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Upper bound limit analysis of support pressures of shallow tunnels in layered jointed rock strata

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ABSTRACT

With more and more large-span shallow underground projects being built in layered jointed rock strata, there is an increasing interest in the study of stability problems of such projects. The upper bound theorem of limit analysis has been found to be a valid method for analyzing such problems and it is crucial to ensure the accuracy of the failure mode when applying this method. In the present paper, for tunnels in layered jointed rock strata, 8 factors including the thickness of the weathered overburden, the states of the rock joints, and the depth of the tunnel were considered by analyzing the failure mode. By using the orthogonal array testing strategy and the distinct element method, 64 different numerical simulation models based on an actual tunnel project were simulated. The test results showed that the range of the loose zone was determined by the stretch, slippage, and fracture area of the joints. Two kinds of loose zone were obtained, i.e. the arch collapse loose zone and the caving collapse loose zone. The loose zone boundary was analyzed and fitted with linear and non-linear models; such as parabola and power function curves, respectively. The rational failure mode was studied by analyzing the recognition method, the classification, and the failure mechanism of the caving collapse loose zone. By using the liner least squares method, an empirical formula of the boundary of the caving collapse loose zone was obtained, and its boundary were divided equally with identical angles, then a kinematically admissible velocity field was established. Based on the virtual power principle and virtual work principle, the upper bound theorem of limit analysis was adopted to study the support pressures and a limit analysis model was established. A real tunnel project case was studied as an example, and the results were compared with the Terzaghi theory and the Fraldi theory, so as to demonstrate the applicability of the proposed method.

1. Introduction

In recent years, more and more large-span shallow railway tunnels and metro station caverns are built in heavily jointed rock strata. In most cases, such tunnels have a highly weathered overburden in which the structural planes are weak and broken; with the depth of tunnel increases, the physical and mechanical properties of the rock strata are change, and the upper soft rocks are different from those of soils. In additional, the support pressures of such tunnels are affected by the thickness of the overburden, the structures of the rock strata, the depth of the tunnel, the configuration of the rock joints and some other factors. It is worthy pointing out that, previous studies on stability problems mostly concentrated on the influence of in situ conditions and tunnel structure types such as the environment, the depth, the span, and the height of tunnel, there is a lack of understanding about the influence of the joints on the stability of tunnels. The joints play a dominant role in the failure process of rock masses, especially the low strength rock mass is due to the presence of the rock joints. Because of the lower shear strength of the joints, they are critical in rock mass stability studies and must be considered. Therefore, whether the calculation of the support pressures could reflect the actual characteristics of the strata is a key problem to the design of such tunnels.

Until now, many research results on the calculation of the support pressures were conducted technically. The classical calculations include the pillar theory (Peng and Liu, 2009) and Terzaghi theory (Terzaghi, 1943). On the basis of retaining wall theory, these methods suggest that the cross section of the loose zone of the surrounding rock is rectangle; the shape and boundary of the loose zone are affected only by the depth of the tunnel, the height of the tunnel, and the internal friction angle of the stratum. However, for layered jointed rock strata, the loose zone and the support

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pressures of a tunnel are obviously affected by some other factors such as the thickness of the overburden and the configuration of the rock joints. Because of the characteristics of the rock joints and the variability of the strata, there would be errors in the results when applying these methods. In recent years, main research methods include site tests, model indoor tests, and numerical simulations. However, the site tests method and model indoor tests method are limited by technical means and environment conditions. The low reliability of sensors and high cost limit the use of the site test method. For indoor tests method, the difference between experimental conditions and actual projects limits the wide use of this method; furthermore, how to simulate the states of the rock joints is a key problem that needs to be solved. For numerical simulations, the traditional solutions of limit equilibrium and slip line methods have difficulties in solving large deformation problems. On the one hand, the failure mechanism of the surrounding rock cannot be accurately reflected; on the other hand, when the failure mechanism is simulated, finite element method has to perform large number of iterative calculations, which are time-consuming and difficult to converge.

Compared to the above solutions, the upper bound theorem of limit analysis is a more efficient and effective approach. This approach assumes a perfectly plastic medium with an associated flow rule; it is a useful tool for predicting the stability problems in soil and rock mechanics. Because of its distinct concept and solid theory, it had been widely used in tunnel engineering. Some scholars had published some articles for the stability problems of tunnels in soil strata, such as those in Atkinson and Potts (1977), Davis et al. (1980), Sloan and Assadi (1993), Soubra (2000), Subrin and Wong (2002), Huang and Yang (2011), and Lei et al. (2014). For shallow tunnels in rock strata, there are a number of analytical solutions for the stability problems of rock masses. By using the generalized Hoek–Brown criterion, Merifield et al. (2006) studied the limit analysis solutions for the bearing capacity of rock masses. Fraldi and Guarracino (2009, 2010, 2011, 2012) discussed the solution for collapse mechanisms, progressive tunnel failure of tunnels and capacity load in tunnels with arbitrary excavation profiles in plastic Hoek–Brown rock masses, presented an exact solution in the realm of plasticity theory with the help of classical tools of the calculus of variations.

The achievements referenced above promote the use of the limit analysis method in tunnel engineering and have undoubtedly developed basic tunnel theory. However, the previous research has the following limitations: (1) Some failure modes were proposed based on subjective assumption, lack numerical tests or field validation. (2) The thickness of the overburden, the structure type of the rock strata, the state of the joints and some other factors are bound to affect the range and shape of the failure zone, the existing failure modes cannot reflect the influence of these factors. More rational failure modes are needed to be developed. (3) For shallow tunnels in layered jointed rock strata, the most concerned issues in engineering such as the support pressures, so far, there is little research that has applied the upper bound theorem of limit analysis.

Therefore, the present study focus on shallow tunnels in layered jointed rock strata, the support pressures were calculated by using upper bound theorem of limit analysis. Firstly, in order to get the rational failure mode of the loose zone of such tunnels, from the perspective of numerical experiments and theoretical analysis, by using orthogonal array testing strategy (OTAS) (Megson and Evans, 1990) and distinct element method (DEM), simulations of shallow tunnel excavations have been carried out for different depths of tunnels, thickness of overburden, and geometric distributions of the joints. The failure mode was studied by analyzing the recognition method, the classification, and the failure mechanism of the loose zone. On this basis, a kinematically admissible velocity field was established. Secondly, in order to reduce the number of the unknowns of the failure mode and simplify the calculation process, by analyzing the influence of the key factors, the prediction formula of the boundary of the caving collapse loose zone was established. Thirdly, a limit analysis model was developed to calculate the support pressures of shallow tunnels in heavily jointed layered rock strata. Finally, a practical case was studied to verify the proposed approach.

2. Calculation of support pressures

2.1. Basic concepts and assumptions

The upper bound theorem of classic plasticity theory, which assumes a perfectly plastic model with an associated flow rule, is a useful for solving the stability problems in soil mechanics. It states that the power dissipated by any kinematically admissible velocity field can be equated to the power dissipated by the external loads, and so enables a strict upper bound on the true limit load to be deduced. A kinematically admissible velocity field is one which satisfies compatibility, the flow rule and the velocity boundary conditions.

In material mechanics the virtual power principle can be expressed in the following form

$$\int_{\Omega} W^{*} v^{*} d\Omega + \int_{A} T^{*} v^{*} dA = \int_{\Omega} \sigma_{ij}^{0} \varepsilon_{ij}^{*} d\Omega + \int_{S_D} (\tau - \sigma_n \tan\varphi) \Delta v_t^{*} dS_D \tag{1}$$

where Ω represents the bulk of the block; W^* and T^* denote the body force and the surface force, respectively; v^* and ε_{ij}^* stand for velocity and strain, respectively; A denote the plastic zone; σ_{ij}^0 denotes the stress in static force field; S_D represents the velocity discontinuity line; τ and σ_n represent the shear and normal stresses on discontinuity line, respectively; φ denotes the internal friction angle; $\triangle v_t^*$ denotes the tangential change on both sides of discontinuity line.

This paper assesses the stability problems by modeling the rock mass with a Mohr–Coulomb yield condition and postulating a number of rigid block mechanisms. In these mechanisms, power is assumed to be dissipated solely at the interfaces between adjacent blocks, and the geometry is optimized to yield the minimum dissipated power.

In the present paper, upper bound theorem of limit analysis was adopted to study the support pressures. Make the following assumptions as prerequisites for the application of this method:

(1) It is assumed that the ground surface is horizontal plane, the surrounding rock is elastic perfectly plastic, and obeying the Mohr–Coulomb yield criterion.
(2) Assume the tunnel arch was under vertical uniform pressure q, the tunnel side walls were under horizontal uniform pressure e, $e = kq$, where k is a parameter to be determined.

2.2. The failure mode of the loose zone

2.2.1. Failure mode overview

The support pressures calculated by using the upper bound theorem of limit analysis depend on the choice of the failure mode. The failure mode is composed of displacements of the rigid slide blocks, by using the velocity consistency condition and plastic flow rule, the kinematically admissible velocity field can be easily identified with the corresponding failure mode. Then the linear or non-linear mathematical programming problems will be solved ultimately. It is worthy pointing out that, the number of the unknowns of the failure mode is a key problem, with the increasing