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Three dimensional face stability of a tunnel in weak rock masses subjected to seepage forces

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ABSTRACT

Reliable prediction of tunnel face stability is a key challenge for tunnel engineering, especially when drilling in highly fractured rock masses under the water table. This work aims to study face stability of a circular tunnel in weak rock masses under the water table based on an advanced three-dimensional (3D) rotational collapse mechanism in the context of the kinematical approach of limit analysis. The fractured rock masses are characterized by the Hoek-Brown failure criterion. A 3D steady-state seepage field obtained numerically is used to interpolate hydraulic heads of the 3D collapse mechanism and seepage force is incorporated into this predicting model by directly considering it as a body force. The results provided by the presented approach are compared with those of numerical calculations, showing a good agreement. The proposed work also provides an improvement with respect to other existing solutions. Thanks to the high computational efficiency of the presented method, four sets of normalized charts are obtained for a tunnel driven in weak rock masses under the water table.

1. Introduction

Tunnel excavation mainly refers to the closed-face tunneling by means of the tunneling boring machine (TBM) and the open-face conventional tunneling. The closed-face TBM technique, including the slurry-shield tunnelling and the earth pressure balance (EPB)-shield tunneling, is widely used for tunnel constructions in recent decades, especially in urban region, due to the advantages of rapid tunnelling and effective controlling of ground movements. One of the most important issues for safe excavation is the face stability in the tunnel engineering. For TBM tunnelling, shield machines can provide continuous supports on the tunnel face to compensate earth pressures and underground water pressures with freshly excavated soil or pressurized mixture of bentonite and water.

At the preliminary design stage, it is of highly practical value to predetermine a reasonable range of face pressures to avoid both the ground subsidence (if the face pressure is not enough) and the ground uplift (if the face pressure is too high). This stability issue has been investigated by several researchers by means of numerical approaches (Vermeer et al., 2002; Lambrughi et al., 2012; Mollon et al., 2013a), experimental tests (Kamata and Mashimo, 2003; Kirsch, 2010). Besides, many theoretical models, e.g. the silo wedge model (Anagnostou and Kovari, 1996; Anagnostou and Perazzelli, 2015) and the triangular base prism model (Oreste and Dias, 2012) within the framework of limit equilibrium method, the classical cone models (Leca and Dormieux, 1990), the horn model (Subrin and Wong, 2002), the multi-blocks models (Mollon et al., 2009), the 3D rotational models (Mollon et al., 2011; Pan and Dias, 2017), the continuous velocity models (Mollon et al., 2013b) in the context of limit analysis theory were also developed to predict face pressures. The comparisons with numerical simulations or experimental measurements show that these analytical models work well to estimate required face pressures. Particularly, the advanced 3D rotational collapse mechanism generated by the spatial discretization technique improves existing solutions significantly with respect to translational failure mechanisms (Mollon et al., 2011).

In practical engineerings, tunnels are often constructed in aquifers, like subsea tunnels, cross-river tunnels and many urban tunnels. Therefore the destabilizing effect induced by the underground water (seepage forces or excessive pore-water pressures) should be taken into account. Many contributions have been devoted to study the face stability when tunnelling in water bearing zone. In addition to experimental investigation (Pellet et al., 1993) and numerical researches (Anagnostou, 1995; De Buhan et al., 1999), simplified approximate approaches, mainly including the limit equilibrium method and the kinematical approach, are common techniques to deal with this problem. Based on the silo wedge model, Anagnostou and Kovari (1996) and Perazzelli et al. (2014) studied the face stability under seepage flow, while Bezuijen et al. (2005), Broere (2015) investigated the

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Notations

a, m, m_i, s	Hoek-Brown constants
δ_β, n	discretization parameters
c_t	equivalent cohesion
C	tunnel overburden
D	tunnel diameter
D_i	disturbance factor
F_y, F_z	components of the resultant seepage force
GSI	geological strength index
h	hydraulic head
$\bar{h}_k$	average hydraulic head at each element surface
h_F	piezometric head on the tunnel face
H_w	undisturbed hydraulic elevation measured from the tunnel crown
i	hydraulic head gradient
$n_{y,k}$, $n_{z,k}$	direction cosines of the unit normal vector of each element surface
N_γ	non-dimensional coefficient representing the contribution of soil weight
N_c	non-dimensional coefficient representing the contribution of cohesion
N_s	non-dimensional coefficient representing the contribution of surcharge loading
N_w	non-dimensional coefficient representing the contribution of seepage forces
$R_{i,j}$, $\beta_{i,j}$	polar coordinates of the barycenter of the triangular facets $F_{i,j}$
R_i, β_i	Polar coordinates of the point on the possible outcropping surface
$R_{i,0}$, $\beta_{i,0}$	polar coordinates of point on the tunnel face
s_k	area of the element surface
S_i	area of the element at the outcropping surface
$S_{i,0}$	area of the element at the discretized face
$S_{i,j}$	area of the triangular facet $F_{i,j}$
$V_{i,j}$	volume of the element corresponding to facets $F_{i,j}$
v_x, v_y, v_z	velocity components
$W_{seepage}$	work rate of seepage force
γ_d	dry unit weight
γ_w	water unit weight
γ'	submerged unit weight
σ_1	maximum effective principal stresses
σ_3	minimum effective principal stresses
σ_c	uniaxial compressive strength of the intact rock.
σ_s	ground surface surcharge
σ_t	effective face pressure
ω	velocity angle of the failure mechanism
φ_t	equivalent friction angle

influence of excessive pore-water pressure, for slurry-shield tunnels, induced by the slurry infiltration. With the application of the corn failure mechanism, Lee and Nam (2001); Lee et al. (2003) and Park et al. (2007) investigated tunnel face stability subjected to seepage forces. Pan and Dias (2016) studied the effect of pore-water pressure on the tunnel face stability with application of the 3D rotational failure mechanism. All these researches highlight that both seepage forces and the excessive pore water pressures exert a greatly adverse effect on the face stability. In these studies, the critical issues are how to calculate seepage forces or pore-water pressures at the vicinity of a tunnel face and how to incorporate the contribution of seepage forces into the predicting models. Several approximated and simplified expressions for the hydraulic head distribution according to numerical simulations (Perazzelli et al., 2014) and field measurements (Broere and Van Tol, 2000; Bezuijen et al., 2005) were presented to address this problem. Lee et al. (2003) directly calculated the seepage forces using finite element simulations, but the seepage forces were not regarded as a body force acting on the soil particles when it is incorporated into the computational model. Pan and Dias (2016) interpolated the pore-water pressure in the failure mechanism by using numerical results, in which the pore-water pressure is used to account for the contribution of seepage forces and buoyancy forces.

Besides, all these aforementioned theoretical models related to the face stability under the water table are based on the linear Mohr-Coulomb failure criterion. However, the non-linear character of the failure envelopes of geo-materials has been observed in many experimental works, among which the non-linear Hoek-Brown criterion, e.g. the original Hoek-Brown criterion (Hoek and Brown, 1980, 1997) and its modified version (Hoek et al., 2002), has been widely applied to characterize the strength of isotropic rock masses. Several attempts have been made to evaluate the tunnel face stability (Saada et al., 2013; Senent et al., 2013) and the tunnel roof stability (Yang and Huang, 2013) using the modified Hoek-Brown failure criterion in the light of the kinematical approach. Saada et al. (2013) studied the tunnel face stability in the context of the modified Hoek-Brown strength criterion, in which both the corn failure mechanism and the horn failure mechanism were employed to assess the lower-bound solutions of face pressure, and the classical tangential line technique is adopted to incorporate the Hoek-Brown strength criterion into the kinematical approach of limit analysis. Based on the advanced 3D collapse mechanism proposed by Mollon et al. (2011), Senent et al. (2013) computed necessary face pressures of a tunnel face in weak rock masses characterized by the modified Hoek-Brown yield criterion. The distribution of normal stresses along the failure surface, which is identified by 3D numerical finite difference simulations, is required in an attempt to finding the lower-bound solutions of face pressure. However, the distribution of normal stresses is generally intractable. Yang and Huang (2013) investigated the three-dimensional collapsing shape and collapsing range for a deep cavity roof in the Hoek-Brown medium. Nevertheless, the Hoek-Brown failure criterion has never been taken to examine the tunnel face stability in the presence of seepage forces. This work will fill this gap.

This paper aims to study the face stability of a circular tunnel in highly degraded rock masses characterized by the modified Hoek-Brown failure criterion in the context of the kinematical approach of limit analysis. The advanced 3D collapse mechanism proposed by Mollon et al. (2011) is extended to analyze the effect of seepage forces, which represent a destabilizing factor that contributes to the failure of a tunnel face. Numerical calculations are employed to compute hydraulic head distributions under a steady state flow due to tunnel excavations. Then interpolated calculations of hydraulic heads on each point of the 3D collapse mechanism are done using numerical results. In order to validate the presented method, the obtained results are compared with those of hydro-mechanical numerical simulations as well as with previously published solutions when the modified Hoek-Brown failure criterion is reduced to a Mohr-Coulomb (MC) one. This paper ends up with providing several sets of charts, respectively corresponding to different water table elevations and rock strength parameters.

2. The problem statement

2.1. Schematic diagram for a circular tunnel advancing under the water table

The schematic diagram of the problem under consideration is sketched in Fig. 1. A circular tunnel with diameter of D at a buried depth of C is excavated under the water table. The water table elevation H_w is measured from the tunnel crown; h_F refers to the piezometric head