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Determination of longitudinal convergence profile considering effect of soil strength parameters

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ABSTRACT

To investigate the stability of ground surrounding shallow tunnel, an important step is to study the medium using the stress-strength method. The method includes the longitudinal convergence along tunnel. The studies done up to now are concentrated on the deep tunnels in the form of presenting a longitudinal deformation profile (LDP). It expresses relation for unsupported tunnel wall/crown by various researchers in terms of distance from excavation face along the tunnel. Of course, the effect of soil strength parameters is not considered in the relations yet. It is attempted in the current research work to propose a new concept of Longitudinal Convergence Profile (LCP) as alternative to Longitudinal Deformation Profile LDP. Then, a series of 3-dimensional analyses are conducted on a sample with conventional stratified environment observed in metropolitans. Finally, to include the effect of soil strength parameters, i.e., modulus of elasticity, cohesion and internal friction angle of soil on the LCP, a new set of relations is suggested.

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1. Introduction

The convergence-confinement method is an efficient tool for estimation of required support during tunnel excavation. To make the adjacent ground stable, the matter is mostly dependent on the three-dimensional extent and the tunnel excavation advance rate (equivalent to the unloading due to excavation). The method has been proposed and further developed during last fifty years by various researchers and has become a conventional tool to study the ground and support behaviors during excavation. The method is simple but capable of predicting complex conditions during tunneling. It consists of three main concepts: ground reaction curve (GRC), support characteristics curve (SCC) and Longitudinal Deformation Profile (LDP). The GRC and LDP express cross-sectional and longitudinal ground behavior, respectively. The LDP is the most efficient tool for support estimation along the tunnel while the ground is unsupported and self-balanced. Therefore, the current study concentrates on LDP. The majority of available and reliable literature for LDP is about deep tunnels with hydrostatic stress field. Most of urban tunnels are shallow. Therefore, it is very important to study the ground behavior along the shallow tunnel. The quaternary deposits are stratified in layer with various properties especially in levels adjacent to ground surface in Iranian cities such as Isfahan. This is due to naturally deposited flood plains along the river bed. The typical stratification is assumed in the current study to simulate the actual case.

2. Relations expressing Longitudinal Deformation Profile

The LDP is a convenient tool to determine the desired location of temporary and permanent supports or optimize the support installation considering a predetermined displacement. The maximum radial deformation happens in a location far enough from the face as plane strain case. However, a part of the displacement happens in unexcavated point ahead of the face. The tunnel boundary is further converged towards tunnel axis while the excavation is in progress. The longitudinal displacement is expressed as LDP. Most of researchers have used the radial displacement normalized with respect to the maximum plane strain displacement. Various relations are proposed as follows in which the distance from the face is itself normalized with respect to tunnel radius.

Based on the research by Panet and Guenot, the following relation is presented for LDP[1]:

$$U^* = 0.28 + 0.72\left[1 - \left(\frac{0.84}{0.84 + X^*}\right)^2\right] \quad (1)$$

Corbetta et al. proposed the following relation[2]:

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$$U^* = 0.29 + 0.71\left[1 - \exp\left(-1.5\left(\frac{X}{R}\right)^{0.7}\right)\right] \tag{2}$$

Another relation by Panet is as follows[3]:

$$U^* = 0.25 + 0.75\left[1 - \left(\frac{0.75}{0.75+X^*}\right)^2\right] \tag{3}$$

Carranza-Torres and Fairhurst[4] proposed the following relation based on the data by Chern et al.[5]:

$$U^* = \left[1+\exp\left(\frac{-X^*}{1.1}\right)\right]^{-1.7} \tag{4}$$

Unlu and Gercek discussed the fact that the LDP does not follow a unique continuous function; for the elastic case, the dual function is as follows[6]:

$$U_a = U_o + A_a\left[1 - exp(B_a X^*)\right] \ for \ X^* \le 0 \tag{5}$$

$$U_b = U_o + A_b\left\{1 - \left[\frac{B_b}{(B_b + X^*)}\right]^2\right\} \ for \ X^* \ge 0 \tag{6}$$

$$U_o = 0.22\nu + 0.19 \tag{7}$$

$$\begin{cases} A_b = -0.22\nu + 0.81, B_b = 0.39\nu + 0.65 \\ A_a = -0.22\nu - 0.19, B_a = 0.73\nu + 0.81 \end{cases} \tag{8}$$

where u_0 is the radial displacement at face $X^*=0$, $X^* = \frac{x}{R}$, $U_o = \frac{U_{r0}}{U_{r\infty}}$, U is the radial displacement at the desired distance X from the face, $U_{\max}$ is the maximum radial displacement, and R is the tunnel radius.

Vlachopoulos and Diederichs also presented the following equation for LDP based plastic radius as[7]:

$$U^* = \frac{U}{U_{\max}} = U_0^*. e^{X^*} \ for \ X^* \le 0 \tag{9}$$

$$U^* = 1 - (1 - U_0^*). e^{-\frac{3X^*}{2R^*}} \ for \ X^* \ge 0 \tag{10}$$

$$U_0^* = \frac{U_0}{U_{\max}} = \frac{1}{3}e^{-0.15R^*} \tag{11}$$

$$R^* = \frac{R_P}{R} \tag{12}$$

$$X^* = \frac{X}{R} \tag{13}$$

where R_p is a maximum plastic radius and R is the tunnel radius.

Recently, Alejano et al.[8] extended and used the elastoplastic approach/equations by Vlachopoulos and Diederichs[7] for strain-softening rock masses ($25 < GSI < 75$) using FLAC3D applying Hoek–Brown model. They proposed a simplified approximate equation to calculate the plastic radius of a tunnel excavated in a strain-softening rock mass. Alejano et al. showed that this approach gives good results for expressing the LDP of a strain-softening rock mass.[8]

Eqs. (1)–(4) are valid for excavated ground ($x \ge 0$). As stated earlier, it seems that the above Eqs. (1)–(13) are proposed for deep tunnel ($k=1$). Also, it is understood from the literature that Eqs. (4) and (9)–(13) are presented for elastoplastic material and the rest of Eqs. (1)–(3) and (5)–(8) belong to the elastic case.

A more thorough review of the literature especially regarding the behavior and characterization of the material is given in Refs. 9 and 10. The issue of the tunnel LDP in supported or brittle materials may be an interesting research topic considering equivalent material parameters.

3. Numerical simulation

The effect of soil strength parameters (modules of elastic, cohesion and internal friction angle ϕ) are investigated conducting three-dimensional numerical continuum analyses by finite difference method software FLAC3D version 3.0[11] using 20736 zones and 22540 grid points.

3.1. The domain geometry

The domain consists of four layers as shown in Fig. 1. The layers thicknesses are also constant (Table 1). The overall dimensions of the domain ($L \times W \times H$) are 60 m × 20 m × 40 m. The tunnel diameter (D) is 5 m. The top of most up layer is assumed as ground level.

3.2. The materials properties

The properties of 1st, 2nd and 4th layers from top (e.g., soil1, soil2, soil3) are taken as constant (Table 1) whereas the 3rd layer (soil3) property varies (Table 2). The relations expressing bulk modules (K), modules of elasticity (E), shear modules (G), Poisson's ratio (ν) and lateral earth pressure (k) are as follows:

$$K = \frac{E}{3\times(1 - 2\nu)} \tag{14}$$

$$G = \frac{E}{2\times(1+\nu)} \tag{15}$$

$$k = \frac{\nu}{(1-\nu)} \tag{16}$$

The choice of constitutive model and failure criterion are elastoplastic and Mohr-Columb criterion. The criterion utilizes major and minor principal stresses and widely used for geomaterials normally with shear type of failure. The intermediate principal stress is not important in the failure process.[12] The materials are ranged from loose to very stiff fine-grained soil and almost weak as compared to rock. The analyses were also performed to investigate the effect of dilation angle varying in a relevant range. The normalized LDPs were almost not affected by the change in dilation angle. The matter is also investigated and proved in detail in.[8]

3.3. Boundary condition

The boundary condition at the bottom of the model is supposed to be fixity. At the sides though only the horizontal displacement (normal to the side) is fixed while the other displacements are not constrained (Fig. 1). The half of the domain is simulated. This makes the simulation time much reduced. Considering the longitudinal symmetry of the domain against the vertical plane passing through the tunnel axis, the displacement and velocity of nodes on the plane of symmetry are set to zero at horizontal direction.

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