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Construction principles for large-sized grid shield tunnelling in soft clay

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ABSTRACT: This paper is based on extensive field measurement from a large-sized grid shield tunnel project. The paper presents the construction principles of shield tunneling in saturated soft clay areas during normal advancement as well as during suspension of tunneling operations. In particular, the paper focuses on the relationship among the most relevant construction parameters, such as frontal face earth pressure of the tunnel, the amount of excavated soil, the advancement speed of tunneling, and the amount and quality of the grouting. These parameters were shown have great influence on the ground surface settlement, which is one of the major concerns when a tunnel is advanced under populated urban areas. In addition, the paper presents issues related to mechanical models of continuous ground surface settlement and the rheological phenomenon and the deformation mechanisms during suspension of tunneling.

1 INTRODUCTION

Shield tunneling methods have become more and more popular in urban areas, especially in soft soil deposit because of the resulting small ground surface settlement, which minimizes potential damage to the congested buildings and other civil infrastructure. The tunnel introduced in this paper is an urban highway tunnel under the Huang Pu River (overlaid with 8m of soft clay and 13m of water in the deepest location). This tunnel, serving one of the major thoroughfares connecting the urbanized regions on the two sides of the river, is located in East Yanan Road. The tunnel is 2261m long with a circular section of 11.3m in diameter.

A semi-opened grid shield tunneling (GST) machine was used for excavation. This GST machine (11.3m in diameter and 8.9m in length) was pushed forward by 48 hydraulic jacks, each having maximum force of 2250kN. The direction and speed of the advancement were controlled by adjusting 30 hydraulic lockable apertures installed on the breastplate in the front of the machine.

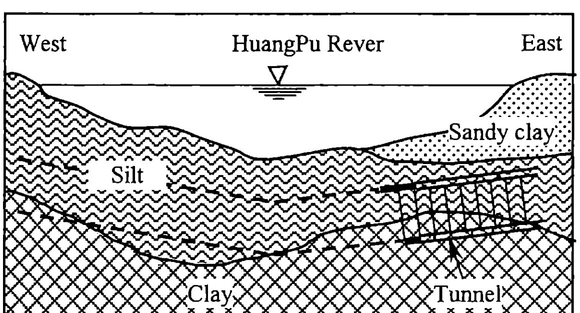


Figure 1 Geological profile.

The deposit is a highly compressible and sensitive saturated sandy clay, silty clay and clay, as shown in figure 1.

2 CONSTRUCTION PRINCIPLES DURING ADVANCEMENT

2.1 Face pressure vs. surface settlement

The distribution of the earth pressure on the frontal face of the tunnel machine was measured with 20 earth pressure cells installed on the breastplate (shown in figure 2). However, to calculate the ground surface settlement, only the average face earth pressure was used. Figure 3 presents the relationship between settlement and lateral earth pressure from which the following relationship was obtained:

$$p_o - p^a = 2.27\delta \tag{1}$$

where, p^a is the average value of face earth pressure on breast plate (MPa), p_o is the lateral earth pressure at rest (MPa), and δ is the ground surface settlement

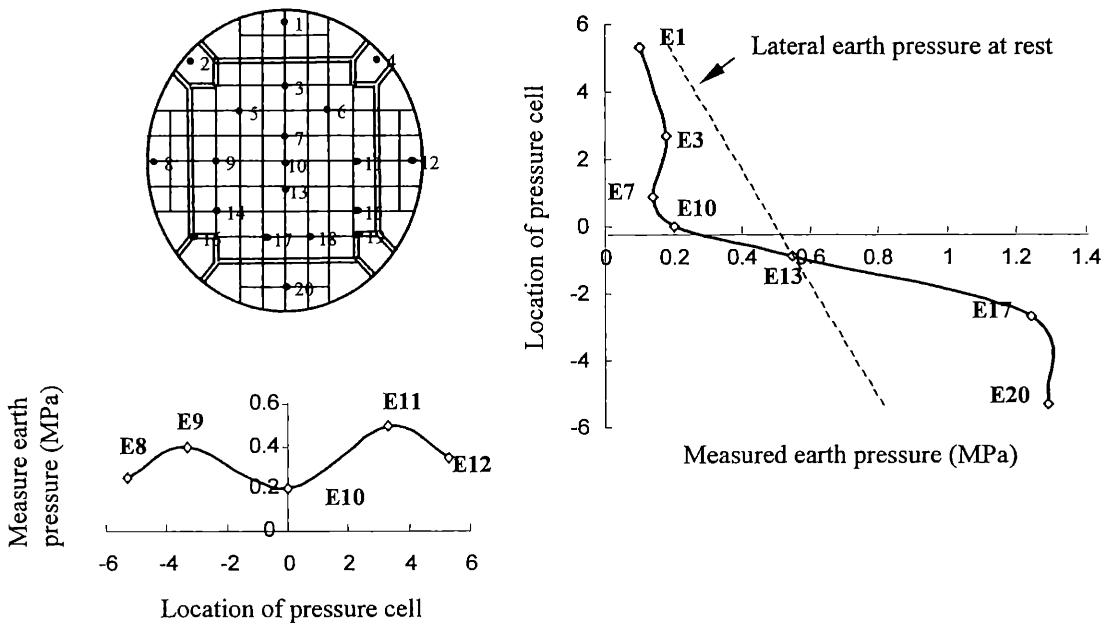


Figure 2 Distribution of face earth pressure.

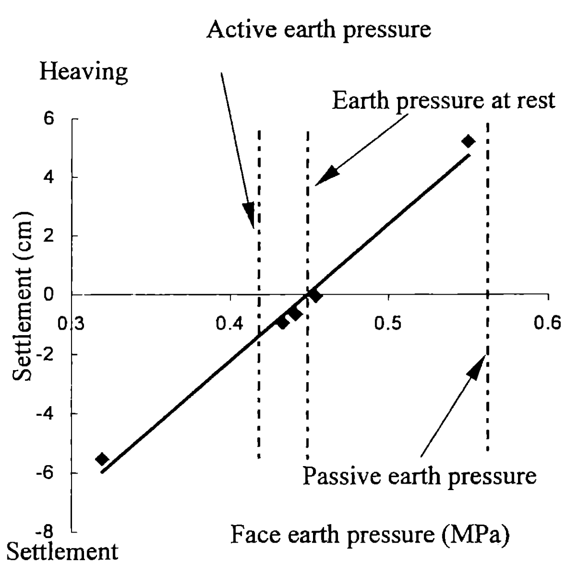


Figure 3 Relationship between face pressure and ground surface settlement.

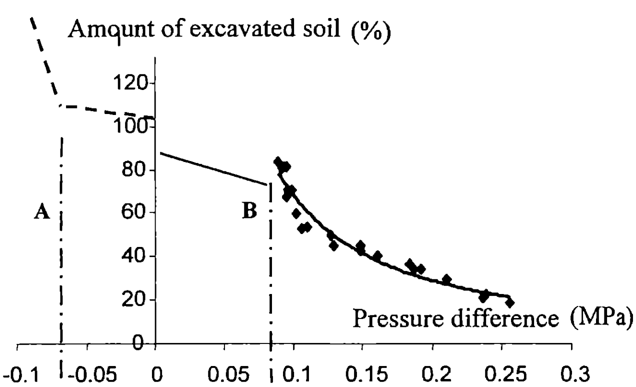


Figure 4 Relationship of amount of excavated soil and pressure difference.

at a distance 2D (22.6m) in front of tunnel face. ("+" indicates settlement and "-"heaving).

This relationship indicates that the ground surface displaces upward if the face earth pressure exceeds the lateral earth pressure at rest, and no surface settlement occurs if the face earth pressure approaches a force approximately equal to the lateral earth pressure at rest.

2.2 Amount of excavated soil vs. face earth pressure

According to Peck's principle of ground loss, the ground deformation is closely related to the amount of excavated soil, defined as the ratio v of volume of excavated soil and volume of tunnel. The relationship between the amount of excavated soil and earth pressure difference $(p^a - p_o)$ can be studied by plotting the measured values as shown in figure 4. In figure 4, the dotted line, which represents the ratio v over 100%, was drawn according to [1]. Therefore, to reduce the ground surface settlement, the amount of excavated soil v should be close to 100% and the pressure difference should be maintained between lines A and B, which are the limits of active and passive earth pressure respectively.

2.3 Advancement speed vs. face earth pressure

When the tunnel advances too fast and the soil in front of the tunnel face is not removed in time, the face earth pressure will increase, which in turn

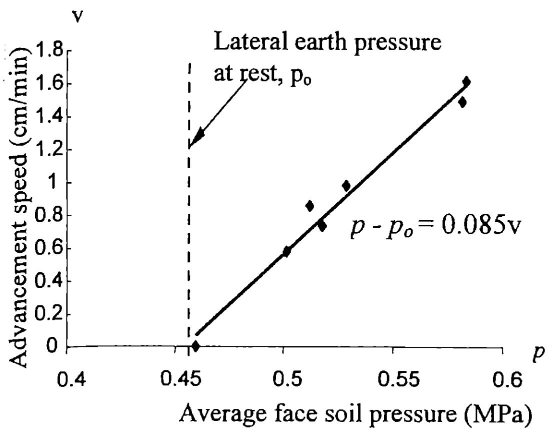


Figure 5 Relationship between advancement speed and face earth pressure.

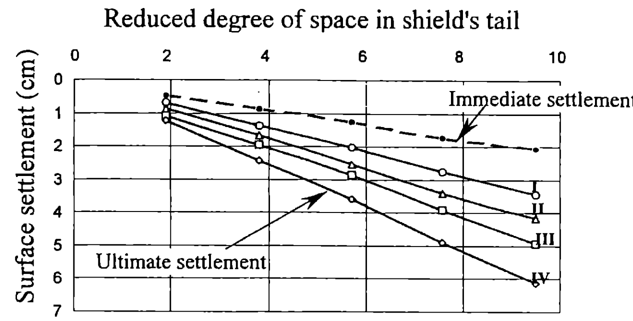


Figure 6 Relationship between ground surface settlement vs. the time to start grouting.

causes excessive ground surface deformation. Since the face earth pressure is affected by many factors, in order to study the relationship solely between face earth pressure and the advancement speed, the paper present data measured between Oct. 23 and Oct. 24 when other factors remained unchanged.

Figure 5 indicates that continuous advancement at a given speed will always compress the soil in front of the tunnel but when tunnel advances at a speed of 1.4cm/min, the ground approaches a state of passive failure.

2.4 Effects of grouting on surface deformation

To reduce the ground surface settlement, the space between GST shield tail and the circular lining segment should be filled up as soon as possible. It is important to carefully design the grouting pressure, appropriate time to start grouting, and the amount of grouting, as discussed below.

Suitable grouting pressure
Grouting pressure should not be very high nor very low. Very high grouting pressure (for example, greater than soil split pressure p_f, might fracture the ground causing grout leaks and soil disturbance. On the other hand, very low grouting pressure may result in voids in the liner and potential local failures.

The ground split pressure p_f can be calculated according from experimental results of [2], which is:

$$p_f = \sigma_3 + (0.9\ln R + 0.73)\, q_u \quad (2)$$

where, R is diameter ratio, $R = (2H + D) / D$

For the current problem, the ground split pressure p_f was calculated to be 0.465MPa. In practice, grouting pressures between 0.4 – 0.5MPa are recommended in soft clay formations.

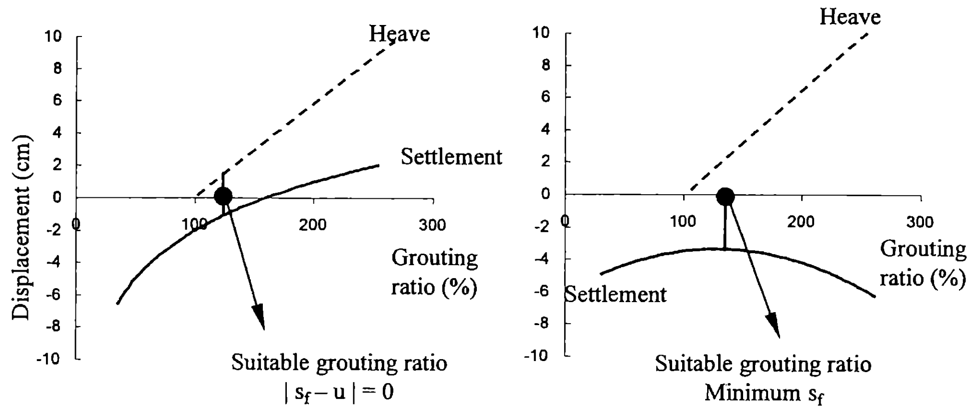
Suitable time to start grouting
Ideally, it is better to grout simultaneously with the advancement of tunnel. Because of added cumbersome construction operations, simultaneous grouting was not used in this tunnel. Figure 6 shows the predicted relationship between ground surface settlement and grouting startup as obtained from FEM calculation [3].

Amount of grouting
Theoretically, the volume of grouted materials should be equal to that of the to-be-grouted space. However, the amount of grouting usually exceeds the space of shield tail because of abnormal construction (adjusting directions, etc.) in advancement and other factors such as clay adhering around the shield shell, grouting leaking, and contraction of grouts, etc. Suitable grouting ratio can be determined according to figure 7 [3]. The grouting ratio for this tunnel was 119%.

2.5 Ground deformation

Surface settlement in longitudinal direction
Observations show that the ground starts to deform at a location 2D before GST machine arrives and continues to deform long after it has passed. According to the measured surface deformation at the position just above No. 20 lining segment, deformation mechanisms can be divided into four stages, as shown in figure 8.

- *Prior deformation.* Deformation at this stage refers to the deformation before GST machine arrives. About 35% of the total deformation developed during this stage.
- *Deformation during GST machine passing.* This deformation refers to the deformation during the period when the face of the machine arrives until



Case (a) Settlement has no peak   Case (b) Settlement has peak

Figure 7 Determination of suitable grouting ratio.

the shield tail leaves. About 20% of the deformation occurred during this stage.

- *Deformation after GST machine leaving.* This deformation is due to the collapse of space created after the shield tail separates from the lining segment. About 30% of the overall deformation occurred during this stage. Reports indicate that as much as 50% to 96% may occur during this stage [4].
- *Long term deformation.* This refers to the deformation after grouting and due to the consolidation of the ground. About 10% of the total deformation occurred up to present time.

The deformation mechanisms for each stage are shown in Table 1.

Transverse surface settlement trough

Figure 9 presents the transverse surface settlement profile measured at a location 15 meters away from No. 2 shaft. The surface settlement approximately conforms to a Normal distribution with a maximum

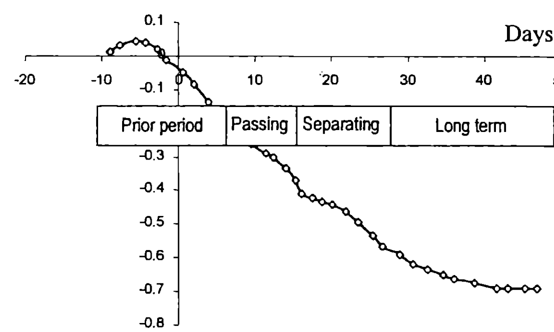


Figure 8 Ground surface deformation above the tunnel axis.

settlement right above of the tunnel. This result is in agreement with Peck's ground loss theory.

Surface settlement in a plane view

The contour of surface settlement has the shape of a cone whose tip is in line with the direction of advancement and it expands as the tunnel advances.

Table 1 Causes and mechanism of Deformation at each stage.

Stage	Reasons	Changes in ground conditions	Deformation type
Proceeding settlement	• Collapse of face • Excessive excavation	• Stress releaseSettlement (m) • Disturbance	• Elastic & plastic
Proceeding heaving	• Compress the ground • Less excavation	• Increased earth pressure	• Elastic & plastic
GST machine passing	• Compress the ground • Shearing by shield	• Disturbance	• Compression • Shear
GST machine leaving	• Occurrence of tail space	• Stress release • Disturbance	• Elastic & plastic
Long term deformation	• Consolidation • Creep • Lining deformation	• --	• Consolidation • Creep

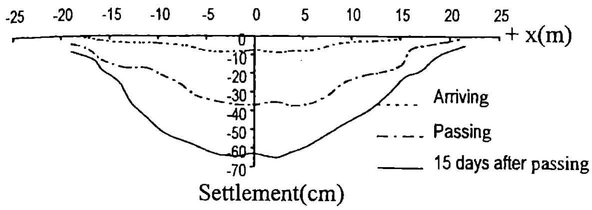


Figure 9 Transverse surface settlement trough.

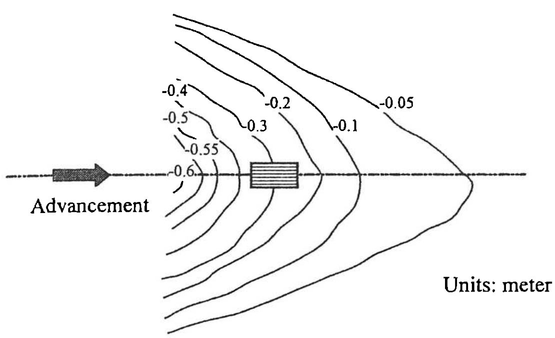


Figure 10 Surface settlement contour.

Contours of surface settlement created by this tunnel are shown in figure 10.

2.6 Empirical formula for overall surface settlement

The overall surface settlement is given as:

$$\delta_{max} = \delta_1 + \delta_2 + \delta_3 + \delta_4 \ \text{(m)} \tag{3}$$

where, δ_1: Proceeding deformation, "+" indicates heaving and "-" settlement; δ_2: Deformation during GST machine passing; δ_3: Deformation after GST machine leaving; δ_4: Long term deformation.

Prior deformation

From statistical analyses one may obtain the relationship of average face earth pressure p^a and surface settlement at a distance of 2D in front of tunnel face, as:

$$p^a = 0.65 - 1.56\,\delta_i \tag{4}$$

or $\delta_i = 0.64(0.65 - p^a)$ (5)

Deformation during GST machine passing

As mentioned before, the deformation during GST machine passing is mainly due to the soil disturbance, which decreases the deformation modulus of the soil deposit. The general formula for calculating deformation δ_2 is given as:

$$\delta_2 = \sum_i \sigma_{zi}^a h_i \left(\frac{1}{\mathbf{E}_{si}^R} - \frac{1}{\mathbf{E}_{si}} \right) \tag{6}$$

where, σ_{zi}^a: average gravitational stress per layer (kPa); h_i : thickness of each layer (m); E_{si}^R: disturbed modulus of each layer (kPa); E_{si}: initial modulus of each layer (kPa).

According to [4], about 30% reduction of deformation modulus for sand and 60% for clay is usually happened due to disturbance as GST machine passing by. Presuming that the reduction of deformation modulus in clay is as twice as that in sand for current tunnel problem, the reduced deformation modulus can then be back-calculated based on measured deformation δ_2 according to equation (6).

Deformation after GST machine leaving

δ_3 is calculated according to Peck's principle of ground loss which states that the volume of ground surface settlement trough equals to the volume of space left behind the shield tail. Therefore, the equation for calculating δ_3 can be expressed as:

$$\delta_3 = \frac{\sqrt{2\pi}}{4i}(1 - R_A)(D^2 - d^2) \tag{7}$$

where, R_A: filling ratio, depends on the amount of grouting, 41% is applied for current problem;D: outer diameter of the shield (m); d: outer diameter of lining segment (m); i: width parameter of settlement trough (m).

$$i = \frac{(H + R)}{\sqrt{2\pi}} \tan\left(45^\circ - \frac{\phi}{2}\right) \tag{8}$$

where, H is the depth of overlaid soil; R is radius of tunnel.

Long term deformation

The behavior of long term deformation can be described using the Voigt rheological model and δ_4 is calculated as:

$$\delta_4 = \frac{a}{G}\tau_0\left(1 - e^{-\frac{G}{\eta}t}\right) \tag{9}$$

where, G: shear modulus of soil; η: viscosity coefficient; a: radius of tunnel; τ_0: average shear stress; t: time from when machine stops, in days.

According to the experimental results provided by the Wuhan Institute of Rock and Soil Mechanics, the average value of G and η were 900kPa and 1600Mpa-min in this case study, and the average shear stress was 9.1kPa.

Deformations are calculated at each of the 4 stages according these empirical equations, and the results are shown in table 2.

Table 2. Surface deformation at each stage (m).

	δ_1	δ_2	δ_3	δ_4	δ_{total}
Calculated	0.24	0.15	0.22	0.06	0.67
Measured	0.26	0.12	0.27	0.1	0.75

3 CONSTRUCTION PRINCIPLES DURING SUSPENSION

There are many factors that may cause temporary suspension of tunneling, for example, machine repairs, work shifts, other construction problems. It has been proven in practice that suspension of advancement causes extra surface settlement. Hence, it is better to resume advancing soon after temporary suspension.

3.1 Relaxation phenomenon of face earth pressure

Face earth pressure on breastplate is usually greater than lateral soil pressure at rest during normal advancement. When the machine stops and the hydraulic jacks have not been released, shear stresses developed previously will relax because of the rheological nature of soils. Therefore, the face earth pressure decreases as time elapses until it finally reaches the lateral soil pressure at rest. Again a rheological model is used to describe this phenomenon:

$$p_t = p_o + (p_k - p_o)\exp(-Et/\eta) \qquad (10)$$

where, E: elastic modulus of soil; η: viscosity coefficient; p_t: average face earth pressure on breast plate at any moment after stopping; p_o: lateral earth pressure at rest; p_k: average earth pressure on breast plate at the moment of stopping; t: time from when machine stops, in hours.

The model parameters E and η can be determined through laboratory soil tests or back calculated based on measured face earth pressure.

3.2 Stress release in the ground and machine retreat

After the hydraulic jacks on the breastplate have been released, the machine will move back under the unbalanced force from face earth pressure. The machine retreats until face earth pressure reduces to a value that is balanced by the frictional force between soil and shield shell. The amount of retreat δ can be estimated as:

$$\delta = \frac{2P_c - H}{kA} \qquad (11)$$

where, δ: machine retreating (m); P_c: total force on breastplate when stopping (kN); H: force when hydraulic jacks are released (kN); k: subgrade coefficient (kN/m^3); A: area of breastplate (m^2).

4 CONCLUSIONS

One of the major advantages of using shield tunnels in urban areas is that the construction of the tunnel has very little influence on the existing structures, infrastructure, and traffic. This is assured by limiting the induced ground surface settlement to an allowable value. According to this study, many factors may affect the amount of settlement during construction. In particular, the frontal face earth pressure, the amount of excavated soil, and the advancement of the tunnel have direct influence on the ground surface settlement. These construction parameters must be carefully adjusted in order to control the settlement. The empirical relations of these parameters as they relate to settlements, provide a helpful guide in the optimization of construction parameters during shield tunneling.

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