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Lessons learnt from unusual ground settlement during Double-O-Tube tunnelling in soft ground

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ABSTRACT

The DOT (Double-O-Tube) tunnelling method has been adopted in the construction of various types of tunnels in soft ground both in Japan and in China. Recently, an unexpected ground surface settlement of approximately 0.8 m was observed in a DOT construction site in Shanghai, China. The backfill grouting injection rate had to be increased by up to 500% to control the settlement. In order to find out the reasons for the large settlement, and to reduce it to an acceptable level, in-situ monitoring, including surface settlement and subsurface settlement, was undertaken to obtain the change in ground deformation during DOT machine driving. It was found that the conventional settlement control methods, such as adjusting the earth pressure balance on the cutter face, and simultaneous backfill grouting at a normally acceptable injection rate, could not reduce the large settlement. It was also noticed that the settlement started as the DOT machine was passing, as well as after the tail had passed through. Subsequent field investigations found cement accumulation attaching to the skin plate. This was due to improper backfill grouting at the early construction stage, and the concave shape of the DOT machine. The mechanism for large settlements due to improper immediate backfill grouting was analysed. After taking countermeasures, the ground settlement was reduced to approximately 0.02 m.

1. Introduction

The DOT (Double-O-Tube) tunnelling method can be employed to construct two tunnels simultaneously using one shield machine. It provides economic advantages by shortening construction time and reducing discharged soil volume. After its first application in Japan in 1989, it has been adopted successfully in the construction of several types of tunnels in soft ground, both in Japan (Moriya, 2000; Sakakibara and Watanabe, 2001; Koyama, 2003) and in China (Chow, 2006). Unexpectedly, a ground settlement of approximately 0.8 m took place during DOT tunnelling in Shanghai recently. The aim of this paper is to clarify the mechanism of this unusual settlement and to suggest countermeasures.

Due to the large cutter face and the two interlocking spoke-type cutters, the ground settlement and the rolling associated with DOT machines have been the main focus of attention for engineers. In Japan, most of the DOT tunnels have been constructed in hard ground, such as silty sand in Hiroshima city, and sandy ground in Nagoya city (The Shield Tunnelling Association of Japan, 2004). A multipurpose underground utility conduit (Yokoyama and Yonei, 1995) in the Ariake-kita district of the Tokyo metropolitan area was constructed in diluvial cohesive soil using a large diameter DOT machine (9.36 m in diameter and 15.86 m in width). The ground conditions were the softest of those investigated, but were more suited to DOT tunnelling than those of Shanghai. The in-situ monitoring data in Tokyo showed that the final ground surface settlement was around 0.02 m. A part of the Taoyuan International Airport Access MRT (Mass Rapid Transit) in Taiwan (Fang et al., 2012) was constructed in silty sand and silty clay layers using a DOT machine 6.42 m in diameter, and 11.62 m in width. The observed maximum settlement during the construction period was less than 0.04 m.

In Shanghai, the subsoils up to a depth of 30 m are soft silty clays. The ground conditions are difficult for single-circular shield tunnelling (e.g., Wang, 1982; Xu et al., 2011; Shen et al., 2014; Bai et al., 2014), as well as for DOT tunnelling. Parts of Shanghai Metro Lines M8 (2003–2004) and M6 (2004–2005) were

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constructed using a DOT machine. Since then, settlement and rolling problems have been the biggest challenge for DOT engineers (Shen et al., 2009, 2010). Chow (2006) summarised the construction experiences of the M8 Line and concluded that the maximum ground surface settlement, and the width of the ground surface settlement trough, were almost equal to that created by two single circular shield tunnels. Gui and Chen (2013) also found similar results for the Taiwan DOT project. Based on the monitoring data for the utility conduit in Tokyo and the Shanghai M6 Line, Yokoyama and Yonei (1995), Sun (2007) suggested that the DOT-induced ground settlement can be approximated to that resulting from a single-circular tunnel which has the same cross-sectional area. The general settlement over Shanghai metro tunnels (diameter 6.34 m, single-circular) during construction was less than 0.03 m. The settlement of a 15.43 m diameter shield tunnel in Shanghai was around 0.05–0.06 m (Wu et al., 2010). According to the above approximation methods, the estimated DOT-induced settlement should be around 0.06 m. This is consistent with the typical observed settlement of 0.04 m (<1% volume loss) for the M8 and M6 Lines (Chow, 2006; Sun, 2007). Apart from the collapse of a Shanghai metro tunnel due to an accident in 2003 (Xu et al., 2009), no reports of large settlements over 0.1 m during tunnelling construction have been recorded in Shanghai.

In this paper, a systematic in-situ monitoring programme, including ground surface settlement and subsurface settlement, was carried out to investigate the mechanism of the unusual settlement observed during DOT tunnelling. The major factors, such as the earth pressure balance on the cutter face and the backfill grouting, are analysed carefully. The countermeasures are also provided.

2. Background

In preparation for the 2010 Shanghai World Expo, Shanghai Metro Line 2 was expanded east to the Pudong International Airport. The length of the extension line is 29.9 km. Three sections (CS-A, -B, and -C) were constructed by the DOT method, as shown in Fig. 1. The construction commenced on July 2007, and was completed by the end of 2009.

Three earth pressure balance DOT machines (Fig. 2) with a spoke-type cutter face were used in the three sections. The shield machine was 6.52 m in diameter and 11.12 m in width and the tunnel was 6.30 m in diameter and 10.90 m in width. Reinforced concrete segments were assembled in a stagger-jointed arrangement. Each ring was separated into 8 segments. The thickness and the width of the segments were 300 mm and 1200 mm, respectively.

Fig. 2. DOT machine used in the construction of the Shanghai Metro.

A simultaneous backfill grouting system with a two-component grouting liquid was employed in the DOT machines. The simultaneous backfill grouting was carried out in shield tunnelling for the first time in 1982 in the construction of the No. 4 line of the Osaka Subway in Japan, and has been proven to be an effective measure for reducing shield-induced settlement in soft ground (Hashimoto et al., 2004). Two simultaneous backfill grouting pipes (35 mm dia.) were installed in the top and bottom concave 'seagull' (the V shape formed at the centre of the DOT where the two tubes meet) respectively, with one pipe in each 'seagull'.

It is important to highlight two factors relating to the research topic. Firstly, the DOT machines had previously been used in the construction of the Shanghai Metro Line M8 (2003) and Line M6 (2004). They were reused in the current project after a basic and hurried maintenance. In the first few months, the advance of the TBM had to be stopped frequently for the repair or replacement of worn parts, such as sensors, valves and hydraulic tubes, and due to the simultaneous backfill grouting pipes becoming blocked. Secondly, since many tunnels were undergoing construction

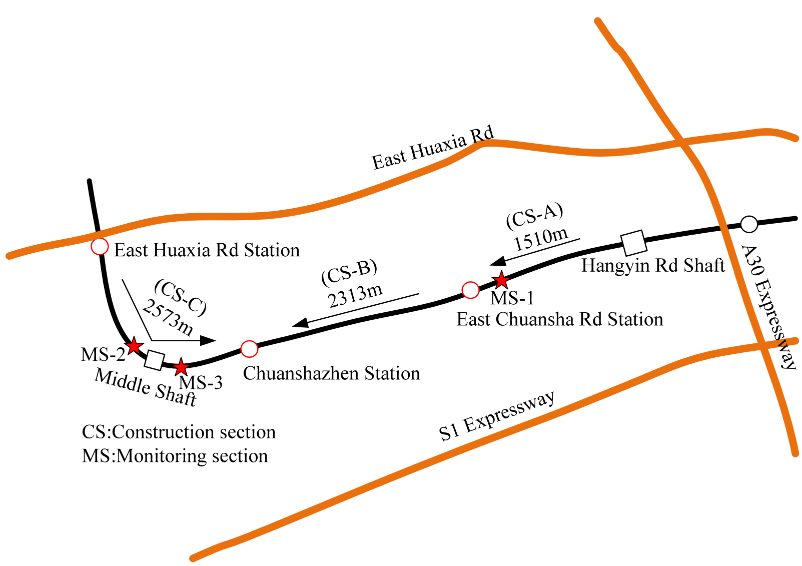

Fig. 1. Layout of tunnels constructed by DOT in the eastward extension of Shanghai Metro Line 2.