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An analytical solution for the arching effect induced by ground loss of tunneling in sand

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ABSTRACT

Because the earth pressure above tunnel crown was assumed uniform and the effect of particle flow of sand and ground loss were not considered, Terzaghi method generally produces discrepancies from model tests and field observations. To overcome this deficiency, the flow of sand particles above a tunnel was investigated firstly to define the shape and size of loosening zone by following the gravity flow principles. Then, by assuming non-uniform distribution of earth pressure and incorporating the factor of ground loss, a modified Terzaghi method has been developed. It can not only determine the loosening pressure on tunnel, but also the shape and size of loosening zone corresponding to ground loss and properties of sand particles. The research results reveal that the shape of loosening zone is ellipsoidal or a part of ellipsoid affected by the eccentricity and loosening factor of sand. The height of loosening zone increases with ground loss of tunneling, resulting in the propagation of loosening zone from deep in ground to ground surface. For most shield tunnels, with ground loss ratio less than 4.0%, the loosening zone is formed only at the upper tip of the ellipse and its shape resembles to a curved arch. According to the proposed method, the height of the loosening zone for shield tunnels in sandy ground is approximately 0.1D–0.7D (D, tunnel diameter) and the earth pressure is about 35–90% of the total overburden earth pressure for typical ground loss within the range of 0.5–4.0%. Via detailed comparison with model tests and Terzaghi method, the proposed method is proved to be closer to the model tests than the Terzaghi method. For the sake of convenience in application, simplified design curves for the height of loosening zone and earth pressure were plotted against ground loss, which is of great importance for engineers to set reasonable goal of ground loss in tunneling practice.

1. Introduction

Arching is one of the most universal phenomena observed in field and laboratory tests (Terzaghi, 1943). Field measurements showed that the vertical earth pressures acting on tunnel linings in sandy ground were about 40–80% of the total overburden earth pressure (Inokuma and Ishimura, 1995; Suzuki et al., 1996). The arching effect was generally considered for deep tunnels in sand (cover depth to diameter ratio $C/D > 2$) in design practice (ITA, 2000), despite how much ground displacement or ground loss actually occurred during tunneling. However, the magnitude of arching effect can vary with ground displacement (Peck, 1969) induced by ground loss in the process of tunnel excavation. Therefore, it is an important task to establish relationship between arching effect and ground loss.

In some circumstances where ground loss or displacement should be strictly controlled to protect adjacent buildings or infrastructures, it is difficult to decide whether or not to consider the arching effect in the design of tunnels in soils. On one hand, arching effect can be significantly mobilized in deep ground for deeply buried tunnels if ground loss or displacement develops to some extent. On the other hand, the arching effect could be reduced or even ignored when ground loss or displacement was controlled within very small values by small disturbance tunneling (SDC) techniques (Liao et al., 2009). If so, the pressure on tunnel crown would approach to the total overburden pressure of soils and the concrete lining would be designed to be too thick or otherwise over-reinforced.

Therefore, a reasonable suggestion would be that the ground volume loss should be maintained at such a level that the loosening zone above a tunnel should be restrained and not propagate to the ground surface; In this way, the earth pressure acting on the tunnel lining could be reduced remarkably, while the nearby surface and subsurface infrastructures would not be threatened.

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Nomenclature

B	half width of the yielding strip
C	cover depth of tunnel
D	excavated diameter of tunnel
D'	external diameter of lining ring
C/D	cover-to-diameter ratio
V_{el},	volume of the limit ellipsoid
V_{em}	volume of the ellipsoid of motion
Δ_g	gap between the ground and the tunnel lining
H_{GU}	upper height of the limit ellipse truncated by the outlet
H_{GL}	lower height of the limit ellipse truncated by the outlet ($H_{GL} = 2a_G - H_{GU}$)
H_S	height of the zone from the ground surface to the arcing boundary
H_T	total height of the loosening zone of tunnel
k	coefficient of lateral earth pressure
k_0	coefficient of lateral earth pressure at rest
k_a	coefficient of active earth pressure
m	pressure distribution factor
N	vertical force acting on the interface $o'd'$
N_1	normal force acting on the interface $d'f'$
T_1	frictional force mobilized on the sliding surface d' f'
V	theoretical volume of excavation per unit tunnel length
V_L	ground volume loss ratio
ΔV	excavated volume in excess of the theoretical volume of excavation per unit tunnel length
W_1	weight of soil of Wedge $od'f'$
a_G	major semi-axes of the limit ellipse
b_G	minor semi-axes of the limit ellipse
a_N	major semi-axes of the ellipsoid
b_N	minor semi-axes of the ellipsoid
c	cohesion of soil
h_c	height of loosening zone above tunnel crown in Terzaghi formulation
p_c'	supporting pressure of the lining at point o'
q	surcharge at ground surface
β	loosening factor
α	angle of minor principal plane to horizontal
δ	sand-to-wall friction angle
δ_c	crown deformation of tunnel
ε	eccentricity of sand particles
γ	average unit weight of sand
γ_{dmax}, γ_{dmin}	maximum and minimum unit weight of sand
ds	specific unit weight of sand
γ_e	unit weight of sand after dilation
φ	friction angle
μ	Poisson's ratio
θ	angle of sliding interface to the horizontal line
σ_h	horizontal stress on the vertical sliding surface
σ_v	average vertical stress at the yielding strip
σ_{v0}	initial vertical stress on the tunnel crown
n, A, c_ε	intermediate parameters used in the derivations

Until present, three kinds of methods have been involved to investigate the mechanism of soil arching attributed to tunnelling-induced displacement: (1) the analytical methods including the limit equilibrium methods (Marston, 1930; Terzaghi, 1943; Balla, 1963; Dancygier et al., 2016; Ji et al., 2018) and elastoplastic solutions (Finn, 1963; Vardoulakis, 1981; Evans 1983; Sloan et al., 1990; Ono, 1993); (2) the numerical methods including finite-element method (Koutsabeloulis et al., 1989; Jao et al., 1998; Hejazi et al., 2008), discrete element method (Chevalier et al., 2011, 2012; Jiang et al., 2012) and discontinuous deformation analysis (He et al., 2015); (3) the model tests (Atkinson et al., 1975; Lee et al., 2004; Lee et al., 2006; Shahin et al., 2007; Ahmed et al., 2010). These achievements have provided comprehensive understandings about the arching phenomenon from various perspectives of mechanics. It is noted that the achievements by He et al. (2015) and Kong et al. (2018) revealed the arching mechanism in jointed rock mass and the significant influence of initial stress ratio on the arching by numerical simulations. However, the difficulties in defining accurate mechanical parameters of various soil/rock constitutive models in numerical simulations inevitably bring about discrepancies and inconveniences in their applications. Besides, the dilative properties of sand, which are affected by loosening factor (Vardoulakis et al., 1981; Shirlaw, 1994; Marshall et al., 2012), are hard to be considered in numerical analysis. Although discrete element method (DEM) serves an option to modeling the properties of sand particles, it is time-consuming and unfeasible to establish a real-scale DEM model for an actual engineering project at present. Laboratory model tests for tunnel excavations could provide good scientific facts for validating theoretical approaches, but their conclusions are generally much limited by the variation of test modes with different ground losses or buried depths.

Although Terzaghi method has been widely used to evaluate the soil arching and earth pressure on deep buried tunnels, its assumptions on the initio stress ratio k_0 and pressure distribution above tunnel crown result in discrepancies from model tests and field observations. Furthermore, Terzaghi method does not account for the particle flow properties of sand and the effect of ground loss induced by tunneling. To overcome this deficiency, a new method was developed by considering the initial stress ratio k_0, non-uniform distribution of stress in loosening soil mass and the effect of ground loss induced by tunneling. And parametric studies were conducted on the proposed method for eccentricity ε, loosening factor β, friction angle φ, cohesion c of sand etc.. In order to check the validity and accuracy of the new method, predictions from the proposed method were compared with the results from model tests and Terzaghi method. Finally, simplified design charts were developed based on the proposed method for convenient application in tunneling practice.

2. Limit ellipsoid of loosening zone

The gravity flow of granular materials in bins or silos can be described by the theory developed by Janelid and Kapil (1966), which predicts the mechanics of the gravity flow of blasted or caved ore in sublevel mining. The key to their approach is the concept of the motion ellipsoid in Fig. 1, where a bin or hopper is filled with granular material. When the bottom outlet is opened, the material will begin flow out under the gravity. After a given period of time, all the extraction of material, which is initially from within an approximately ellipsoidal zone known as the ellipsoid of motion, are truncated by the outlet. The remaining material between the ellipsoid of motion and a corresponding limit ellipsoid will replace this loss by its loosening, but will not reach the discharge opening. The limit ellipsoid is also truncated by the outlet. However, the material outside the limit ellipsoid will maintain stationary. The shape of ellipsoid of motion is a function of both distribution of particle sizes within the flowing mass and width of the discharge opening (Brady and Brown, 2004). The shape of a given ellipsoid of motion is described by its eccentricity as follows:

$$\varepsilon = \frac{1}{a_N}(a_N^2 - b_N^2)^{1/2} \tag{1}$$

where a_N and b_N are the major and minor semi-axes of the ellipsoid. Janelid and Kvapil (1966) suggested that, in practice, ε varied between 0.90 and 0.98 with values from 0.92 to 0.96 being found to apply most