# CASE STUDY OF SETTLEMENT DURING DOUBLE-O-TUBE TUNNELING IN SENSITIVE SOFT GROUND

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**ABSTRACT**

DOT (Double-O-tube) tunneling method has been adopted in constructing various tunnels in soft ground both in Japan and China. Early practice of such method in China has been reported in Shanghai metro network construction during Line 8 and 6, in which the ground surface settlements were controlled within several cm. However, in a recent line construction, the practice of DOT tunneling was not so satisfying. The ground is sensitive alluvial clays of 20~30m thick, which is not competent for shield tunneling. Among three tunnels which were conducted by DOT shield machine, settlement of the ground surface has gone beyond allowable level, and even 80 cm of settlement were measured in the worst case. In this paper, the ground conditions and the construction process are checked carefully first. Special attentions are paid to earth pressure at the cutter face and the injecting parameters of backfill grouting. An in-situ monitoring, including the surface settlement and subsurface settlement was conducted to obtain the change of ground deformation during shield driving. Based on the monitoring and corresponding field investigation, the reasons related to the unexpected large settlements are discussed. From this case study, it is found out that the backfill grouting during the construction play a very important role in controlling the ground surface, and unsuitable grouting is accounted for the large surface settlement.

**Key Words :** settlement, DOT (double-o-tube shield), field investigation, soft ground

## 1 INTRODUCTION

DOT (Double-O-tube) tunnelling method can construct two tunnels simultaneously by one shield machine. In the DOT shield machine, two cutters are arranged in the same plane, and a Y-shape so-called seagull segment is used to connect the two tunnels. After its first application in Japan on 1989[1)], it has been adopted in constructing various tunnels in soft ground both in Japan[2), 3)] and China[4)].

DOT method was first applied in Shanghai metro Line 8 and 6 from the year of 2003 to 2006. The rolling of the shield machine and the ground settlement during DOT tunneling have drawn most attentions of the Chinese engineers. Zhou[4)] summarized the construction experiences of Line 8 and he concluded that the ground settlement and influenced range were larger than that of single circular shield tunnel. Zhang et al.[5)] pointed out that increasing the volume of backfill grouting could reduce the settlement effectively. The optimized volume should be 6.2m$^3$ per ring. Shen et al.[6)] applied FEM to analyse the behavior of lining caused by the rolling of the shield machine.

The practice of DOT method in Line 8 and 6 showed that the ground surface settlements could be controlled within several cm. However, in a recent line construction, the practice of DOT shielding is not so satisfying. The settlement of ground surface has gone beyond allowable level, and even 80 cm of settlement were observed in the worst case. In this paper, the earth pressure balance at the cutter face and the backfill grouting will be analyzed. Furthermore, in-situ monitoring, including surface settlement and subsurface settlement, is carried out to study the mechanism of the ground deformation due to the DOT shield tunnelling

## 2 PROJECT PROFILE

Three DOT machines with a spoke type cutter face were used in the project. Their geometry size were Φ6520mm×W11120mm. Reinforced concrete segments were stagger-jointed assembled. Each ring was separated into 8 pieces of segments. The thickness and the width of segments were 300mm and 1200mm.respectively.

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As shown in Fig.1, the strata from up to down are described in the following. Layer ①1 is filled soil. Layer ②1 is brown ~ yellow silty clay. Layer ③ is grey silty clay. Layer ③$_T$ is fine sand mixed clay. Layer ④ is muddy silty clay. Layer ⑤1 is grey clay. Layer ⑤3 is grey silty clay. Layer ③, ④ and ⑤1 are soft marine clay with SPT-N values of 0~2.

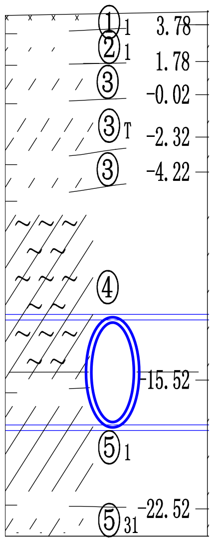


Fig.1 Profile of typical ground condition

## 3 IN-SITU SETTLEMENT MONITORING

In order to clarify the mechanism of ground settlement due to DOT shield tunneling, in-situ settlement monitoring was carried out and the observed data were analyzed carefully by comparing with the shield driving data.

### 3.1 Instrumentation

Two monitoring sections were set to study the difference of ground movement due to the excavation, section 1 is for the original TBM driving and section 2 is for the improved TBM driving based on the analysis of the original one. Each monitoring section has ground surface settlements and subsurface ground movements. The measurement in section 1 is used to analyze the features of ground response caused by the planned shield driving parameters. And the measurement in section 2 is used to check the effect of the improved shield driving based on the above analysis.

(1) Ground surface settlements

Ten sub-sections of surface settlements measuring points were setup before and after each monitoring session. The distance between adjacent sub-sections was approximate 3m. In each section, two measuring points located above the axial lines of two tunnels, another points located at the edge of the tunnel. Totally about 30 points were setup.

(2) Subsurface ground movements

Four subsurface settlement monitoring lines were setup in each monitoring section. Magnet gages for settlement in the ground (symbol ◆ in Fig.2) were installed inside the bored holes from the ground surface with an interval of 2m. As shown in Fig.2, one monitoring lines located above the center line and two axial lines of tunnels respectively. The space between the bottoms of three monitoring lines and the shield machine was 2m. Another monitoring line was installed beside the tunnel with a space of 1m.

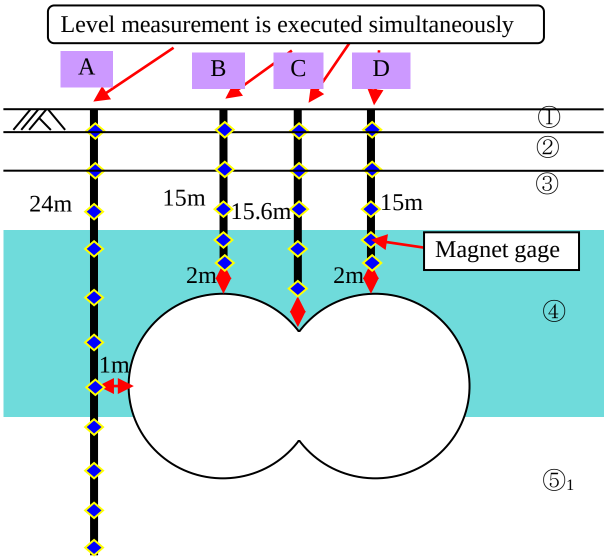


Fig.2 Instrumentation of monitoring section

### 3.2 Construction data

The shield driving data of 40 rings (Ring No.960~1000) around the monitoring section 1 were summarized in the following.

(1) As shown in Fig. 3, the earth pressure at the chamber was 350±10 kPa (middle left position). It was almost equal to the in-situ earth pressure at the crown (340 kPa). However, the chamber pressure was larger than the theoretical value (about 280 kPa). Besides the unsuitable operation of the shield machine, there exists the possibility of malfunction of the pressure gauge.

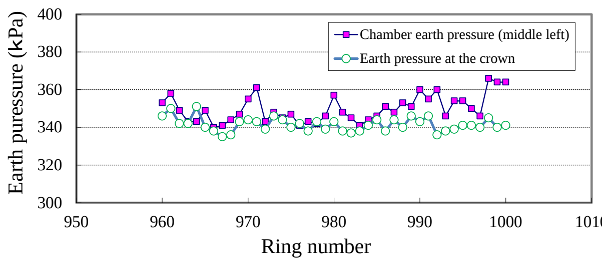


Fig.3 Earth pressure around section 1

(2) Since the pipes for simultaneous backfill grouting got clogged, the grouting was injected from two points in the 3rd~5th segment. Two injection points located at the top left and bottom right of the tunnel. It was thought that this kind of injection method can reduce the rotation of the whole tunnel. Two liquids type grouting was used. The grouting volume was 12m$^3$ per ring (theoretical backfill void is 4 m$^3$).

(3) Both screw conveyors were opened for discharging soil. The open ratio of screw gates was 30% before Ring No.968, and up to 35% after then.

(4) Advance speed of shield machine was 45～50mm/min at most time. It dropped down to 40mm/min

occasionally.

### 3.3 Monitored results

Fig.4 shows the observed ground surface settlement of section 1. The horizontal axial is the advance distance of shield machine, which is presented by the ring number. The vertical axial is settlement. The position of the shield machine is plotted in the figure. Although no obvious settlement or upheave can be seen before shield machine arrived and during machine passed by, settlement occurred after tail passed. A maximum settlement about 80 cm occurred in measure point C, where is the center of the DOT tunnel. A smallest settlement about 43cm was observed in point A, where located at the side of the tunnel. It can be seen that the settlements above the tunnel center and two tunnel axial lines are almost the same, while those at the sides are much smaller. All settlements converged after 16 rings.

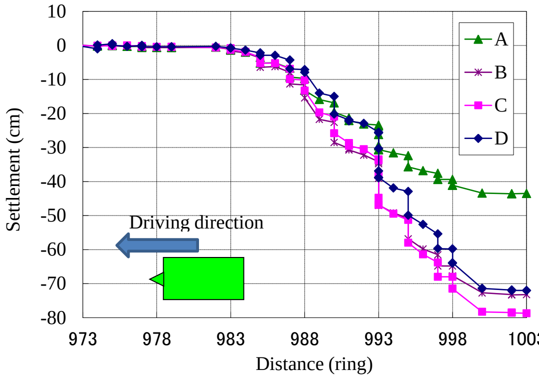


Fig.4 Observed surface settlements versus distance (Section 1) due to shield driving

Fig.5 shows the subsurface settlement of section 1. The horizontal axial is the advance distance of shield machine, which is presented by the ring number. The vertical axial is depth from ground surface. The settlement scale, the position of the shield machine, and the 45º influence lines of cutter face and tail void are plotted in the figure.

(1) Before the shield arriving, no obvious deformation can be seen in the ground. It indicated that the chamber earth pressure was under control.

(2) During the shield passing by, no obvious deformation can be seen. It indicated that the friction of the skin plate did not affect the ground significantly.

(3) During the tail passing by, the ground 2m above the tunnel crown upheaved. The maximum upheave of 16.7cm occurred above the seagull segment (the center line of the tunnel). The upheaving also can be seen in the ground 4m above the tunnel. However, due to the large upheave, the magnet settlement gauge at the bottom failed.

(4) After the tail passing by, the ground above the tunnel subsided together. The maximum settlement was -94cm, which was observed in the magnet of 12m depth above the seagull segment. At the distance of No.1000 ring, this magnet upheaved a little due to the complementary grouting from the segment.

Aforementioned phenomena indicate that the earth balance at the cutter face and the friction of the skin plate did not affect the ground very much. However, the improper backfill grouting squeezed the surrounding ground, resulting an upheaving of the ground near the shield machine. The tail void was not filled in time, a large settlement occurred right after the tail passing by. It also can be seen that in Shanghai soft clay ground, the backfill grouting from segment, even though a complementary grouting is executed, cannot avoid the settlement.

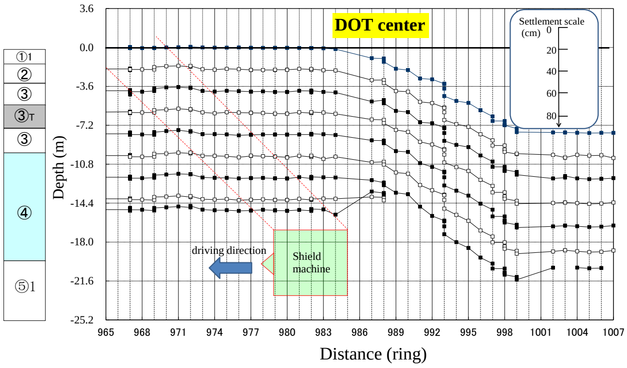


Fig.5 Change of subsurface settlements (Section 1)

### 3.4 Field investigation

After the DOT shield machine entered a middle shaft, it is found that a layer of cement-like agglomeration attached on the skin plate (Fig.6). The maximum thickness of the agglomeration was about 20cm. From the scrape on the agglomeration, it can be deduced that the agglomeration has been cut by the entrance. Therefore, the original thickness of the agglomeration should have been at least 40~50 cm. The staff of the construction company confirmed that no other material have been added to the ground during the shield excavation, except the bentonite slurry in the chamber and the backfill grouting. Therefore, the agglomeration should be the cementation of the two liquid type backfill grouting.

Fig.6 Agglomeration on the skin plate

The mechanism for the large ground settlement can be concluded as following. After the pipes for simultaneous backfill grouting got clogged, the grouting was injected from the 3rd~5th ring of segment.

However, the soft ground has already fallen down to fill the tail void before the grouting from the segment. The grouting broke through the weak zone of the ground, or ran back along the gap between the ground and the skin plate. The two-liquid grouting got hardening quickly, and attached on the skin plate gradually, especially on the concave seagull segment. Consequently, the tail void became much larger than the theoretical value, result in a large settlement.

## 4 COUNTERMEASURE

Two countermeasures were taken in the middle shaft. The two liquid type backfill grouting is compose of A (mainly cement) and B (mainly water glass) liquid. B liquid is mixed with A liquid at the operation platform of shield machine. Then the mixture is sent to the simultaneous injection pipe at the tail of shield machine through a transportation pipe. The mixture is sent by injection pump to fill the tail void during the shield advancing. The transportation pipe is about 6 m. On the other hand, the gel time is set within 10 seconds. It is easy to block the transportation pipe if the pipe is not cleaned in time after every injection. However, in this case, it was difficult for the shield machine operator to handle. Besides that, the pump for B liquid often failed due to lack of maintenance. Under these situations, it is decided that the priority should be set to filling the tail void in time and avoiding the conglutination of the grouting material on the skin plate.

Two-liquid type backfill grouting was changed to one-liquid type (non-cement type). At the same time, a complementary injection of cement fluid was carried out from the segment on the first gantry. By this way, the long term strength of the grouting material can be enhanced.

After the improvement, the shield advanced from the middle shaft toward the arrival shaft. The in-situ monitoring was executed in Section 2 to verify the effect of the improvement. The shield machine data of 40 rings (Ring No.1140~1180) around the monitoring section 2 were summarized in the following.

(1) The earth pressure at the chamber was 260±10 kPa (middle left and middle right positions). It was within the rational range of the theoretical lateral earth pressure (286 kPa).

(2) One liquid type simultaneous backfill grouting was used. The grouting volume was 6 $m^3$ per ring, almost half of that before reformation.

(3) Both screw conveyors were opened for discharging soil. The open ratio of screw gates was 30%.

(4) Advance speed of shield was 30～40mm/min.

Fig.7 shows the ground surface settlement of monitoring section 2. A vertical displacement of ±0.5 cm was observed before the shield arriving and during the shield passing by. A settlement occurred when the tail passing by, and finally settlement was about 2 cm. The subsurface settlements gauges also showed the same tendency. Comparing with Fig.4, it can be said that the reformation have reduce the settlement effectively.

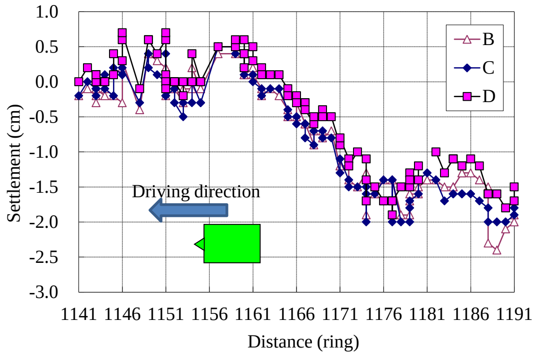


Fig.7 Change of surface settlements (Section 2) due to the reformed TBM driving

## 5 CONCLUSIONS

The in-situ monitoring and site investigation were carried out to study the main factors for unexpected settlement of DOT shield. It is found that the backfill grouting is the key issue for controlling the shield induced settlement in soft ground. The two liquid type grouting has such merits as: high fluidity before hardening, early hardening after mixing, so that it is suitable for reducing the immediate and long-term settlements of soft ground. However, it requires a good construction management and device maintenance system. One liquid type grouting is relatively easily handled. It can fill the tail void in time so as to avoid the large settlement. However, it will not harden, which will possibly cause larger long-term settlement. Therefore, more study should be carried out to develop a grouting method that can be executed easily and has long-term stability.

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