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Safety factor assessment of a tunnel face reinforced by horizontal dowels

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ABSTRACT

The use of dowels as a reinforcement technique has been successfully applied to improve the tunnel face stability during excavation, for the sake of safety and for the construction speed. The conventional tunneling, e.g. the New Austrian Tunneling Method, promotes the use of such techniques in design for a maximum optimization of the tunnel support. In this work, the kinematic approach in combination with the strength reduction technique is employed to evaluate the safety factor of a reinforced tunnel face. The discretization technique is extended to generate the failure mechanism for a realistic tunnel face shape (non-circular shape). An interaction zone with finite thickness is used to model the interaction between the soils and the dowels. The width of the interaction zone introduces a new parameter in the optimization process. In order to validate the implemented method, the results are compared with those of numerical analysis, which shows that the developed approach is an efficient design tool for the safety factor assessment of a reinforced tunnel face. Several charts are provided for parametric analysis to discuss the influence of the bolt length, the bolt density and the soil shear strength.

1. Introduction

Tunnel excavation mainly refers to the closed-face case like the tunneling boring machine (TBM) or the open-face conventional tunneling. One of the most important issues for the safe construction is the face stability in tunnel engineering. During TBM excavation, the shield machine can provide a continuous support on the tunnel face to compensate the earth pressure as well as the underground water pressure. For conventional tunneling, no supporting pressure is exerted at the face, but some auxiliary techniques, like ground improvement with grouting, face reinforcement with dowels and umbrella pipes, have been developed to ensure a safe excavation.

The issue of the stability of a reinforced tunnel face has been investigated by numerous researchers through numerical simulations, experimental tests and theoretical analysis. The numerical simulation methods were adopted by many investigators to deal with this problem, since this method can offer detailed information on the behavior of the bolts and the ground at the tunnel face. All these works proved that the face reinforcement is an effective and economical reinforcement technique to enhance the face stability and control the ground settlements for open face excavations in poor grounds. Peila [1] investigated the face reinforcement of longitudinal fiberglass pipes with a finite element method. This author found that a distributed pressure on the tunnel face can be employed to model the effect of the face reinforcement as this pressure seems to depend only on the number of pipes but not on the ground properties. Dias et al. [2] investigated the tunnel face reinforced by bolts using 3D numerical analyses with the homogenization approach and show that the homogenization approach is an efficient way to design the reinforced tunnel faces by horizontal bolting. Dias et al. [3] also discussed the soil-bolt interaction using pullout tests on site. Yoo [4], Dias and Kastner [5] performed 3D finite element modellings to study the reinforced effect of longitudinal pipes on the tunnel face stability. Special attentions were paid to the tunnel cover depth, the reinforcement density, the length as well as the pipe axial stiffness. These authors show that a critical value for the reinforcement density exists (independent of the tunnel cover depth ratio and of the soil type), the dowels length (independent of the tunnel cover depth ratio but dependent on the soil type) as well as the dowels axial stiffness, on which the maximum reinforced effect can be mobilized but beyond which the reinforced effect keep the same. Ng and Lee [6] employed a finite element method to study the influence of soil nails on the heading stability of an open-face excavation tunnel, in which the axial rigidity of the soil nails was mainly investigated. The numerical results indicate that the stability of the tunnel face is improved with the increase of the axial rigidity, and a so called optimum axial rigidity also exists. Dias [7] proposed a simplified convergence-confinement approach for designing the tunnel face reinforcement by horizontal bolting. This approach is based on a

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parametric study using 3D numerical calculations. Perazzelli and Anagnostou [8] investigated the stability of reinforced tunnel faces with 3D numerical stress analyses. The mesh-sensitivity of the soil and of the dowels were discussed in order to clarify the approximations induced by the use of structural cable elements which cannot take into account of the real diameter of the bolt and of the borehole.

Several other authors carried out experimental investigations on this topic, which mainly focus on the measurement of the ground displacements as well as of the bolt and soil stress state. Kamata and Mashimo [9] adopted a centrifuge model test to study the strengthening effect of typical auxiliary bolting methods, e.g. horizontal face bolting, vertical pre-reinforcement bolting and forepoling on the tunnel face stability. The model test shows that the axial force is generated along the whole length for which its maximum value is located at the middle of the bolt. The strengthening effect of face bolting mainly depends on the tensile axial force. Shin et al. [10] used a large scale model test to study the pipe-reinforced tunnel heading in a granular soil. Four kinds of reinforcing pattern, e.g. non-reinforced, crown-only reinforced, face-only reinforced and crown and face-reinforced cases, are analyzed under different pipes length, in terms of ground displacements and stress changes. The results showed that the crown pipes considerably reduce the vertical settlements by 18–24% in average, while the face reinforcement reduces slightly the vertical settlements. For the stress variations, both the crown reinforcement and the face reinforcement increase the soil stress ahead of the tunnel face. The ground stress increases with the pipe length. Juneja et al. [11] investigated the influence of the forepoles length as well as the unsupported length on the face stability by centrifuge model tests. The model tests show that the forepoles impact the settlement trough ahead of the tunnel face, but did not influence its width. The results suggest that the face stability depends not only on the unsupported length but also on the forepoles length. Sterpi et al. [12] developed an innovative nailing technique for tunneling in poor rock mass and high pore-water pressure. An analytical method which combines the lower-bound technique and the strength reduction technique was developed to assess the face stability. The performance and the specific advantages of this new nailing technique were discussed using a comparison with site testing results.

The analytical methods, also named simplified analysis method due to the fact that some simplifying and complementary assumptions are often made on the tunnel geometry and on the interaction between the bolts and the surrounding soils, have also been employed to investigate this problem. This method primarily refers to the limit equilibrium method and to the upper-bound limit analysis method. Lee et al. [13] studied the tunnel face stability reinforced by multi-step pipe grouting under seepage flow state. The limit analysis theorem and the limit equilibrium method were used respectively to obtain analytical solutions of supporting forces. A coupled numerical simulation was used to verify the obtained results and the permeability anisotropy was also investigated. Anagnostou and Serafeimidis [14] used the classical silo and wedge model to develop a computational method for a reinforced tunnel face using fiberglass or steel bolts. The supporting pressure offered by the bolts is assumed to act on the tunnel face and rely only on the strength of the interface. This computational model can be applied to heterogeneous, layered soil masses as well as arbitrary reinforcement layouts with respect to spacing, length, longitudinal overlapping and installation sequence of the bolts. Pinyol and Alonso [15] studied the stability of a tunnel face reinforced by umbrella micropiles in the light of the upper bound theorem. A beam model which is similar to the response of vertical piles under horizontal load was used to consider the interaction between the micropile and the surrounding soil. However, the two-dimensional, plan strain failure mechanism was employed to derive the upper-bound solutions, which is the limitation of this analysis. Oreste and Dias [16] developed a new prism model with a triangular base in the context of the limit equilibrium method, for a tunnel face reinforced by fiberglass dowels, to calculate the safety factor which takes into account the tensile resistance, the shear resistance and the bending resistance of the reinforcement element. The obtained results by the proposed model are close to those computed by 3D numerical analysis. The effectiveness of the analytical model has permitted to develop parametric studies on the bolts number and on the bolts length. Anagnostou and Perazzelli [17] extended the work of Anagnostou and Serafeimidis [14] which assumed a constant bond strength of the bolts to a more general computational model which considered the stress-dependent bond strength. The results were compared with results of numerical analyses and several design monograms were also presented for the evaluation of the tunnel face stability. The simplified methods mentioned above can also be categorized as a mixed approach, since in these methods the soil is considered as a continuum model and the reinforcements as separate structural elements [18,19]. Another approach, referring to as the homogenization method, in which the soil as well as the reinforcements are considered together as a homogeneous material with anisotropic properties, was proposed by De Buhan et al. [20] to assess the stability of reinforced earth walls. The so-called homogenization idea further inspired many subsequent investigations, e. g. the analysis on extrusion movements of a reinforced tunnel face [21–23].

In this work, the kinematical approach of limit analysis in combination of the strength reduction technique is adopted to analyze the stability of a reinforced tunnel face. The 3D rotational collapse mechanism proposed by Mollon et al. [24] is improved to generate a failure mechanism for a non-circular tunnel face, e.g. a horseshoe or an elliptical tunnel. An interaction zone with finite thickness is assumed to compute the energy dissipation of the inclusions on which only tensile efforts are considered. In order to validate the presented method, the obtained results are compared with those computed by a three dimensional numerical analysis (FLAC 3D). Several charts are provided for the parametric analysis at the preliminary design phase.

2. The upper-bound limit analysis of a reinforced non-circular tunnel face

The so-called spatial discretization technique was developed by Mollon et al. [24] to generate a rotational failure mechanism for a circular tunnel. This rotational collapse mechanism has been shown to yield the best upper-bound solutions [24,25] for frictional soils. It has further inspired many subsequent investigations on the topic of the Hoek-Brown failure criterion [26], and non-homogeneous stratums or layered ground [25,27]. In this work, the discretization technique is extended herein to generate a rotational failure mechanism for a non-circular tunnel face reinforced by bolts. A non-circular tunnel with height H, width W and buried depth C is schematically sketched in Fig. 1(a), points A, B and E representing, respectively, the crown, invert and center of the tunnel face. Fig. 1(b) plots the longitudinal section of the rigid-block collapse mechanism along the vertical symmetry plane. The whole failure mechanism rotates around a horizontal axis passing through the point O with an angular velocity ω, assuming a cylindrical rotational velocity field used in this failure mechanism. For any point of the failure mechanism, the velocity is equal to the product of the angular velocity and the distance between the rotating center and the point under consideration.