aspect to ensure an adequate safety of the slopes in both short and long terms. Due to the practical importance, slope stability has drawn much attention from many investigators, including two-dimensional slope stability under a plane-strain condition (Griffiths and Koutsabeloulis, 1985; Yu et al., 1998; Michalowski, 2002; Li, 2006; Martin, 2011; Griffiths and Yu, 2015), and three-dimensional (3D) slope stability (Griffiths and Marquez, 2007; Li et al., 2009, 2010; Michalowski, 2010; Xie et al., 2011; Lu, 2015; Lim et al., 2016; Kelesoglu, 2016). In many practical and theoretical considerations of the problem, the plane-strain condition is commonly assumed in a conventional analysis of slope stability (e.g. Zheng et al., 2009; Chen and Huang, 2011; Yang et al., 2011; Li et al., 2014; Yao et al., 2014; Ghanbari and Hamidi, 2015). However, an inclined slope in an axisymmetric condition, called conical slope, can be generally found in various practical applications. For example, unsupported vertical circular excavations are fairly common especially in the construction of cast in situ piles or piers. In addition, an unsupported square excavation with all-around side slope may be reasonably approximated as a conical slope. A cut slope with a rectangular shape may also be simplified as a conical slope with an equivalent radius that produces the same cross-sectional area of the rectangular slope. Furthermore, conical slopes can be employed to construct underground conical pits for energy storage applications (Dincer, 2010; Lee, 2013), known as pit thermal energy storages (Ochs et al., 2009; Schmidt and Miedaner, 2012), and underground structures, such as conical concrete storage tanks for molten salt solar power plants (Salomoni et al., 2008).

A number of studies for unsupported axisymmetric excavation were performed in the past to study the stability problems, especially unsupported vertical circular excavations in both cohesive and cohesive-frictional soils. These include analytical lower bound (LB) and upper bound (UB) analyses for homogeneous clays (Britto and Kusakabe, 1982; Pastor and Turgeman, 1982), and LB and UB finite element limit analysis (FELA) for linearly increasing cohesive (Khatri and Kumar, 2010; Kumar et al., 2014) and cohesive-frictional soils (Kumar and Chakraborty, 2012; Kumar et al., 2014). Recently, Keawsawasvong and Ukritchon (2017a) investigated the unsupported conical excavation in both homogeneous and non-homogeneous clays using FELA for a wide range of height ratios, dimensionless strength gradients and slope inclination angles, while a closed-form approximate expression was proposed for the LB solutions to predict the stability factor for an unsupported conical excavation in a generalized linearly increasing undrained strength profile. Till now, there have been very few studies of the conical slope stability in cohesive-frictional soils in the literature, except for the special case of unsupported vertical circular excavations, as mentioned earlier (Kumar and Chakraborty, 2012; Kumar et al., 2014).

This paper extends the previous study of Keawsawasvong and Ukritchon (2017a) for a conical slope in an undrained material to cover the general case of the problem in a drained material. In this study, OptumG2 (Krabbenhoft et al., 2015), the computational limit analysis using FELA for axisymmetric problems, was employed to investigate the drained stability of unsupported conical slopes in cohesive-frictional soils. The OptumG2 was chosen based on several successful investigations of the authors on a variety of stability problems in geotechnical engineering under both plane-strain and axisymmetric conditions, including planar suction caissons (Keawsawasvong and Ukritchon, 2016a), cylindrical suction caissons (Ukritchon and Keawsawasvong, 2016), circular shallow foundations (Ukritchon and Keawsawasvong, 2017a), laterally loaded piles (Keawsawasvong and Ukritchon, 2016b, 2017b; Ukritchon and Keawsawasvong, 2017b, d), limiting pressure of soil gaps between stabilizing piles (Keawsawasvong and Ukritchon, 2017d; Ukritchon and Keawsawasvong, 2017c), active trapdoors (Keawsawasvong and Ukritchon, 2017c), cantilever flood walls (Keawsawasvong and Ukritchon, 2017e), and opening in underground walls (Ukritchon and Keawsawasvong, 2017c). Results of the parametric study of drained conical slopes were summarized in the form of the dimensionless parameters, including stability factor, slope height ratio, soil friction angle and slope inclination angle. The influences of these input parameters on the predicted failure mechanism of conical slopes were discussed and compared. A new design equation developed from a nonlinear regression of the LB solutions of conical slope was proposed as a convenient tool for a stability analysis of this problem in practice. An application of the proposed equation was demonstrated through examples of a conical slope with both associated and non-associated flow rules.

2. Description of numerical models in FELA

Fig. 1 shows the problem definition of an unsupported conical slope with height (H), radius at the bottom of slope (b) and slope inclination angle (β). The soil profile corresponds to a homogeneous cohesive-frictional soil with a constant unit weight (γ), effective cohesion (c) and effective soil friction angle (ϕ). The cohesive-frictional soil corresponds to an intermediate soil, and is modeled by a perfectly plastic Mohr-

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