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MONITORING AND EVALUATION OF CONSTRUCTION IMPACT OF SHANGHAI BUND TUNNEL ON NEIGHBORING HISTORICAL BUILDINGS

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Abstract. *The monitoring and evaluation of the entire construction process of Shanghai Bund tunnel was performed for protection of the neighboring historical buildings. It was conducted in three stages regarding the different stages of the entire construction process. In the first stage, which consisted of the preparation work of the construction, the structural system and the damages of the historical buildings were identified, based on which quantitative indicators of the critical deformation and damages were established. During the second stage, during which the tunnel was constructed, the structural deformation responses and damage developments of the neighboring buildings were recorded and analyzed. The results were used as reference for early-warning. The third stage was performed right after the construction, and the monitoring data were integrated and analyzed to assess the final effect of the construction activity on those buildings. The results indicated that the relationship between the tunnel construction and the increase of the structural deformation or the development of the damages of the neighboring buildings was established reasonably. It was also found that the tunnel construction did not cause substantial impacts on the neighboring buildings, e.g., the induced deformation and damages were all within specified limits. The generated knowledge of this study can be used as reference for protective monitoring of historical buildings subjected to impact of neighboring construction activities.*

1 INTRODUCTION

As the symbol of the modernization of Shanghai for more than a hundred years, there are 33 major historic buildings in the bund area along the Huangpu River. These buildings are generally used as banks, hotels, clubs and office buildings. All the buildings are conserved by Shanghai municipal government for their unique architectural styles. As a part of a project for the world Expo 2010, a reconfiguration of traffic flow along the Bund was carried out in 2007: part of the Yan'an East Road elevated expressway was demolished and was reconstructed in two levels with six lanes in a new tunnel to generate more space on the ground for the pedestrians (Figure 1).

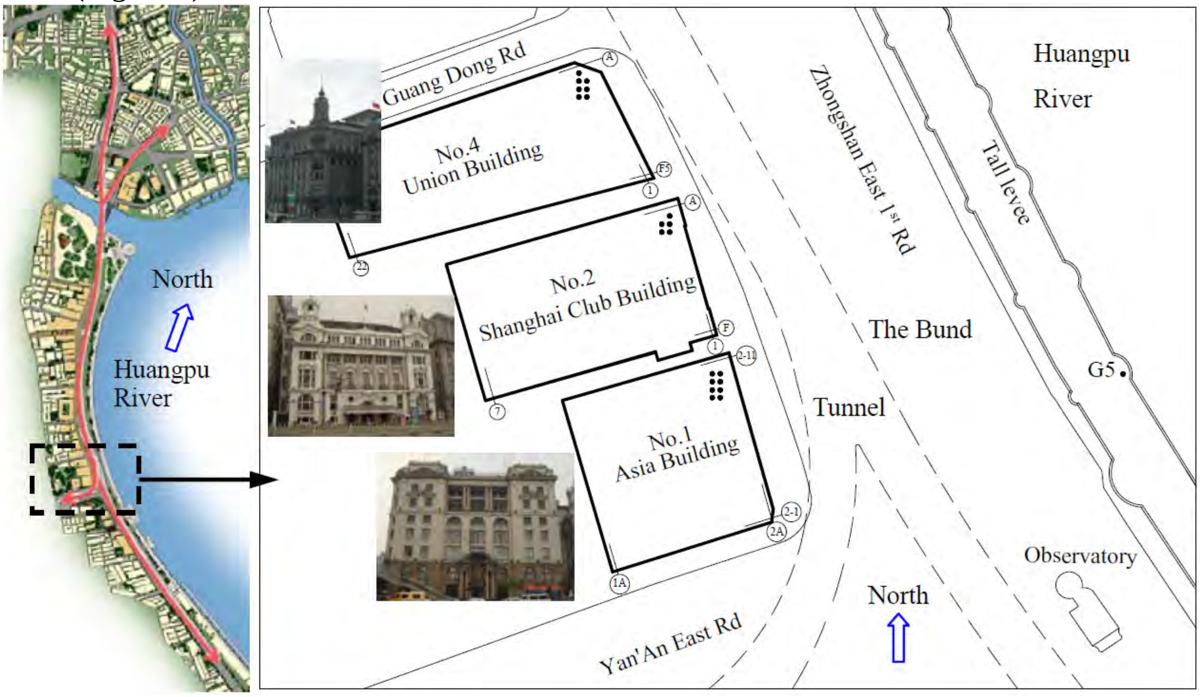


Figure 1: General layout plan of the Bund.

The tunnel was constructed by two different kinds of methods: digging in south part and shielding in north part, as shown in Figure 1. In order to guarantee safety of the neighboring buildings, which were constructed on the soft soil foundation, a monitoring system was established and performed [1,2]. Hence, the structural status of these buildings was identified before construction, and the critical deformation and damage values were determined. It could help to adjust working schedule and estimate structural reliability after construction.

This paper presents the monitoring process of the first three historical buildings in the south part of the bund. Before the construction, the structural system and the damage status of these three historical buildings were identified, based on which the structural deformability, i.e., the maximum allowable deformation, and the quantitative indicators of the critical deformation and damage were established. During the 32 months of the construction period, the structural deformation and damage development of these three buildings were recorded and analyzed. The results were used as reference for early-warning. After the construction, the monitoring data were integrated and analyzed. The impact of the tunnel construction activities on the neighboring buildings was then identified with respect to the development of the deformation and damages.

2 OUTLINE OF MONITORING BUILDINGS

The information of the three buildings was collected beforehand. The architectural and structural drawings were studied; mechanical properties of the structural materials were determined by nondestructive testing methods or local damage methods. The details of the three buildings and the tunnel are introduced separately in the following sections.

2.1 Asia Building

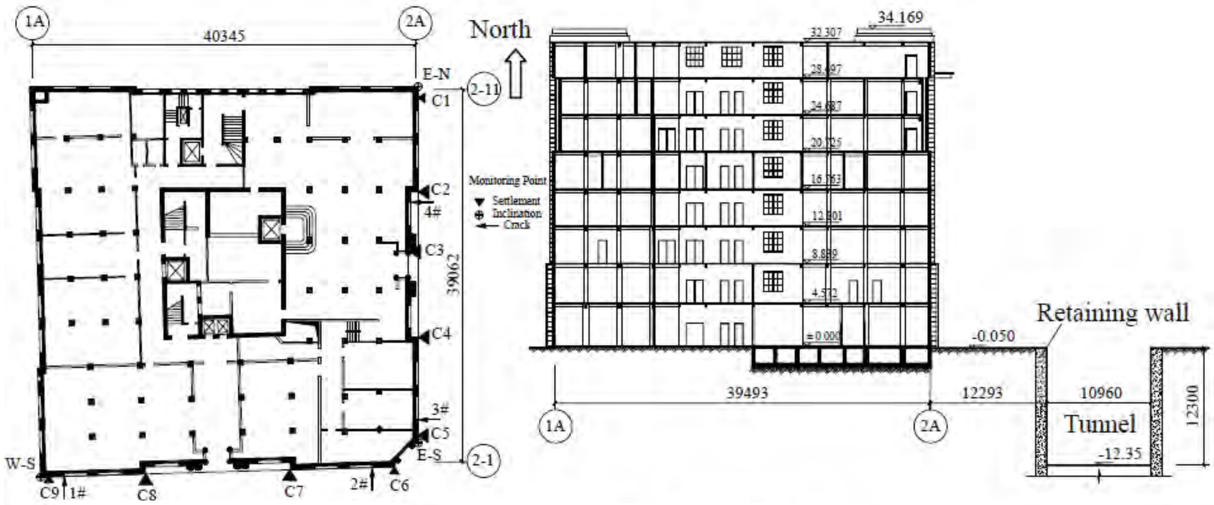
The Asia Building, located at 1 East Zhongshan 1st Road, is one of the first batches of the Consecrated Historical Buildings in Shanghai and the State Cultural Relics Protection Units. The building was designed by R. B. Moorhead and S. J. Halse, and was constructed by Yu Chang Tai Co. in 1913. It was the first 8-story building of the Bund in history. The floor area and the total area of the building are 1739 m^2 and 11984 m^2, respectively. It embodies eclectic style appearance, baroque local ornaments, and transverse and longitudinal three-segment style on the south and east elevations. The building was first put in use in 1915 by Mcbain Company as an office building, and then used by the Royal Dutch Shell's Asiatic Petroleum division, and later it housed the Shanghai Metallurgical Designing & Research Institute and Industrial & Commercial Bank.

The structural system of Asia Building is reinforced concrete beam-slab-column structure with local reinforced concrete walls. The foundation is reinforced concrete raft foundation. As shown in Figure 2, the structural plan is in a rectangular shape, spanning 40.3 m from east to west and 39.1 m from south to north. The first and the second floors are 4.6 m and 4.3 m high, the 3rd to 6th floors are3.9 m high and the top two floors are 3.8m high, respectively. The thickness of the reinforced concrete slab is about 102 mm, most of the beams are 229×419mm or 203×405mm in cross-section. The dimension of the square columns decreases from 558 mm of the first floor to 254 mm of the 8th floor. The thickness of the reinforced concrete wall is 256 mm or 152 mm. The exterior walls of the reinforced concrete structure are in-filled with masonry walls.

Based on in-situ rebound tests and core sampling tests, the compressive strength of the concrete was evaluated as 38.7MPa for the basement and 21.5 MPa for the superstructure. The shortest horizontal distance between the tunnel and the eastside of the building was 7.6 m. The depth of the tunnel varies from 12.3 m to 13.5 m. Nine monitoring points for foundation settlement were marked along the east façade and the south façade. The three corners were also used to determine the inclination tendency during the construction.

2.2 Shanghai Club Building

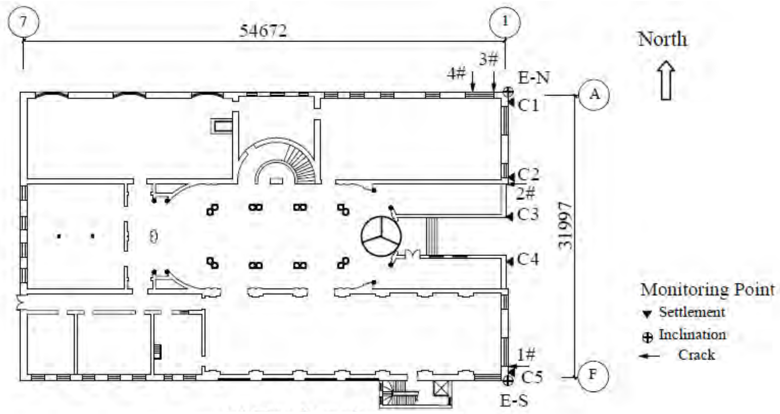
The Shanghai Club Building, located at 2 East Zhongshan 1st Road, was the most exclusive club since 1910 (Figure 3). The architectural design of the building was done by H. Tarrant and A. G. Bray. The interior design was finished by Shimoda Kikutaro. It had the famous 34-metre-long bar in the world. The building's main façade uses a tripartite design, and the middle section is featured with six ionic columns. The roof section of the façade has two symmetrical Baroque-style cupolas, with intricate carved details. A massive Italianate Grand Hall is located on the first floor, with ceilings over 11 m high, supported by 8 pairs of Tuscan double-columns. The building footprint is 1,811 m^2, while the total floor area is 10,208 m^2. The club was closed in 1941 and was taken by the Japanese occupation force until the end of the Second World War. It was used for Seamen club and Dongfeng hotel from then on. It is currently a part of the Waldorf-Astoria Hotel in Shanghai.



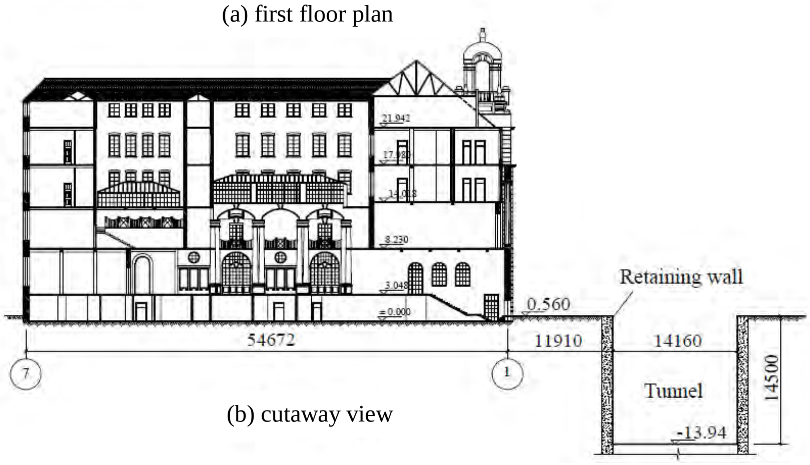
(a) first floor plan

(b) cutaway view

Figure 2: Asia Building (No.1).



(a) first floor plan



(b) cutaway view

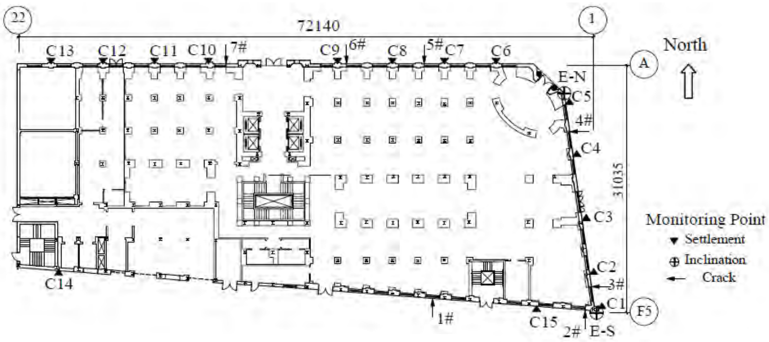
Figure 3: Shanghai Club Building (No.2).

The Shanghai Club Building is a 5-story hybrid structure with masonry wall in-filled steel frame, timber roof truss and reinforced concrete floor slabs. Its structural plan is in a rectangular shape, spanning 54.7 m from east to west and 32.0 m from south to north. The story heights are between 3.05 m to 5.79 m, while the total height of the building is 26.9 m. The reinforced concrete slabs, about 120 mm in thickness, are supported by steel beams. The beams, enclosed by low-strength concrete, are connected with the steel column or supported by masonry walls. As a special construction method employed in the construction of this building, the steel columns are always enclosed with masonry materials. The thickness of the masonry walls varies from 381mm to 510 mm. It was the first project that used raft foundation in Shanghai. The depth of foundation is over 0.70 m. The interior space of the building at each story is irregularly partitioned for residency. Many localized retrofits were made and some openings in the walls have been filled.

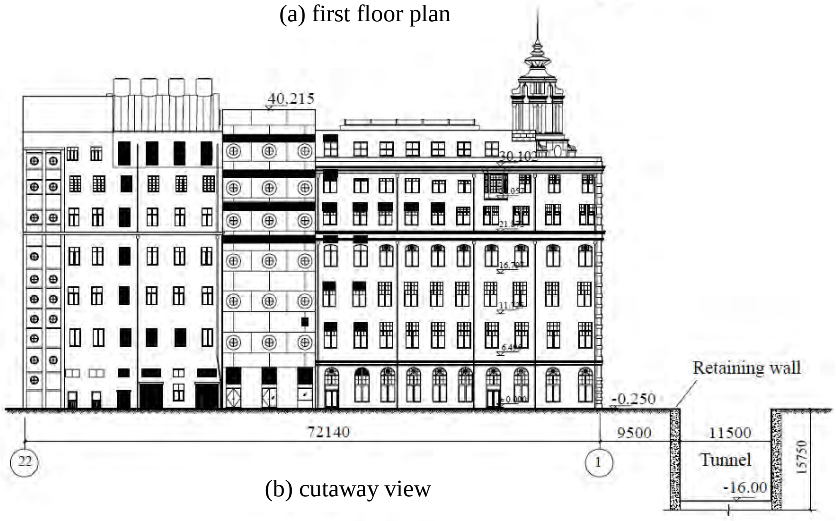
The depth of the tunnel was about 14.5m, the horizontal distance at the northeast and the southeast corner of the building varied from 7.44 m to 14.44 m. Limited by the field condition, the northeast corner (point marked as ‘E-N’ in Figure 3) and the southeast corner (point marked as ‘E-S’) were used as the inclination monitoring points. Five settlement points were used on east façade walls.

2.3 Union Building

Union Building, located at No.4 Zhongshan East 1st Road, was first used by a number of insurance companies. The Union Bank purchased the building after the Second World War and gave its name. It was the first work of P&T Architects and Surveyors in Shanghai, designed by Palmer and Turner, construction completed in 1918. The building is in Neo-Renaissance style with a symmetrical façade, but with some Baroque style details. The roof features a domed corner pavilion. It covers 2241 square meters area, with a total floor area of 11493 square meters. From 1953 the building was used by the Shanghai Civil Architecture & Design Institute, by whom extra four floors were added on top of the building. In 1997, a private equity fund from Singapore purchased the building, and converted it into a shopping centre in 2004.



(a) first floor plan



(b) cutaway view

Figure 4: Shanghai Union Building (No.4).

As the first steel frame structure used in Shanghai, the columns and beams of the Union Building were covered with concrete or masonry for fire protection. The foundation is reinforced concrete raft foundation. The structural plan is a rectangular shape, spanning 72.1m from east to west and 31035mm from south to north. Total heights are 21.87 m, 30.10m and 40.22m to the 4th floor, 6th floor and roof respectively. The design thickness of reinforced concrete slab is 152mm. The height of steel I-beams are 152mm to 457 mm, the width of their flange are 76mm to 177 mm. Two kinds of H-columns were used, whose height×width are 177×177mm and 304×342mm. The frame was in-filled with masonry walls outside. Part flanges of columns were strengthened with additional steel plate in reconstruction, the masonry wall were covered with wire and high-strength mortar.

Based on the original design drawings, the tensile strength of steel can be converted to 403 MPa. The compressive strength of concrete, clay brick and mortar were 23.8MPa, 10 MPa and 7.3MPa, respectively, by in-situ tests. The relative location between the tunnel and the building was shown in Figure 4. Fifteen monitoring points for settlement were marked along four façade walls, two corners were used to determine the inclination tendency during the construction.

3 INITIAL SURVEY AND EARLY-WARNING INDEX

Based on “Specification for Excavation Engineering Construction Monitoring” [3], initial survey of the neighboring buildings was carried out. It was the basic work for further monitoring and could help to determine the control indexes for early-warning.

3.1 Asia Building

Before tunnel construction, there were 17 cracks observed on the façade walls of the first floor (“↑” marked in Figure 2). The maximum width of the cracks was measured (less than 0.4 mm) and marked for further measurement (Figure 5a). It was also found that some concrete slabs on the 6th, the 7th and the 8th floors cracked in the corners of the building (Figure 5b). These nonstructural cracks were usually caused by thermal expansion and shrinkage of structural materials.

Since the tunnel construction may cause ground movements, the absolute altitudes of the monitoring points (C1~C9 in Figure 2) and the initial inclination of the building were measured, which would be used as the reference to assess the development of settlements and inclination of the building in the construction of the tunnel (Figure 5c and Figure 5d).

(a) crack detection (b) slab clacks on roof (c) elevation measurement (d) inclination measurement

Figure 5: In-situ survey

3.2 Shanghai Club building

In addition to the steel corrosion and external wall seepage, there were a lot of hairline cracks on the buildings before the tunnel construction. Most cracks were on the east side of the Shanghai Club building. Limited by site condition and for convenience of measurement, 17 cracks in the first floor were selected as monitoring point (marked "↑" in Figure 3), 5 points on the east exterior wall were set as settlement monitoring points (C1~C5 in Figure 3), northeast and southeast corners of the building were selected as the measuring points for inclination observation. The initial values of the crack widths, absolute altitudes of the monitoring points and the inclination of the building were measured also.

3.3 Union Building

Different from the other two buildings, the bottom plate of the foundation of this building was damaged due to the two stories added on the top of the original building. There was half meter depth water in the basement before tunnel construction. A few small cracks were observed on the interior members, but a lots of medium cracks, whose width were between 0.2mm to 1.0mm, were found on the south outside wall. Fifteen leveling points were fixed around the building (C1~C15 in Figure 4), Two corners of the building beside the tunnel were taken as the inclination monitoring points. The corresponding initial values were measured too.

3.4 Early-warning indexes

Based on the initial field survey and the existing test results [4,7,8,9], the early-warning indexes were determined as follows:

(1) Development rate of settlement reaches 2.0 mm/day and lasts for 2 days, or the cumulative settlement exceeds 20 mm.

(2) The cumulative inclination increment reaches 0.1%.

(3) The new crack width on walls, or increment of existing one, reaches 1 mm.

(4) The crack width of reinforced concrete member exceeds 0.2 mm, or width increment of old one reaches 0.1mm.

If the limit value of any one of the above-listed indexes is reached, an early-warning signal will be sent to the constructer and particular measures should be taken.

4 MONITORING AND EVALUATION

Considering the structural situation and construction method, the monitoring program of the neighboring buildings was designed as follows:

(1) Before tunnel construction, settlements were monitored every month.

(2) When retaining walls were constructed, the settlements were monitored every week. When the tunnel was excavated, the settlements were monitored every day until concrete bottom plate was cast. Then, the settlements were monitored twice every week.

(3) If the monitoring results reached the detection limit or alarm value discussed in section 3.4, the settlements should be monitored twice a day at least, the working schedule should adjust.

(4) The inclinations of the buildings were monitored every month regularly. If the settlements were monitored every day, the corresponding inclination of the building should be measured once a week.

(5) The monitoring frequency of cracks was the same as that of inclination measurement.

4.1 Settlement monitoring

Being sensitive information for evaluating structural safety, settlements of three buildings were measured. Before construction, the monitoring results of the Asia Building always fluctuated around zero line, but C8 and C9 went up due to expressway dismantlement (Figure 6a). When the retaining wall was constructed, all of the points sank obviously, especially the points at the southeast corner. The cumulative settlements of points C1, C5 and C6 exceeded the alarm limitation for a long time, but they decreased at last. Half year later, these settlements tended to be stablized after construction. As shown in figure 6b, the building sloped away to the east and north in three stages.

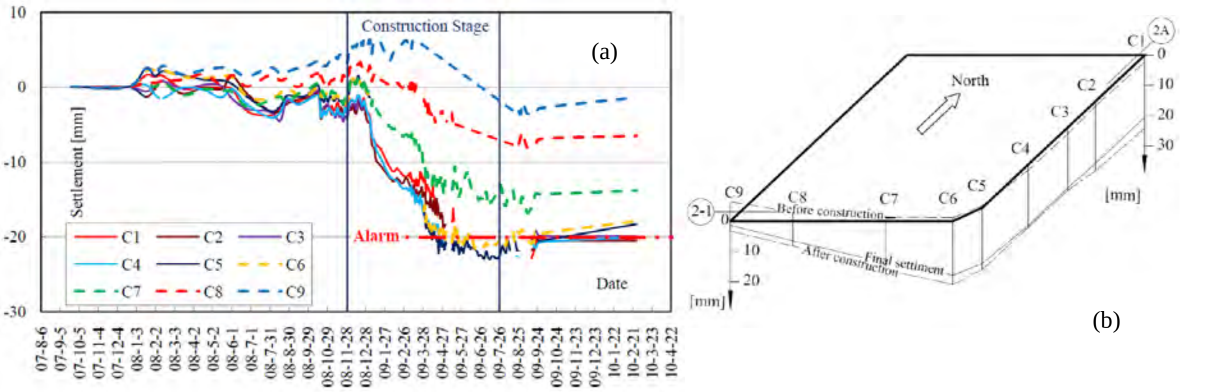


Figure 6: Settlements of Asia Building (No.1).

Similar to the Asia Building, the vertical movement of the Shanghai Club Building varied slightly at the first stage. After the soil was removed in the tunnel construction, the settlement increased significantly (Figure 7a), the cumulative settlements of three monitoring points exceeded the alarm line before the tunnel roof was constructed. From the south end to the north, the settlement increased gradually, in an inverse proportion with their distances to the tunnel (Figure 7b). The east wall of the building sloped to the north after the construction. The settlements were finally recovered slightly.

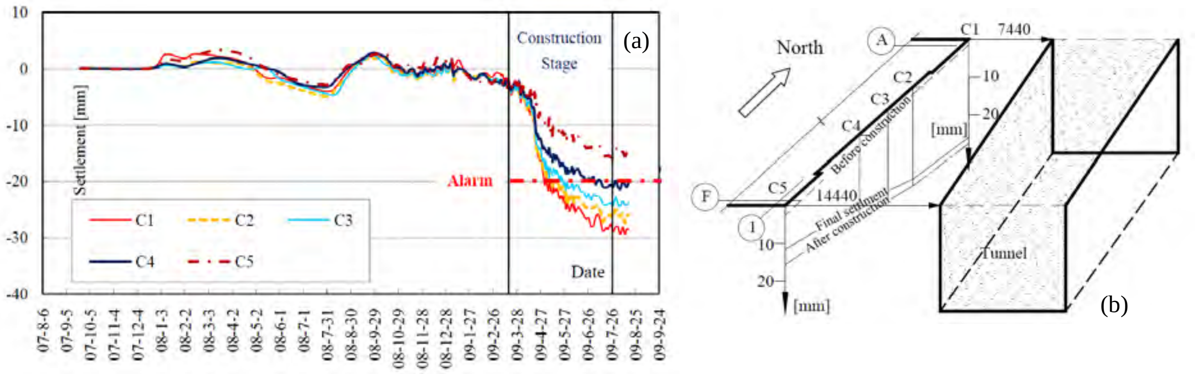


Figure 7: Settlements of Shanghai Club Building (No.2).

The structural settlements of the Union Building increased gradually after the construction, especially point C1 at the southeast corner of the building, which was the nearest monitoring point to the tunnel (Figure 8a). Three months later, the cumulative settlements of some points exceeded the alarm value. The shoring system of trench was strengthened. Though the maximum settlement rate reduced 0.0011 mm/day gradually, the development tendency of the settlements was clear until the project was finished in 2010. As seen in Figure 8b, the building sloped away to the east and south finally.

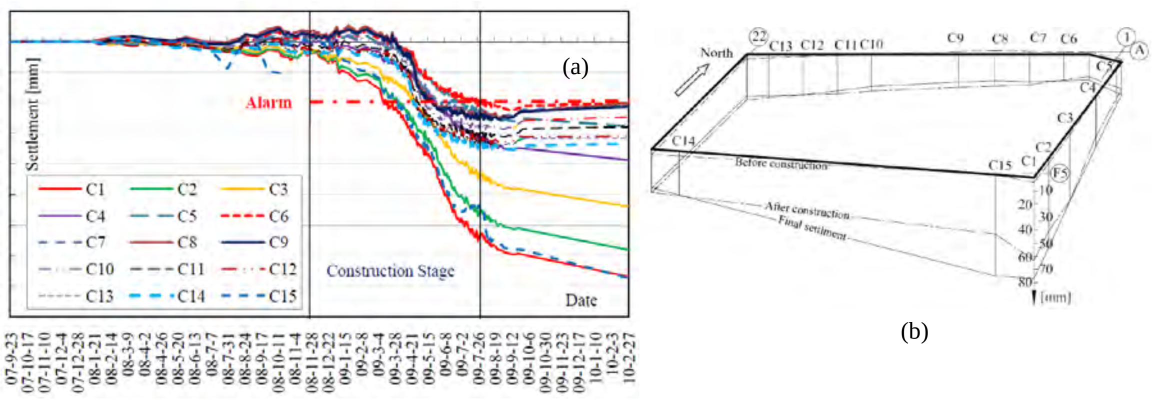


Figure 8: Settlements of Union Building (No.4).

4.2 Inclination measurement

Inclinations of structures are very important responses for evaluating structural safety and stability [7,8,9]. The changes in slope were measured by use of the free station method. The measurement results, as listed in Table 1, indicated that the inclinations of the buildings varied within a narrow range before the construction of the tunnel. During the construction, every structure inclined perceivably. The Asia Building and Shanghai Club Building leaned to the north and the east, Union Building tilted to the south and the west. The inclination tendencies of the three buildings matched the results determined by settlement measurement. After construction, the maximum increment of the inclination was 0.085% (1/1176), which was acquired at the southeast corner of Union Building.

Table 1: Measured values of inclinations at the corner of the historical buildings.

Building	Measure Point	Initial record	Before construction	After construction	Final record	Inclination increment
Asia Building (No.1)	E-N	N 0.025% W 0.532%	N 0.036% W 0.521%	N 0.041% W 0.503%	N 0.043% W 0.501%	N 0.018% E 0.031%
	E-S	S 0.160% W 0.449%	S 0.137% W 0.443%	S 0.133% W 0.428%	S 0.134% W 0.421%	N 0.026% E 0.028%
	W-S	N 0.004% W 0.521%	N 0.017% W 0.501%	N 0.031% W 0.491%	N 0.033% W 0.489%	N 0.029% E 0.032%
Shanghai Club Building (No.2)	E-S	S 0.768% E 0.190%	S 0.765% E 0.183%	S 0.746% E 0.193%	S 0.197% E 0.740%	N 0.028% E 0.007%
	E-N	S 0.425% E 0.062%	S 0.414% E 0.081%	S 0.396% E 0.093%	S 0.093% E 0.390%	N 0.035% E 0.031%
Union Building (No.4)	E-S	W 0.196% N 0.516%	W 0.209% N 0.500%	W 0.213% N 0.436%	W 0.218% N 0.431%	W 0.022% S 0.085%
	E-N	E 0.551% N 0.735%	E 0.554% N 0.730%	E 0.531% N 0.702%	E 0.523% N 0.695%	W 0.028% S 0.040%

Note: N,E,S,W in the table were the inclination directions of measured walls at the corners.

4.3 Crack development

The excavation-induced building damages in the neighboring buildings were primarily in the form of cracking of exterior masonry walls. Periodic detection was performed to monitor the propagation of the building damage throughout the duration of the construction activities. A summary of the typical cracks and the corresponding construction activity is presented in Table 2. The maximum increment of the crack width in the Asia Building was 0.3mm at last, and did not exceed the alarm limit. As for the Shanghai Club Building, new cracks (red line in Figure 9) were found on the east wall, with the crack width ranged between 0.35mm to 0.8mm, after construction. The crack width on the Union Building was bigger than that on the other two buildings due to its larger settlement. Not only the east wall but also the north and the south wall of the Union Building cracked during the construction. The maximum width of the new cracks was 0.60 mm finally.

Table 2: Crack widths of outer walls in the first floor [mm]

Building	Monitoring point	Crack description	Initial width	Before construction	After construction	Final record
Asia Building (No.1)	1-1	vertical crack at window corner	0.20	0.30	0.50	0.50
	1-2	vertical crack at window corner	0.30	0.40	0.50	0.50
	1-3	vertical crack at window corner	0.30	0.40	0.50	0.50
	1-4	vertical crack at window corner	0.30	0.30	0.35	0.35
Shanghai Club Building (No.2)	2-1	vertical crack	No	No	0.35	0.35
	2-2	diagonal crack on the top of piers	No	No	0.80	0.80
	2-3	vertical crack at window corner	0.30	0.50	0.50	0.50
	2-4	vertical crack in the mid of window	3.00	3.00	3.00	3.00
Union Building (No.4)	3-1	vertical crack at building corner	1.00	1.00	1.30	1.30
	3-2	diagonal crack at window corner	0.20	0.20	0.40	0.40
	3-3	vertical crack	No	No	0.20	0.20
	3-4	vertical crack at window corner	No	No	0.30	0.30
	3-5	diagonal crack at window corner	No	No	0.50	0.50
	3-6	diagonal crack at window corner	No	No	0.60	0.60
	3-7	diagonal crack at window corner	No	No	0.15	0.15

(a) Shanghai Club Building (No.2) (b) Union Building (No.4)

Figure 9: New cracks detected on the east walls.

4.4 Evaluation

As a readily parameter to evaluate the response of a structure during settlement, the angular distortion, β, of the building is defined as:

$$\beta = \frac{\delta}{L} \tag{1}$$

where δ is the relative settlement between the adjacent two monitoring points, and L is the horizontal distance between these two monitoring points.

Based on the structural systems of the three buildings, β=1/300 was recommended as the limitation value for load-bearing walls or masonry infilled panels in traditional frame buildings by case studies and the existing numerical analysis [7,10]. As listed in Table 3, angular distortions of the three neighboring buildings are less than 1/515 finally. Except point C14 and C15 on Union Building, the calculated angular distortions are in fair agreement with the corresponding inclinations shown in Table 1. According to the results shown in Table 3, it can be concluded that the impact of the tunnel construction on the three buildings can be neglected.

Table 3: Angular distortions of the historical buildings.

Building	Measure Points	Distance [mm]	β before construction	β after construction	β final record
Asia Building	C1 & C5	36150	N 0.008%	N 0.004%	N 0.006%
	C6 & C9	37250	E 0.014%	E 0.047%	E 0.044%
Shanghai Club Building	C1 & C5	32690	S 0.003%	N 0.036%	N 0.044%
Union Building	C1 & C5	25310	S 0.022%	S 0.160%	S 0.194%
	C6 & C13	56160	W 0.009%	W 0.024%	W 0.020%
	C13 & C14	26058	S 0.004%	S 0.003%	S 0.007%
	C14 & C15	60280	W 0.006%	E 0.032%	E 0.073%

As the quantitative indicator of the critical deformation and damage, cracking is usually be grouped into two types: nonstructural cracks and structural cracks. Nonstructural cracks are usually caused by thermal expansion and shrinkage of materials. Structural cracks are caused by load stresses and constrained strains. Structural cracks may cause safety problems. Usually, when the maximum width of cracks exceeds 0.3 mm in reinforced concrete structures, or 1 mm in masonry bearing walls, the cracked component should be checked to ensure its safety. Since the increments of widths of cracks observed in the construction is not very big, the conclusion about the limited impact of the construction on the buildings mentioned before is confirmed.

5 CONCLUSIONS

The objective of this paper is to propose a monitoring strategy to trace the impact of tunnel construction on the neighboring historical buildings. The practice showed that the strategy was effective. And also we can conclude:

1. The monitoring of the entire process during the construction of Shanghai Bund tunnel is a positive and effective method for the protection of the neighboring historical buildings. Early-warning system can serve as a guide to improve the construction program.
2. The early-warning indexes proposed in the paper are reasonable.
3. The final impact of the tunnel construction on the neighboring historical buildings can be easily evaluated by using the parameter of angular distortion.
4. Theoretic analysis of the responses of historical buildings caused by the neighboring construction is in need and will be studied by the authors in future.

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