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# Pressures on the lining of a large shield tunnel with a small overburden: A case study

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ABSTRACT

The pressure on a tunnel lining is an important issue in shield tunnel design, because it is related to the safety and durability of the lining. There is an increasing need for short (about 1 km) but wide traffic tunnels in parts of China near rivers. In order to satisfy the gradient requirement of the road over such a short distance, the depth of the overburden is inevitably very shallow. The non-uniform distribution of the pressure on the lining of this kind of tunnel may result in damage to the tunnel segments. However, little published research is available on this topic. In this study, in-situ monitoring was carried out to measure the pressure on the lining of a large cross-river shield tunnel (diameter D = 11.36 m) with a shallow overburden (0.7 D) in silty-sandy ground. A pad type earth pressure gauges and pore-water pressure gauges were used to measure the pressures on the tunnel lining, including the tail brush pressure, grouting pressure, earth pressure and pore-water pressure. The time history and the distribution of pressures on the lining during tunnel construction and post-construction were obtained. A comparison between the measured values and theoretical values was carried out. This showed that the tail brush pressure had a considerable effect on the segments while the shield machine was passing through. Non-uniform tail brush pressures caused cracking and water leakage in the concrete segments. The maximum pressure induced by the backfill grouting was twice that of the theoretical earth pressure. However, the non-uniformity of the backfill grouting induced pressure was not as great as that induced by the tail brushes. In the silty-sandy ground, the earth pressures were generally stable 24 h after segment assembly. The final stable values were close to the total overburden pressure, particularly at the tunnel crown. The pore-water pressure generally was equal to the hydrostatic pressure and accounts for a large proportion of the total earth pressure.

## 1. Introduction

As the permanent tunnel lining structure, shield tunnel segments account for a large part of the overall budget for a tunnelling project. Shield tunnel lining designs not only affect the quality and durability of tunnel structures, but also their economic efficiency. The key issue in shield tunnel lining design is to determine the pressure on the tunnel lining reasonably and accurately. Many researchers have studied earth pressures on shield tunnel linings (e.g. Atkinson and Potts, 1977; Ohta et al., 1995; Nomoto et al., 1999; Hashimoto et al., 2002, 2008; Mashimo and Ishimura, 2003; Kim and Eisenstein, 2006; Leung and Meguid, 2011; Lei et al., 2014; Han et al., 2015; Lin et al., 2015). The earth pressure on the segments depends on the soil type, the construction parameters and the contact characteristics between the segments and the soil. Earth pressure can be considered to comprise two elements, the vertical and horizontal pressures, when following the most commonly used shield tunnel lining design method. The horizontal earth pressure is derived from the vertical earth pressure multiplied by the coefficient of horizontal earth pressure. Therefore, it is very important to determine vertical earth pressures. Currently, Terzaghi's loose earth pressure theory and whole overburden theory are the most commonly used methods for vertical earth pressure calculation. Some countries adopt the whole overburden theory (Working Group No. 2 and I.T.A, 2000; Yin et al., 1999). However, many studies have demonstrated that the vertical earth pressure on the tunnel lining is lower than the whole overburden soil weight in good ground conditions or when the tunnel is very deep (Mashimo and Ishimura, 2003, 2006; Koyama, 2003; Yao et al., 2006).

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Apart from the earth pressure from the surrounding soils acting on the lining, construction loads are also an important factor affecting tunnel linings. As shield tunnel construction technologies have become more advanced, construction loads have been given more attention by researchers (e.g. Koyama, 2000, 2003; Sramoon et al., 2002; Sugimoto and Sramoon, 2002; Bezuijen et al., 2004; Mashimo and Ishimura, 2006; Tajima et al., 2006; Bakker and Bezuijen, 2008; Mo and Chen, 2008; Chen and Mo, 2009; Ramoni et al., 2011; Oh and Ziegler, 2014; Sugimoto et al., 2014). Some researchers have suggested that the construction loads should be considered in the shield lining design (e.g. Koyama, 2003; Mashimo and Ishimura, 2006; Bakker and Bezuijen, 2008; Bilotta and Russo, 2013). However, little research dealing with the pressure on the tunnel lining induced by the tail brushes has been conducted to date. In-situ monitoring showed that the pressure acting upon the segments reached a maximum while the shield tail brushes were passing, and this was twice as large as the earth pressure (Koyama, 2003). Mashimo and Ishimura (2006) found that the pressure caused by the tail brushes had a great influence on the sectional forces which occurred in a segment during the assembly of a tunnel ring. Sramoon et al. (2002) pointed out that the force of the wire brushes may change the shield behaviour, especially the yawing of the shield machine.

With the rapid development of urban traffic, there is an increasing need for short, wide traffic tunnels in areas near rivers in China, such as the Yangtze River Delta. Typically, the length of a cross-river tunnel is about 1 km and the diameter is more than 10 m. In order to satisfy the slope requirement of the road over such a short distance, the depth of the overburden has to be very limited. Accordingly, small earth/water pressures are adopted in the design of linings. Thus the design bending moments and axial forces will be small, resulting in thin segments and small number of reinforcement bars. In this case, if unexpected non-uniform loads act on the lining, the lining may be damaged due to the excessive bending moment. Therefore, the pressure on the lining of a short but wide cross-river tunnel with a small overburden is a critical issue for tunnel design. However, little literature can be found on this topic. In this study, based on a traffic tunnel project, in-situ monitoring was carried out to measure the pressure on the lining of a large shield tunnel with a small overburden. The time history and the distribution of the pressures on the lining during tunnel construction and post-construction were obtained. A comparison between the measured values and the theoretical values is carried out.

## 2. Brief introduction to the tunnel project

The West Chengjiang Road tunnel is the first large cross-river road tunnel in Jiangyin City, Jiangsu Province, China. It is a twin-tube shield tunnel consisting of the north and south lines, as shown in Fig. 1. The total length is 1.27 km, of which 660 m was constructed by the shield tunnelling 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 outer and inner diameters of the tunnel are 11.36 m and 10.36 m respectively. Each ring of the tunnel is composed of eight reinforced concrete segments with a thickness of 0.5 m and a width of 1.5 m. The staggered assembly method was used to form the rings. The total length of the shield tunnel beneath two rivers was about 250 m. In most areas the overburden was less than the diameter of the tunnel (D), and the minimum overburden was only 7 m. Most of the tunnel is located in the silty-sandy strata. In this study, in-situ measurements were made to record the tail brush pressure and grouting pressure during tunnel construction, and the earth pressure and pore-water pressure post-construction.

Simultaneous backfill grouting is widely utilized in the soft ground area (Ye et al., 2015), so does this project. The backfill grout was a one-component grout, composed of river sand, slaked lime, bentonite, fly ash, a stabilising agent and water. The proportion and properties of this one-component grout are shown in Tables 1 and 2 respectively.

In general, there are three rows of wire brushes in the shield tail, together with grease to prevent water, soil and grouting material leaking through the tail void. In recent years, however, the third row of wire brushes was replaced by steel plate brushes. This is because the tunnelling engineers found that the wire brushes they used were wearing out too quickly to maintain a sealing function.

## 3. In-situ monitoring procedure

### 3.1. Outline of in-situ monitoring

In-situ monitoring was conducted at two sections in the south line tunnel, sections A and B, as shown in Fig. 1. Section A (ring No. 118) and section B (ring No. 340) are located under two different rivers. The ground conditions of the two sections are shown in Fig. 2. The water depth and overburden depth of section A are 7 m and 7.69 m. Those of section B are 3 m and 7.77 m. The ratios of overburden depth to diameter (H/D) of both sections are approximately 0.7, which is classified as shallow overburden.

In order to measure the earth pressure and the pore-water pressure at the same depth, the earth pressure gauges and the pore-water pressure gauges were installed on two adjacent rings in the same section. The pore-water pressure gauges were installed on ring No. 117 and ring No. 339, respectively, the neighboring rings of those installed earth pressure gauges. The installed positions of the earth pressure gauges and the pore-water pressure gauges of sections A and B are shown in Fig. 2. It can be seen that the earth pressure gauges and the pore-water pressure gauges were all installed within the silty-sandy ground except for the one at the bottom of the tunnel in section A. The diagrams in Figs. 9-11, showing pressure distributions in the tunnel, indicate the angle taken from the starting point of the right spring line, in an anticlockwise direction.

### 3.2. Earth pressure gauges and pore-water pressure gauges

A pad type earth pressure gauge with a very thin pressure cell, 750 mm in length and 450 mm in width, was used to measure the pressure acting upon the tunnel segments (Hashimoto et al., 1993, 2002). The inside of the pressure cell is filled with incompressible liquid. The pressure acting on the pressure cell can be transferred to the pressure sensor by the incompressible liquid. The pressure cell is flexible, so that it can be mounted on the outer surface of the shield tunnel segments smoothly. The installation method for the earth pressure gauge is shown in Fig. 3. The installation positions were determined when the segments were manufactured. The pressure cell of the earth pressure gauge was fixed onto the outer surface of the segment. Epoxy resin was applied between the segment and the pressure plate to ensure a tight contact. A metal frame surrounding the edges of the pressure plate was mounted onto the segment to prevent detachment. The sensor and cable were placed in pre-formed holes. The pore-water pressure acting upon the segment was measured with a vibrating wire type pressure gauge. The installation method of the pore-water pressure gauge is shown in Fig. 4. The pore-water pressure gauge was mounted in a grouting hole. The hole was drilled through after the backfill grouting materials were solidified, so that the pressure gauge could be in direct contact with the groundwater.

The output signal of the pad type earth pressure gauge and the pore-water pressure gauge is a vibration frequency that can be measured by a vibrating wire data logger. Throughout this paper, ‘earth pressure’ refers to ‘total earth pressure’.