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Revisiting crown stability of tunnels deeply buried in non-uniform rock surrounds

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ABSTRACT

A kinematic analysis procedure is presented to investigate the crown stability of deep-buried tunnels in non-uniform rock strata. The non-uniformity of rock properties is considered using the discretized approach with finite thickness layers. In the realm of upper bound theory, kinematic analysis is briefly presented for a single layer so as to provide basis for multi-layer analysis. A 2D collapse mechanism is postulated to depict the potential falling block with an arbitrary tunnel cross-section, although rectangular tunnels are considered in the 3D kinematic analysis for ease of calculation. An impending collapse is likely to occur, provided that the width of the excavation is no less than the collapse width. In order to reflect the nonlinear characteristics of rock materials at failure, the Hoek-Brown criterion is employed for tightly interlocked and very poor rock masses, with its form expressed by normal and shear stresses to facilitate calculations of internal energy dissipation rate. Based on the variational principle and power-based balance equation, the effective collapse mechanism is derived in closed form. Comparison is carried out to verify the robustness of the proposed approach. Sensitivity analysis is performed to depict the influence of each non-uniform rock strength parameter on crown stability. As expected, such a discretized approach incorporated into kinematic analysis enables one to account for non-uniformity of rock surrounds, which would fill the knowledge and design gap of similar tunnelling issues much needed at present state of practice.

1. Introduction

Along with the growing demands for underground highways and high-speed rail networks, an increasing number of tunnels are constructed. In order to ensure excavation safety, stability of tunnel roof and face should be checked. A commonly used approach is to apply kinematic analysis where the upper bound solution could be derived under the ultimate limit state. In this study, focus is placed on roof stability of a deep-buried tunnel constructed in non-uniform rock strata.

The linear Mohr-Coulomb (MC) failure criterion is commonly used in soil mechanics. In order to represent the nonlinear constitutive relationship of the rock whose strength depends on normal stress level, the Hoek-Brown (HB) criterion is employed instead. The merit of the HB criterion is its dimensionless relationship in terms of the geological information and characteristics of the rock mass (Hoek and Brown, 1997). The widespread use of the HB failure criterion was also attributed to the establishment of Bieniawski's rock mass rating system (1976, 1989). Notice that this criterion is based on the assumption that the rock failure is controlled by individual rock pieces rather than the intact rock, hence it can be applied to tightly interlocked hard rock mass. As an alternative, the HB criterion is also applied for very poor quality rock masses provided that the rock mass can be deemed isotropic with 'chaotic' joint pattern and no preferred failure directions. The original HB failure criterion was developed based on the principal stress, and till date, it has been updated to the generalized pattern. A pattern expressed by normal and shear stresses is applied for ease of calculation of internal energy dissipation rate.

The limit analysis has been widely adopted in predicting tunnel stability. The preliminary study was principally performed based upon the wedge block collapse mechanism. Yang et al. (2013) derived the kinematic solution of supporting pressure required for maintaining tunnel crown stability, considering an arc-sandwich and a log-sandwich failure mechanism. For generalization, a random curved velocity discontinuous line was postulated by Fraldi and Guarracino (2009, 2010, 2011), to investigate the stability of tunnel crown with the analytical upper bound solution derived from variational principle and plasticity theory. Although complex, the use of HB failure criterion considers the random variability of mechanical properties of rock masses as well as geological conditions in its input. Such an analysis together with the employment of the HB failure criterion was then extended further to

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account for other complicated scenarios, such as pore water effect (Huang and Yang, 2011) and seepage force (Yang and Qin, 2014). It is worthwhile noting that the actual rock failure above tunnel roof is three-dimensional (3D) rather than a simplified two-dimensional (2D) case. Yang and Huang (2013) proposed a 3D collapse mechanism for this specific purpose to investigate the crown stability within the framework of limit analysis theory. Such a 3D mechanism is sensible for rectangular tunnels while just an approximation for circular tunnels, because of the assumptions made in the failure mechanism and complicated integrals (Qin et al., 2013; Huang et al., 2013). The above mentioned analyses provide useful avenues for assessing the stability of tunnel crown in two and three dimensions. However, these analyses were carried out on a homogeneous/uniform rock mass, and hardly able to consider non-uniformity of surrounding rocks with diverse rock properties. Because of this limitation in this respect, an attempt was made by Qin et al. (2015b) to investigate the progressive failure occurred in partly weathered rock medium. Such a progressive failure was proven to occur in iron mines and limestone caves (Whittaker and Reddish, 1989), and was also substantiated in Qin et al. (2015b) under certain situations. Further, the progressive failure was discussed on account of the pore water effect in partly saturated rock materials (Qin et al., 2015a). In order to essentially deal with the random variation of mechanical properties of rock masses, a novel approach is necessitated, which will be elaborated later.

A general case with non-uniformity of rock surrounds is considered. For simplification the non-uniform rock mechanical parameters are represented separately in each finite thickness layer upon which the kinematic analysis is carried out. The 2D and 3D failure mechanisms are established to predict the falling blocks and the failure area. Moreover, the comparison analysis gives meaningful physical insights to the influential parameters on tunnel crown stability, thereby providing guidance on the design and excavation of deep tunnels.

2. Methodology

As discussed earlier, this study aims to investigate the tunnel crown stability with considerations of non-uniformity of rock strength parameters. The rock surrounds are divided into finite thickness layers with different rock properties including rock unit weight and strength parameters. According to the nature of most geological formation, the choice of horizontal layer is sensible in many cases. This is achieved using discretized analysis which allows for the discretization of a complicated problem into various components. The discretization technique helps to consider non-uniform rock properties in the kinematic analysis, and has insignificant effect on the whole collapse mechanism, and therefore yielding reliable upper bound solutions. More importantly, the employment of the discretization technique can account for the variation of rock properties in sub-layers with ease.

Apart from the discretization technique used in the pre-processing of non-uniform rock strata, the core analysis lies in the application of upper bound theorem. It states that if a kinematically admissible velocity field can be constructed, then the external load computed from the equilibrium of power-based balance equation, will be either higher or equal to the actual failure load (Chen, 1975). The merit of the kinematic analysis is no stress involved in the specific calculations, hence popular in resolving geotechnical stability problems. The prerequisite of such an analysis is to postulate a kinematically admissible velocity field, based on which the rates of work done by external and internal forces are calculated to form the objective function.

3. 2D kinematic analysis

The crown stability of deeply buried tunnels is investigated herein in two dimensions. Prior to the kinematic analysis, a 2D collapse mechanism is established to depict the potential falling block. The work rate calculations are performed considering one-layer (uniform) and multi-layers (non-uniform) rock strata. The upper bound solutions of critical failure area are formulated based on the work rate balance equation.

3.1. 2D collapse mechanism

The rock surrounds are assumed to be treated as isotropic with no inclined and failure directions. Although the rock masses present some anisotropy in the presence of certain circumstances, such as faults, weak interlayers and joints, this may be valid provided the following conditions are satisfied: (1) there exist no faults or bedding planes, (2) directions of discontinuity surfaces are uniformly distributed, (3) the joint separation is small when compared with the magnitude of rock structures, and (4) the discontinuity surfaces must be sufficiently dense (Qin et al., 2017). The assumptions imply that the spacings between adjacent discontinuities are sufficiently small compared to the overall dimension of rock structures. The potential failure block falls from the overlaying rock above tunnel crown, indicating a translational failure pattern under plane strain and symmetric conditions. In this case, the kinematic admissibility condition can be satisfied, as long as the falling velocity at failure in each layer remains the same and under continuous deformation boundaries.

The potential collapse mechanism is illustrated in Fig. 1 where the velocity discontinuities are composed by curved lines, $f_1(x)$, $f_2(x) \ldots f_n(x)$. The failure area in each sub-section, demarcated by the layer interfaces and $f_i(x)$, is directly influenced by the specific rock properties. For a specific problem, the overall failure height is unknown but unique. Since the surrounding rock is composed by finite thickness layers, it is logical to adopt the equipartition approach to consider the whole failure height in n layers. When n is made equal to 1.0, it implies a homogenous/uniform rock mass, and multi-layer rock masses for n larger than 1.0. Manifestly, a continuous rock media with constant or varying properties is simulated for the case of $n > 1$. However, it consumes too much computational effort under higher n values. On the other hand, to little n may produce unreliable results. The choice of n value is hence of vital importance. It is affected by and proportional to the total collapsing height H, which will be discussed in further details in the next section. Another quantity used to characterize the failure region is the (half) failure width, in terms of L_1, $L_2 \ldots L_n$ in each layer. Accordingly, a total of $n + 1$ variables are necessitated to depict the whole collapse area. In order to encompass wider scenarios, the tunnel with an arbitrary cross-section is considered.

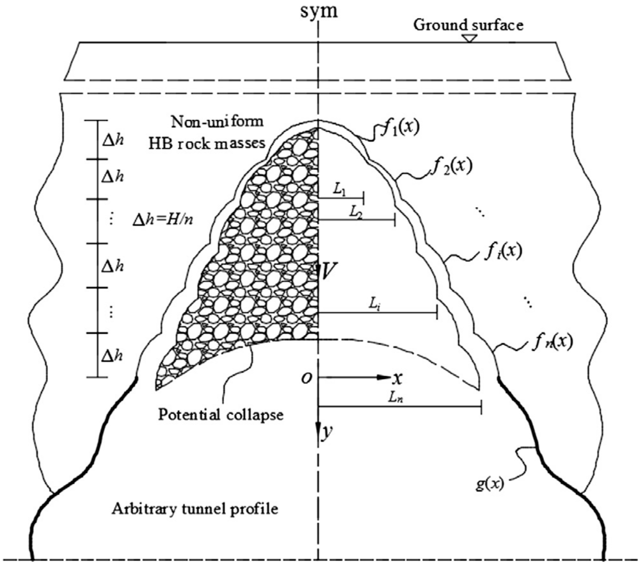

Fig. 1. 2D potential collapse mechansim of tunnel crown in non-uniform rock surrounds.