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In-situ monitoring of earth pressures upon large shield tunnel with small overburden

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ABSTRACT: The earth pressure on shield tunnel is an old but important issue in tunnel design. It is well known that the earth pressure is depending on the soil type and construction conditions. There are increasing needs for short but large traffic tunnel in the area with many rivers, such as the Yangtze River delta of China. The overburden of the short cross-river tunnel (normally less than 1 km) is a crisis issue for tunnel design, especially in silty sand ground. However, few literatures can be found on this topic. In this study, an in-situ monitoring was carried out to measure the earth pressure and pore-water pressure acting upon a large cross-river shield tunnel with small overburden (7 m). A PAD type earth pressure gauge was used to measure the earth pressure. The distribution and the time history of earth pressures and the distribution of pore-water pressures on segments are obtained. A comparison between the measured values and theoretical values calculated by the Japanese conventional design method is carried out. It is showed that the pore-water pressure accounts for a large portion in the total earth pressure in silty sand ground. Tail brush pressure and backfill grouting pressure had a large effect on the earth pressures during shield machine passing through. Excessive grouting pressure resulted in the measured earth pressures much higher than the design values. However, the measured earth pressure dropped down a lot after several rings, and the final values were close to the total overburden pressure.

1 INTRODUCTION

The earth pressure on shield tunnel is an old but important issue in tunnel design. The key issue of the shield tunnel lining design is to confirm the earth pressure on the lining reasonably and accurately. The earth pressure on segments depends on the soil type, construction parameters, segments properties and the contact characteristics between segments and soil and so on. Currently, Terzaghi loose earth pressure theory and the whole overburden theory are most commonly used methods for vertical earth pressure calculation. Some countries adopt the whole overburden theory (Working Group No. 2, I.T.A. 2000, Yin et al. 1999). However, many studies have demonstrated that the vertical earth pressure on the lining is smaller than the whole overburden soil weight in stiff ground or when the depth of the tunnel is large (Mashimo & Ishimura 2003, Koyama 2003, Yao et al. 2006).

With the rapid development of urban traffic, there are increasing needs for short but large section traffic tunnel in the area with many rivers, such as the Yangtze River delta of China. The length is normally less than 1 km and the diameter is larger than 10 m. In order to satisfy the slope requirement of the road in such a short distance, the depth of overburden has to be very limited. The earth pressure of the short but large cross-river tunnel is a crisis issue for tunnel design. However, most of existing researches are concerning with the earth pressure in clayey or sandy ground. Few literatures on silty sand ground can be found. In this study, based on Jiangyin West Chengjiang Road tunnel project, an in-situ monitoring was carried out to measure the earth pressure and pore-water pressure by PAD type earth pressure gauges and water pressure gauges. The distribution and the time history of earth pressures and the distribution of pore-water pressures on segments were obtained. A comparison between the measured values and theoretical values calculated by the Japanese conventional design method is carried out.

2 PROJECT SUMMARY

West Chengjiang road tunnel is the first large cross-river road tunnel in Jiangyin City. It is a twin-tube shield tunnel including north and south two lines with a total length of 1.27 km, among which 660 m was constructed by the shield tunneling method. A slurry shield machine with a diameter of 11.58 m was used to excavate the north line first and then the south line. The outside and inner diameters are 11.36 m and 10.36 m respectively. Each ring of the tunnel is composed of 8 reinforced concrete segments with a thickness of 0.5 m and a width of 1.5 m. Staggered assembly method was used between the rings. The shield tunnel runs across two rivers with a distance of about 250 m. Most overburdens were less than one time of the diameter (1D). The minimum overburden was only 7 m and most of the tunnel locates in silty sand ground. Based on the project, in-situ measurements were carried out to measure the earth pressure and pore-water pressure on tunnel segments.

3 IN-SITU MONITORING METHOD

3.1 *Outline of in-situ monitoring*

In-situ monitoring was conducted at two sections (section A and section B) in south line as shown in Figure 1. Section A and section B are located under two rivers

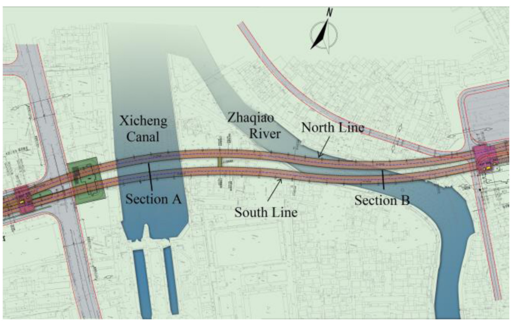


Figure 1. Plane view of monitoring sections.

respectively. Stratigraphic distribution of monitoring sections is shown in Figure 2. The river is 7 m deep at measurement section A and the overburden height is 7.69 m. Another river is 3 m deep at measurement section B and the overburden height is 7.77 m. The ratios of overburden height to diameter of both sections are approximately 0.7. So the monitoring sections in this study are typical shallow overburden condition.

3.2 *Pressure gauge*

A PAD type earth pressure gauge of 750 mm × 450 mm in length and breadth was used to measure the earth pressure acting upon tunnel segments (Hashimoto et al. 1993; Ye et al. 2010). The installation method of the PAD type earth pressure gauge is given out in Figure 3. The pressure plate of the earth pressure gauge was fixed on the outer surface of the segment.

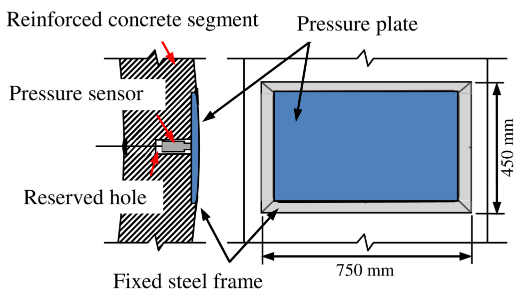
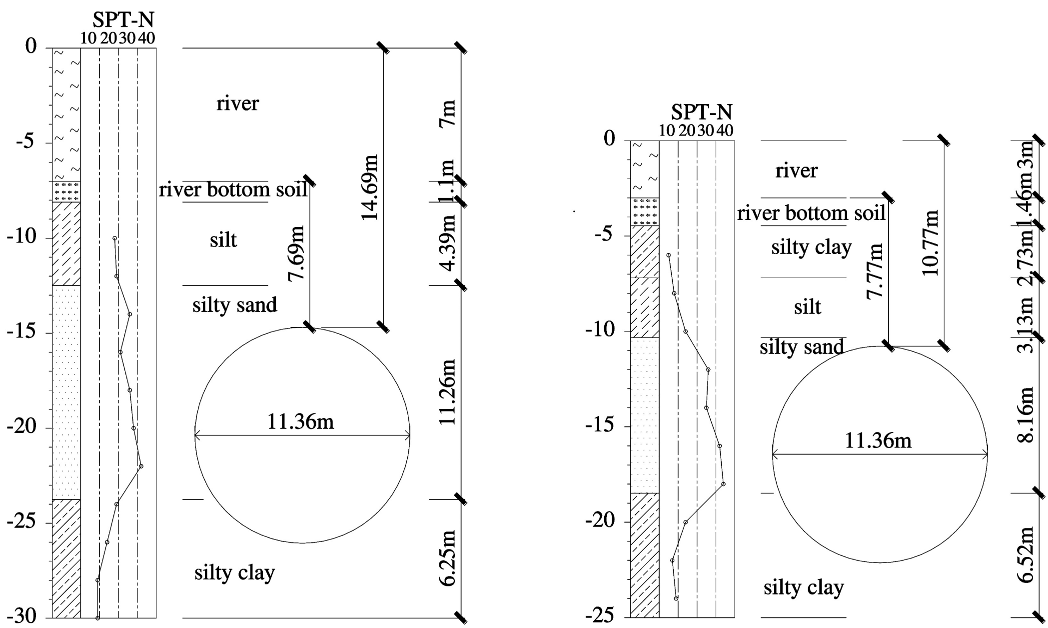


Figure 3. Installation method of PAD type earth pressure gauge.



(a) Section A

(b) Section B

Figure 2. Stratigraphic distribution of monitoring sections.

The sensors and cables were placed in the existing holes reserved at the time of segment fabrication and then seal the holes with cured resin. The earth pressure gauge after the installation is shown in Figure 4. The pore-water pressure acting upon tunnel linings was measured by a type of vibrating wire pressure gauge. Pore-water pressure gauges were mounted in grouting holes, drilled through the segments after the backfill grouting materials were solidification. The installation method of the pore-water pressure gauge is given out in Figure 5 and the gauge after the installation is shown in Figure 6. The output signal of PAD type earth pressure gauge and pore-water pressure gauge is vibration frequency and can be read with general vibrating wire readout. The measured earth pressure is considered to be the total ground earth pressure, including pore-water pressure. Without mentions, the earth pressure means total earth pressure in this paper.

3.3 *Layout of measuring points*

In order to measure the earth pressure and water pressure at the same height, the earth pressure gauge and the pore-water pressure gauge were installed on two adjacent rings in the same section. Install positions of earth pressure gauges and pore-water pressure gauges of section A and B are shown in Table 1. From Figure 2 and Table 1, it can be seen that the earth pressure gauges and pore-water pressure gauges were all installed in silty sand ground. This article assumes the right spring-line of the shield advancing direction is 0° and counterclockwise rotation is positive.

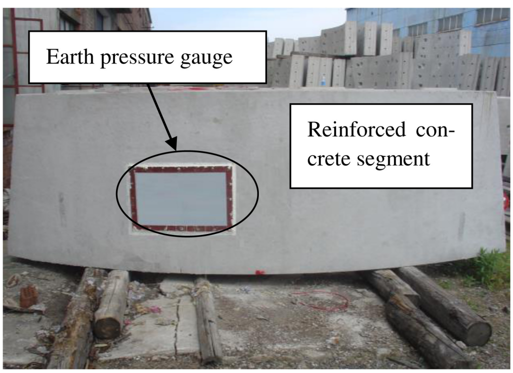


Figure 4. Detail of earth pressure gauge.

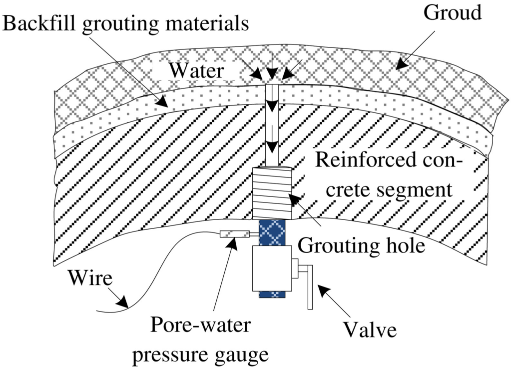


Figure 5. Installation method of pore-water pressure gauge.

3.4 *Monitoring process*

In order to read data conveniently, the cables of all sensors were connected into one data box to read data intensively. The data is collected by the universal automatic data logging instrument which can measure 15 vibrating wire strain gauges and store 5 million data points. It needs 220 V AC power supply (±5 V) to protect the data collection instrument as the voltage can be easily influenced by the construction. In order to obtain earth pressure changes as complete as possible, the data were read once per minute during and after the segment assembling one week. A week later, the data was collected every three minutes until the end of the monitoring.

4 ANALYSIS OF MONITORING DATA

4.1 *Theoretical earth pressure*

In this study, the theoretical values were calculated by the Japanese conventional design method (Japan

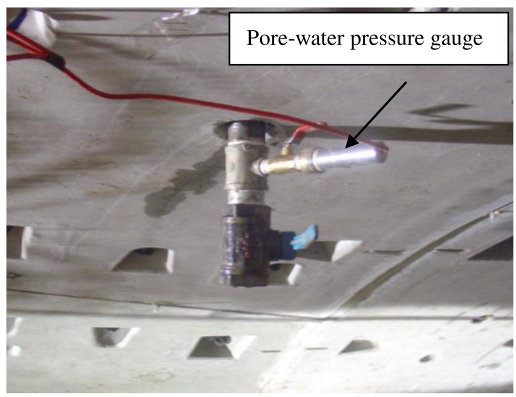
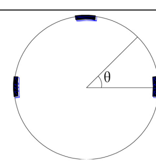
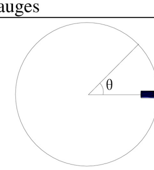
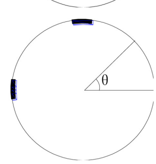
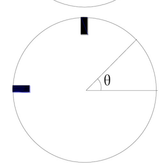


Figure 6. Detail of pore-water pressure gauge.

Table 1. Install positions of earth pressure gauges and pore-water pressure gauges.

Measurement sections	Earth pressure gauges	Pore-water pressure gauges
A		
B		

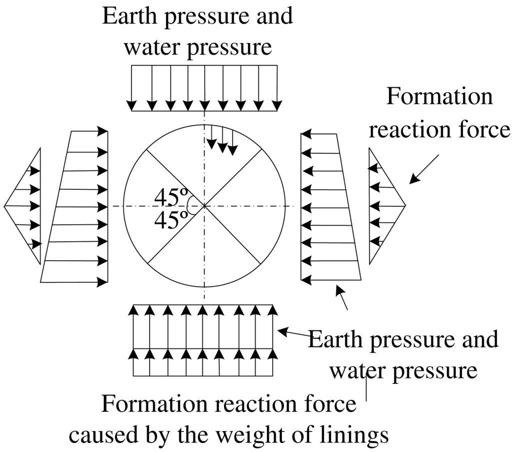
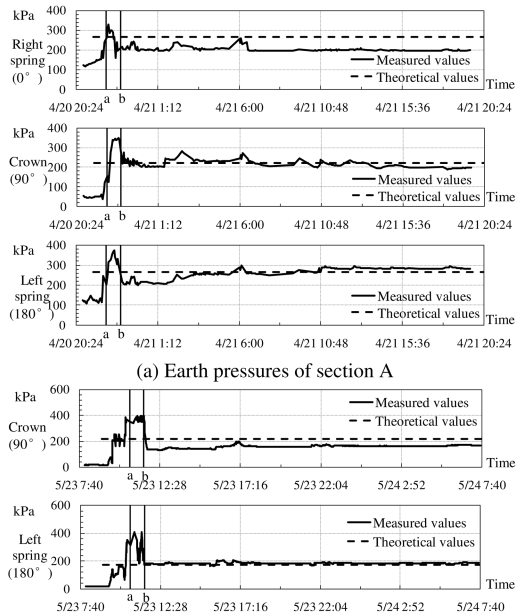


Figure 7. Conventional design method in Japan.



(a) Earth pressures of section A

(b) Earth pressures of section B

Figure 8. The time history of earth pressure on segments.

Society of Civil Engineers 2001) as shown in Figure 7. When the thickness of the overburden is small compared with the diameter of tunnel, generally adopt the whole overburden as vertical load. When the thickness of the overburden is large, generally adopt the Terzaghi loose earth pressure as the vertical design load. In this study, whole overburden theory was adopted to calculate the vertical earth pressure acting upon shield tunnel linings. Pore-water pressure and earth pressure were calculated separately. The lateral earth pressure coefficient λ is 0.45 and do not consider the deformation reaction force.

4.2 *Comparison between the measured values and theoretical values during construction stage*

The distribution and the time history of earth pressure on segments of two monitoring sections within 24 hours after segment assembly are shown in Figure 8. Theoretical values are also given out in Figure 8, which are calculated by the Japanese conventional design method with whole overburden theory. The time between a and b is the period from the last row of shield tail brushes passing away to the end of the grouting.

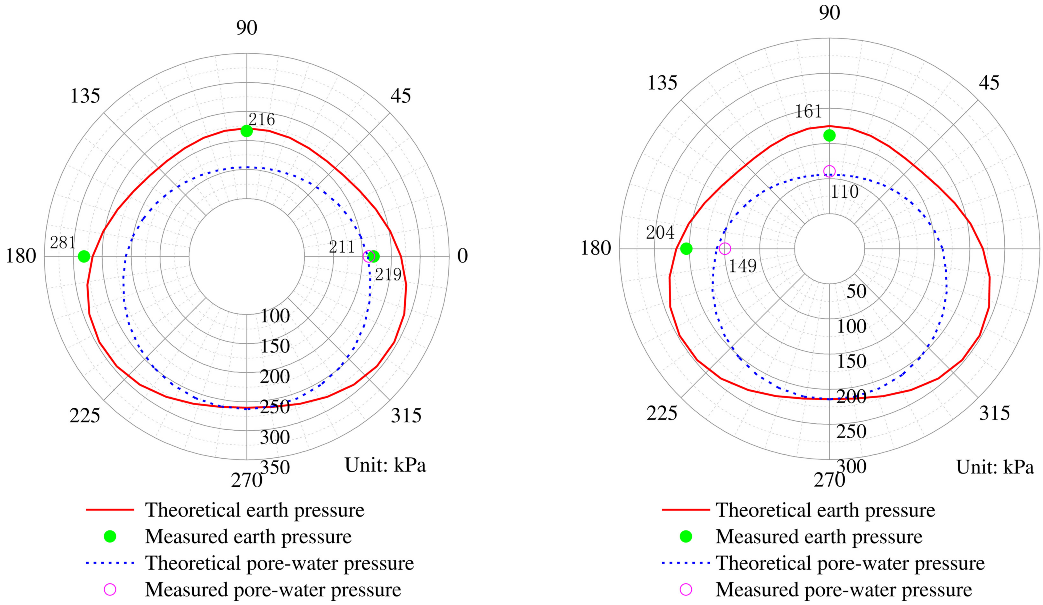
Figure 8 shows when the first row of the tail brushes reaches the earth pressure gauge, shield tail brushes and shield tail grease begin to exert pressure on the earth pressure gauge. The measured values are about 100 kPa to 200 kPa. When the last row of the tail brushes reaches the earth pressure gauge, grouting pressure begin to act on the earth pressure gauge. The maximum earth pressure caused by the grouting pressure is nearly 400 kPa and most measured values are nearly up to twice of the theoretical values during backfill grouting. Grouting pressure is an important factor in the growth of steel stress and concrete stress of shield segments during the segments installation (Chen et al. 2004). Koyama's (2003) physical model test also indicated that excessive grouting pressure would cause local destruction of ground and uneven earth pressure distribution. Therefore, excessive grouting pressure not only has great influences on segment safety but also on the surrounding strata.

As shown in Figure 8, the impact of grouting pressure basically disappeared after five rings away from the shield tail. Measured earth pressure values of all monitoring points are basically stable one day after backfill grouting, some points even within 12 hours. And the stable values are close to the theoretical values. This result is different from the conclusion of Hashimoto et al. (2008). They concluded that the initial earth pressure that built up gradually by backfill grouting remained in the long-term earth pressure in the sand ground. It may be due to the difference type of grouting materials are used in Japan and China. Therefore the final stable earth pressure is strongly related to the grouting materials.

4.3 *Comparison between the measured values and theoretical values after stabilization*

Figure 9 shows the comparison of earth pressure and pore-water pressure between the measured values and theoretical values calculated by the Japanese conventional design method. The measured values are collected three months after the backfill grouting. The solid line in Figure 9 is theoretical values calculated by the Japanese conventional design method with whole overburden theory. And the dotted line is theoretical values of pore-water pressure. The solid dots and hollow dots are measured values of earth pressure and pore-water pressure respectively.

As shown in Figure 9, the measured values and theoretical values of earth pressure are very close,



(a) Section A (b) Section B

Figure 9. Comparison of measured values and theoretical values of earth pressure and pore-water pressure.

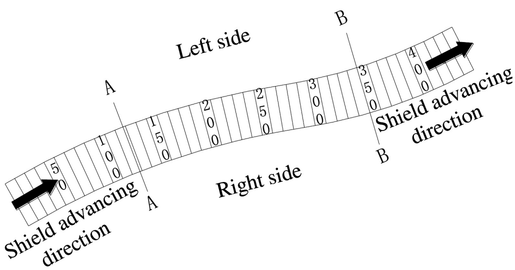


Figure 10. Plane view of the south tunnel.

especially at the tunnel crown of both sections. In section A, the measured value at left spring-line is larger than the theoretical value, while the measured value at right spring-line is smaller than the theoretical value. The measured value at left spring-line is smaller than the theoretical value in section B. The reason will be given out in the following. The plane view of the south tunnel is shown in Figure 10. During curved advancing, jacks will produce eccentric thrust on the segments. The force diagram of a ring of segments at tunnel curve excavation is shown in Figure 11. Jack eccentric thrust will produce a component to the outward segments of the curve. Then segments at the outward side of the curve will subject to larger ground reacted forces, and vice versa.

Comparing the measured earth pressure and pore-water pressure shown in Figure 9, the pore-water pressure accounts for a large portion of the total earth pressure. And the measured pore-water pressure basically equals to the hydrostatic pressure.

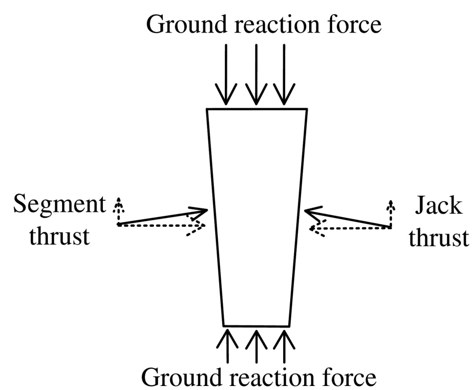


Figure 11. Force analysis of a ring of segments at tunnel curve excavation.

5 CONCLUSIONS

An in-situ monitoring of earth pressure and pore-water pressure upon segments of large section cross-river shield tunnel with small overburden in silty sand ground was carried out in this study. The distribution and the time history of earth pressures and the distribution of pore-water pressures on segments were obtained. A comparison between the measured values and theoretical values calculated by the Japanese conventional design method was carried out. Following conclusions are obtained.

(1) In the process of shield advance, the forces acting on the segments are primarily from the shield tail brush, shield tail grease and shield tail grouting,

of which shield tail grouting is the largest factor. The tail brush, brush grease and backfill grouting produced a noticeable pressure upon segments. In the case of large tunnel with a small overburden, the grouting pressure was twice of the design earth pressure.

(2) In silty sand ground, the measured earth pressure values were basically stable one day after the backfill grouting. The stable values are close to the theoretical values calculated by the Japanese conventional design method considering the whole overburden as vertical load.

(3) In the silty sand ground, the pore-water pressure accounts for a large portion of earth pressure. The measured pore-water pressure basically equals to the hydrostatic pressure.

(4) By comparing the measured earth pressure values at spring-lines of two sections, it proved that earth pressure is also influenced by tunnel curve excavation. Segments at the outward side of the curve will subject to larger ground reacted forces than the inward side.

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