Tunnelling and Underground Space Technology 83 (2019) 1–17

Contents lists available at ScienceDirect

Tunnelling and Underground Space Technology

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

Face stability of a tunnel excavated in saturated nonhomogeneous soils

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ARTICLE INFO

Keywords:
Nonhomogeneity
3D rotational collapse mechanism
Pore water pressure
Face stability
Limit analysis

ABSTRACT

Most subways excavated in nonhomogeneous and water-bearing soils but few existing analytical models focus on the combined effect of soil nonhomogeneity and pore water pressures. To address this issue, a three-dimensional (3D) rotational collapse mechanism is improved to investigate the effect of vertical variability of soil strength on the face stability of a circular tunnel excavated in saturated nonhomogeneous soils by means of the kinematical approach of limit analysis. The pore water pressure distribution obtained numerically is interpolated on the 3D improved collapse mechanism by a linear interpolation technology. The effectiveness of the developed model is verified by comparing the required face pressures with the existing solutions, the numerical simulations and the monitoring data of the Shenzhen urban rail transit line 9 project. The effects of nonhomogeneous friction angles and cohesion and water table elevation on the face stability are investigated.

1. Introduction

The popularity of a new concept of the development of underground spaces in the sustainable development of cities has led to the rapid development of shield tunnel construction technology in the construction of underground engineering because of the minimal disturbance on the surrounding strata (Broere, 2016; Zou et al., 2018b); however, a large number of construction accidents still emerged during the construction process, especially face collapse caused by groundwater flow.

The effect of groundwater on the face stability have been investigated in previous works using different methods: (a) analytical methods on the basis of the limit equilibrium method (Anagnostou and Kovari, 1994, 1996; Broere and Van, 2000; Perazzelli et al., 2014; Zingg and Anagnostou, 2016) and limit analysis method (Huang and Yang, 2011; Lee and Nam, 2001; Lee et al., 2003; Park et al., 2007; Pan and Dias, 2016a), (b) numerical analysis (Buhan et al., 1999) and (c) experimental investigations (Bezuijenet al., 2005; Broere and Van, 2000; Pellet et al., 1993). However, these published literature studies were mainly focused on the face stability of tunnels excavated in homogeneous soils. Several early published works showed the important influence of nonhomogeneity with respect to the shear strength on the foundation bearing capacity (Reddy and Rao, 1981) and the slope stability (Chen et al., 1975; Farzaneh and Askari, 2003).

A two-dimensional (2D) limit analysis failure mechanism was presented by Mollon et al. (2011b) for the determination of the critical collapse pressures of a pressurized tunnel face in the case of a soil exhibiting spatial variability in its shear strength parameters. More promisingly, compared with those (Augarde et al., 2005; Sloan and Assadi, 1991) successfully combined the FEM and limit analysis theory, the model by Mollon et al. (2011b) is preferred for stochastic analysis of pressurized tunnels because of costing less time. Based on the multi-rigid-block upper-bound analysis, Huang and Song (2013) developed an improved simple collapse mechanism for a plane strain tunnel driven in a cohesive soil where the undrained shear strength increases linearly with depth. Although these works gave a good insight into the topic regarding the effect of soil nonhomogeneity on face stability, these studies were limited to the two-dimensional (plane strain) condition.

For 3D analyses of tunnel faces considering nonhomogeneous strength parameters of soils, a study with two- and three-layered frictional soils was conducted by Ibrahim et al. (2015) to observe the tunnel face collapse behaviour. The authors also investigated the effect of the position of a loose layer, which is varied from the tunnel invert to the ground surface, on the critical face pressure, and determine the critical position for which the face stability is the most affected. Surprisingly, different with 2D stability analysis by Mollon et al. (2011b) who found that the most critical position for a weak layer is the one at the tunnel invert, the most critical position for a weak layer is not the lowest one, but is located at about one third of the diameter measured from tunnel invert. Senent and Jimenez (2014) extended the 3D rotational mechanism from Mollon et al. (2011a) to address partial collapse

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https://doi.org/10.1016/j.tust.2018.09.007
Received 12 November 2017; Received in revised form 17 August 2018; Accepted 14 September 2018
0886-7798/

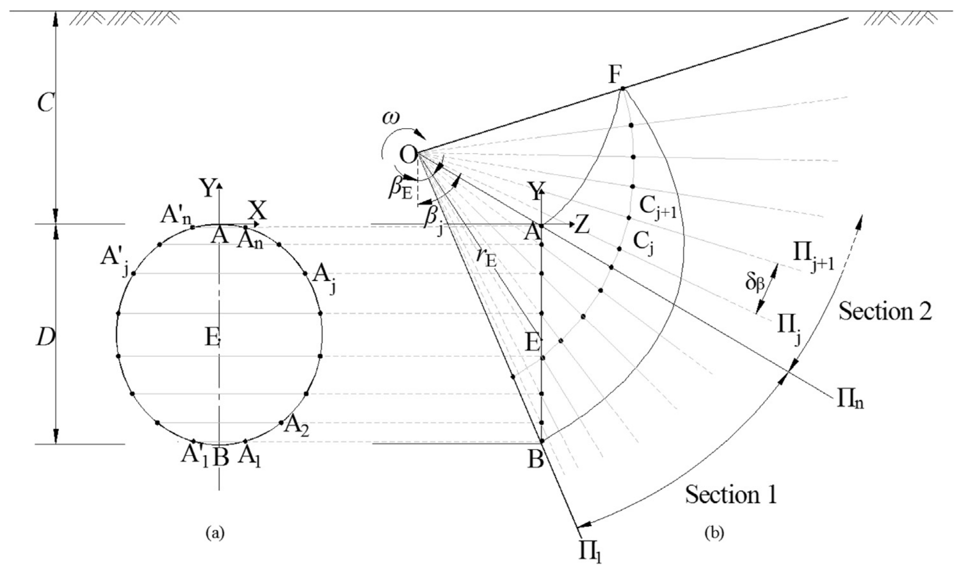

Fig. 1. Schematic of the 3D rotational mechanism.

in a two-layered ground without the need to scale mechanisms that were derived for global collapse. Han et al. (2016) proposed a new mechanism incorporating main features, i.e., a shear failure band in the lower part and a pressure arch effect in the upper part for the case of multilayered cohesive-frictional soils. The effects of soil anisotropy and nonhomogeneity on the face stability were investigated by Pan and Dias (2016b), in which the upper bound theorem of limit analysis incorporating the linear variation of the soil cohesion was used to access the stability of a tunnel face. Interestingly, they found that nonhomogeneous cohesion hardly influences the shape of the optimal collapse mechanism, but the anisotropy and nonhomogeneity of cohesion have great influence on the critical face pressures.

Some researchers investigated the effects of nonhomogeneous strength parameters on tunnel face stability were studied by the finite element limit analysis method. Sloan and Assadi (1991) obtained the upper and lower bounds the collapse pressure for the square tunnel in undrained uniform soil using the finite element limit analysis method as well as the rigid-block upper bound method, and the solutions given by the authors are fully rigorous, since they satisfy all the conditions of the static and kinematic theorems. An investigation by Wilson et al. (2013) employing both semi-analytical upper bound limit analysis and FEA provided a significant improvement on the results of Sloan and Assadi (1991). Augarde et al. (2005) investigated the effects of linearly increasing shear strengths with depth on the load factor for different tunnel geometries and soil conditions using the finite element formulation of limit analysis. The face stability of a plane strain square tunnel driven in undrained clay, where the shear strength profile increases linearly with depth, was evaluated by the combination of upper bound methods and finite element limit analysis. The procedures of finite element analysis employed a discrete form of the bound theorems of classical plasticity.

However, these previously published works concerning the effect of soil nonhomogeneity on face stability consider the dry soil condition. In reality, most tunnels are drilled beneath the groundwater table. To overcome this gap, Park et al. (2007) improved the two-conical mechanism of Leca and Dormieux (1990) and derived an analytical solution for the face stability of a tunnel excavated in cohesive-frictional and water-bearing soils with a linear increase in cohesion with depth. However, he oversimplified the expression of the dissipation power by assuming a constant lateral area parameter for each block's interface instead of double integrating the change in the unit surface and cohesion with depth.

Most of the aforementioned literature reports concerning 3D analyses of tunnel face stability only involved nonhomogeneous cohesions because it is difficult to make the failure mechanism satisfy the normality condition (based on the kinematic theorem of the limit analysis theory) in the case of a spatially varying friction angle. In summary, there is still a limited amount of literature on tunnel face stability that considers variations of the cohesion of the soil with depth below groundwater, let alone the nonhomogeneity of the friction angle.

In this paper, based on the kinematic approach of limit analysis, the effects of cohesion and friction angle vertical variability on face stability are incorporated in a 3D rotational collapse mechanism from Mollon et al. (2011a). In addition, the pore water pressure obtained by *FLAC^{3D}* is interpolated on the improved 3D rotational collapse failure mechanism by linear interpolation, including three searches and three linear interpolations. The developed model is used to investigate the effect of strength (cohesion and friction angle) nonhomogeneity on the face stability of a tunnel driven in the water-bearing soil. The results of the collapse pressures obtained from the developed model are compared with the existing solutions when the cohesion and friction angle degenerate into the homogeneous case. The linear changes of the friction angle and cohesion with depth for the case of two-layered soil are analysed. Furthermore, the influence of the interface position of two layers on face stability is emphasized. Finally, an engineering example of the Shenzhen urban rail transit line 9 project currently under construction for the case of multilayered soil is discussed, which shows that the predicting model can quickly provide a great assessment of the face stability of a tunnel driven in water-bearing soils.

2. Computational model

2.1. Failure mechanism

2.1.1. 3D rotational mechanism

An advanced 3D rotational collapse mechanism by Mollon et al. (2011a) for homogeneous soils, as shown in Fig. 1, was proved to provide the best kinematical solution (critical face pressures) as compared to those obtained from classical failure mechanisms (Leca and Dormieux, 1990). Then this advanced 3D rotational collapse failure mechanism inspired a series of works (Ibrahim et al., 2015; Pan and Dias, 2016a; Pan and Dias, 2016b; Pan and Dias, 2017a; Pan and Dias, 2017b; Pan et al., 2017; Senent et al., 2013; Senent and Jimenez, 2014; Zou et al., 2018a), which highlight that it performs well in estimating the required face pressures and the corresponding failure mechanisms. Therefore, the advanced 3D rotational collapse mechanism proposed by