Numerical Analysis and Risk Assessment on Face Stability of Large-Diameter Tunnels

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Abstract. For the two types of shield tunneling such as Slurry and EPB shield the stability of tunnel face depends on the prevailing support pressure. The support pressure at the tunnel face has to be applied to a value that gives as well sufficient safety against a collapse of the tunnel face as the against uplifting. The paper aims at a better understanding of the mechanics of face failure for those larger-diameter tunnels. And some different determination methods of the applied support pressure are compared and given a risk assessment, which are illustrated their application by numerical analysis in the Yangtze River Tunnel of Shanghai.

Keywords: face stability, risk assessment, numerical analysis, large-diameter tunnel.

1 Introduction

With underground excavations and construction works progress into much larger diameter tunnels and more complex geological environments, Slurry shield and EPB tunneling have been successfully applied worldwide in recent years, which allow the control the surface settlement and limit the risk of tunnel face failure through the continuous support the face. However, face instabilities may occur under extremely unfavorable geological conditions, especially some larger-diameter tunnels like the Yangtze River Tunnel of Shanghai whose outside diameter is about 15.0m.

As is known, Peck [1] introduced the one of main issues to be addresses for the design and construction of tunnels: stability of the opening during construction with particular attention to the tunnel face stability. The stability of tunnel face is of paramount importance for construction the larger-diameter tunnel works. Several approaches have been developed to analyze and calculate the support pressure of tunnel face over the past thirty years. Early works on face stability were concerned with tunnels constructed in clays (Broms and Bennermark [2]; Peck [1]). Then a more theoretical approach based on limit analysis was presented for clays by Davis et al [3]. Within the framework of limit analysis, some lower bound solutions were presented to analyze tunneling in sandy ground by Muelhaus [4], Leca and Panet [5] and Leca and Dormieux [6]. And the approaches were checked against model tests performed with Fontainebleau sand in the centrifuge of the Laboratoire Central des Ponts et Chaussées (LCPC) in Nantes, France (Chambon and Corté [7,8]). Another approach,

taking full account of the 3-dimensional geometry at the tunnel face, was proposed by Anagnostou and Kovári [9, 10, 11], using limit equilibrium principles based on the Horn [12] (see figure 1) model. Recent developments allowed the computational methods of tunnel face support pressure were proposed and performed by many researchers, Chen Z.L. [13], W. Broere [14], Vermeer P.A. & Ruse N. [15].

There are so many methods for calculating the support pressure of tunnel face, and it is not easily to select the best one for design and construction large-diameter tunnel. The paper aims at a better understanding of the mechanics of face failure for those large-diameter tunnels by 3-Dimensional numerical simulation. And some different determination methods of the applied support pressure are compared here and given a risk assessment, which are illustrated their application by numerical analysis in the Yangtze River Tunnel of Shanghai.

2 Different Computational Methods on Support Pressure of Tunnel Face

In order to analyze the mechanics of face failure for those large-diameter tunnels by 3-D numerical simulation, 6 different computational methods were introduced as follows.

- (1) The computational model of passive earth pressure [16]
- (2) The computational model of earth pressure at rest [16]
- (3) The computational model of active earth pressure [16]
- (4) The computational model of Chen Z.L. [13]

$$p_z = (0.6 \sim 0.7) \tan^2\left(\frac{\pi}{4} - \frac{\phi'}{2}\right)(\sigma_v - u) + u \quad (1)$$

Where u is the pore water pressure, and ϕ' is soil effective friction angle.

- (5) The computational model of Ruse. N. [15]

$$p_R = -c' \cot \phi' + \gamma D \left(\frac{1}{9 \tan \phi'} - 0.05 \right) \quad (2)$$

Where c' and ϕ' are soil effective cohesion and soil effective friction angle respectively, γ is the unit soil weight at the depth of tunnel axis, and D is tunnel diameter.

- (6) The computational method of the minimal support pressure based on the Multilayered Wedge model

To construct a wedge stability model, as sketched in Fig.1, which could handle heterogeneous soil conditions by Anagnostou and Kovári [9, 10, 11], the horizontal slice model described by Walz [17] for slurry-filled trenches might serve as a starting point. The failure wedge is subdivided in N smaller bodies by W. Broere [14], see Fig. 2, possibly of different thickness, inside each of which the soil conditions are homogeneous. The soil conditions would vary between these slices, as may the wedge angle θ_i between the i th slice's slanted failure plane and the horizontal. The conditions of horizontal and vertical equilibrium could lead to calculate the minimal support pressure as follows.

Fig. 1. Wedge-loaded model of three-dimensional tunnel face failure mechanism by soil silo

Each slice i is loaded by the resulting forces from the slice above $(i-1)$ and below $(i+1)$, $Q_a^{(i)}$ and $Q_b^{(i)}$ respectively, the effective weight of the slice itself G_w^i and an overburden force G_s^i . At the slanted failure plane there is a cohesive force $K^{(i)}$ acting parallel to the plane, as well as a friction force $R^{(i)}$, which results from the normal force $N^{(i)}$, working perpendicular to the failure plane. The side faces of the wedge are each assumed to be loaded by the shear force $T^{(i)}$, which act in the same direction as $K^{(i)}$, against the deformation direction of the wedge. Force equilibrium will yield the effective earth force $E^{(i)}$ at the face which, combined with the water force $W^{(i)}$, is equal to the support force $S^{(i)}$.

Fig. 2. Multilayered Wedge model of three-dimensional tunnel face failure for calculating the minimal support pressure

$$p_{\min} = 4 \cdot S / (\pi \cdot D^2), \quad S = E + W \tag{3}$$

$$E = -\frac{\xi'_-}{\xi'_+} [G_s + G_w + \sum_{i=1}^N \frac{1}{\xi^{(i)}_-} (2T^{(i)} + K^{(i)})], \quad \frac{\xi'_+}{\xi'_-} = \frac{1}{N} \sum_{i=1}^N \frac{\xi^{(i)}_+}{\xi^{(i)}_-} \tag{4}$$

Where all computational parameters are given in Fig. 2, and some functions were explained [14] and [16].

3 Numerical Analysis Model and Risk Assessment

3.1 The Model of Numerical Analysis

According to all above computational methods of support pressure of tunnel face, some different support pressure of tunnel face may be calculated. When large-diameter tunnels were designed and constructed, the factual support pressure at the tunnel face had to be applied to a value that gives as well sufficient safety against a collapse of the tunnel face as the against uplifting. So the appropriate support pressure should be selected through analyzing the mechanics of face failure for large-diameter tunnel. In order to analyze the mechanics of tunnel face failure through numerical simulation, there were some problems which needed to be considered in advance.

(1) The method of numerical analysis. There are so many softwares such as ANSYS, ABAQUS, Plaxis and FLAC3D etc., which could be used to simulate and analyze the process of tunneling. Because the method of numerical analysis aimed at a better understanding and simulating of the mechanics of face failure for those lager-diameter tunnels, the selected software should calculate the 3-D tunnel built of soil that undergo large deformation, plastic flow and face collapse. As is known, FLAC3D offers an ideal analysis tool for solution of 3-D problems in geotechnical engineering. And it could accord with the requirement of numerical analysis for engineering mechanics computation of tunnel face instability.

(2) The criterion to judge the face failure of tunnel. The key problem is to establish a criterion for judging the plastic or collapse condition of tunnel face. There are two criteria [18], one is to set the non-convergence of force and displacement of tunnel face as a judgment of numerical analysis; and the other is to set the plastic flow or the yield stress state as determining the face failure condition. After considered that the distribution of plastic zone was influenced by many factors such as Poisson's ratio, flow rule, etc, non-convergence of displacement in numerical analysis program could be taken as a suitable evaluating criterion for estimating the tunnel face failure.

(3) How to apply the support pressure to tunnel face. When tunnel face was excavating by slurry shield or EPB, the force distribution of in-suit tunnel face was trapeziform from the top to bottom of tunnel. So how to apply the support pressure to balance the in-suit earth pressure is a big problem. There are two application modes, one is to apply the support pressure to balance the earth pressure of tunnel face at the center of tunnel axis, and the other is to apply the support pressure to balance the earth pressure of tunnel face at the point of composition forces of tunnel face. Because the numerical simulation was to analyze the face stability of large-diameter tunnel, the latter mode was selected as a application mode of support pressure.

3.2 Risk Assessment

During the excavation of tunnel face, the distribution of earth pressure would change with tunneling. The face stability was a dynamic condition (see Fig.3). That is, the face stability would be undergone from a stable state to limit equilibrium and to instability even face collapse. So the risk about face stability of large-diameter tunnel

could be assessed through the criterion for judging the face failure with the ratio of support pressure to vertical earth pressure at the centre of tunnel face.

$$\lambda = p / \sigma_v \tag{5}$$

Where p is the support pressure at tunnel face, and σ_v is the vertical earth pressure at the centre of tunnel face.

Fig. 3. The face stability condition and displacement of tunneling when the support pressure was decreased gradually

3.3 Case Study

Yangtze River tunnel is the south crossing way from Pudong to Changxing Island in Shanghai. This tunnel has about a 7.5km in length and 15m in outside diameter. In order to illustrate the method of numerical analysis and risk assessment, the tunnel alignment pile K0+589 was studied [16]. Based on the geology investigation data and tunnel structure design, the computational parameters of soil and tunnel at No K0+589 are shown in Table 1.

Table 1. The computational parameters of soil at Pile No. K0+589

Soil type	thickness	γ	c	φ	c'	φ'	q_u	E_s	K_0
	m	kN/m ³	kPa		kPa		kPa	MPa	
② ₃	4	18.7	8	27	-	-	-	10.84	-
③ ₁	3.5	17.5	13	12.5	8	30.3	43	3.27	0.57
③ ₂	2.5	18.3	7	28.5	-	-	-	9.06	-
④	16.5	16.9	14	10.5	10	26.8	52	2.62	0.63
⑤ ₁	1.2	17.3	16	12	15	25.2	58	3.19	0.61
⑤ ₂	17.3	18	12	22	-	-	-	5.99	0.38
⑦ ₁₋₂	10.45	18.2	12	24	-	-	-	5.86	0.37

The different support pressures of large-diameter tunnel face were calculated by all above methods. And the deformation of the large-diameter tunnel could be studied by the different support pressure using the software Flac3D. And the risk assessment [19] could be given by the ratio of support pressure to vertical earth pressure at the centre of tunnel face shown as Table 2.

Table 2. Risk assessment of different support prrssure applied on the tunnel face

Support pressure	p_p	p_0	p_a	p_z	p_R	$p_{\min}$
p/kPa	473.356	202.891	197.519	91.417	65.804	51.75
$\lambda=p/\sigma_v$	1.56	0.67	0.65	0.30	0.22	0.17
Risk class	serious	insignificant	considerable	serious	serious	severe

Fig. 4. The relation of displacement and support pressure of tunnel face

As the support pressure of tunnel face was decreased from p_p to p_0 , the +z direction displacement along tunnel alignment was also decreased, otherwise, the -z direction displacement along tunnel alignment was increased (See Fig.4 (a)). When the support pressure was decreased from p_0 to $p_{\min}$, the +z direction displacement along tunnel alignment was still reduced to 0m, simultaneously, the -z direction displacement along tunnel alignment was increased the maximum, that is face collapse or instability when support pressure was null. The relation of displacement velocity and support pressure of tunnel face was shown in Fig.4 (b).

When the large-diameter was excavated by shield machine, the safety support pressure could be estimated by the displacement velocity of tunnel face to which was applied different support pressure. And the safe zone of support pressure of pile No.K0+589 was shown in Fig.5 (a) and Fig.5 (b).

4 Conclusions

(1) There were so many method which could be used to calculate the support pressure of large-diameter, and the actual support pressure was a value that gave as well sufficient safety against a collapse of the tunnel face as the against uplifting. So it is essential that the mechanics of face stability should be studied before the design and construction. And the method of numerical analysis and risk assessment could provide a new approach to determinate the safe support pressure.

(2) The face stability of tunnel was a dynamic process when the support pressure was changed during shield tunneling. The numerical analysis could give an elaborate simulation of the displacement process while the support pressure was decreased gradually. Compared the displacement and displacement velocity of different support pressure, the risk of tunnel face stability may be assessed simultaneously. And the risk management of tunnel construction should also be paid much attention to consider and adopt when the large-diameter tunnel was excavating.

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