Tunnelling Induced Deformation of a Historic Building in Shanghai

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ABSTRACT: Tunnelling induced deformations of a historic building, Chongsi Building, in Shanghai, China, are reported. The construction site located in Xuhui District, along the Metro line 11, and at the site the thickness of soft soil layer, soft clay and clayey silt, is about 30 m. The tunnelling method used is the earth pressure balance (EPB) shield tunnelling. The building with masonry structure was built about a century ago, and there were already considerable deformations. Considering this situation, the criteria for total and incremental deformations have been proposed; especially the twist criteria have been newly established and applied to the project. Controlling both the total and incremental deformations is called Dual-control criteria (DCC). The measured maximum settlement, differential settlement, and twist during tunnelling construction were 13.29 mm, 0.67 mm/m, and 3.23×10^{-5} rad/m respectively. Based on the monitoring results, the deformations of the historic building during and after tunnel construction were very small and, causing no serious damage to the building, and it is considered that the construction control is successful.

Keywords: tunnelling, historic building, underground crossing, deformation criteria

1. INTRODUCTION

Tunnelling will cause disturbance to the stress state of a ground as well as loss of soil mass. As a result, it can induce ground deformations above and around the tunnels (Peck, 1969; O' Reilly & New, 1982; Attewell et al., 1986). In case there are buildings in the nearby area, this kind of ground deformation may cause damage or influence the serviceability of the buildings (Burland et al., 1977; Rankin, 1988; Boscardin & Cording, 1989). Therefore, to control tunnelling induced deformation on the buildings in the nearby area within the allowable limit is an important task for engineers involved in a tunnelling project.

The damage to an existing building can be caused by excessive settlement, differential settlement, tension, and angle twist in facade and so on (Burland & Wroth, 1974; Rankin, 1988). Several criteria have been proposed for controlling the deformation of a building or assessing the damage level of a building (Burland et al., 1977; Bhattacharya & Singh, 1984; Yu et al., 1988; Rankin, 1988; Boscardin & Cording, 1989; Forth et al., 1995; Mair et al., 1996). These criteria are varied with the structure of a building, as well as the importance of a building (Saeidi et al., 2009). Saeidi et al. (2008) pointed out that the application of these criteria and the corresponding analysis methods to the same site does not always give the same results because each method was developed with a different set of parameters in a specific context (geology, tunneling method, etc.). For example, Bhattacharya & Singh (1984) and Yu et al. (1988) established assessment criteria only considering the horizontal strain of the building; Rankin (1988) established assessment criteria considering the settlement and differential settlement of a building; and Boscardin & Cording (1989) established assessment criteria considering the horizontal strain and angle twist in facade of a building. Note that the uniform settlement may influence the serviceability of a building, but cause little or no damage to its structure. For a masonry building, the main factors causing damage to it are differential settlement, extension and angle twist in facade (Son & Cording, 2005). However, the reported field data (Boscardin & Cording, 1989; Houlsby, 1999; Standing, 2001; Dimmock, 2003, 2008) indicate that underground tunneling induced horizontal strain on the buildings above or around it was very small and negligible. Therefore, the remaining factors are differential settlement and angle twist in facade; they are both "in-plane" assessment criteria without considering the influence of three-dimensional deformation. While twist is a three dimensional criterion for building damage assessment (Franzius et al., 2004, 2006; Han, 2006), the damage limits have not been well established yet.

For all existing buildings, there have been some deformations developed during their service period. The deformations induced during the underground construction are incremental ones. However, the existing criteria are all "gross" values which are not suitable to be used for assessing a building damage during an underground construction. It is considered that the deformation of a building should be surveyed before the underground construction, and allowable incremental deformation should be determined by considering the existing deformation. During a construction process, both the total and incremental deformations should be controlled, and it is designated here as Dual-Control-Criteria (DCC).

Metro line 11 in Shanghai, China, passes through the area where a masonry historic building, Chongsi Building, is located. Considering that the underground construction might cause damages to the building, the survey before the construction and prevention and monitoring measures during and after the construction were carried out. This paper presents the details of the project, and the survey and monitoring results. The discussions are made on the suitable criteria for preventing the historical building from being damaged.

2. PROJECT DESCRIPTION

The historic building is located between Xujiahui Station and Shanghai Stadium Station of Metro line 11, Shanghai, China. The soil strata at the project site are shown in **Error! Reference source not found.** and the physical properties of the main soil layers are summarized in Table 1. The ground is mainly consisted of very soft silty clay (③ and ④), clay (⑤1), and silty clay (⑤3) (**Error! Reference source not found.**).

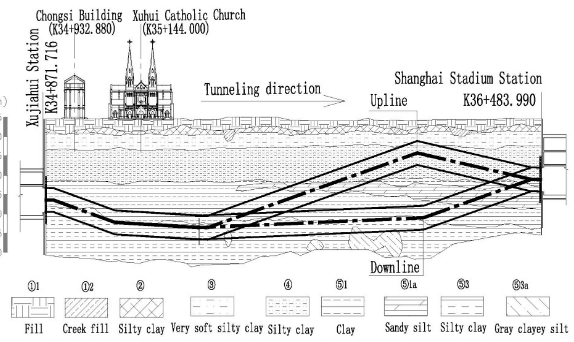


Figure 1 Soil profile and the location of tunnels

2.1 Chongsi Building

The both lines (up and down) of Metro line 11 are undercrossing Chongsi Building of Xuhui Middle School, which is a historical building and located at the right side of Xujiahui Station.

Figure 2 is the picture of the building.

Four-story Chongsi Building was built in 1918. From the first to the fourth floor, the heights are 4.877 m, 4.267 m, 4.887 m, and 3.887 m respectively. The main structure of Chongsi Building was made of bricks with some concrete beams. The total length of the building axis in east-west direction is 66.140 m, and 25.144 m in south-north direction. The distance between the axis of the tunnel and ground surface is about 17.2 m, and the horizontal distance between the two axes of the tunnels is 18.4 m. The relative position of building and the tunnels is shown in Figure 3 (a) and (b).

Figure 2 Chongsi Building

2.2 Tunnelling methods

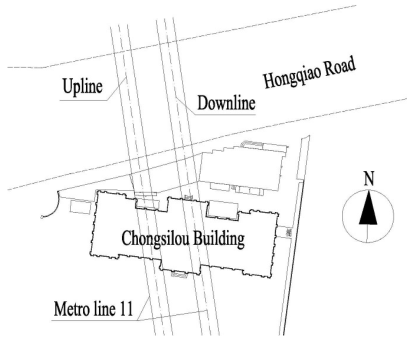
The earth pressure balance (EPB) shield tunnelling method was used in this project. The shield body is 8.8 m in length and 6.34 m in diameter. The main properties/features of the EPB machines used for the project are listed in Table 2. A schematic diagram of the EPB shield is shown in Figure 4(a). The outer and inner diameter of the tunnel is 6.2 m and 5.5 m respectively as shown in Figure 4(b). The linings of the tunnels are made of reinforced concrete segments and the length of each ring is 1.2 m.

With allowances for the tail seals, construction tolerances, and the skin thickness of the shield tail, the tail void left between the soil and the outside of the liner, called physical gap (G_p), was 70 mm. The physical gap is one of the main sources of the ground surface settlement. During the construction the pressurized grouting material was injected into the gap simultaneously with the lining process. The grouting material was composed of a mixture of sand, fly ash, bentonite, lime, and various additives. Compositions of the grouting materials are given in Table 3. The volume injected was approximately 1.5 times of the volume of the physical gap (G_p).

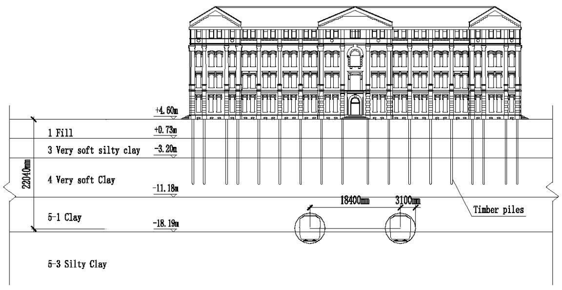
3. Building damage assessment criteria

3.1 Definition of twist

Let's only consider the settlement (z direction) of a small (infinitesimal) area of a foundation, *abdc*, as shown in Figure 5, and its location after deformation is *a'b'd'c'*.

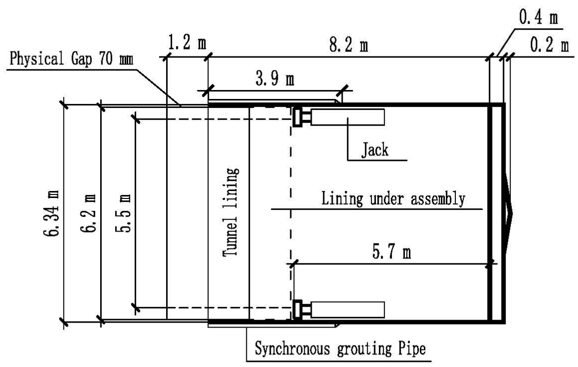


(a) Plan view of the tunnels and Chongsi Building

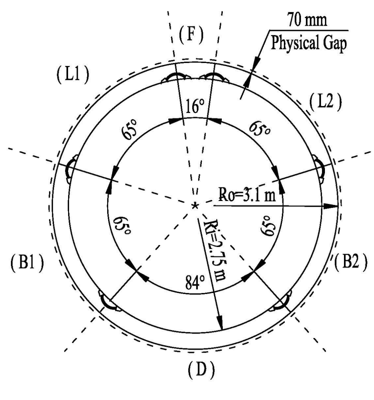


(b) Cross-sectional view of the tunnels and Chongsi Building

Figure 3 Schematic diagram of relative position of the building and the tunnels



(a)



(b)

Figure 4 Earth pressure balance shield tunneling machine and Lining cross-section

Table 1 Soil properties

Symbol	Soil layer	Water content w (%)	Unit weight γ (kN/m^3)	Specific gravity G	Void ratio e_0	Liquid limit W_L (%)	Plastic limit W_P (%)	Plasticity index I_P	Liquidity index I_L
α	Silty clay	31.3	18.7	2.73	0.89	39.5	23.5	16.2	0.51
β	Very soft silty clay	44.2	17.3	2.73	1.23	39.1	22.8	16.4	1.24
χ	Silty clay	50.4	16.7	2.74	1.43	45.1	24.8	20.3	1.27
δ1	Clay	39.8	17.6	2.74	1.15	42.9	24.3	19.1	0.82
δ1α	Sandy silt	28.2	18.4	2.70	0.87				
δ3	Silty clay	33.4	17.9	2.73	0.99	37.7	23.0	14.7	0.71
δ3α	Clayey silt	31.5	18.0	2.71	0.98				

Table 2 Main Technical specifications of 863 EPB shield

	Parameters	Parameter values
Propulsion system	Total thrust of Jacks (kN)	35200
	Maximum speed($cm/\min$)	5
Automatic correction system	Power(kW)	37
	Deviation Angle(^{o})	$\pm$ 1.5
	Total thrust (kN)	23800
Cutting knife dish	Excavated diameter(mm)	6340
	Power (kW)	540
	Rotation speed of cutter head ($r/\min$)	0.177 or 0.155
	Moment of torsion ($kN \cdot m$)	(120%)7992 (100%)6660
Erector	Rotation speed ($r/\min$)	0.75 or 1.58
	Rotation angle (^{o})	$\pm$ 220
	Thrust (kN)	220
	Hoisting force (kN)	150
	Handling mass (kg)	3878

Table 3 Compositions of grouting material (kg/m3)

Sand	Fly ash	Bentonite	Lime	Additives	Water
900～1100	300～400	50	80	3	360

The settlement at points *a*, *b*, *c* and *d* are S_a, S_b, S_c and S_d respectively. The deformation of *abdc* can be divided into three parts, uniform settlement (or upheaval), rigid rotation and twist. As shown in Figure 5, there is only uniform settlement when it comes to the dashed line position and only rigid rotation from the dashed line to the dotted line position, and only twist from the dotted line position to the final position. Designating $\overline{ac} = \overline{bd} = \Delta x$, and $\overline{ab} = \overline{cd} = \Delta y$, the twist ($T_w$) of *abdc* can be calculated as follows:

$$T_w = \frac{(S_a - S_b) - (S_c - S_d)}{\Delta x \cdot \Delta y} \tag{1}$$

The twist unit can be expressed as rad/m.

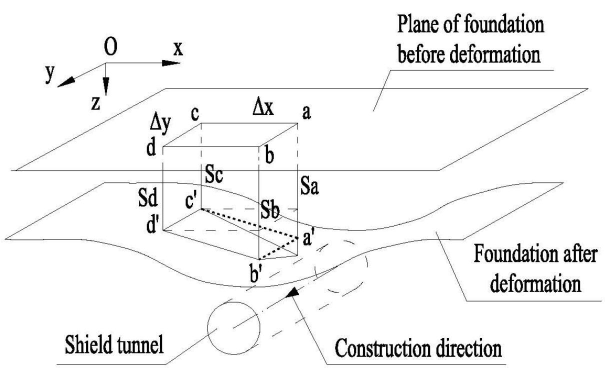


Figure 5 Twist of building foundation

3.2 Dual-control criteria (DCC)

In general, it should be realized that the potential influence to a building caused by adjacent construction cannot be completely avoided (Leca & New, 2007). However, strict criteria and corresponding countermeasures can be implemented during the construction to control the influences and/or damages within tolerable limits.

For this project, both total and incremental deformations were controlled, and the method has been named as dual-control criteria (DCC). There are three aspects that should be considered in developing DCC: (1) the incremental deformation should be within the incremental limit (*r*) and not cause visible damage to buildings; (2) the total deformation should be less than the total limit (T); and (3) the emergency measures should be prepared when any one of the incremental or total deformation limits is approaching.

The total deformation limit at a given point should be established by considering both total allowable absolute deformation and the allowable differential deformation. The incremental limit should be established by considering micro-disturbance due to construction as well as the total limit (T). The concept of DCC (see Figure 6) is when the existing deformation plus the incremental limit is below the total limit, we control the incremental limit; and if it is over the total limit we control the total limit. To leave enough time to take countermeasures, generally the incremental limit (r) should be smaller than the gap between the total limit (T) and the existing deformation before the construction, such as the point A and C in Figure 6 (b). However, for a building and a given controlling item, only one incremental criterion is defined. There are locations at which existing deformation plus the incremental limit can over the total limit. In these locations, the controlling criterion will be the total one, such as the point B in Figure 6 (b).

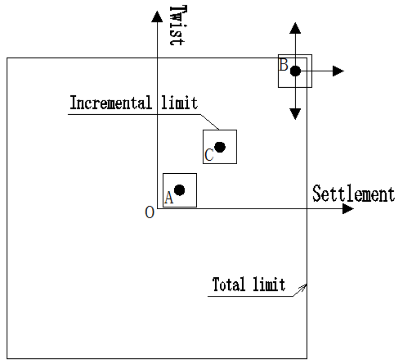


Figure 6 Concept diagram of the DCC method

3.3 Damage assessment criteria for the masonry building

Based on the assessment criteria proposed by Rankin (1988), four levels damage criteria have been proposed for assessing and/or controlling the deformation of a masonry building as listed in Table 4. There is no criterion for twist in the literature. The limit values of twist given in Table 4 have been established by considering the most unfavorable combinations of differential settlements in two perpendicular directions using the limits for differential settlement as listed in the second column of Table 4.

Table 4. Criteria for differential settlement and twist

Risk category	Differential settlement (mm/m)	Twist (rad/m)	Description of risk
1	<2	$<4\times10^{-3}$	Negligible
2	2-5	$4\times10^{-3}\sim1\times10^{-2}$	Slight
3	5-20	$1\times10^{-2}\sim4\times10^{-2}$	Moderate
4	>20	$>4\times10^{-2}$	High

4. SURVEY RESULTS AND COUNTER MEASURES

During the long service period, there had been already deformations of the historic building, and the incremental deformations due to the tunnel construction might cause damage to the building even through the advanced shield tunneling technique was applied. To ensure that the tunneling will cause no damage to the historic building, the detailed survey was carried out firstly to obtain information about the status of the buildings before the construction. Then for some critical locations, counter measures were implemented before the tunnel construction.

4.1 Survey results

4.1.1 Results about façade tilts

The survey results about the facade tilting of the building are shown in Figure 7. The building tilted to north and west. The maximum tilt rate directing to north was 10 ‰ and to west was 15.3 ‰.

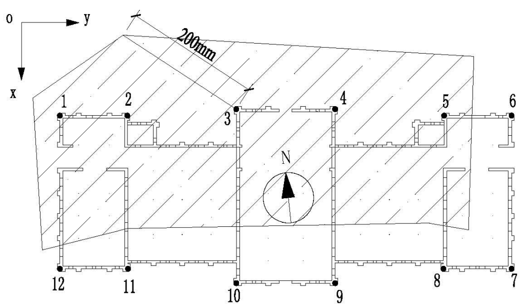


Figure 7 Comparison of the original building outline and the outline after deformation

4.1.2 Relative heights of bottom windowsill

Relative heights of bottom windowsills are shown in Figure 8. The results indicate that the settlement was bigger in northwest and smaller in northeast, which coincides with the measured results of building facade tilt.

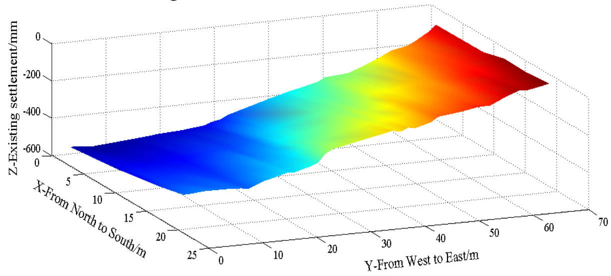


Figure 8 Relative height of bottom windowsill (unit: mm)

4.1.3 Differential settlement and twist

The original maximum twist of building before the tunnel construction was 2.41×10-3 rad/m and the original maximum differential settlement was 34.3 mm/m. The variations of the differential settlement and twist along west-east direction are shown in Figure 9.

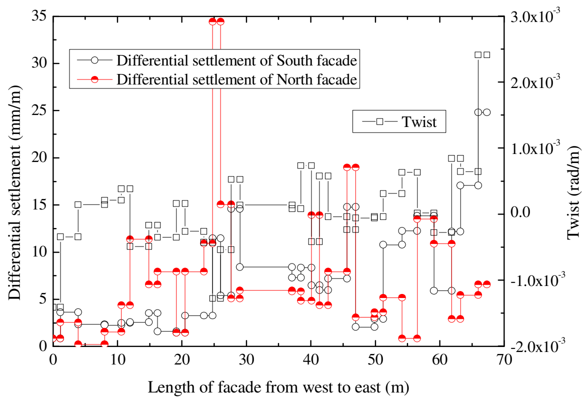


Figure 9 Original differential settlement and Twist of Chongsi Building

4.2 DCC for the building

The survey results indicate that the existing deformations of the building were relative large, meaning that the incremental deformation must be controlled strictly. According to the risk level 1 in Table 4, the maximum tilt of a building is less than 1/500 which means that in this condition the building will not have damage. The allowable incremental differential settlement of the building was set as half of the value for damage level 1 in Table 4, i.e., 1/1000 or 1 mm/m. The total differential settlement of the building was set as the value of damage level 4, i.e., 20 mm/m (see Table 4). The corresponding limits for twist were determined using the values of differential settlement under the most unfavorable combinations of the differential settlements. The DCC for the building were proposed as in Table 5.

In practice, to ensure that there is enough time to implement emergency measures, the early warning criteria should be established. For example, the attention limit can be defined as 30% of the allowable limit and the alarm limit can be defined as 60% of the allowable limit

Table 5 DCC for Chongsi Building

Total differential settlement (mm/m)	Total twist (rad/m)	Incremental differential settlement (mm/m)	Incremental twist (rad/m)
<20	$<4\times10^{-2}$	<1	$<2\times10^{-3}$

5. FIELD MEASURED RESULTS DURING THE TUNNEL CONSTRUCTION

The construction progress and the propulsion pressure of shield tunnels crossing the building are shown in Figure 10 and Figure 11. The vertical axis of the Figure 10 is the "Number of ring", and the length of each ring is 1.2 m.

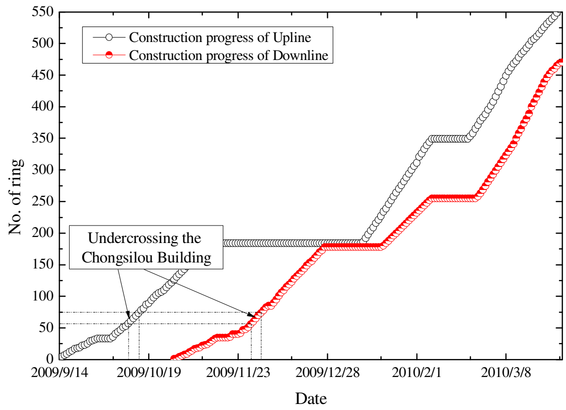


Figure 10 Construction progress of shield tunnels crossing historic buildings

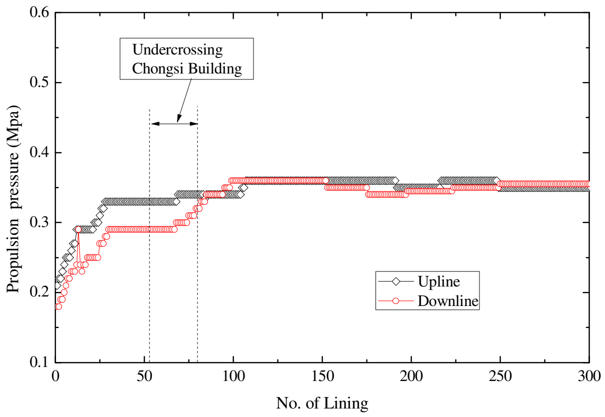


Figure 11 Propulsion pressure of shield tunnels crossing the historic building

5.1 Monitored deformations of Chongsi Building

The deformation monitoring system had been installed around and on Chongsi Building before the tunnel construction. The plan view of the monitoring points is shown in Figure 12. The Arabic numbers indicate the building segments for twist calculation.

5.2 Measured results

The incremental settlements at the monitoring points of Chongsi Building during the tunnel construction are shown in Figure 13. The variations of the incremental settlements and the incremental twists of some key monitoring points are given in Figure 14 and Figure 15 respectively. Figure 16, Figure 17, and Figure 18 show the comparison of the existing, incremental and total differential settlements and twists. The maximum incremental settlement of the monitoring points was 13.29 mm, and the maximum incremental differential settlement was 0.67 mm/m, and the maximum incremental twist was 3.23×10^{-5} rad/m. It can be seen that the incremental twists were very small. In other words, the field data show that the tunnelling adopted induced deformation is not beyond the incremental limit, which indicate the construction of underground crossing is very successful and well controlled.

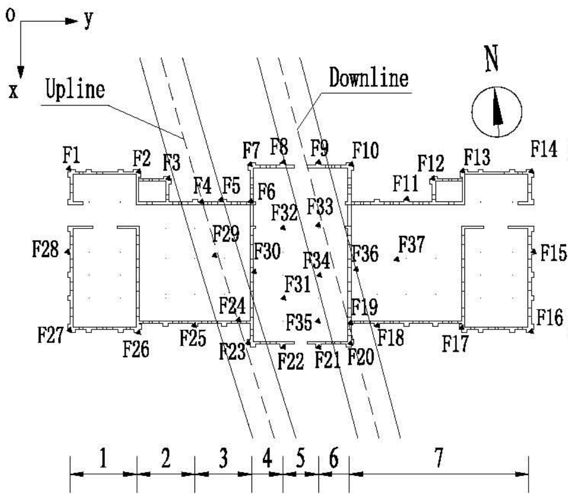


Figure 12 Plan of monitoring points of Chongsi Building

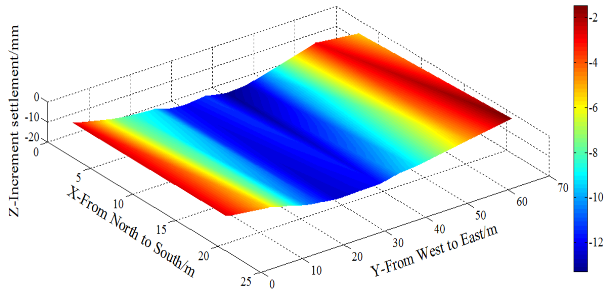


Figure 13 Contours of the settlements

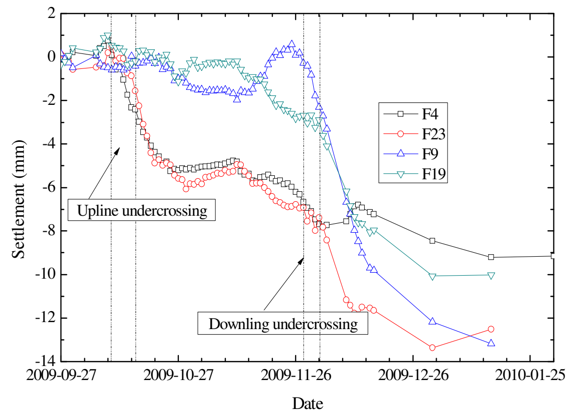


Figure 14 Settlement development with the construction process for sme key measuring points

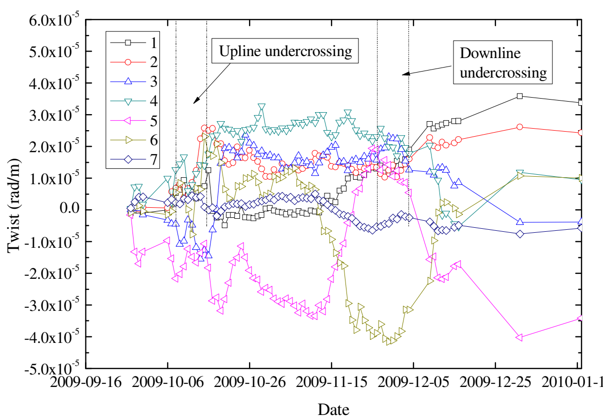


Figure 15 Development of twist with the construction process

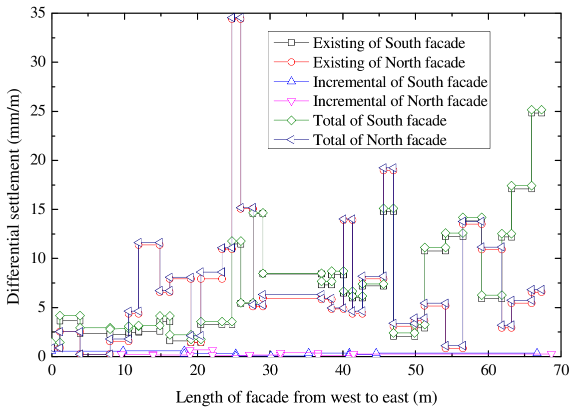


Figure 16 Comparison of existing, incremental and total differential settlements of Chongsi Building

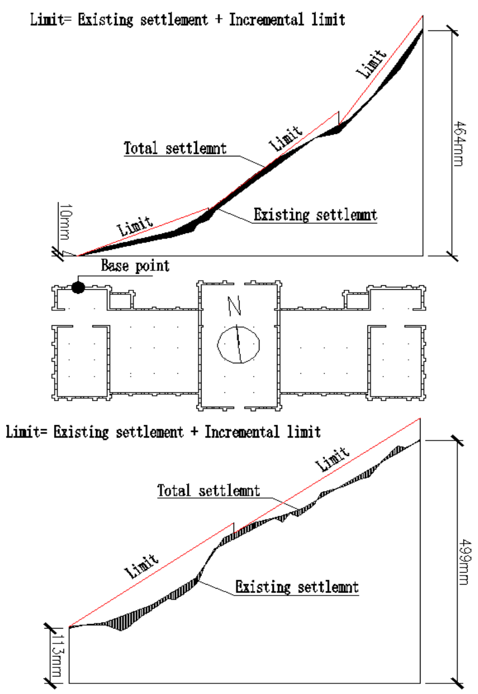


Figure 17 Comparison of existing, total settlements and incremental limit of Chongsi Building

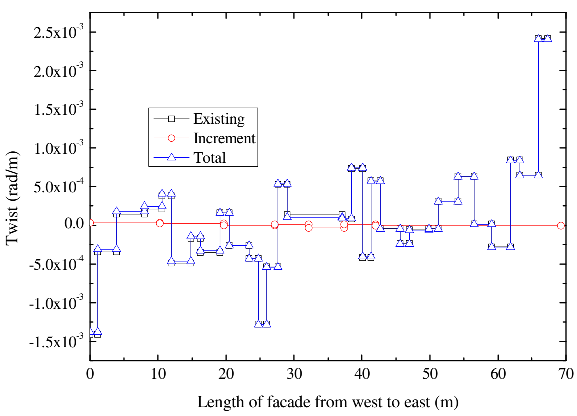


Figure 18 Comparison of existing, incremental and total twists of Chongsi Building

5.2.1 Safety assessment for Chongsi Building

The maximum incremental twist of Chongsi Building, 3.23×10^{-5} rad/m, was much less than the limit of 2×10^{-3} rad/m (Table 5). The original twist plus the incremental twist caused by the tunneling was also less than the limit of 4×10^{-2} rad/m. The maximum incremental differential settlement of the building was 0.67 mm/m which was also less than the limit of 1 mm/m. However, the maximum total differential settlement was 34.6 mm/m on the north facade which was larger than the maximum allowable differential settlement given in Table 5. But the mean value of the differential settlements of Chongsi Building was 7.40 mm/m which was much less than the limit of 20 mm/m. The locations at which the differential settlement was larger than 20 mm/m were only 2. Therefore, it was considered that some local repair may be needed but the main structure of the building was safe during and after the tunneling.

5.3 Discussion

The measured maximum settlement during and after the tunnel construction was 13.29 mm which were smaller compared with the settlements values developed during the construction of Metro line 2 in Shanghai, China (Lee et al., 1999) under the similar conditions. The most commonly recorded settlement values of Metro line 2 were in the range of 35-40 mm. Therefore, strict controlling criteria and careful construction operation are effective ways to minimize the tunneling induced ground deformation. For this project, the grouting material simultaneously injected into the physical gap between the lining system and excavated soil surface was about 1.5 time of the volume of the gap. This number can be a reference for other project under the similar condition.

The criteria for twist have been proposed under the condition of most unfavorable differential settlements in two perpendicular directions. The measured incremental twist of the building was very small. It is suggested that the limits may be revised by accumulating more field data.

6. SUMMARIES AND CONCLUSIONS

The deformations (settlement, differential settlement and twist) of a historic building, Chongsi Building, in Shanghai, China, induced by tunneling are reported and analyzed. The site is in Xuhui District, along Metro line 11 in Shanghai. At this site, the thickness of soft soil alyers, softclay and clayey silt layers, is about 30 m. The earth pressure balance (EPB) shield tunneling method was used for tunnel construction.

Since the building had considerable deformations before the tunnel construction, and to ensure that the tunnel construction will not cause serious damage to the building, both total and incremental deformation criteria were proposed and used to control the construction induced deformation. This kind approach is called Dual-Control-Criteria (DCC). The criteria for the twist of masonry buildings have been newly proposed in this study.

The tunneling induced deformations of the building were small. The measured maximum settlement, differential settlement, and twist occurred during and after the tunnel construction were 13.29 mm, 0.67 mm/m and 3.23×10^{-5}rad/m respectively and there were no serious damages to the building. Therefore, the construction was successful.

The criteria for the twist have been proposed considering the most unfavorable combinations of the limit differential settlements. The measured results indicate that the tunneling induced twists are small and the criteria may need to be modified and revised with accumulation of more field data.

7. ACKNOWLEDGEMENT

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