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Technical note

Design equations for undrained stability of opening in underground walls

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ABSTRACT

Undrained stability of an opening in underground walls in clays with constant and linearly increasing shear strengths with depth was investigated by two-dimensional finite element limit analysis under plane strain condition. Three parametric studies were performed to study the effects of the cover depth ratio, overburden stress factor and linear strength gradient ratio on the load factor of the opening in underground walls. Predicted failure mechanisms associated with these parameters were discussed and examined. New design equations for the undrained stability of an opening in underground walls in clays with an arbitrary linear increase in strength with depth were developed for a practical application in the field of trenchless constructions.

1. Introduction

In recent years, a concrete diaphragm wall is commonly employed as a permanent retaining structure for deep excavations in soft soils in various constructions including basements, underpasses, shaft stations of tunnels, cut-and-cover tunnels, and among others (e.g., Ou, 2006; Puller, 2003). This paper concerns with the study of undrained stability of an opening in underground walls in clays, as shown in Fig. 1. The problem statement consists of a rigid underground wall with an opening in cohesive soils in which the wall is completely supported by lateral bracings. The active collapse of this problem is caused by the driving force generated from the soil self-weight (γ) and a uniform surcharge on the ground surface (σ_s), and resisted by the mobilized soil shear resistance (s_u), a pressure at the opening (σ_t) and a side friction along the underground wall. The study of the problem is important for the stability evaluation of an opening in underground walls for many practical trenchless constructions such as the opening for a launch of a tunnel at a working shaft (Guglielmetti et al., 2008; Li et al., 2009), ventilating shaft (Wu et al., 2017), microtunnelling and horizontal drilling (Barla et al., 2006; Chapman and Ichioka, 1999; Cui et al., 2015), underpass constructions (Zhang et al., 2016), etc. In addition, it can be practically applied for the opening that may occur due to a failure of some segmental linings of underground walls and other circumstances. The soil collapse at the opening can induce the failure zone that propagates up to the ground surface resulting in severe damages to adjacent structures and facilities.

The stability of this problem was firstly studied by Broms and Bennermark (1967) who performed experiments of extruding clay under pressure through vertical circular openings and proposed the stability ratio (N) as:

$$N = (\sigma_s + \gamma H - \sigma_t)/s_u \quad (1)$$

where γ = soil unit weight, s_u = undrained shear strength of soil, $H = C + D/2$ is depth measured from the ground surface to the center of opening, C = cover depth and D = opening height (see Fig. 1). This equation has become widely referred by practicing engineers and researchers for empirically estimate expected deformations of being “collapse” or “unstable” for $N \geq 6$ and: “elasto-plastic” for N = 2–4. As shown in Fig. 2, a problem closely related to the opening stability in underground wall corresponds to the tunnel face stability that were firstly studied by Mair (1979) using a centrifugal model test. Later, the analytical upper and lower bound limit analyses were employed by Davis et al. (1980) to derive classical plasticity solutions of the problem in a purely cohesive material, considering the two-dimensional (2D) plane strain heading of tunnel in a longitudinal direction (Fig. 2a) and the 2D plane strain unlined circular tunnel in a transverse direction (Fig. 2b).

Since then, a large number of researches using experimental tests and numerical simulations were carried out to investigate the stability of tunnel face, including centrifugal model tests (Kimura and Mair, 1981; Chambon and Corté, 1994), 1*g* model tests (Kirsch, 2010; Berthoz et al., 2012; Chen et al., 2013), limit equilibrium method (Anagnostou and Kovári, 1994; Anagnostou and Kovári, 1996; Jancsecz and Steiner, 1994; Broere, 2001), finite difference method (Li et al., 2009; Chen et al., 2013; Senent et al., 2013; Senent and Jimenez, 2015), finite element analysis (Vermeer et al., 2002; Lu et al., 2014; Ibrahim et al., 2015; Ukritchon et al., 2017), discrete element method (Funatsu et al., 2008; Zhang et al., 2011; Chen et al., 2011), kinematic approach of

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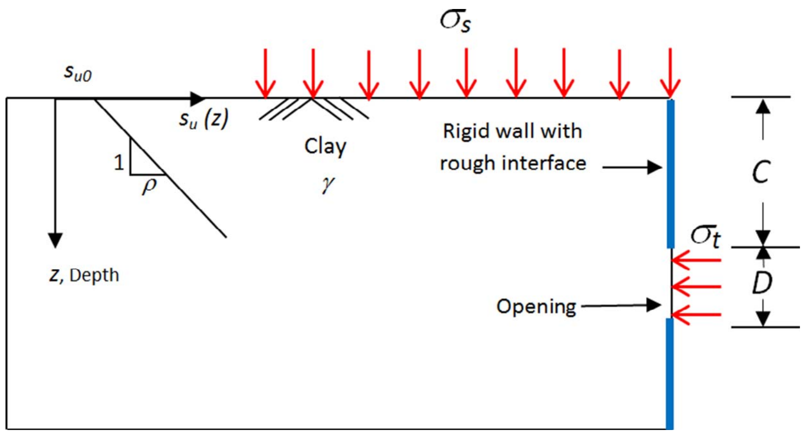

Fig. 1. Problem definition of an opening in underground wall in clay.

upper bound limit analysis (Leca and Dormieux, 1990; Li et al., 2009; Mollon et al., 2009, 2010, 2011, 2012; Mollon, 2012; Han et al., 2016a, 2016b), finite element limit analysis (Sloan, 2013). Note that most of those works were involved with three-dimensional (3D) stability of tunnel face. However, Sloan and Assadi (1994) and Augarde et al. (2003) employed finite element limit analysis to assess the stability of 2D plane strain heading in clay layers with profiles of homogeneous and linearly increasing strengths, respectively. In addition, the upper bound solutions of the 2D plane strain heading were obtained by Huang and Song (2013) using the multi-rigid-block mechanisms. Recently, the 3D effects in the different geometry between the 3D tunnel face stability and 2D plane strain heading and unlined circular tunnel were investigated by Ukritchon et al. (2017), whereas the upper bound limit analysis with rigid and deformed elements was employed by Yang et al. (2016) to compute the drained stability of 2D plane strain heading in a cohesive-frictional soil.

A similarity of the stability problem can be observed between the 2D plane strain heading of tunnel face (Fig. 2a) and the opening in underground walls (Fig. 1), in which an opening appears in these two problems. However, existing solutions for the plane strain heading (e.g., Davis et al., 1980; Sloan and Assadi, 1994; Augarde et al., 2003; Huang and Song, 2013) may not be directly applied to the proposed study since there are some differences in their boundary conditions. In particular, there is no rigid horizontal lining of tunnel in the proposed study, while the effect of rigid underground wall is not considered in the stability of 2D plane strain heading. In other words, the stability of tunnel face can be considered of a later stage of the opening in underground wall that is relatively located far away from the tunnel heading. Consequently, the application of existing solutions of the plane strain heading of tunnel face to the proposed study is still questionable. In addition, it is clear that the solutions of unlined circular tunnel (Fig. 2b) (Davis et al., 1980; Sloan and Assadi, 1994; Wilson et al., 2011) are not applicable to the proposed study since their boundary conditions are completely different. This is because the face pressure of the 2D unlined circular tunnel is applied normal to the circumference of the circular tunnel, but that of the proposed study is applied normal to the front face of the opening. So far, there are very few studies of the undrained stability problem of the opening in underground walls. In practice, the conventional calculation of safety analysis for this problem still relies on the empirical Eq. (1) based on Broms and Bennermark (1967) since there is no reliable and accurate formula of hand calculation currently available in the literature.

In this paper, the computational limit analysis, known as the finite element limit analysis (FELA) (e.g., Sloan, 2013), was employed to investigate the undrained stability of an opening in underground walls in clays with linearly increasing shear strength with depth. The results of this study can be applied to the stability evaluation of a vertical opening with relatively long length as compared to its vertical height. Because of its plane strain condition, the studied solutions provide a conservative estimate for a certain length of opening due to the three-dimensional effect of opening shape, as compared to the in-plane opening. Three parametric studies were performed to examine the effects of the cover depth ratio of opening, overburden stress factor and linear strength gradient ratio on the load factor of the problem. Predicted failure mechanisms associated with these parameters were discussed and examined. Based on the computed numerical lower bound solutions, new design equations were developed for the reliable and accurate predictions of the required opening pressure and safety factor (*FS*) of an opening in underground walls in clays with an arbitrary linear increase in strength profile with depth in practice.

2. Method of analysis

FELA is the numerical computational method of limit analysis that

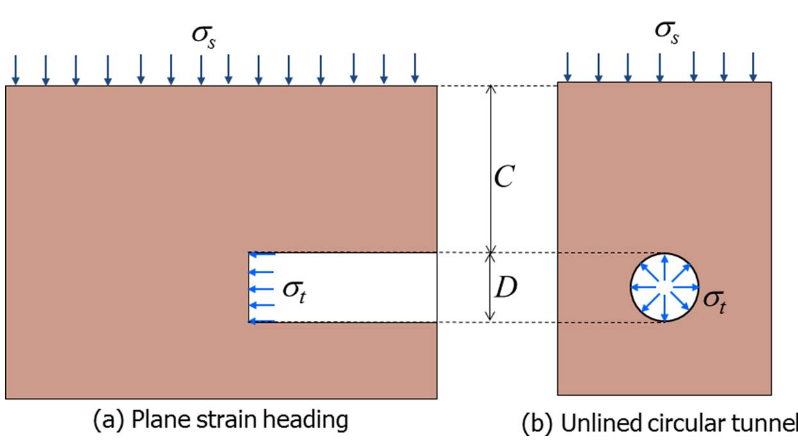

Fig. 2. Two-dimensional stability of tunnel face by Davis et al. (1980).