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Long-term settlement prediction over Shanghai metro tunnels

Prédiction du tassement à long terme des tunnels sur métro de Shanghai

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ABSTRACT
The long-term settlement over Shanghai metro tunnel line No.2 is predicted based on the stress-strain-time relationship of soft clay. The tunnel construction process is considered in the numerical simulation of long-term settlement. The influence of over-excavation during shield tunneling on the evolution of long-term surface settlement, as well as ground loss, is studied. Some conclusions are drawn from the numerical simulations.

RÉSUMÉ
Le tassement à long terme sur tunnel de la ligne 2 du métro de Shanghai est estimé numériquement sur la base d'un modèle de comportement traitant des argiles naturelles en fonction du temps. La résolution est effectuée en utilisant la méthode FEM multi-pas. Le processus de construction du tunnel est pris en compte dans la simulation numérique du tassement à long terme. L'influence d'un surcreusement lors de l'excavation du tunnel, sur l'évolution à long terme du tassement en surface, ainsi que la perte de volume, est étudiée. Les simulations numériques permettent de tirer un certain nombre de conclusions sur la modélisation de ce type de construction et sur la pertinence du modèle de comportement utilisé.

1 INTRODUCTION

Many field observations on long-term settlements of tunnels have indicated that the long-term settlements can be significant, particularly when tunnels are embedded in soft and compressible soils (Mair and Taylor (1997); Lee et al. (1999), Shirlaw (1993, 1995); Cooper et al. (2002); Yi et al. (1993); O'Reilly (1991)). The long-term surface settlement almost doubles in three moths after tunnel construction for Shanghai metro tunnel line No.2 (Lee et al. (1999)). Shirlaw (1995) concluded that typically the increase in settlements over long-term is of the order of 30-90% of the total settlement, and that in many cases a widened settlement trough develops.

The major factors influencing the development of long-term settlements above tunnels could be mainly attributed to the excess pore pressure, the stress-strain behaviour and drainage condition of the tunnel lining according to Mair and Taylor (1997). The influence of drainage condition of tunnel lining on the long-term behaviour of tunnel has been studied by Zhang et al. (2004) based on the concepts of relative finite permeability of the lining. The effect of tunnel construction process combined with the time-dependent properties of soft soils on the long-term settlements of tunnels is studied in this paper.

The magnitude and distribution of excess pore pressure indeed depends to a large degree on the tunnel construction process. The over-excavation is often encountered during shield tunneling especially at the tunnel portal and its effect on the long-term behavior of tunnels is considered in this paper.

The consolidation and creep deformation due to shield tunneling will occur when the tunnels are constructed in so soft clay soils as in Shanghai. Accordingly, it is necessary to build a constitutive law that can be used to predict the time-dependent deformation around the tunnel in long-term. Consequently, an elastic-viscoplastic constitutive model coupled with Biot's consolidation theory is developed and used in the long-term settlement prediction over urban tunnels.

2 ELASTIC VISCO-PLASTIC CONSTITUTIVE MODEL

The visco-plastic constitutive model is established using the results of both triaxial and oedometer tests (Zhang et al. (2003)). The construction of the viscoplastic model is undertaken based on the framework of the Modified Cam-clay model (Roscoe and Burland (1968)). The viscoplastic strain rate follows the framework proposed by Perzyna with associated flow rule shown as equation (1) (Perzyna (1963,1969)).

$$\dot{\varepsilon}^{vp} = \mu \langle \exp(n\, f / f_0) - 1 \rangle \frac{\partial f}{\partial \sigma_{ij}} \quad (1)$$

Where, μ and n are viscous parameters respectively. f represents the yield function of Modified Cam-Clay model. f_0 is a reference yield function.

The constitutive model is then implemented into the FEM code CESAR_LCPC coupled with Biot's consolidation theory.

3 NUMERICAL SIMULATION PROCEDURE

The numerical simulation is performed with 8-node isoparametric finite elements under the assumption of plane strain conditions. The tunnel lining for Shanghai metro line No.2 is 6.2m in external diameter and 5.5m in internal diameter. The average depth to the center-line of the tunnel is about 1.8D (D is the tunnel diameter). The tunnel was excavated by EPB shield machine. The shield body is 6.24m long with 6.34m in diameter. Correspondingly, the clearance between the external diameters of shield body and the tunnel, which is usually named physical gap G_p according to the definition of Lee et al. (1992), will reach 140mm. The effective grouting pressure is determined as 0.25MPa according to the in-situ measurements. Correspondingly, the FEM mesh of the tunnel is shown in Fig.1.

3.1 *Boundary conditions*

The boundary conditions in the numerical simulation on long-term settlements contain the following two types, one is the displacement boundary condition, and the other is the drainage condition.

A free displacement boundary condition is adopted at the ground surface. It is assumed that no horizontal nor vertical displacement takes place at the lower boundary, for it is beyond the influence of tunnel construction. The lateral displacements at left- and right- hand boundary are both fixed as zero. The left-hand boundary is the line of symmetry.

The drainage condition at the ground surface is assumed to be free, hence the excess pore pressure will be kept as zero along the ground surface; meanwhile the lower boundary as well as the left-hand boundary condition are considered to be impermeable, in order to prevent the pore pressure dissipation across the boundary during the settlement development. However, the right-hand boundary is taken as impermeable, because of the low permeability of the soil around the tunnel during the development of short-term settlement, while the pore-pressure is assumed to maintain the hydrostatic pore-pressure at the right-hand boundary during the long-term settlement evolution. That means the right-hand boundary is taken as impermeable during short-term settlement and if the right-hand boundary is taken as a constant head boundary it is permeable in one direction only during the long-term settlement. The tunnel lining is also assumed to be an impermeable boundary during the short-term settlement, but permeable during the long-term settlement with a finite permeability of $k_t / k_v = 0.01$. Here, k_t and k_v mean the permeability of the tunnel lining and the surrounding soils respectively.

The initial effective stresses and hydrostatic pore pressure are calculated based on the weight of the soil and the underground water condition.

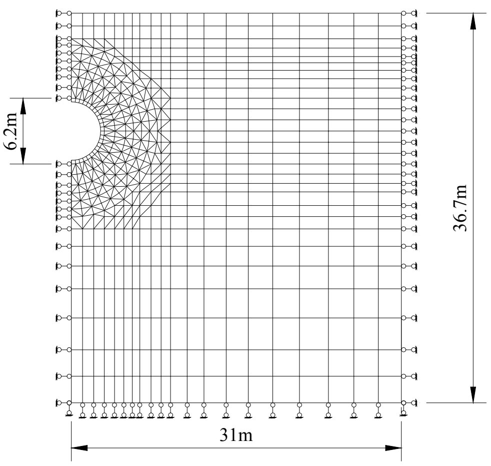

Fig.1 FEM mesh in numerical simulation

3.2 *Numerical simulation procedure*

The evolution of long-term (or post-construction) settlement is simulated using 4 consecutive steps. The 4 consecutive steps correspond to different stages of the development of surface settlement over tunnels, and their correlations are as follows: STEP 0 means the initial state of the ground, STEP 1 represents the heave (or settlement) of the ground when the shield machine approaching, STEP 2 represents the tail void closure because of the tunnel over-excavation, STEP 3 is the final case in the simulation, where the long-term settlement occurs. The grouting is simulated in step 3 by imposing pressure at the tunnel boundary equivalent to the grouting pressure. The numerical results for each step are the initial state of the next step since the 4 steps are consecutive both in time and stress state. Among the 4 steps, STEP 0, 1 and 3 are simulated using the stress boundary conditions, while the displacement boundary condition is adopted in STEP 2 to simulate the closure of the tail void during the tunnel advances. The imposed displacement is equivalent to the magnitude of over-excavation that will be discussed later in the paper.

3.3 *Determination of parameters*

The parameters involved in the numerical simulation can be divided into two types. One type is the mechanical parameters of soils and tunnel segments. The other type is related to the tunnel construction process. The parameters used in the numerical simulation could be found in the reference of Zhang et al. (2004).

3.4 *Simulation of over-excavation*

The over-excavation denoted as G is defined in terms of over-excavation ratio R_G and physical gap G_p .

$$G = R_G \cdot G_p \quad (2)$$

Here, G is the over-excavation during tunnel construction. G_p means the physical gap during shield tunneling. R_G represents the over-excavation ratio and is usually within the range of 1-1.2 for EPB tunnels. Correspondingly, the magnitude of over-excavation studied in this paper varies from 140mm to 168mm.

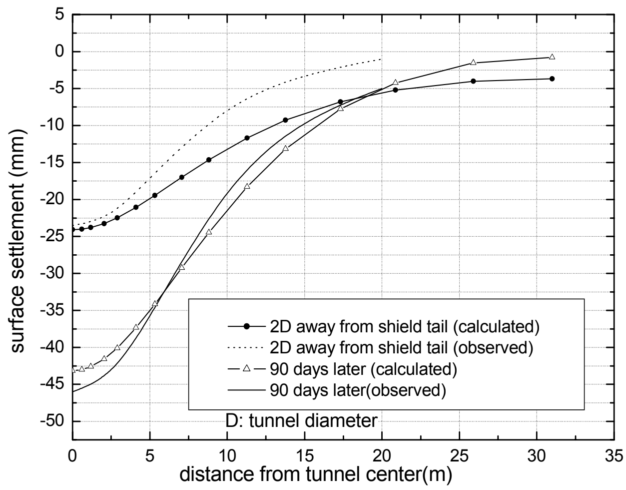

Fig.2 Comparison of calculated and in-situ measured surface settlements

4 DEVELOPMENT OF LONG-TERM SETTLEMENTS

Fig.2 compares the calculated and the observed surface settlements of Shanghai metro tunnel line No.2. It is found from Fig.2 that the long-term settlements of Shanghai metro tunnel line No.2 are significant. The maximum surface settlement almost doubles; meanwhile the width of the settlement rises from 2.4d to 2.7d (d is the radius of tunnel) in three month after tunnel construction. The transverse long-term surface settlement troughs corresponding to different tunnel excavation methods are presented in Fig.3 to illustrate the development of long-term surface settlement troughs of tunnels in clays.

Fig.3 shows that the shape of normalized surface settlement troughs do not change much during the long-term if the EPB tunnelling is adopted, and can be well described by Gaussian distribution. However, the shape of long-term surface settlement troughs varies significantly between TBM and open shield methods. Hence, the evolution of long-term surface settlement troughs seems to be dependent on the tunnel excavation method, and it is consistent with the findings of Mair and Taylor (1997) and Shirlaw (1993).

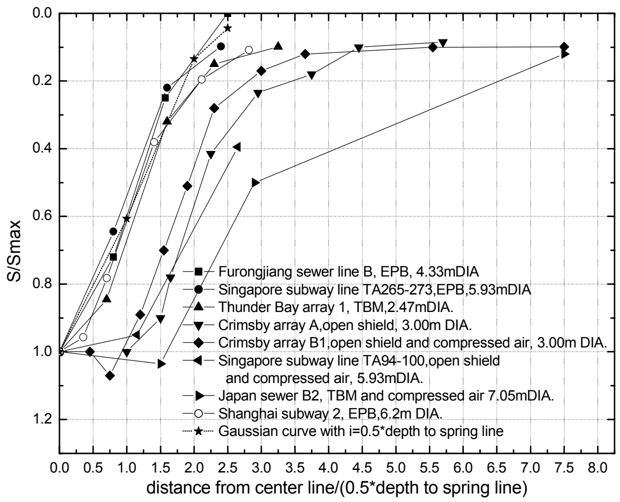

Fig.3 Long-term surface settlement troughs corresponding to different tunnel excavation methods

5 INFLUENCE OF OVER-EXCAVATION ON THE EVOLUTION OF LONG-TERM SETTLEMENTS

The evolutions of long-term surface settlements over tunnels with different over-excavation ratio are presented in Fig.4 and Fig.5, where the long-term surface settlements corresponding to the final equilibrium state of settlement. The measured correlation between long-term surface settlement and the over-excavation ratio of Shanghai metro tunnel line No.2 is also illustrated in Fig.6, where the observed long-term surface settlements are of 3 months after the tunnel construction. It should be pointed out that the short-term surface settlement is corresponding to the terminated moment of the grouting process in time-scale.

Fig.4 reveals that larger over-excavation results in larger long-term surface settlements. The correlation between long-term surface settlement and over-excavation ratio is almost linear. However, it is known that the over-excavation will enlarge the short-term surface settlement over tunnels because of tail void closure. For eliminating the influence of the short-term surface settlement, the post-construction surface settlement, which excludes the short-term surface settlement, with over-excavation ratio is plotted in Fig.5. Fig.5 indicates that the higher the over-excavation ratio, the larger the post-construction surface settlement. The calculated slope between long-term surface settlement and over-excavation ratio reaches 36 in Fig.4, while this value is smaller than that of 88 obtained based on the observed data in Fig.6. This error may rise from the numerical simulation assumptions combined with the different time-scale of the calculated and observed long-term settlements covers.

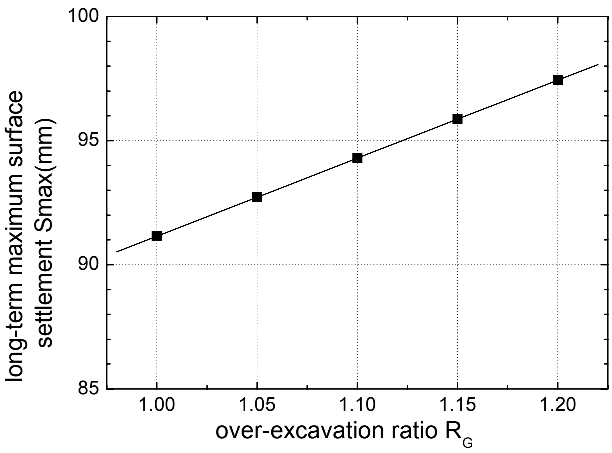

Fig.4 Evolution of long-term surface settlement with over-excavation ratio

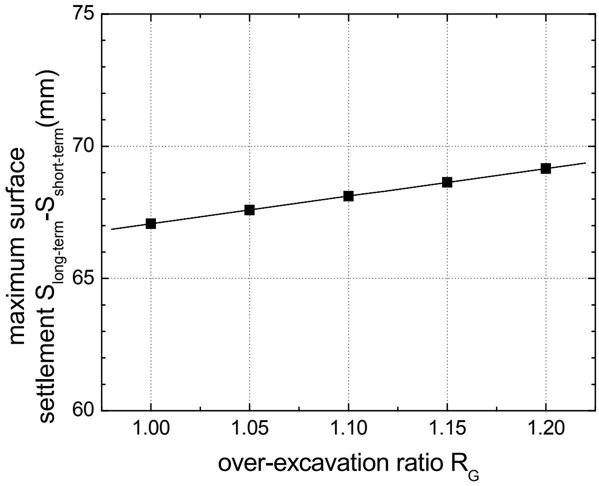

Fig.5 Development of post-construction surface settlement with over-excavation ratio

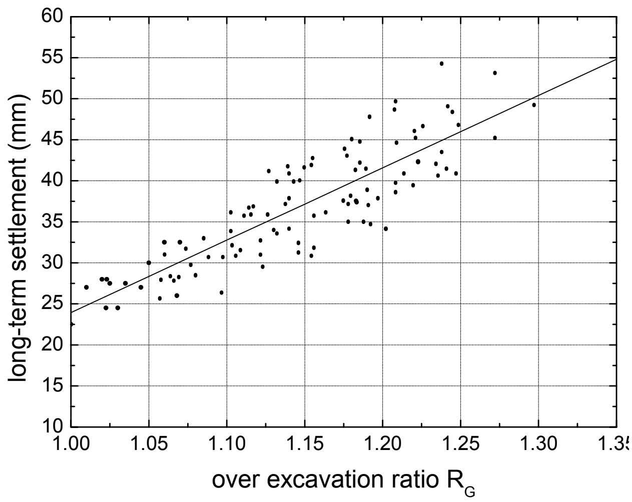

Fig.6 Correlation between long-term surface settlement and the over-excavation ratio(Lee, et al. 1999)

The short-term as well as long-term transverse surface settlement troughs, normalized to the corresponding maximum surface settlements, are shown in Fig.7 and Fig.8 respectively.

Fig.7 indicates that the normalized short-term transverse surface settlement troughs could be described by peck's empirical formulation (equation 3) (Peck (1969)). However, the normalized long-term transverse surface settlement troughs presented in Fig.8 varies significantly from the short-term ones. The long-term transverse surface settlement troughs exhibit the characteristic of open shield tunnel because of the larger over-excavation.

$$s(x) = S_{\max} \exp(-x^2/2i^2) \quad (3)$$

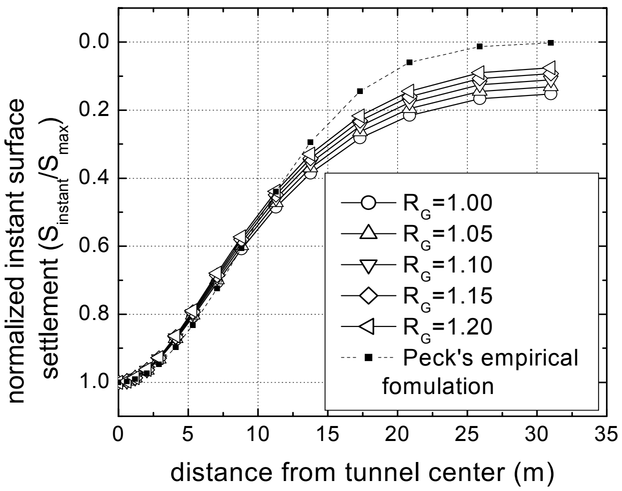

Fig.7 Short-term surface settlement troughs

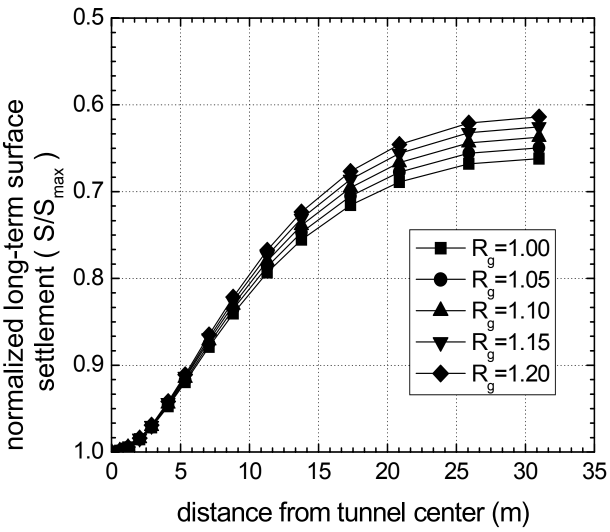

Fig.8 Long-term surface settlement troughs

6 CONCLUSIONS

Coupling the time-dependent stress-strain behavior of soils with the tunnel construction process, the evolution of long-term settlement of tunnels in clays is studied and the following conclusions are obtained:

1. The tunnel construction process has a very significant effect on the long-term settlement of tunnels in clay. The larger the over-excavation ratio, the larger the long-term surface settlement.

2. The long-term settlement of Shanghai metro tunnel line No.2 is significant.

3. The evolution of long-term surface settlement troughs is dependent on the tunnel excavation methods. The shapes of surface settlement troughs do not change much in the long-term using the EPB tunnel excavation method with small over-excavation. However, the evolution of long-term surface settlement troughs with time exhibits the characteristics of open-shield tunnel with larger over-excavation during shield tunneling.

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