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The construction and field monitoring of a deep excavation in soft soils

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ABSTRACT: This paper describes the construction of a 40 m multi-propped deep excavation in the downtown area of Shanghai, China and the interpretation of the monitoring data. The entire excavation was 263 m in length, 23 m wide and 38–41 m deep. The excavation was divided in three sections, i.e., the eastern, the middle, and the western pits. Noticeable characteristic of this project are the excavation of a nearly 60 m wide section embedded in the Huangpu River and the presence of many sensitive buildings nearby. In this paper, some construction details of the excavation and the monitoring results are presented and discussed.

1 INTRODUCTION

1.1 *Excavations for underground railway networks in Shanghai*

With the rapid development of Shanghai and the city's underground railway networks, metro construction has become a multidisciplinary and multifaceted project. During construction, regular service of neighboring underground railway lines must remain open. Figure 1 shows the distribution of completed and on-going excavations for underground railway networks in Shanghai as of 2007. 92% of the metro stations are deeper than 15 m and 31% are over 20 m in depth. Zhao & Yang (2004) have suggested that any excavation, which is over 20 m in depth, will impose severe geotechnical challenges in soft soils. This paper describes the construction of a 40 m deep excavation in the downtown area of Shanghai, China and the analysis of its construction impacts to the environment.

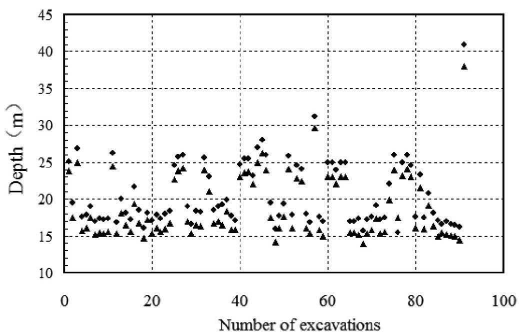


Figure 1. Statistics of depth of completed and on-going excavations for underground railway networks in Shanghai.

1.2 *Engineering background*

The tunnel between the South Pudong Road Station and the Nanpu Bridge Station is a cross-river section on Line 4 of Shanghai's underground railway system (see Figure 2). On 1 July 2003, a failure occurred resulting in flooding of the tunnel from a sub-artesian aquifer. This led to the collapse of some sections of the tunnel, excessive ground settlements and the closure nearby buildings because of the potential danger to the public.

An in-situ restoration program was implemented in which an open cut was made in the damaged sections of the tunnel to expose the collapsed sections, clear the debris, and then to construct a new open structure.

As the extent of the collapse was large, the restoration work was constructed both on shore and in the river. Using a cofferdam, a piled steel platform was constructed above the river to excavate the collapsed tunnel after it had been backfilled. Two undamaged tunnel sections, which were flooded, were de-watered by high-pressure pumps and then reinforced. The entire restoration project included five major components: three deep excavations at the eastern, middle, and western parts of the tunnel, clearance work for

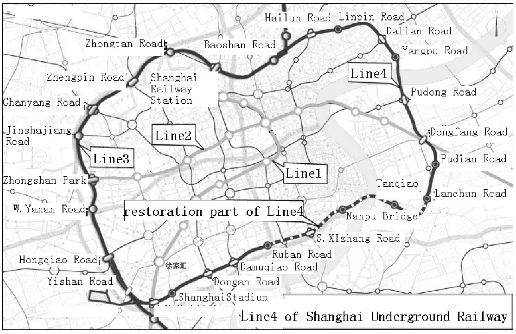


Figure 2. Line 4 of Shanghai's underground railway.

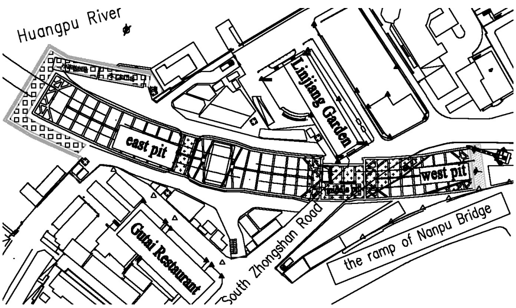


Figure 3. General layout of the restoration project.

the undamaged tunnel in Pudong (1003 m) and in Puxi (760 m), and the connection work at the two ends of the damaged and undamaged tunnel sections. The general layout of the restoration project is shown in Figure 3.

A 65 m deep 1.2 m thick concrete diaphragm wall was used to retain the three excavations (or so-called pits). The total length of the excavations was 263 m in length and 23 m wide (see Figure 3). The depth of the excavations varied from 38 m to 41 m. Ten and nine levels of concrete propping slabs were installed to support the diaphragm wall at the eastern and the western pits, respectively (see Figure 4). In the middle pit, 35 m long, 1.2 m in diameter cast-in-place piles were constructed to support the steel columns whose cross-sectional area is $650 \times 650\,\mathrm{mm}^2$. In turn, these columns were used to carry the horizontal propping slabs.

2 GEOLOGICAL CONDITIONS

The restoration project was located adjacent to Outer River Road, Dongjiadu Road and Zhongshan South Road, where the terrain was quite flat. Figure 5 compares the current geological profile obtained from a shift put down after the tunnel had collapsed and the previously surveyed data obtained before the tunnel

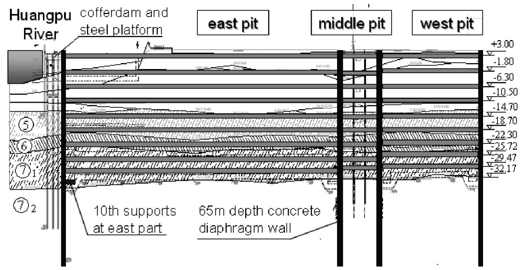


Figure 4. Ground profile at the restoration project site.

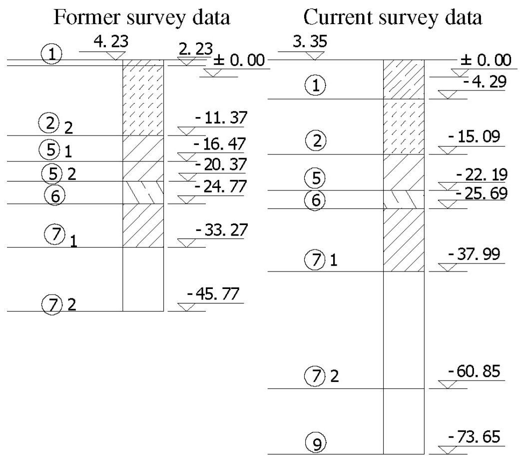


Figure 5. Comparison of strata on site.

collapse. The physical and mechanical properties of the soil layers are summarized in Table 1.

Based on the ground investigations, groundwater was expected along and above the tunnel. The groundwater table is 0.5–1.0 m below the ground surface. The ground comprises clay and silty clay layers at shallow depths and more sandy materials at greater depths. Layer 7 is the first aquifer in Shanghai, while layer 9 the second aquifer. They are connected hydraulically on site but apparently they are not connected to the Huangpu River. The groundwater and the Huangpu River have no obvious hydraulic link on site.

3 ENGINEERING DIFFICULTIES AND CONSTRUCTION TECHNOLOGY

The scale of the restoration work was large and the depth of excavations was the deepest in Shanghai at that time. Around the excavation site, there were sensitive buildings nearby such as the Linjiang Garden Building and the Nanpu Bridge which required protections. Ground conditions were very complex owing to the tunnel collapse and the materials left from the

Table 1. Physical and mechanical properties of the soils at the restoration project site.

Layer No.	Soil Type	Thickness (m)	Depth below ground (m)	Water content, w (%)	Unit weight, γ (kN/m^3)	Void ratio, e	Cohesion, (kPa)	Friction angle (°)	Average SPT N values
①	Fill	7.70	−4.29	33.5	18.7	0.98	14	27.5	–
②$_2$	Silt clay	1.8	−15.09	30.9	18.7	0.90	7	32.0	10
⑤$_{1\&2}$	Gray clay	7.10	−22.19	43.3	18.2	1.24	14	12.5	–
⑥	Green silty clay	3.5	−25.69	24.4	20.2	0.70	43	15.5	–
⑦$_1$	Silty sand	12.30	−37.99	35.1	20.3	1.04	0	33.0	40
⑦$_2$	Silty fine sand	22.86	−60.85	28.2	19.8	0.78	0	37.0	50
⑨	Silty fine sand	–	–	25.2	–	0.71	0	35.5	50

rescue of the tunnel including slurry, polyurethane, freezing agents, rails, and reinforced concrete pipes. Since the depth of excavations reached the confined water aquifer at layer 7 (see Figure 4), dewatering was therefore required. As the pumping rate of a single well from dewatering tests was found to be about 90 m^3/h, the loss of groundwater was expected to high during pumping. Special measures were taken to minimize ground settlements and hence to protect the surrounding buildings. Several important construction processes of this restoration project are described below.

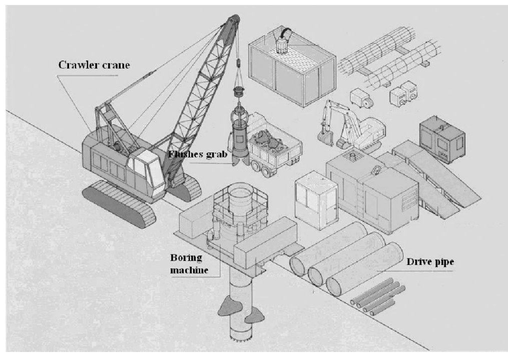


Figure 6. Cutting of the former tunnel by boring machine.

3.1 *Treatment of underground materials*

The restoration work covered the main areas affected by the tunnel collapse. Within the collapsed areas, there were materials from building foundations and abandoned underground pipelines, emergency rescue materials, construction waste, sand backfill, previously abandoned buildings (e.g. the Wenmiao Pumping Station), and the septic tanks of the Linjiang Garden building. In the deep strata, there were two refrigeration units, tracks, sleepers, tunnel reinforced steel supports, a large number of water pipes and the collapsed reinforced concrete tunnel debris.

Materials at 10–15 m depth were excavated and removed using a heavy plant. The materials further below were removed from excavation pits. Cutting equipment was used to remove any obstructions, which were taken away with the earthworks. When deep underground obstructions affected the construction of the diaphragm wall, a boring machine was used to clear the obstructions (see Figures 6 and 7). The diaphragm wall was then constructed after backfilling.

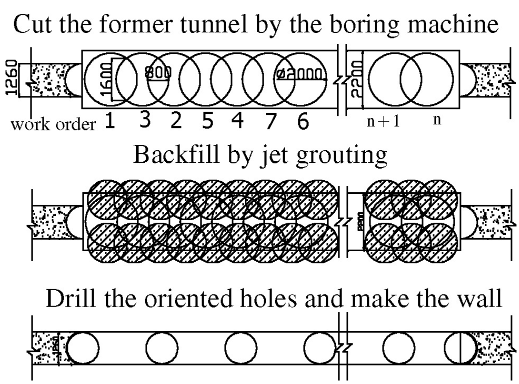


Figure 7. Barrier removal at the position of the diaphragm wall.

3.2 *Construction of the diaphragm wall*

To retain the deep excavation pits, which varied from 38 m to 41 m, a record depth of 65 m and 1.2 m thick concrete diaphragm wall in Shanghai was required. The construction of such a deep wall was expected to encounter many difficulties. The available equipment and technology had to be improved for the construction. As shown in Figure 8, the "two-drill-one grab" method was used. The method involves drilling two oriented holes first with a rotary drilling machine and then grabbing the soil between the holes effectively. Using this method, the verticality of the holes was better than 1/300 and the slurry trench excavation in

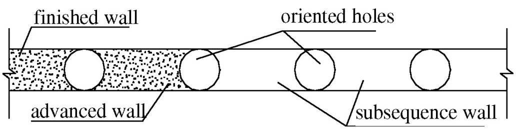


Figure 8. The two-drill-one grab method for the construction of the diaphragm wall.

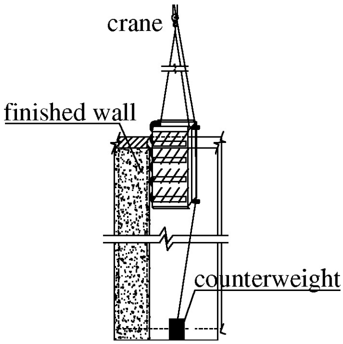


Figure 9. Brushing work for the diaphragm wall.

the strata with obstructions could be carried out much faster.

To achieve better efficiency in cleaning the soil at the previously installed diaphragm wall panel, a counterweight was placed at the bottom of the diaphragm wall trench (see Figure 9). This generated horizontal forces that made the brushing machine cling to the joints by its directional bearings. In addition, the method enhanced the waterproofing performance of the wall.

3.3 *Cofferdam and steel platform*

The cofferdam and the steel platform in the Huangpu River were important temporary structures, which contributed to the success of the restoration work in the river (Figure 10). The foundation of the platform was supported by 0.8 m diameter of steel pipes with a wall thickness of 12 mm and 1.2 m in diameter cast-in-place piles. The superstructure consisted of H700 steel pile cap beams, H700 steel stringers, 18# I beam bridge plan distribution beams, 10 mm bridge deck steel, and Φ45 steel pipe grates. The platform was +3.5 m above ground and its width was 8–9 m.

3.4 *Strengthening of the ground by jet grouting*

In order to reduce the deflection of the diaphragm wall during excavation and construction of the concrete propping slabs, rotary jet grouting (see Figure 11) was carried out below each level of slab, starting from the fourth propping level and around the excavation.

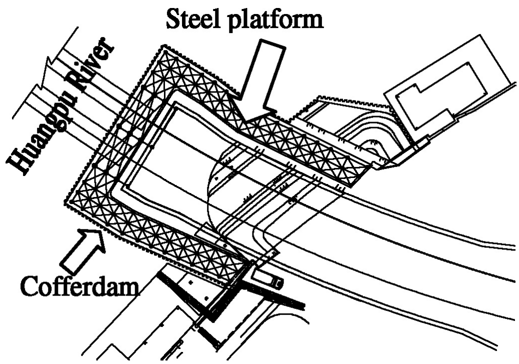


Figure 10. The cofferdam and steel platform in the Huangpu River.

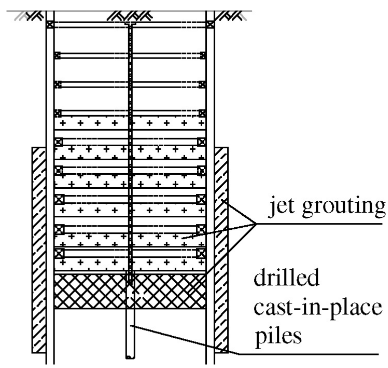


Figure 11. Jet grouting construction.

The grout formed a frame-like earth beam to enhance the shear strength of the soil in the passive zone. Jet grouting was also carried out at the bottom of the excavation. The grouting was combined with dewatering to protect the excavation from any adverse effects such as inflow of water or sand and base heave. Two jet-grouted piles were installed at each joint between diaphragm wall panels to minimize the ingress of ground water into the excavation (see Fig. 7).

3.5 *Dewatering and monitoring*

The excavation depth of the two open cut pits was more than 38 m, which reached the aquifer of layer 7. Dewatering became one of the most vital activities on site. Since the dewatering was at great depth, ground settlement had to be strictly controlled to protect the neighboring buildings such as the Linjiang Garden and the ramp of the Nanpu Bridge from any damage. Based on an optimized design using results from in-situ dewatering tests, 56 wells of 61 m deep were sunk and recharge wells were installed at appropriate positions outside the pits. In addition to monitoring the ground settlements, water level observation

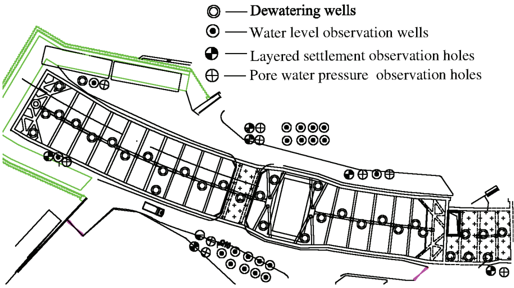


Figure 12. Dewatering monitoring points of the eastern pit.

wells, sub-surface settlement monitoring points, and pore pressure observation holes were installed (see Figure 12).

3.6 *Three excavation pits*

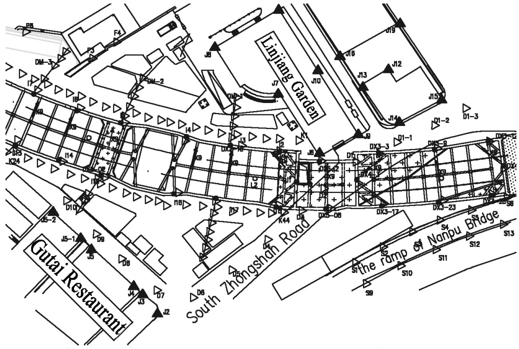
The excavation was 41.2 m deep at the two end sections and 38 m at the middle section (see Figure 4). The pit was 22.3 m wide at the middle section and 23.7 m wide at the two end sections. Due to constraints imposed by the presence of the deep obstructions, a partition wall for dividing the entire excavation, which was 174.1 m long in the eastern pit, and 62.5 m in the western pit, could not be built. Because it was a very long and narrow excavation, the stability of the underground supporting system was very important. A three-dimensional structural supporting frame with high rigidity, formed by upright column piles, reinforced concrete supports and purlins, was used to provide the required stiffness to control the lateral deformations.

4 INTERPRETATION OF MONITORING DATA

Excavation for the eastern pit began on 1 March 2006 whereas that for the western and middle pits on 6 October 2006. The lateral deflections of the diaphragm wall, settlement of the surrounding ground and buildings, and bottom heave at each stage of the excavation were measured at the monitoring points installed before excavation (see Figure 13). Due to the page limit, only selected data are presented.

4.1 *Lateral deformations of diaphragm wall*

Thirty-nine inclinometers were placed in the diaphragm wall to measure its lateral deflections during excavation. A significant increase in the measured deflection of the diaphragm wall was used as a warning signal. Figure 14 shows the measured wall profiles by the inclinometer (I12) at some key stages of excavation in the middle zone of the eastern pit.



Note: ▲ Building settlement monitoring point
△ Ground settlement monitoring point
○ Bottom heave monitoring point
● Inclinometer

Figure 13. Plan showing the instrumentation installed on site.

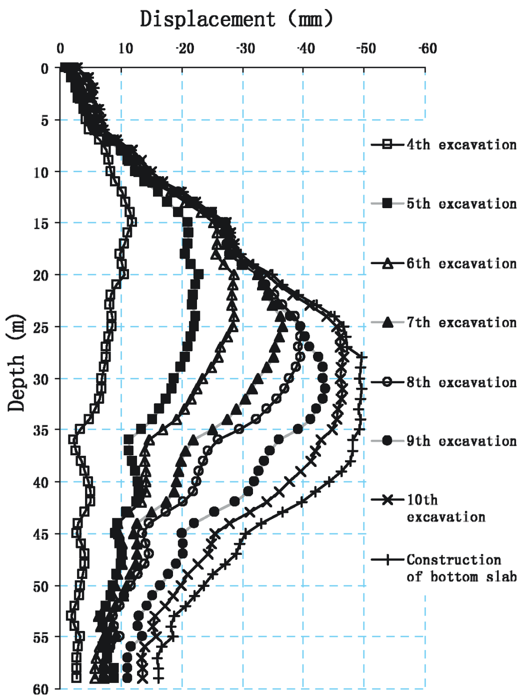


Figure 14. Deflecion profile of the diaphragm wall (at inclinometer I12) at each stage of excavation at the eastern pit.

As shown in Figure 14, the measured deflection profiles of the wall are typical for a multi-propped excavation in Shanghai (Liu et al. 2005; Wang et al. 2005). As the excavation went deeper, the magnitude of inward wall deflection increased as expected. The largest deflection of the wall was 49.6 mm recorded at a depth of 28 m. Figure 15 compares the measured

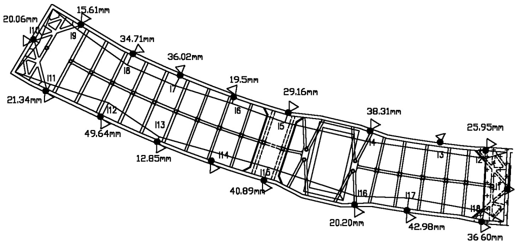


Figure 15. Comparisons of the largest wall deflections measured by all inclinometers.

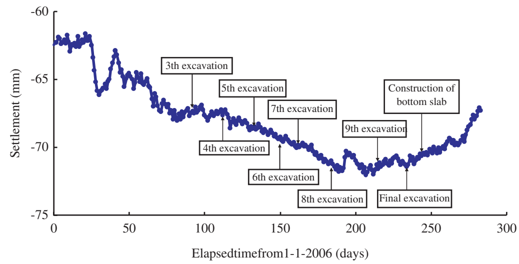


Figure 17. The measured settlement at J5-2 of the Gutai Restaurant versus time.

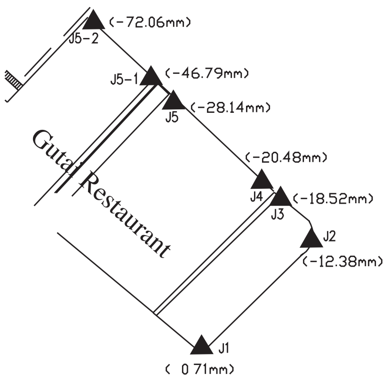


Figure 16. The largest settlement values measured at all the monitoring points installed at Gutai Restaurant.

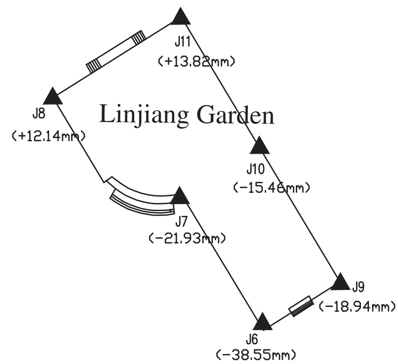


Figure 18. The largest settlement values measured at Linjiang Garden.

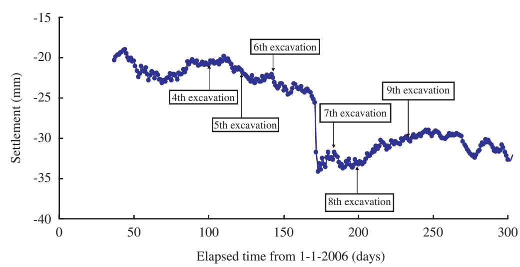


Figure 19. The measured settlement at J6 of the Linjiang Garden versus time.

maximum deflections at all inclinometers. The measured maximum deflections ranged from 20 mm to 50 mm, which are fairly small for a 40 m deep excavation as compared with other shallower excavations in soft clays in Shanghai (Wang et al. 2005). This was because of the large rigidity of the retaining system provided and the early installation of props prior to each stage of excavation.

4.2 *Settlement monitoring*

The adjacent buildings and structures around the excavation such as the Gutai Restaurant, Linjiang Garden and the ramp of the Nanpu Bridge (see Figure 3) required major protective measures and their settlement had to be monitored. Figure 16 shows the largest settlement values measured at the Gutai restaurant. It can be seen that largest recorded settlement of the restaurant was 72.1 mm at the corner J5-2. This was because dewatering was carried out near this corner region. Figure 17 shows the measured settlement at J5-2 versus time. As expected, the measured settlement increased as the excavation progressed. However, upward movement (heave) was recorded after the 9th stage of excavation and the rate of upward movement seemed to accelerate after the construction of the bottom slab. This was probably of the increase in pore water pressure and hence a reduction in effective stress due to the recharging of groundwater after dewatering.

Figure 18 shows the measured maximum settlement values at the Linjiang Garden. As expected, the measured maximum settlement of 38.9 mm was at the corner closet to the excavation (i.e. at J6). Figure 19 shows the measured settlement at J5-2 versus time. Similar to that shown in Figure 17, soil swelling was recorded by J6 after the 8th stage of excavation but the rate was smaller than that recorded by J5-2.

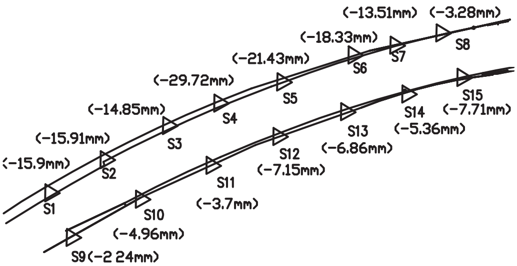


Figure 20. The largest settlement values measured at the ramp.

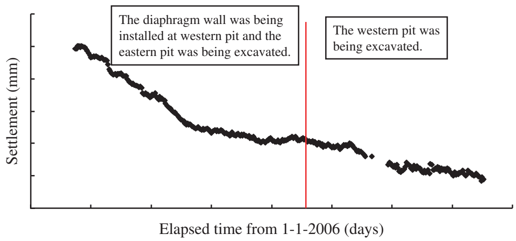


Figure 21. The measured settlement at the middle of the ramp (S4) against time.

Figures 20 and 21 show the measured maximum settlement at all monitoring points at the ramp of the Nanpu Bridge and the settlement history of S4, respectively. The measured maximum settlement ranged from 2.2 mm at S9 to 29.7 mm at S4, which was located at the middle of the ramp. As expected, the measured settlement along the ramp closer to the west excavation pit was much larger than the values recorded away from the pit. However, no soil swelling was recorded at S4. This was probably because the duration of monitoring at this point was not long enough after the completion of the western pit.

5 CONCLUSIONS

This paper provides a case history which illustrates that a complex multi-propped deep excavation in saturated soft soils can be effectively engineered by proper design and construction. The maximum lateral deflection (49.6 mm) of the 1.2 m thick diaphragm wall is relatively small for a 40 m deep excavation in soft clays in Shanghai.

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