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A case study of ground control mechanisms of EPB shield tunnelling in soft clay

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ABSTRACT: This paper presents the observed ground surface movement and the corresponding construction details during advance of an Earth Pressure Balanced (EPB) shield driven tunnel of the Shanghai Metro Tunnel-Line 2 in China. Based on the field results, the influences of tunnel construction control processes on the resulting ground movement are interpreted and discussed in this paper. Correlation between the ground surface settlement is developed taking into consideration of the control factors in the excavation process as well as the grouting process.

1 INTRODUCTION

Shanghai Metro Line 2, which runs across the city from east to west, is currently under construction. It is estimated that the entire line can be put into service at the end of 1999. Significant portions of the line 2 tunnels are being constructed underneath busy commercial districts with a large number of tall buildings and underground utilities lines. Ground settlements and structure movements, therefore, are strictly controlled during the tunnel construction. In this project, compensation grouting injection technique to fill-up the tail void created by the clearance between the shield and segmental concrete lining was used in order to reduce the ground settlement to an acceptable amount. An extensive system for monitoring ground surface movement was installed along the tunnel alignment and corresponding construction details are recorded at the same time. Based on these field data, the influences of tunnel construction control processes on the resulting ground movement are interpreted and discussed.

1.1 *Geology*

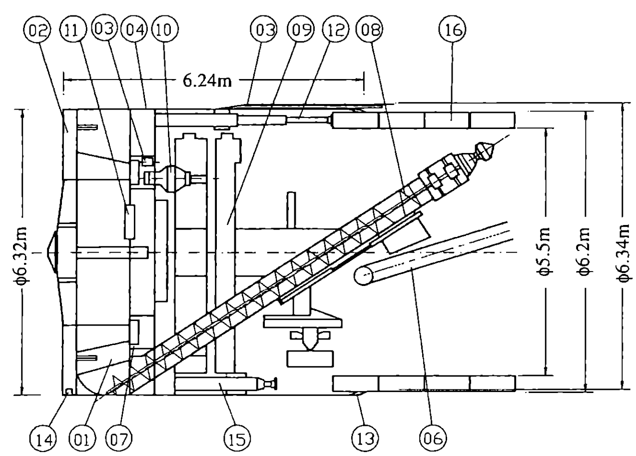
Shanghai is situated on the Yangtze River Delta. The geology consists of alluvial and marine sediments deposited during the Quaternary geologic period. According the site investigation results, Shanghai soils can be differentiated into a number of well defined strata based on physical properties and soil types. The various soil strata near the observation section are described in Table 1.

Table 1. Soil layers in Shanghai

Layer	Name	Thick-ness	State
1	Miscellaneous fill	1.4m	Loose
2	Silty clay	0.7m	Low to middle plasticity
3	Mucky-silty clay	3.3m	Middle to high plasticity
4	Mucky clay	8.8m	high plasticity
5-1	Silty clay	10.2m	Middle plasticity
5-2	Silty clay with thin silty layers	10.2m	Middle to low plasticity
6	Silty clay	1.8m	Low to hard plasticity
7-1	Silty sand with silty clay	7.0m	

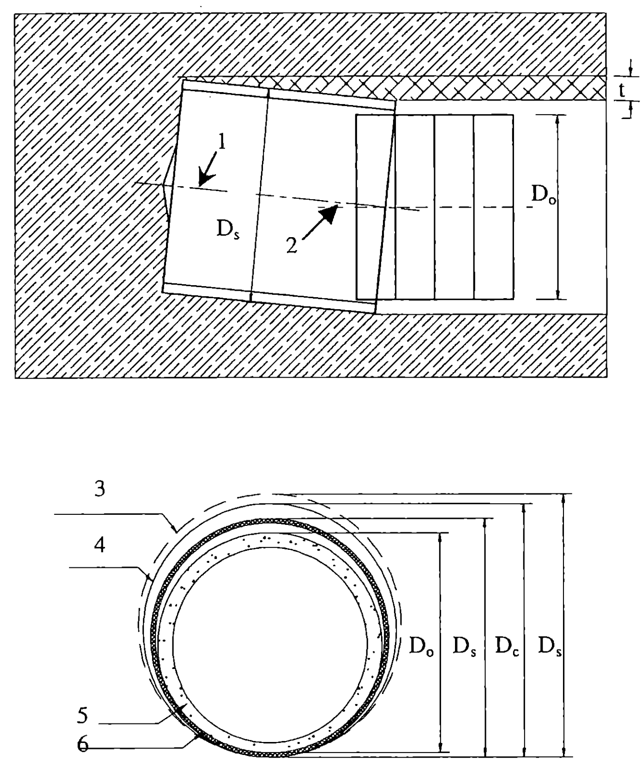
1.2 *Earth pressure balanced tunneling shield*

The earth pressure balance (EPB) machines were made by Fives-Cail Babcock Ltd. (FCB) in France incorporated with the patent licensed by Kawasaki Heavy Industries Ltd. in Japan. A schematic figure of the EPB shield is shown in Fig. 1. A novelty in the design of the EPB shield is that the pressurized grouting material can be injected into and fill-up the



1	Soil Chamber	9	Segment Erector
2	Cutter Disc	10	Motor of Cutter Disc
3	Driving System Cutter Disc	11	Man Lock
4	Shield Body	12	Shield Jack (Double Extension)
5	Grouting Pipe	13	Tail Seal
6	Belt Conveyor	14	Over Cutter
7	System Sealing	15	Shield Jack (Single Extension)
8	Screw Conveyor	16	Lining Segments

Figure 1. Earth pressure balance shield tunneling Machine.



Note:

1. Actual grade
2. Design grade
3. Equivalent grouting
4. Equivalent cutting
5. Lining
6. Shield body

Figure 2. Definitions of construction parameters in terms of the equivalent "Gap" concept.

gap leave between the tail skin and the concrete lining ring with the protection of shield tail. This grouting material is designed by a local contractor and is composed of a mixture of fine round sand, fly ash, lime, and various admixtures. The main physical properties of this grouting material are easy flowing, slow setting, and non-segregating, with good mechanical behaviors after consolidation.

2 OBSERVATION AND INTERPRETATION

2.1 *Observation of ground surface movement*

In order to study the ground movement due to the construction of the tunnel, settlement markers were installed along the alignment every 2.5 m and in several cross-sections for settlement troughs measurement.

2.2 *Construction Procedures*

The construction parameters during shield driving were recorded by a computer. These parameters included: the control of tunnel shield, earth pressure at the cutting surface, jack pressure, cutting force, position of shield body, grouting volume and grouting pressure. The information will be used for the analysis of the ground responses and the interpretation of observed results.

2.3 *Results of field observation and their interpretation*

The surface movement induced by advancing EPB shield is highly dependent upon the control and operation of the tunneling shield. On the other hand, the monitored results of surface movement become key feedback to shield operators for the control of tunnel advancement. For this reason, these data are highly correlated with each other, and a proper interpretation of results must consider all these information

These construction parameters were recorded by a computer connected to the control panel of the EPB shield. In order to facilitate the presentation of results, the construction parameters are expressed as the following non-dimensional ratios. The definitions of these construction parameters are also graphically illustrated in Fig. 2.

The muck pressure maintained within the soil chamber is expressed as the earth pressure ratio (EPR):

$$EPR = \frac{p_{chamber}}{p_o} \tag{1}$$

where $p_{chamber}$ is the soil pressure measured by the load cell installed near the center of the soil chamber in the bulkhead of the EPB shield; and p_o is the in-situ total horizontal earth pressure at the depth of tunnel axis.

The volume of grouting materials injected into the tail void between the tail-skin and tunnel lining is expressed as the grout volume ratio (GVR):

$$GVR = \frac{G_{grout}}{G_p} \tag{2}$$

where G_p is the physical gap as defined by Lee et al. (1992). The physical gap ($G_p = 2\Delta + \delta$) represents the geometric clearance between the outer skin of the shield and the lining, and it is composed of the thickness of the tailpiece (Δ) and the clearance required for erection of the lining (δ). In other words, the physical gap is the difference between the diameter of the tunnel shield and the outer diameter of the tunnel liner (i.e., $G_p = D_s - D_o$) as shown in Fig. 2. G_{grout} represents the volume of grout injected into the tail void and it is expressed as an equivalent thickness of grouting material. i.e.,

$$G_{grout} = \frac{Grout\ \ volume\ \ per\ \ unit\ \ length}{\pi D_o} \tag{3}$$

The volume of ground loss caused by over-cutting of the tunneling machine is expressed as the over-excavation ratio (OER):

$$OER = \frac{G_{oc}}{G_p} \tag{4}$$

where G_{oc} is the equivalent volume of ground-loss caused by over-excavation of the shield As suggested by Cording and Hansmire (1975), the volume of lost ground caused by over-excavation (V_{shield}) can be expressed as:

$$V_{shield} = \frac{\pi D_s L}{4}(t) \tag{5}$$

where D_s is the outer diameter of the shield body; L is the length of the shield; and t is the maximum shield deviation from the designed alignment.
It is easy to get,

$$G_{oc} = G_p + \frac{t}{4} \tag{6}$$

The efficiency of the grouting material in filling the void spaces created by over-excavation of the shield can be expressed in terms of the relative volume of grout injection and ground loss created by over-cutting, which can be expressed as the grout filling ratio (GFR):

$$GFR = \frac{G_{grout}}{G_{oc}} \tag{7}$$

From the observed variation of vertical surface movements above the center line of the tunnel and the development of settlement troughs at various distances from the tunnel face, it is quite obvious that the surface movements can be divided into five distinct phases :

(i) Phase I - The approach of the tunnel shield. Movements of the ground start to develop when the tunnel machine is about three diameters away from the instrumentation section. The ground surface may display a slight heaving or settlement pattern depending on the bulkhead pressure as expressed by the earth pressure ratio (EPR). When EPR > 1, the ground will heave; when EPR < 1, the ground will settle.

(ii) Phase II - The passing of the shield body. Surface settlement slightly increases due to the stress release effect induced by the two over-cutting bits located on the edges of the cutting surface. Ground movements may also be induced by shear stress generated on the excavation surface during the passage of the shield body.

(iii) Phase III - Tail void closure. The yielding soils around the tunnel opening try to deform into the tail void left between the excavation surface of shield body and the outside diameter of the lining. However, the EPB shield adopted in the current project is equipped with a specially designed grout injection system. The exact volume of tail void and how it might be filled up with grout material are rather complicated issues. They should be somehow reflected by the over-excavation ratio (OER) and the grout filling ratio (GFR). When the tail void is not properly filled with grouting material, the ground settlement associated with tail void closure can develop very quickly once the shield tail advanced beyond the section.

(iv) Phase IV - Consolidation of grouting material and disturbed soil. The consolidation settlement around the tunnel generally will last for at least 2 months. However, the development of consolidation settlement seems to be the major component of ground settlement induced by the tunneling process. The relative magnitude of consolidation settlement seems to be somehow affected by the excavation and control processes of the shield advancement.

(v) Phase V - Secondary consolidation of disturbed soils. Although the observation did not last long enough to determine the behaviour of secondary consolidation induced by the tunneling process. Previous observations on Line 1 of the Shanghai Metro Tunnels showed that the secondary consolidation settlement could last for two years. The secondary consolidation settlement of the ground could contribute up to 10% of the total surface settlement (Liu and Bai, 1997).

3 CONSTRUCTION CONTROLS AND THEIR INFLUENCE ON OBSERVED BEHAVIORS

To obtain an overall view of the surface movements induced by the EPB shield process, settlements along the tunnel center line measured at various times were plotted along the observed tunnel alignment (Fig. 3(a)). In order to examine the influence of various construction control parameters on the resulting surface settlement, various non-dimensional control ratios as defined in the previous section were also plotted along the same alignment for direct comparison with the observed surface settlements (Fig. 3(b)). It is observed that the short-term and long-term settlements are quite fluctuating, which can be attributed to the various construction control parameters adopted along the alignment. From Fig. 3(a), it can be observed that the trend of long-term surface settlements (3 months after construction) does not bear any correlation with the trend of ground movements developed ahead of the tunnel face (2D before cutting face); however, the long-term surface settlements bear a close resemblance with the trend of ground movements observed after the grouting process (1D after grouting). In fact, the long-term settlements are simply 25 to 30 mm more than the settlements observed after the grouting process. These additional settlements are probably contributed mostly by the consolidation of the grouting material and the disturbed soil around the tunnel opening. This implies that the final long-term surface settlements eventually developed in the ground surface are significantly affected by the efficiency of the tail-void grouting process, which occurred at a relatively early phase of the tunnel construction.

In order to examine the correlation between various construction parameters and the resulting ground movements, Figs 4 to 8 present the relationships between various non-dimensional construction ratios with observed surface settlements. Fig. 4 shows the relationship between the short-term ground movements observed at a distance of two diameters ahead of the cutting face and the earth pressure ratio (EPR). When the EPR is in the range of 0.95 to 1.05, the ground movements induced by the approaching tunnel are very small (close to 0 mm). While EPR > 1.05, ground heaving is resulted. On the other hand, when EPR < 0.95, ground settlement is resulted.

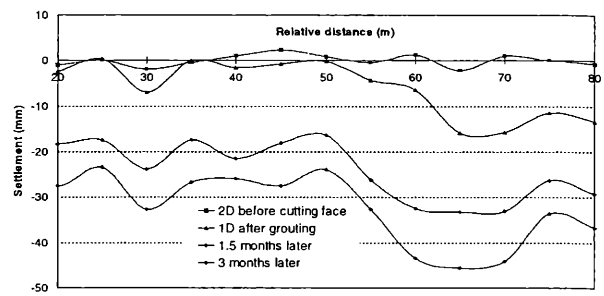


Figure 3(a). Ground settlements along tunnel alignment.

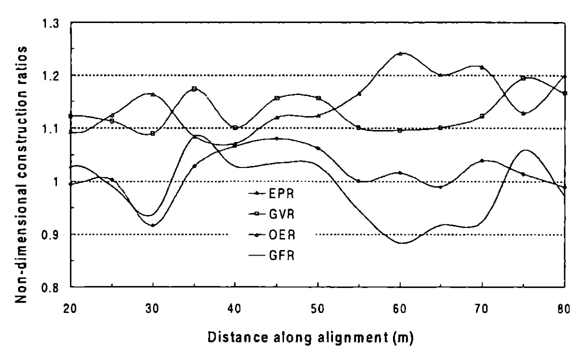


Figure 3(b). Construction details

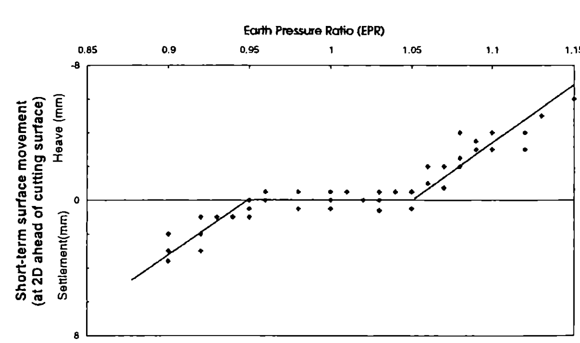


Figure 4. Relation between short-term surface movement with the Earth Pressure Ratio (EPR).

The correlation between long-term surface settlements and the earth pressure ratio (EPR), grout volume ratio (GVR), over-excavation ratio (OER), and grout filling ratio (GFR) are shown in Figs. 5 to 8, respectively. It is interesting to note that although the earth pressure ratio (EPR) bears a strong correlation with the short-term ground movements ahead of the tunnel cutting face, no correlation can be established between the EPR and long-term surface settlements. Correlation also cannot be established between the long-term surface settlements and the grout volume ratio (GVR). On the other hand, strong correlation can be observed to develop between the long-term surface settlements and the over-excavation ratio (OER), and between the long-term surface settlements and the grout filling ratio (GFR). This indicates that the long-term ground settlements are significantly affected by the over-cutting actions induced by the pitching and yawing motions of the tunneling shield. Thus, the control of shield alignment during thrusting remains one of the most important tunnel control parameters. More importantly, the actual volume of grouting material injected into the tail-void created by the over-cutting actions of the shield as reflected by the grout filling ratio (GFR) is the key parameter to limit the long-term settlement developed on the ground surface. It is observed that a well defined trend of linear relationship (with coefficient of correlation, R^2 = 0.7829) between the long-term surface settlement and the GFR can be established. Increasing the GFR would significantly reduce the long-term surface settlements. It is therefore recommended that a proper shield control system be incorporated with a feedback mechanism to reduce the actual volume of over-excavation created at the tail-void by over-injecting it with appropriate volume of grouting material (i.e., increase the grout filling ratio, GFR). From the observation made at the Shanghai Metro tunnels, the most effective GFR is about 1.1 to 1.15 (i.e., the total volume of injected grouting material is about 10 to 15% more than the volume of actual tail-void created by over-excavation). This is contrary to the common

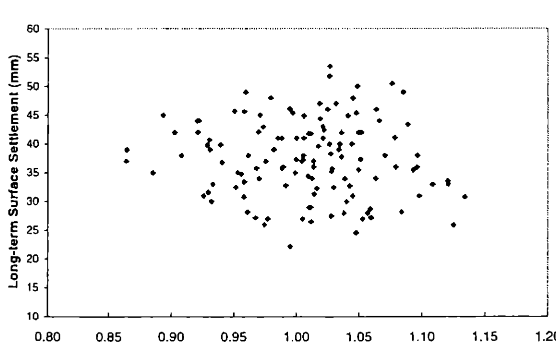


Figure 5. Relationship between long-term surface settlement with the earth pressure ratio (EPR).

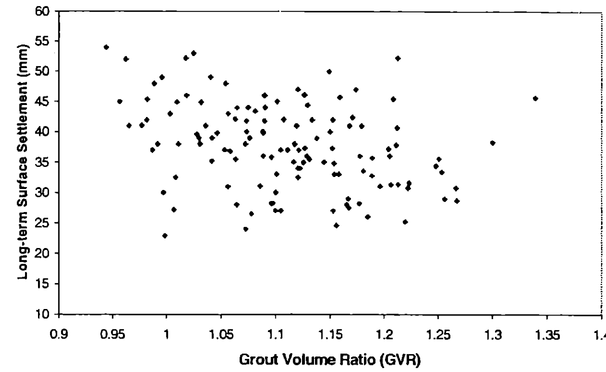


Figure 6. Relation between long-term surface settlement with the grout volume ratio (GVR).

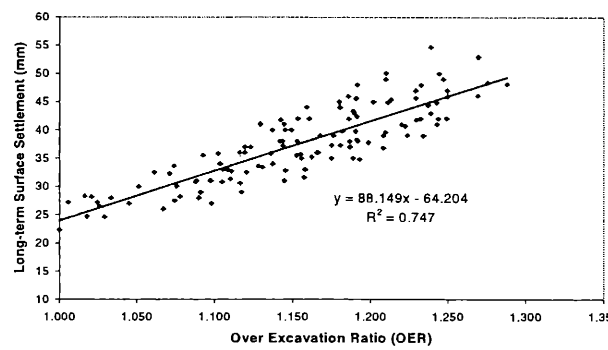


Figure 7. Correlation between long-term surface settlement and the over excavation ratio (OER).

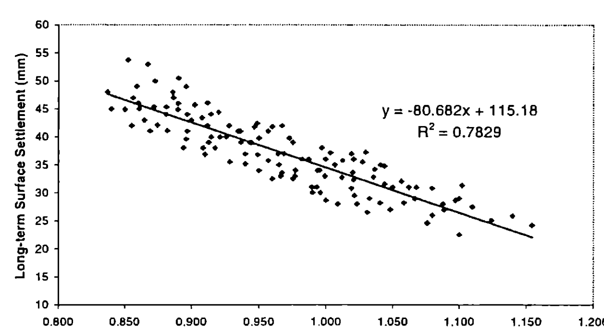


Figure 8. Correlation between long-term surface settlement and the grout filling ratio (GFR).

practice of over-injecting 10% grouting material into the theoretical tail-void volume (i.e. GVR = 1.1). The poor correlation between surface settlements and the GVR is well illustrated in Fig. 6, which can clearly explain the inappropriate nature of using GVR as a control parameter.

4 CONCLUSION

The results of this instrumentation program show that the EPB shield at the Shanghai Metro Tunnel -

line 2 project performed successfully. Ground movements were held within limits which were typically much smaller than what would be expected with a conventional shield. Typical long-term surface settlement is in the range of 33 to 41 mm with the maximum surface settlement being not more than 55 mm. Principal conclusions drawn from the observed performance are as follows:

1. The advance of the EPB shield at the instrumentation site led to initial outward movements from the shield, movements that were largely lateral and confined to the soil immediately to the side and in front of the shield. The magnitude of the initial heaves correlated directly with the level of the earth pressure measured inside the soil chamber in the shield. The earth pressure developed inside the soil chamber can be represented by the earth pressure ratio (EPR). When the EPR is in the range of 0.95 to 1.05, the initial ground movements induced by the approaching tunnel are very small. Excessively high EPR would induce initial ground heaving, while excessively low EPR would result in initial ground settlement.

2. From the observation of ground movements, the ground response to an advancing EPB shield can be classified into five distinct phases, namely: (i) Phase I - the approach of the tunnel; (ii) Phase II - the passing of the shield body; (iii) Phase III - tail void closure; (iv) Phase IV - consolidation of grouting material and disturbed soil ; and (v) Phase V - secondary consolidation of disturbed soils. The relative proportions of settlements at each phase are highly dependent upon the construction controls adopted during the shield tunneling. A properly controlled tunneling process could successfully reduce the magnitude of surface settlement.

3. The control of shield alignment during the advance of the shield remains one of the most important tunnel control parameters. Most importantly, the actual volume of the grouting material injected into the tail-void created by the over-cutting actions of the shield as reflected by the grout filling ratio (GFR) is the key parameter to limit the long-term settlement developed at the ground surface. For the Shanghai Metro Tunnel, increasing the GFR to about 1.1 to 1.15 would significantly reduce the long-term surface settlement.

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