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Research Paper

# Analysis of earth pressure for shallow square tunnels in anisotropic and non-homogeneous soils

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ABSTRACT

Tunnels are becoming more popular in the transportation system, which makes it imperative to study the surrounding soil tunnel stability. However, in previous studies, researchers generally regarded soil as an isotropic and homogeneous material, which is not consistent with real conditions. Therefore, on the basis of the upper bound theorem, the influence of the anisotropy and non-homogeneity of soil on the earth pressure and the failure mechanism of shallow square tunnels is studied in this paper. The failure mechanism of the surrounding soil for excavation tunnel is obtained using a discrete technique. Considering the anisotropy and non-homogeneity of soil, the earth pressure formula is derived and the optimal solution is obtained. Compared to other results, it is shown that the present approach is feasible and effective. In addition, taking the tunnel of Daganxi II, Longyong expressway of Hunan province as an example, a numerical calculation is conducted, in which the displacement field corresponds to the theoretical one proposed in this paper. After discussing the impact of the anisotropy and the non-homogeneity of soil on earth pressure, the tunnel stability is studied with the presence of the pore water pressure. The effect of pore water pressure and the change of the water table level are then investigated.

## 1. Introduction

Tunnels are becoming popular in the transportation systems. Many works were done to study the stability of the tunnel surrounding soil and the soil-support interaction. Several methods are able to estimate the stability of tunnels, such as monitoring methods, theoretical analysis, and numerical analysis. The limit analysis, as a theoretical analysis method, is applied to solve the problems in the field of engineering, like the analysis of tunnel stability [1], slope stability [2,3], bearing capacity of the foundation [4], and etc.

The issue of the stability of shallow tunnels was studied by many researchers by means of the limit analysis method. Comprehensive discussions of the application of limit analysis to geotechnical problems may be found in Davis [5] and Chen [6]. Atkinson and Potts [7] investigated theoretically the stability of a circular tunnel in the cohesionless soil based on the upper and lower bound theorems. Davis et al. [8] estimated the safety of a shallow tunnel by means of the lower and upper bound theorems of plasticity. The upper and lower bound stability solutions were derived under undrained conditions to assess the risk of blow-out failure caused by excessive high fluid pressures. Sloan and Assadi [9] studied the undrained stability of a shallow square tunnel in a soil whose shear strength increases with depth. The rigorous bound solutions were derived on the basis of the finite element formulations of the classical limit theorems. Soubra and Dias [10] calculated the active and passive pressures of a tunnel excavated by a pressurized shield based on the upper-bound method of the limit analysis theory. By means of the limit analysis, Yang and Wang [11] investigated the stability of shallow tunnels subjected to seepage with settlement. On the basis of the upper bound method of limit analysis, Yang [12] assumed two rigid-block translational collapse mechanisms for determining the earth pressure of a shallow tunnel in the isotropic and homogeneous soil. Zhang and Yang [13] derived the active and passive earth pressures of a shallow tunnel and obtained upper bound solutions in nonassociative soil. Zhao et al. [14] studied the surrounding rock pressure of the shallow bias tunnel by introducing the horizontal bias loading coefficient.

Even though a lot of works were done to investigate the tunnel stability, it can be found that there are few studies which consider the non-homogeneity and anisotropy of soil for shallow tunnels, except Pan and Dias [1], who studied the face stability analysis of a shield-driven tunnel in anisotropic and nonhomogeneous soil by kinematical approach.

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failure mechanism of a shallow square tunnel is studied in this paper. The failure mechanism is obtained using a discrete method proposed by Mollon et al. [15]. The obtained solutions are compared with solutions from the literature and it is shown that the present approach is effective. In addition, the tunnel of Daganxi II, Longyong expressway of Hunan province is considered to validate the theoretical approach. A numerical calculation is conducted, in which the displacement field corresponds to the theoretical one proposed in this paper. After discussing the impact of the anisotropy and the non-homogeneity of soil on earth pressure, the tunnel stability is studied with the presence of the pore water pressure. The effect of pore water pressure and the change of the water table level are then investigated.

## 2. Upper bound theory of limit analysis

The limit analysis was widely used in civil engineering. The basic assumption of the upper bound theorem is that the load calculated by equaling the rate of internal energy dissipation to the rate of external force should not be less than the actual collapse load for the any given strain rate filed $\dot{\varepsilon}_{ij}$ and kinematic admissible velocity field $\dot{v}_i$. Further, the surrounding soil mass is assumed to be a perfectly plastic material with an associated flow rule. The failure block is regarded as rigid. The expression of the upper bound theorem is:

$$\int_V \sigma_{ij}\dot{\varepsilon}_{ij}dV \geqslant \int_s T_i\dot{v}_i ds + \int_V F_i\dot{v}_i dV \quad (1)$$

where $\sigma_{ij}$ is stress field respecting the flow rule; $T_i$ is the surcharge load on boundary $s$; $F_i$ is the body force on area $V$.

## 3. Upper bound analysis of a shallow square tunnel in anisotropic and non-homogeneous soils

Due to the influence of environmental factors, such as the natural deposits of soil, the soil usually shows non-homogeneity and anisotropy. It means that the geomechanical parameters of soil are not constant. To be able to consider these parameters variations, the discrete method is presented in this paper.

### 3.1. Anisotropy and non-homogeneity of soil

The nonhomogeneous and anisotropic soil is assumed to follow the Mohr-Coulomb failure criterion during the analysis. It is assumed that only the cohesion $c$ of soil is nonhomogeneous and anisotropic in the following analysis [17].

#### 3.1.1. Non-homogeneity of soil

A non-homogeneous cohesion $c$ which increases with the increase of the depth $z$ is considered as mentioned in Chen [6]. The linear variation of cohesion $c$ with depth $z$ is shown in Fig. 1, and the value of horizontal cohesion strength $c_h$ at depth $h$ is given by [16–19]:

$$c_h = c_{h0} + \lambda_c h \quad (2)$$

in which $c_{h0}$ is the value of horizontal cohesion strength at ground surface; and $\lambda_c$ is the gradient.

#### 3.1.2. Anisotropy of soil

Based on the study of Casagrande and Carillo [20], the anisotropy of cohesion can be estimated by (see Fig. 2):

$$c_\xi = c_h + (c_v - c_h)\cos^2\xi \quad (3)$$

in which $c_v$ is the value of vertical cohesion strength; $c_h$ is the values of horizontal cohesion strength; $\xi$ is the angle between the maximum principal stress and the vertical direction. The maximum principal stress of $c_v$ occurs in the horizontal direction, and the maximum principal stress of $c_h$ happens in the vertical direction.

The anisotropic coefficient $k$ ($k = c_h/c_v$), which is a constant, was

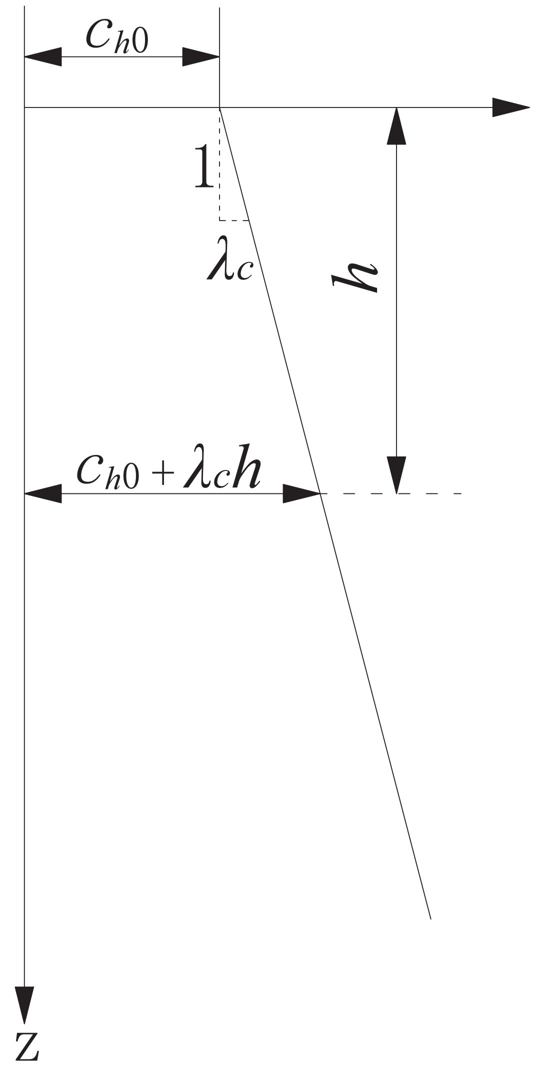


**Fig. 1.** Non-homogeneity of soil used in this analysis: the variation of cohesion with depth.

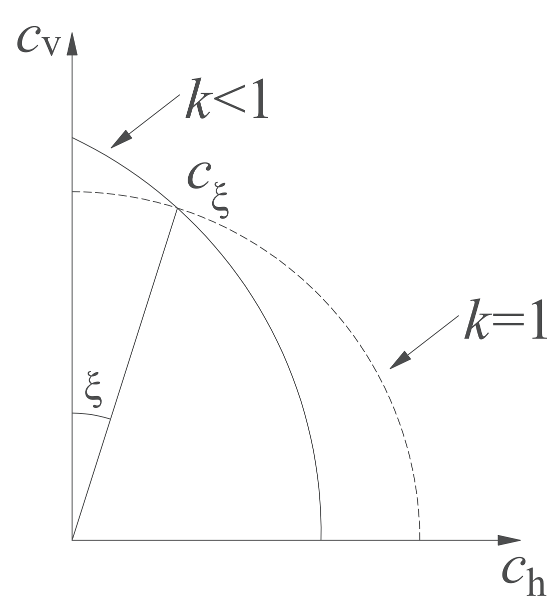


**Fig. 2.** Anisotropy of the cohesion.