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A tunnel face failure mechanism for layered ground, considering the possibility of partial collapse

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ABSTRACT

A recent rotational face collapse mechanism is extended to compute critical pressures, in the context of the upper-bound limit analysis, for tunnels in layered (or stratified) ground. The mechanism can consider both (i) cases in which contacts between layers intersect the tunnel face; and (ii) cases in which they are located above the tunnel crown. In addition, the mechanism is extended to address partial collapse in a two-layered ground (with a softer-top and a stronger-bottom), without the need to scale mechanisms that were derived for global collapse. A 3D numerical model is employed to validate the predictions of the limit analysis mechanism, demonstrating that it provides, with a significantly reduced computational effort, good predictions of critical pressure, of the type of collapse (global or partial), and of its geometry. The mechanism is then employed to conduct parametric studies of the influence of several geometrical and mechanical parameters on face instability, considering the possibility of partial collapse, of tunnels in layered soils. Results show that a weak material in the upper section of the tunnel face can lead to a significant increase of the collapse pressure; it also makes a partial collapse possible. They also show that, when partial collapse is not critical and a constant face pressure is considered, the lower layer has a stronger influence on the computed values of collapse pressure. Finally, the results of the proposed mechanism are compared to a recent limit analysis solution for layered soils.

1. Introduction

One way to analyze the stability of a tunnel face is to compute its collapse (or critical) pressure, σ_c, defined as the minimum face pressure that needs to be applied at the face—for instance through a TBM—to avoid its collapse.

Tunnels are usually constructed in layered (or stratified) soils, and there is ample evidence that tunnel failures, and in particular face collapses, are often associated to such layering. This is the case, for instance, when tunnels excavated in a lower (and stronger) layer intersect a weaker layer—e.g., due to a different composition or to weathering—on top (see e.g., Health and Safety Executive, 1996; Arnáiz and Melis, 2003; Babendererde et al., 2006; Sousa, 2010). However, despite recent efforts to consider the influence of stratified soils on face stability (Broere, 1998; Vermeer et al., 2002; Hu et al., 2012; Berthoz et al., 2012; Tang et al., 2013), most research in this area—either experimental, analytical, or numerical—has focused on tunnel faces in homogeneous ground (see e.g., Anagnostou and Kovári, 1996; Kirsch, 2010; Mollon et al., 2011a; Chen et al., 2011, 2013), so that significant uncertainties remain on tunnel face stability in layered ground. The problem of partial collapse also needs to be addressed, since most works in the literature do not consider it or resort to scaling global failure mechanisms (see e.g., Li et al., 2009).

In this work, we address the problem of tunnel face stability in layered (or stratified) ground. We build on a recent rotational face collapse mechanism to compute critical pressures in the context of the upper-bound limit analysis (Mollon et al., 2011a), and on its extension to consider variable properties (Senent et al., 2013). In addition, we further extend the mechanism so that partial collapse can be addressed without the need to scale mechanisms that were derived for global collapse. Because it is both a more common and more relevant situation in practice—see e.g., the typical cases of tunnels in Madrid (Arnáiz and Melis, 2003) and Munich (Health and Safety Executive, 1996)—, such extension is carried out considering a soil formation with two different layers that intersect the tunnel face, with the upper layer being weaker than (or equal to) the lower layer. After validating the new mechanism using numerical simulations, we study the influence of different factors on the stability of the tunnel face in layered soils, considering the possibility of partial collapse. Finally, we apply the mechanism to a tunnel with an homogeneous face but with a layered soil formation above

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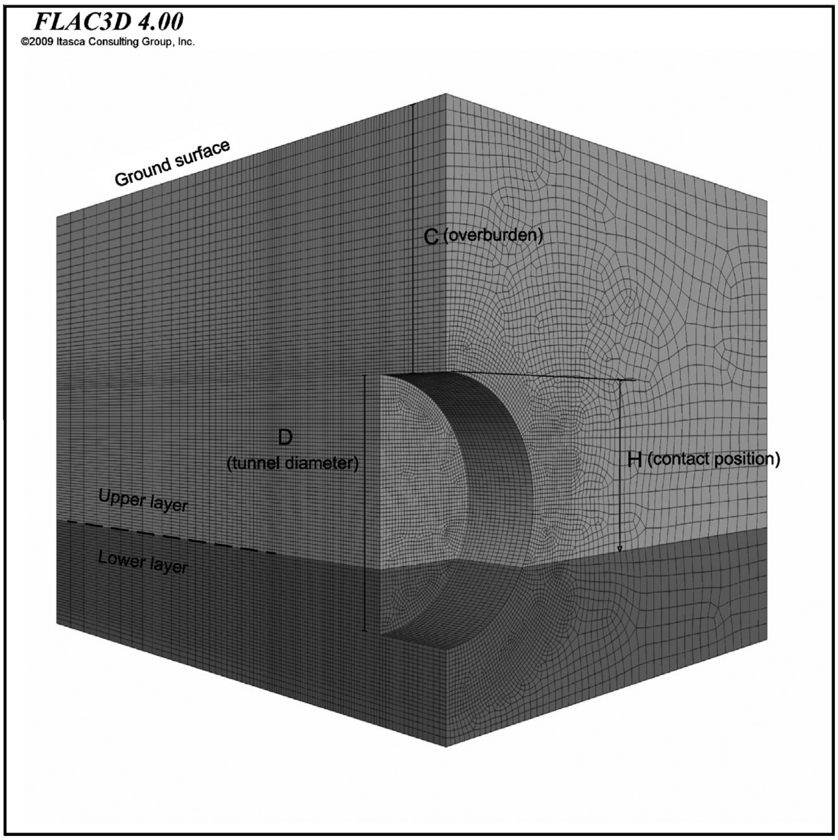

Fig. 1. Developed numerical model and parameters employed to characterize its geometry.

the tunnel crown; comparing our results with other results in the literature illustrates the capability of the proposed methodology.

2. Mechanism for face collapse in layered soils

We build on the recent three-dimensional limit-analysis rotational mechanism developed by Mollon et al. (2011a) to analyze tunnel face stability, as this solution has been shown to provide results that outperform previous approaches, at the same time that it can be generalized to consider stratified soils and non-circular sections. The mechanism is a single block which rotates, with uniform angular velocity, around an axis perpendicular to the vertical plane of symmetry of the tunnel. The contours of the mechanism in such vertical plane of symmetry are approximately logarithmic spirals. The slip surface is generated point-to-point from the contour of the tunnel face affecting the whole excavation front.

For layered soils, the mechanism needs to be extended to consider (i) variable properties; and (ii) the possibility for partial collapse. Senent et al. (2013) extended the mechanism to consider variable properties, with an application to tunnels in fractured rocks with the (non-linear) Hoek–Brown failure criterion. (See also Mollon et al., 2011b for a two-dimensional mechanism.) Here, we address the problem of partial collapse considering a two-layered ground in which the upper layer is softer than the lower one.

To gain insight on partial collapse of tunnel faces, we conducted 24 numerical analyses using a tunnel face model developed with the finite-difference code Flac 3D (Itasca Consulting Group, 2009). Fig. 1 presents the Flac 3D model and the parameters employed to characterize it. (Note that D is the tunnel diameter and H is the vertical distance from the tunnel crown to the contact between the "upper" and "lower" soils that intersect the face.) The model is similar to that presented in Senent et al. (2013). The only differences are that the constitutive behavior of the materials has been characterized by a Mohr–Coulomb model; that the overbur-

Table 1
Parameters employed to analyze the geometry of partial collapses. Strength parameters for the lower layer are $c_{lower} = 100$ kPa and $\phi_{lower} = 40^{\circ}$, and $\gamma_{lower} = 20$ kN/m^3 for both layers.

Case	Contact position H/D	Upper layer	
		ϕ_{upper} (°)	c_{upper} (kPa)
1.1	0.25	20	0
1.2		30	0
1.3		40	0
1.4		20	1
1.5		30	1
1.6		40	1
1.7	0.50	20	0
1.8		30	0
1.9		40	0
1.10		20	2
1.11		30	2
1.12		40	2
1.13	0.75	20	0
1.14		30	0
1.15		40	0
1.16		20	5
1.17		30	5
1.18		40	5
1.19	1.00	20	0
1.20		30	0
1.21		40	0
1.22		20	10
1.23		30	10
1.24		40	10