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Field measurements from two tunnels in Shanghai

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ABSTRACT: In the past 12 years, two tunnels have been built under the Huangpu river in Shanghai. Field instrumentation has been taken to study the ground settlement law. The advantages and disadvantages of different kinds of shields are discussed in relation to ground settlement.

INTRODUCTION

In Shanghai's urban area, crowded with buildings, and services, it's necessary to construct below ground. Since the subsoil in Shanghai is mainly soft clay, most tunnels are constructed by shields such as grid shield, earth pressure balance shield, and slurry shield to reduce environmental effect. To date, the biggest problem of tunnelling in soft clay is the disturbance of the ground, especially when the shield is passing through ground below groups of buildings and pipelines. The degree of disturbance of ground is different for different shield tunnelling methods, so it's important to select proper shield method. In the past 12 years, two tunnels have been constructed under Huangpu river in Shanghai using different tunnelling methods. The settlements of these two tunnels are very different. A comparison and analysis of the settlement laws are introduced below.

GENERAL SITUATION

These two tunnels are 60 ~ 100m apart. The ground properties, burial depth and the cross sections of them are very similar.

Tunnel I was constructed from 10/1983 to 10/1988, using a closed-face shield with hydraulic and mechanical excavating and transporting method. The outer diameter is 11.3m, the inner diameter is 11.1m, and the cover is 11 ~ 22m. The total length is 2261m, the part constructed by shield tunnelling is 1476m long.

The construction of Tunnel II began in 5/1994, and will be completed in 4/1996. A slurry shield is used, with outer diameter 11.22m, inner diameter 11.08m, and cover 10 ~ 24m. The total length is 2207m, the part constructed by shield tunnelling is 1310m.

The two tunnels both begin at the west side of the river and end at the east. The east ends merge into one. The ground are mainly loam, sandy loam and silty clay. This stratum is saturated, of high compressibility and sensitivity. On the east side of the river, there're crowded buried pipelines, buildings and streets. The river transport is busy and the tide influence is significant. The covering layer is thin to 5 ~ 6m, less than half of the diameter.

Fig.1 shows the profile of the tunnel in the stratum.

Fig.2 shows the position of the two tunnels on the map.

Fig.3 is the geological profile.

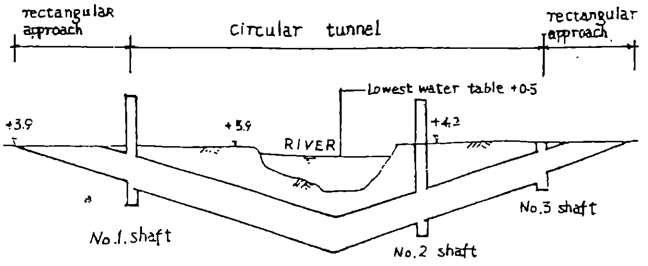

Fig.1 profile of the tunnel

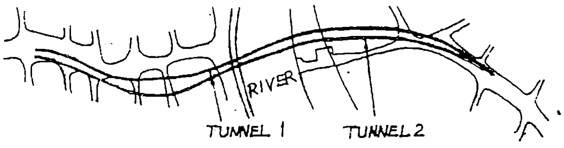

Fig.2 position of the two tunnel on the map

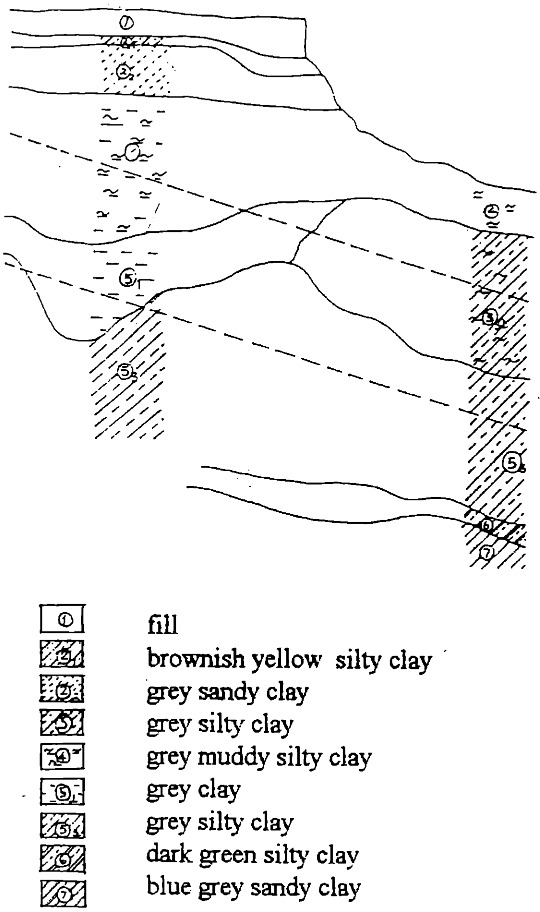

Fig 3 the geological profile

FIELD INSTRUMENTATION

During construction of Tunnel I, because of lack of previous research of settlement law induced by tunnelling in soft clay. A large number of instrumentation points are laid out. The monitoring included:

1. Vertical settlements of ground surface and building foundations —- leveling aparatus.

2.Horizontal displacement in layers —- inclinometer.

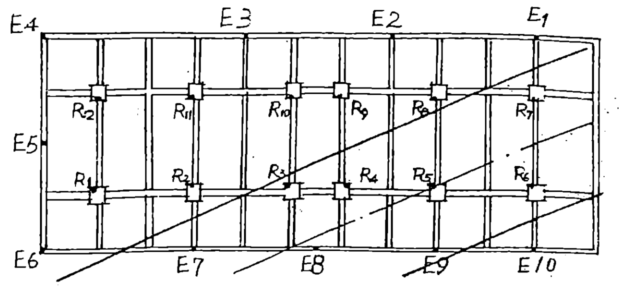

Fig.4 layout of instrumentation points on the foundation of medicine store house

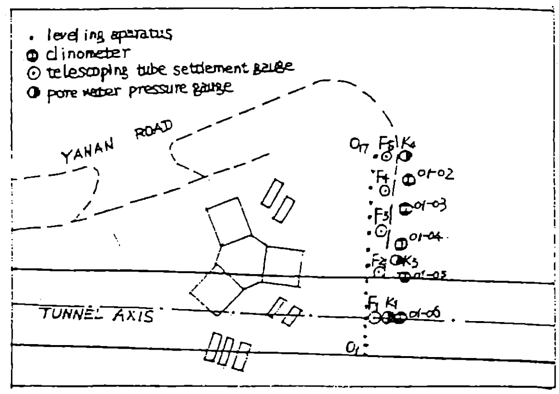

Fig.5 monitoring plan on the surface around the gas station

3.Settlement of soil layers —- telescoping tube settlement gauge.

4.Pore water pressure —- pore pressure gauge.

5.Investigating and monitoring of cracks and damage to the buildings and ground.

Fig.4 shows the layout of instrumentation points on the foundation of the medicine store house.

Fig.5 is the monitoring plan on the surface around the gas station.

On the Tunnel II project , pore water pressure gauges, inclinometers, and telescoping tube settlement gauges are laid out only in the initial 100m trial, and because of low quality of grouting, these monitoring points actually not function. Therefore the research is concentrated on ground surface settlement. The distance between two points along the line above the tunnel axis is 4m. The monitoring is only taken in the affected area. 15m ahead of the excavation face and 25m behind the tail of the shield. In order to protect the buildings and pipelines, monitoring points were also set on buildings and pipelines that might be affected. At the same time there was close investigation of cracks and damage to the buildings and ground.

Fig.6 is the layout of settlement points in the residential area of Sichuan Road.

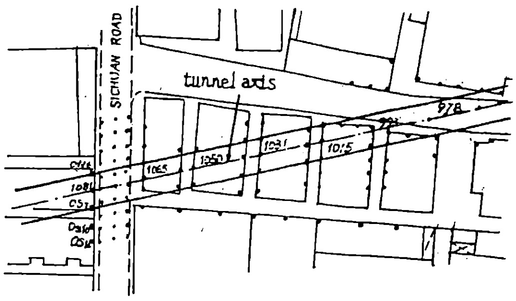

Fig.6 layout of settlement points in the residential area near Sichuan Road

LONGITUDINAL SETTLEMENT LAW

The trend of longitudinal displacement during advance of the two tunnels are similar, and the total settlement can be divided into four featured stages: initial settlement, passing settlement, tail settlement and long-term settlement.

Fig.7 shows longitudinal displacement developing with time on Tunnel I.

Fig.8 is the longitudinal displacement developing with time on tunnel II.

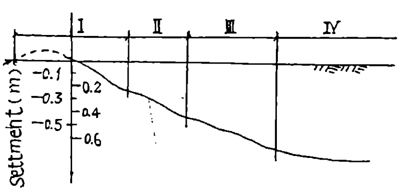

Fig.7 Longitudinal displacement developing with time on Tunnel I

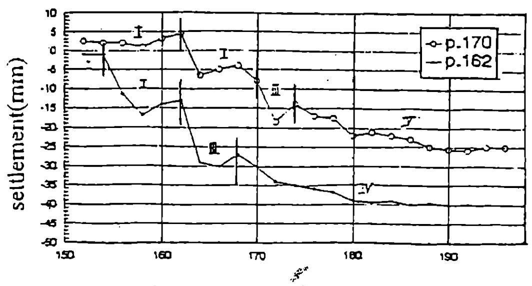

Fig.8 longitudinal displacement developing with time on Tunnel II

(1). Initial Settlement

This refers to settlement induced before the arrival of the shield face. On Tunnel I project, the opening ratio of the shield face is only 6%, the excavated soil ratio is 60% ~ 80% of the theoretical volume, and the soil at the face is squeezed significantly, which leads to the large heave ahead of the excavation face and disturbance of the subsoil. However, for the Tunnel II project, the soil pressure at the face is balanced by slurry pressure, which is automatically controlled by the central control system, only related directly with slurry pumping pressure and slurry draining pressure instead of the excavated soil ratio. Therefore overexcavation or underexcavation in a short time has little influence on the stability of the excavation face. Simultaneously, slurry pressure functions at the face directly and evenly, without partial concentration or reduction of supporting pressure, so that face stabilty is high and the disturbance is low. The measurement results show that the displacement ahead of the excavation face is limited within +3mm ~ -3mm, and the affected area is small, even less than 1 H in some places.

(2)Shield Passing Settlement

This refers to settlement induced from the arrival of the shield face to passing of the shield tail. This part of the settlement is mainly caused by disturbance during passage of the shield, especially the friction and shear between the shield shell and the surrounding soil, which destroys the structural strength of the soil and reduces the soil modulus. Additionally, some of the surrounding soil adheres to the shield shell, which increases the space settlement. This part of settlemat in Tunnel I comes to 30% of the total, while the counterpart in Tunnel II is less than 20% of the total. The reason is concerned with the mechanism of the slurry function. See Fig.9. Slurry not only fills the space at the excavation face, but also the space surrounding the shield shell. On one side, it provides vertical balance pressure as well as the horizontal balance pressure. On the other hand, it acts as lubricating oil to reduce the friction and shear between the soil and the shield shell and the quantity of the soil attached to the shield shell. In the measured settlement curve of the slurry tunnelling, this part is flat.

(3)Tail Settlement

This refers to the settlement beginning when the tail space is produced and ending when grouting is finished. Because a truly simutaneous grouting method was not used , and the grouting material was not ideal, this part of the settlement for both tunnels is comparatively large, Tunnel I reaching 30% of the total and Tunnel II reaching 50%.

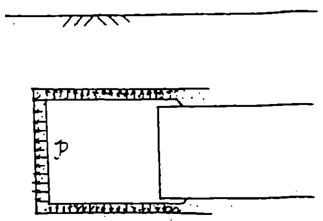

Fig.9 face stability mechanism of slurry shield

(4)Long-term Settlement

This refers to the settlement after grouting is finished. In Tunnel I, the soil at the excavation face was squeezed forward and upward, while the soil at the tail relaxed and moved downward and backward. Therefore , the soil structure and strength around the tunnel was greatly destroyed , and the subsequent consolidation and creep last a long time , ending with a great amount of settlement . In Tummel II , the disturbance of the surrounding soil is small so that the related long-term settlement is small and finishes quickly . After 3 ~ 4 days , most of the settlement finishes.

TOTAL SETTLEMENT

$$\Delta = \Delta 1 + \Delta 2 + \Delta 3 + \Delta 4$$

On the base of field measurement, the experience formula to get the ground surface settlement is introduced here.

1. Δ1—initial settlement

From measured data, there's an obvious linear relationship between the soil pressure at the excavtion face and the initial settlement. There's an empirical equation regressed from a group of points,see Fig 10.:

$$P=6.5+15.6 \cdot \Delta 1$$

where, p is the earth pressure at the excavation face in kg/cm^2.

Δ1 is the initial settlement in meter.

2. Δ2—passing settlement

The main reason of this part of settlement is the disturbance of the soil, which leads to the reduction of soil modulus of deformation ; therefore, the general formula to calculate the subsoil settlement in layers is used here:

$$\Delta 2=\sum \bar{\sigma}_{zi} \cdot h_i \cdot \left(\frac{1}{E'_{si}}-\frac{1}{E_{si}}\right)$$

where, $\bar{\sigma}_{zi}$—the average geostatic stress of each layer

h_i—the thickness of each layer

E'_{si}—the soil modulus of deformation after being disturbed

E_{si}—the initial soil modulus of deformation

According to previous research, the soil modulus of deformation will be reduced by 30% of the original for sandy soil,and by 60% for clay.

3. Δ3—tail settlement

Δ3 can be calculated according to the principle that practical ground loss should be equal to the space volume after the tail of the shield leaves ,as the following function:

$$\Delta 3=\sqrt{\frac{\pi}{2}}\frac{1}{4i}(1-f)\times(D^2-d^2)$$

where,f—filling ratio at the tail

D—the outer diameter of the tunnel

d—the outer diameter of the lining

i— the cross-section trough width factor

4. Δ4—long-term settlement

The law of this part of settlement can be described as a Voigt rheological model:

$$\Delta 4=\frac{a}{G}\tau_0(1-e^{-G/\eta})$$

where,G—the shear modulus of the soft ground in Shanghai, is a viscous modulus with an average value of G=9KPa as measured.

$\eta=0.96\times10^{13}$ Pa,as measured.

t— time ,meaning the number of dates.

τ_0----the average shear stress of the ground.

a----radius of the tunnel.

5. Δ ----the total settlement

$$\Delta = \Delta 1 + \Delta 2 + \Delta 3 + \Delta 4$$

In Tunnel I, it's 20 ~ 30cm with a high ground loss ratio reaching 15% and in Tunnel II, it's only 5cm with a low ground loss ratio less than 2%. It appears that slurry shield is much advantageous in settlement control.

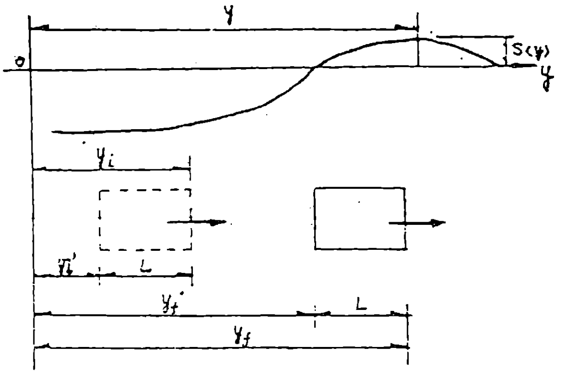

Fig.10 longitudinal ground surface settlement

The longitudinal settlement curve of the two tunnels (see Fig.10)also presented a similar law. By regression ,it can be expressed by a function as following, based on the Peck curve.

$$S_y = \frac{V_{l1}}{\sqrt{2\pi} i}[\phi(\frac{y-y_i}{i}) - \phi(\frac{y-y_f}{i})]$$

$$+\frac{V_{l2}}{\sqrt{2\pi} i}[\phi(\frac{y-y_i'}{i}) - \phi(\frac{y-y_f'}{i})]$$

V_{l1}----ground loss induced before shield face arriving. If heave occurs, the value will be minus.

V_{l2}----ground loss induced after shield face arriving.

i----settlement trough width factor

One case has been studied in Tunnel I .The measured curve and the calculated curve are shown in Fig.11.

Fig.12 is the typical cross-section settlement trough of Tunnel I. The trough width is 20m.

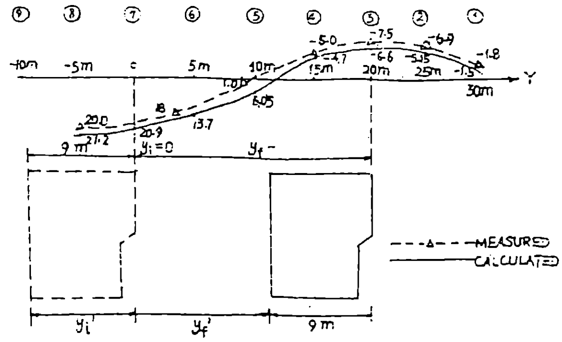

Fig.11 measured and calculated longitudinal settlement curves

COMPARISON OF THE CROSS-SECTION SETTLEMENT TROUGH

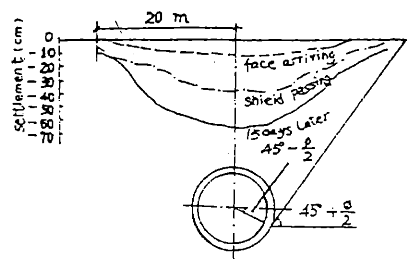

Fig.12 settlement trough in Tunnel I

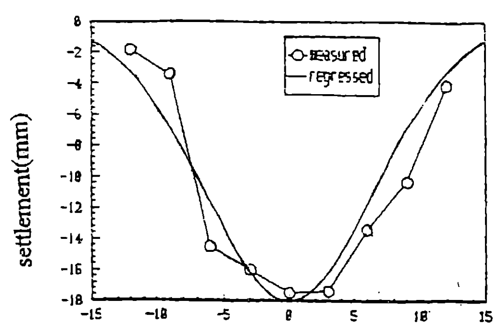

Fig.13 settlement trough in Tunnel II

Fig.13 is that of Tunnel II, with almost the same burial depth, and its trough width is only about 10m. Obviously, the trough width is also related to the degree of disturbance. Accordingly, the trough width factor i had to be modified. In Tunnel II case, it is modified as:

$$i = R_0 \, (Z/2R_0)^{0.23}$$

The results predicted are close to those in practice.

Furthermore, there's a special phenomenon during the construction of Tunnel II, that is the elevation of the 10 ~ 20 meter-long part of the tunnel behind the tail fluctuates for a long time . This fluctuation can be checked from the monitored results of the continuous tubes set inside the tunnel, which tell the fact that the tunnel isn't stable until several days later . In this tunnelling case , two-shot grouting method is used in tail grouting . After the two kinds of grout meet with each other , the mixture hardens very quickly and 6 ~ 7 seconds later it can bear a strenth higher than soil before the space surrounding the tunnel can be fully filled . Slurry then goes through the small spaces to the back part of the tunnel and produces an uplift load . In soil with low permeability the slurry can be kept around the tunnel for a long time , therefore the fluctuation can last long. This kind of phenomenon was also found in the construction of Subway Line 1 . But in Subway Line 1 earth pressure balance shield and slow -hardening grout is used , therefore, the uplift load can only come from the grout for a short period.

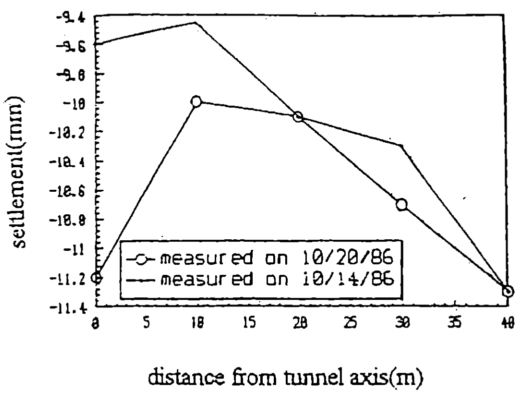

Fig.14 settlement funnel of Tunnel I

In the construction process of Tunnel I, there was a sudden drop of the ground surface about 120m away from the west side of the river , forming an area shaped like a funnel . The lowest point of the funnel was about 2 meters under the surface. The diameter of the funnel is 40m , see Fig14 . When the settlement funnel happened , the shield was just passing this area ,and the greatest settlement took place ahead of the excavation face . Going back to the reason , it was found that the shield stopped for a long time , and the amount of soil excavated was too much . To garrantee the construction safty, a quick measurement was taken to reduce the quantity of the excavated soil and face opening ratio ,and to speeded up the advance rate. The shield then passed through the dangerous thin-covering-layer area safely.

In Tunnel II slurry pressure is under good control and no big settlement funnel occurred when advancing under water . It proved safer to raise the slurry pressure a little. A small heave occurred when the shield was passing through, but after the shield tail left, the settlement counteracted the heave to make the surface of the ground close to the original.

It is found that the shield advance rate is a significant parameter to prevent large settlement . On the Tunnel II , the speed when advancing under water was about 10 ring/day while in Tunnel I the average speed was only 4 ring/day . From this point of view the advancing speed contributes to the safe construction underwater.

CONCLUSION

I . Ground surface settlement caused by shield tunnelling can be divided into four parts : the initial settlement, passing settlement , tail settlement and long-term settlement . The total settlement is the result of this four parts.

II . The longitudinal settlement law can be expressed by following equation :

$$S_y = \frac{V_{l1}}{\sqrt{2\pi}i}[\phi(\frac{y-y_i}{i}) - \phi(\frac{y-y_f}{i})] + \frac{V_{l2}}{\sqrt{2\pi}i}[\phi(\frac{y-y_i'}{i}) - \phi(\frac{y-y_f'}{i})]$$

III. The close-face shield tunnelling induces great disturbance of the ground which leads to a significant upheave ahead of the excavation face , a great long-term settlement and a large affected area .

IV. Slurry shield provides good face support and the slurry pressure covers not only horizontal , but also vertical soil pressures . The slurry surrounds the shield shell , reduces the friction and shear between the ground and the shield shell , fills the space induced by changing direction and finally reduces ground disturbance and the related ground settlement.

V . When the shield is passing underwater, the face supporting condition must be guaranteed to prevent the collapse of the work face and water intrusion. At the same time the advance rate should be increased and stoppages of the shield avoided. When a settlement funnel occurs, a quick measurement should be taken to adjust the face support pressure,to keep it greater than the active soil pressure,and to increase the speed. A small heave ahead of the face is good for the coustruction and leads to small settlements.