Computers and Geotechnics 81 (2017) 284–293

Contents lists available at ScienceDirect

Computers and Geotechnics

journal homepage: www.elsevier.com/locate/compgeo

Technical Communication

Undrained stability of an active planar trapdoor in non-homogeneous clays with a linear increase of strength with depth

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ARTICLE INFO

Article history:
Received 17 June 2016
Received in revised form 6 August 2016
Accepted 28 August 2016

Keywords:
Limit analysis
Numerical analysis
Stability
Trapdoor
Active failure

ABSTRACT

Finite element limit analysis was employed to determine the upper and lower bound solutions of the active failure of a planar trapdoor in non-homogeneous clays that have a linear increase of strength with depth. Influences of cover ratio, dimensionless strength gradient and trapdoor roughness on predicted failure mechanisms and stability factors were determined. In all cases, the exact stability factors were accurately bracketed by computed bound solutions within 1%. Accurate closed-form equations to predict the exact estimates of stability factors, trapdoor pressure and factor of safety using the new proposed factors for the cohesion and strength gradient are presented.

1. Introduction

Active and passive failures of a trapdoor are classical stability problems in geotechnical engineering, in addition to the bearing capacity of shallow foundations, retaining walls and slopes. The active and passive collapses of a trapdoor corresponds to a determination of the limit loads that act on the downward and upward movements of the trapdoor, respectively. The original study of stress distribution on a trapdoor in sand was experimentally investigated by Terzaghi [1]. In addition to being an important benchmark solution in theoretical geomechanics, the stability of a trapdoor is of considerable practical interest in many applications. The passive failure of a trapdoor corresponds to the pullout problem of a vertical plate anchor in soils, and has been studied widely [2,3]. On the other hand, the solution of the active trapdoor can be applied to analyze the collapse of an underground roof in tunnels and mining works [4], the gravitational flow of a granular material through hoppers [5,6], and the stability of buried pipes subjected to the loss of ground support [7].

A relatively large number of studies on the stability of an active trapdoor have been investigated previously and include physical model tests [1,5,8–13], numerical analysis by the limit equilibrium method (LEM) [14], finite element analysis [10,15] and limit analysis [9,16,17]. Some researchers have considered the planar trapdoor problem in a purely and homogeneously cohesive soil [16–19]. However, no study on the undrained active failure of a planar trapdoor in non-homogenous clay with a linear increase of undrained shear strength has been reported, and so is the subject of this note.

The problem definition of an active trapdoor under the plane strain condition is shown in Fig. 1. A depth of a non-homogeneous clay layer (H) rests on a rigid boundary and a rigid trapdoor of width (B). The clay behaves as a rigid-perfectly plastic Tresca material with the associated flow rule. The non-homogeneous clay has an undrained shear strength that increases linearly with the depth from the ground surface (s_{u0}) with a strength gradient (ρ). Despite the strength non-homogeneity, the clay is assumed to have a constant unit weight (γ). The ground surface is fully loaded by a uniform surcharge (σ_s). To produce the active failure, the trapdoor is assumed to move downwards as a rigid body that is resisted by the externally applied uniform trapdoor pressure (σ_t). Such a failure happens due to the actions of the surcharge (σ_s) and the soil unit weight (γ) and is resisted by the trapdoor pressure (σ_t) and the shear resistance of clay (s_{u0}, ρ). This study considers either purely rough or smooth cases, where the former corresponds to a perfectly rough surface at both the trapdoor and the bottom boundary, and the latter corresponds to a perfectly smooth surface of these. It is expected that the true boundary condition should lie somewhere between these two cases.

Following previous studies of an undrained collapse of an active trapdoor in cohesive soils [18,19], the solution of this problem is

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http://dx.doi.org/10.1016/j.compgeo.2016.08.027
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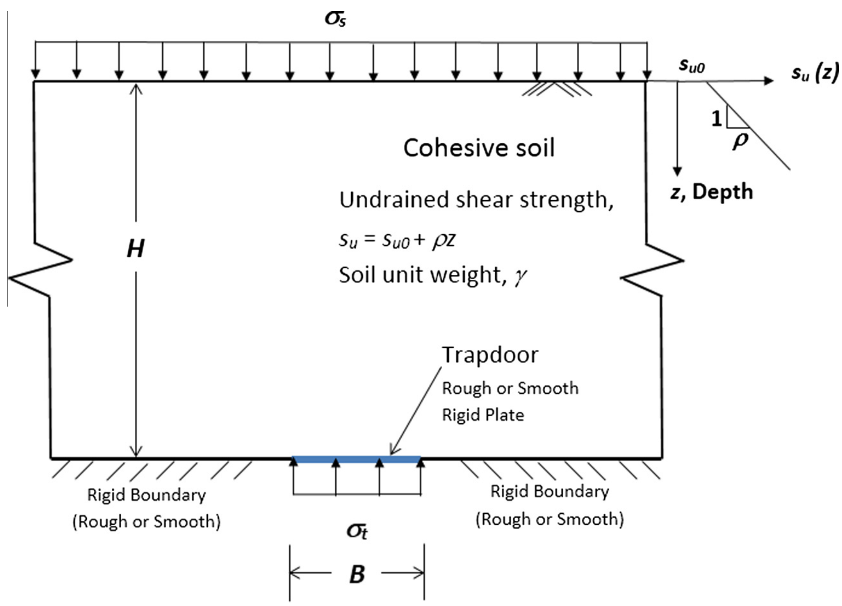

Fig. 1. Active trapdoor under a plane strain condition.

represented by the dimensionless stability factor (N), as shown in Eq. (1);

$$N = \frac{\sigma_s + \gamma H - \sigma_t}{s_{u0}} = f\left(\frac{H}{B}, \frac{\rho H}{s_{u0}}, \alpha\right) \quad (1)$$

where H/B is the cover ratio, $\rho H/s_{u0}$ is the dimensionless strength gradient, α is the adhesion factor at the interfaces of rigid trapdoor and bottom boundary = s_{ua}/s_u, and s_{ua} and s_u are the undrained shear strength at the interfaces and the surrounding soil, respectively.

Note that the negative sign in front of the trapdoor pressure (σ_t) denotes that it is the resistance of the problem, while the surcharge (σ_s) and the soil unit weight (γ) are the driving stresses that cause the active failure. The rough and smooth cases correspond to $\alpha = 1$ and 0, respectively.

With respect to previous studies on the active failure of a trapdoor in a homogeneous clay [16–19], the most accurate solutions were derived by employing finite element limit analysis (FELA) to solve this problem [18,19]. Sloan et al. [18] presented a significant improvement on N bound solutions as compared to previous studies [16,17], especially for deep trapdoors and the influence of interface roughness on the N solutions that became significant when $H/B > 5$. Their bound solutions had an accuracy of 7–11% for all H/B ratios. Subsequently, Martin [19] proposed the stress and velocity fields of new slip-line solutions for a shallow trapdoor (H/B = 0.5–2) and validated the results using FELA with an adaptive mesh refinement and confirmed that the slip-line solutions were actually the exact ones only for $H/B < 1.3$.

This paper extends these previous studies on planar trapdoors [18,19] in homogeneous clays to investigate the influence of the linear strength non-homogeneity of clay on the undrained bound N solutions of active failure, which has not been addressed before. The study employed the state-of-art FELA software, OptumG2 [20], to accurately determine the undrained active collapse of a trapdoor

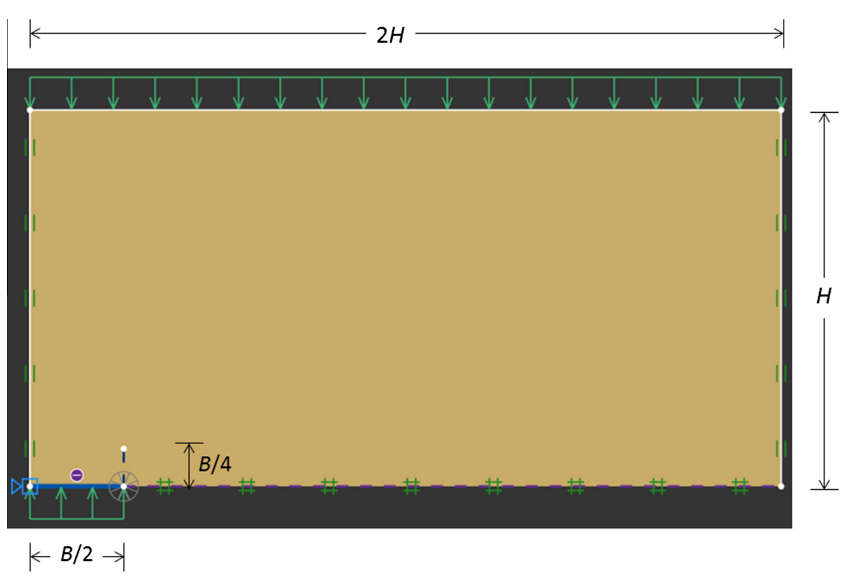

Fig. 2. Numerical model of the undrained stability of an active planar trapdoor in OptumG2.