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A simple analytical approach to simulate the arch umbrella supporting system in deep tunnels based on convergence confinement method

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ABSTRACT

In this study, a simple analytical method is presented to investigate the behavior of arch umbrella supporting system (the forepolling system) in deep tunnels. For this purpose, a qualitative distribution of the load on the arch umbrella elements (the beams) is proposed by using longitudinal deformation profile of unsupported tunnel. The flexural stiffness of an element is then obtained and finally, the deformation of supported tunnel are calculated by convergence-confinement method. That is, further advancement of tunnel leads the more length of umbrella elements to be activated; and therefore, the corresponding stiffness is reduced. Hence, the non-linear support characteristic curve is drown to intersect the ground response curve.

Sensitive analyses are performed, and on the basis of the proposed analytical method, some graphs are prepared to give the ratio of total displacement of supported tunnel to that of unsupported for the various arch umbrella systems installed in the tunnels with different potential of squeezing. Some examples are solved, and the results are compared with those obtained by FLAC^{3D} software.

1. Introduction

In the underground excavations, according to the geological conditions, various excavation techniques and stabilization methods are used. For good rock mass quality in a low depth, a light support system is sufficient while for a weak rock mass at a great depth (i.e. the very squeezing condition), a combination of advanced excavation methods and pre-support approaches are necessary prior to installation of very stiff support system. In fact, the arch umbrella supporting system accompanied by the sequential excavation methods must be used for the safe excavation (Pelizza and Peila, 1993; Hoek and Marinos, 2000; Peila and Pelizza, 2003).

However, the arch umbrella supporting system is utilized in the shallow tunnels, e.g. in urban metro tunnels, too. In these tunnels, in addition to stabilize tunnel face, the control of ground surface settlements is the other important aim. Numerous researches have been conducted to explore different aspects of this pre-support system performance (Peila, 1994, 2013; Peila and Oreste, 1998; Volkmann and Schubert, 2006, 2010; Ocak, 2008; Wang and Jia, 2008, 2009; Aksoy and Onargan, 2010; Song and Wang, 2011; Song et al. 2013, Zhang et al. 2014; Gao et al. 2015).

Regarding the issue of tunnel face stability and ground surface settlements control, Peila (1994) by a tridimensional numerical simulation demonstrated that the displacement of tunnel face was reduced around 40% when the longitudinal bolts in tunnel face were also installed (in addition to foreploes). The ground settlements can be controlled efficiently using arch umbrella (Ocak, 2008), and it is substantially reduced if the longitudinal bolts are accompanied with the pre-supporting (Aksoy and Onargan, 2010). Song and Wang (2011) studied the face stability of excavation using theory of limit analysis.

Considering structural performance of the arch umbrella elements in the shallow tunnels, on the other hand, a number of studies have been carried out. Peila and Oreste (1998) proposed the distribution of load such as that shown in Fig. 1 where the value of load was assumed to be equal to the overburden (i.e. the soil weight from ground surface to tunnel crown). In this analytical study, the system was simulated by cantilever beam element, which the buried side leaned on the tunnel face and the other side on the main support system. The Winkler elastic springs was used to model the reactions of soil (as the elastic foundation). Volkmann and Schubert (2006, 2007) and Volkmann et al. (2006)

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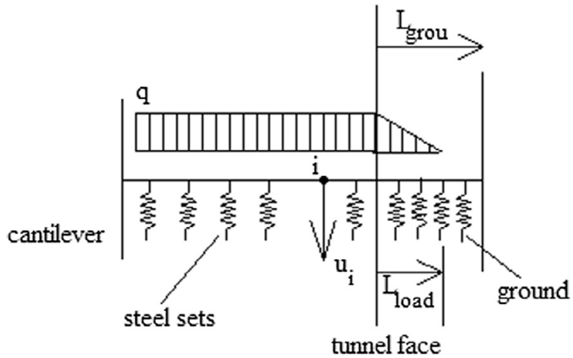

Fig. 1. Simulation of arch umbrella elements by Peila and Oreste (1998).

through calibration of the 3D numerical model (FLAC^{3D}) with in-situ monitoring of settlements a head of tunnel face clarified the influence of the design parameters to optimize the used support system. Based on back-calculations of in-situ measurements, they defined the structural properties for the arch umbrella elements and the changes in load redistribution (Volkmann and Schubert, 2010). In the other study, Galetto et al. (2013) through physical modeling demonstrated that the displacement of umbrella elements in sandy soil starts ahead of the face with a distance of about a tunnel radius. The solutions presented by Wang and Jia (2009), Marchino et al. (2010), Song et al. (2013), Zhang et al. (2014); Gao et al. (2015) are the other attempts to obtain the displacement and (or) load of the arch umbrella system in the shallow tunnels.

The loading mechanism of the arch umbrella supporting system in the deep tunnels is different. That is, unlike shallow tunnels where the load on the umbrella elements can be quickly found through considering overburden, the ground arching effect influences the loading in deep tunnels so that it is not easy task to obtain it in very squeezing conditions.

Oke et al. (2012) conducted a parametric study by a numerical simulation to demonstrate the influence of arch umbrella elements and rock mass interaction. Then, they also investigated the influence of elements number (say density) and their inclination, and concluded that the number of the elements as well as size of the elements are the most important factors in controlling the stability (Oke et al., 2014a). In the other effort, from numerous case studies, they presented a methodology for selection of umbrella arch system based on the geological conditions, stress and required stiffness of support (Oke et al., 2013; 2014b). Recently, they also proposed a second order equation for distributed load through a semi-analytical solution in which, it is assumed, the beam lays on the elastic foundation (Oke et al., 2016). Heidari and Tonon (2015) considered the hardening effect of jet grouting umbrella elements in controlling of deep tunnel convergence.

In fact, design of the arch umbrella supporting system (or any other complicated structure) is often carried out by 3D numerical simulation to take its complex interaction with ground, into account. However, the analytical solutions provide formula to high speed and preliminary design which are sometimes sufficient for practical purposes, and determine the influence of each parameter explicitly. On the other hand, there is no comprehensive analytical solution to explore the unknown aspects of arch umbrella supporting system in deep tunnels i.e. the load distribution as well as the load magnitude on this support system is not still clear.

To bridge this gap, this paper presents a new analytical method to simply explain the behavior of arch umbrella system and provides a tool for preliminary design through the prepared graphs. In this method, the load distribution is obtained by employing convergence confinement method (CCM). As a result, the longitudinal deformation profile (LDP) of supported tunnels is found.

However, some assumptions are made to simplify developing of the simulation as the follows:

- The complex interaction between the single umbrella element and the surrounding ground is not studied. That is, the shear stress which might be developed between the ground and element is ignored, and the connection between the element and ground is assumed to be rigid. Therefore, the stress principle direction does not rotate.
- The effect of the umbrella elements deflection (or displacements) on the load redistribution of elements is ignored.
- The arching phenomenon of ground is not developed between the umbrella elements i.e. the loose rock mass between the elements in the circumferential direction does not fallen into tunnel. As a result, the umbrella elements contribution is considered in the form of uniform pressure to the zone influence of each element.

2. Analytical simulation

The convergence confinement method is used to predict deformation of tunnel wall through considering the interaction of support system and rock surrounding tunnel. In the case of arch umbrella elements as the support system, it is necessary to find the corresponding stiffness which itself depends on load distribution.

2.1. The load distribution on a single umbrella element

The loading process of a single umbrella element is explained in Fig. 2. In each excavation step, tunnel wall displacement causes that the point (A) is much loaded, and at the same time it further moves toward the equilibrium point in ground response curves. Since much length of the umbrella element is loaded in foregoing excavations, the stiffness is reduced, and support characteristic curve (SCC) might be non-linear.

In this study, the behavior of umbrella elements in the entrance section of tunnels to the weak ground are simulated. This section is the critical, because, as shown in Fig. 3, the umbrella elements are supported from tunnel face meanwhile their other side are free. The following advancement of the excavation and then installation of the main support leads the free side of next groups of umbrella elements to be lean on.

As the arch umbrella elements cause to reduce the ultimate total displacement, longitudinal deformation profile (LDP) of the supported tunnel can be considered as that for un-supported tunnel (Heidari and Tonon, 2015). Vlachopoulos and Diederichs (2009) proposed the LDP of a circular tunnel can be calculated by

$$u(x) = U_{ul}\left[1-\left(1-\frac{1}{3}\exp\left(-0.15\frac{r_e}{r}\right)\right)\exp\left(-1.5\frac{x^{'}}{r_e}\right)\right] \qquad for \quad x^{'} \geq 0 \tag{1-a}$$

$$u(x) = \frac{1}{3}U_{ul}\left[\exp\left(\frac{x^{'}-0.15r_e}{r}\right)\right] \qquad for \quad x^{'} \geq 0 \tag{1-b}$$

where the parameters U_{ul} and r_e respectively are ultimate unsupported tunnel convergence and elastic-plastic boundary radius which can be calculated by the standard analytical approaches having been presented till now. The variables r and $x^{'}$ are tunnel radius, and distance of a

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