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Three-dimensional face stability analysis of pressurized tunnels driven in a multilayered purely frictional medium

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ABSTRACT

This paper aims at presenting a three-dimensional (3D) failure mechanism for a circular tunnel driven under a compressed air shield in the case of a dry multilayered purely frictional soil. This mechanism is an extension of the limit analysis rotational failure mechanism developed by Mollon et al. (2011a) in the case of a single frictional layer. The results of the present mechanism are compared (in terms of the critical collapse pressure and the corresponding shape of the collapse mechanism) with those of a numerical model based on Midas-GTS software. Both models were found to be in good agreement. Furthermore, the proposed mechanism has the significant advantage of reduced computation time when compared to the numerical model. Thus, it can be used in practice (for preliminary design studies) in the case of a multilayered soil medium.

1. Introduction

When dealing with tunnels driven by a pressurized shield, two major concerns are addressed, corresponding to both ultimate and service limit states. The first is to ensure face stability by applying a pressure to the tunnel face and thus avoid collapse. The second is to limit ground displacements that propagate to the surface and may have impact on existing structures in case the tolerable deformations thresholds are exceeded. These displacements, in the case of shield tunneling, are affected by the amount of applied face pressure, but they are mostly affected, as per Vanoudheusden (2006), by the shield tail void and to the construction process itself. Therefore, this paper will only focus on the first problem of computing the minimal pressure required to prevent the soil collapse at the tunnel face.

Experimental, analytical and numerical approaches have been developed to determine the critical face pressure. The experimental studies were conducted using small-scale laboratory centrifuge tests (Al-Hallak, 1999; Chambon and Corté, 1994; Takano et al., 2006). On the other hand, the analytical approaches were based on limit equilibrium methods (Anagnostou, 2012; Anagnostou and Kovari, 1994; Broere, 2001; Horn, 1961) or limit analysis methods (Leca and Dormieux, 1990; Mollon et al., 2009a, 2010, 2011a, 2011b, 2012, 2013b; Soubra, 2002; Subrin and Wong, 2002). As for the numerical approach, although computationally expensive, it is nowadays the most popular method due to the development of powerful numerical tools allowing for 3D analysis (Al-Hallak, 1999; Dias, 1999; Mollon et al., 2009b, 2011c, 2013a; Yoo and Shin, 2003).

While most of the developed analytical failure mechanisms target the face stability of tunnels driven in a homogeneous soil layer (considering either frictional or purely cohesive soil), this paper aims at developing a failure mechanism for a multilayered frictional medium. The case of circular tunnels of diameter D and a cover depth C (where $C/D > 1$) supported with a uniform face pressure is considered in the analysis. The applied uniform face pressure may be associated with an air pressurized shield. The present mechanism is based on the three-dimensional (3D) rotational failure mechanism developed by Mollon et al. (2011a) in the case of a single frictional layer. A comparison between the results of the present 3D failure mechanism (in terms of the critical collapse pressure and the corresponding shape of the collapse mechanism) and the ones obtained using the numerical software Midas-GTS is presented and discussed.

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2. Literature review

2.1. Existing experimental tests

Experimental tests have been performed in order to visualize the collapse pattern at the tunnel face and to determine the corresponding value of the critical face pressure (e.g. Ahmed and Iskander, 2012; Berthoz et al., 2012; Chambon and Corté, 1994; Chen et al., 2013; Idinger et al., 2011; Kirsch, 2010; Takano et al., 2006). Meguid et al. (2008) presented a review of numerous physical models that were used to study the excavation of tunnels in soft ground.

Based on centrifuge tests, Chambon and Corté (1994) stated that the failure soil mass was found to resemble to a chimney that outcrops in the case of shallow tunnels and it is limited to 1D above the tunnel for deep tunnels. Takano et al. (2006) have shown by using X-ray computed tomography scanner that the failure shape can be simulated with a combination of logarithmic spirals and elliptical shapes in both vertical and horizontal directions respectively. Kirsch (2010), further to his small-scale model tests at single gravity, emphasized on the effect of soil density on the failure zone: (i) within dense sand, the failure zone is clearly defined and it progressively develops to reach the ground surface and (ii) for loose sands, no discrete collapse mechanism can be identified and movements immediately reach the surface. Idinger et al. (2011) and Ahmed and Iskander (2012) carried out centrifuge model tests, at 50g and 1g respectively, for various cover-to-diameter (C/D) ratios. The measured face pressure at collapse was found to be in good agreement with results from centrifuge tests performed at various gravitational accelerations (50g, 100g and 130g) by Chambon and Corté (1994). Both authors highlighted the influence of the cover-to-diameter (C/D) ratio on the vertical extent of the failure shape. The failure mechanism was found to outcrop for a C/D less than 1.0 as suggested by Idinger et al. (2011) and for a C/D less than 2.0 as stated by Ahmed and Iskander (2012). The local failure observed in front of the tunnel face by Chambon and Corté (1994), Idinger et al. (2011) and Ahmed and Iskander (2012), was also observed recently by Chen et al. (2013) on large-scale model tests. This local failure tends to reach the surface with time (Berthoz et al., 2012). Finally, notice that Berthoz et al. (2012) have observed that frictional soils with cohesion (though very slight of 0.5 kPa) manifest a failure shape in the form of a torus of decreasing section.

For tunnels drilled in multilayered soils, the experimental tests are in short supply since it is only recently that Berthoz et al. (2012) addressed the case of tunnels within stratified ground. In fact, these authors carried out a series of experimental tests on the ENTPE single gravity reduced-scale earth pressure balance shield model to analyze collapse and blow-out failure mechanisms. Among these tests, two (MS2 and MS3 models with two and three layered soils respectively) were performed. The first base layers below the tunnel axis, for both models, were constituted of a self-stable frictional–cohesive soil and are overlaid with purely frictional soil layers. A third cohesive–frictional layer with a small cohesion ($c = 0.5$ kPa) is added above the tunnel crown in the case of MS3 soil model. The failure shape observed for MS2 model resembles to a chimney beginning at the upper part of the excavation chamber. However, the collapse mechanism observed for MS3 model is composed of an extrusion within the purely frictional layer (i.e. upper half of the tunnel face), followed by the failure of a block above the tunnel crown within the frictional–cohesive layer, that extends upwards to reach the ground surface. Although the results by Berthoz et al. (2012) are the only ones that involve the case of a stratified soil medium, these results are limited to particular cases where the failure of the soil can occur only in the upper half of the tunnel face and it does not involve the entire face of the tunnel.

2.2. Limit analysis and existing failure mechanisms

Limit analysis is a method that assesses the failure load of a soil mass by giving upper- and lower-bounds on the exact limit load using kinematic and static approaches respectively. The kinematic approach based on rigid block mechanisms (cf. Chen, 1975 among others) is very popular. The major advantage of this method lies in its simplicity especially when it comes to the number of required input parameters and the fast computation time, making it suitable for preliminary design studies as well as for reliability-based analysis and design that require a great number of calls of the deterministic model. The failure is assumed to occur either by translation or rotation of a rigid body along the failure surface. In order to respect the normality condition of the limit analysis theory, the angle between the failure surface and the velocity vector should be equal to the soil internal friction angle.

The kinematic theorem of the limit analysis theory states that equating the rate of external work done by the external forces to the internal rate of energy dissipation for any kinematically admissible failure mechanism gives an unsafe solution of the limit load. In other words, the failure load deduced from a kinematically admissible mechanism is higher than (or equal to) the exact one. Notice that in the present case where the tunnel face pressure resists failure, the computed limit pressure is actually smaller than the exact one.

As mentioned in the previous section, several experimental tests have been performed in order to visualize the collapse pattern at the tunnel face. The failure soil mass was found to develop following a chimney-like shape (e.g. Chambon and Corté, 1994) that outcrops in the case of shallow tunnels and it is limited to 1D above the tunnel for deep tunnels. Based on these observations, Leca and Dormieux (1990) and Subrin and Wong (2002) proposed 3D failure mechanisms. The failure mechanism developed by Leca and Dormieux (1990) is a two-block translational kinematically admissible failure mechanism that is entirely defined by only one angular parameter. It is composed of two truncated conical blocks with circular cross-sections and with opening angles equal to 2φ in order to respect the normality condition in limit analysis. On the other hand, the failure mechanism developed by Subrin and Wong (2002) is a rotational mechanism depending on two parameters, and it is delimited by two logarithmic spirals in the longitudinal plane and a circle in any rotating plane. More recently, Mollon et al. (2010, 2011a) worked on the improvement of the existing solutions by first proposing a translational multi-block mechanism consisting of n truncated rigid blocks and then a rotational mechanism delimited by two logarithmic spirals in the central vertical plane of the tunnel. The major improvement brought by these new mechanisms is that they involve the entire circular face of the tunnel contrarily to the former mechanisms that only involved an elliptical area inscribed to the circular face (the other parts of the face remaining at rest). This was made possible by generating "point by point" the three-dimensional failure surface using a spatial discretization technique that starts from the contour of the circular tunnel face.

2.3. Comparison between existing experimental and analytical/numerical results

Fig. 1a and b shows the comparisons made respectively by Chen et al. (2013) and Kirsch (2010) involving the normalized face pressures at collapse as obtained by their experimental tests and by the