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Numerical Simulation Analysis and In-situ Monitoring of Long, Narrow and Deep Foundation Pit

Changhong Li[1], Xiaolong Zhou[2], Long Zhang[3], Xiaoming Wei[4] and Wanling Li[5]
School of Civil and Environmental Engineering, University of Science and Technology Beijing, Beijing 100083,China
[1]*E-mail*: lch@ustb.edu.cn

ABSTRACT: According to the characteristics of long, narrow and deep foundation pit, the displacement distribution of X-axis with different length-width ratios of 1:1, 2:1 and 3:1 were emphatically analyzed, and then the displacement distribution of Y-axis at the slope bottom and the displacement distribution of Z-axis at the foundation bottom were studied. Then, the different displacement distribution law of pile-anchor support and soil nailing wall support were analysed in different excavation processes considering in-situ supporting schemes, and the different supporting effects of the two supporting structures were presented on the stability of foundation pit slope. By comparing the monitoring values at the 32 in-situ positions, the numerical simulation result was basically identical with the monitored data, on average 3mm higher than the measured value. By using MIDAS software, the excavation and supporting process of the foundation pit could be simulated, and it can provide guidance for the construction of long and narrow deep foundation pit and adjust the monitoring period appropriately.

KEYWORDS: Long, narrow and deep foundation pit; Stability analysis; Numerical simulation; In-situ monitoring.

1. INTRODUCTION

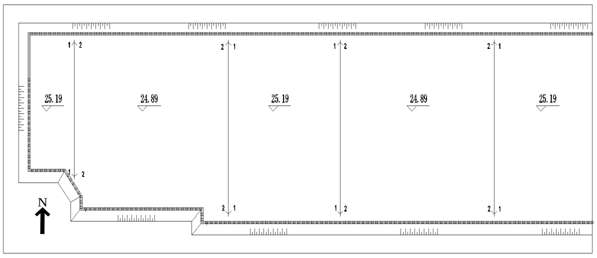
In recent years, with the rapid development of urban construction especially the emergence of high rise and super high rise buildings as well as the development and exploitation of underground space, the scale of foundation pits was developing in a deeper and larger direction(Xia ,Wang and Cao, 2015;Huo and Hou, 2013).In respect of the deep foundation pit slope stability, A.J. Whittle (Whittle, 1993) established the deep foundation pit numerical simulation model and introduced the application of non-linear finite element in simulating the excavation and deformation of foundation pit; C. Yoo and D. Lee (Yoo and Lee, 2008) established the excavation two dimensional finite element model of deep foundation pit (HS), and studied the characteristics of surface soil displacement; Liu Jiguo (Liu,2006) conducted the excavation and support simulation on deep foundation pit with FLAC^{3D} software and calculated the surface subsidence, bottom upheave and horizontal displacement of wall behind soil at different excavation periods; Cao Yanxia (Cao, 2008) adopted FLAC^{3D} software to conduct the numerical simulation on deep foundation pit, and studied the influences of construction conditions, construction progresses and supporting structure parameters on the bearing and deformation of the foundation pit excavation and supporting structure; Xu Ling (Xu, 2016) applied FLAC^{3D} software to conduct the excavation simulation on a deep foundation pit project adopted the braced retaining structure with row piles, and comparatively analysed the real in-situ monitoring data.

The long and narrow deep foundation pit was a special case of deep foundation project. The length-width ratio of the foundation pit was large, which weakened the restriction of the short edge to the long edge. In the middle position of the long edge, the retaining pile supporting effect was weak, which increased the difficulty of the supporting structure in controlling the slope deformation. Hence, the study on long and narrow deep foundation pit had an important and practical significance (Hu, 2009; Jiang and He, 2007).

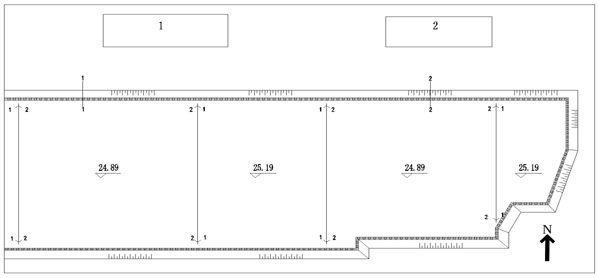
2. PROJECT OVERVIEW AND SUPPORTING SCHEME

2.1 Project overview

Changping Dongxiaokou residential and commercial building deep foundation pit project which located in Dongxiaokou town, Changping district was a typical long and narrow deep foundation pit. The foundation pit was 280m in length and 47m in width. The excavation area was 8300 m^2; buried depth:-11.5m; height of planned building: 40.9-45m; 10-11 floors above the ground with frame-core tube structure; 2 floors underground with raft foundation; the layout of the foundation pit is as shown as Figure 1. There were already two buildings 11m away from the north of the foundation pit; the heights of the two buildings were 35m and 21m respectively; the distance between the two buildings is 25m apart.



（a）Layout of left foundation pit



（b）Layout of right foundation pit

Figure 1 Layout of foundation pit

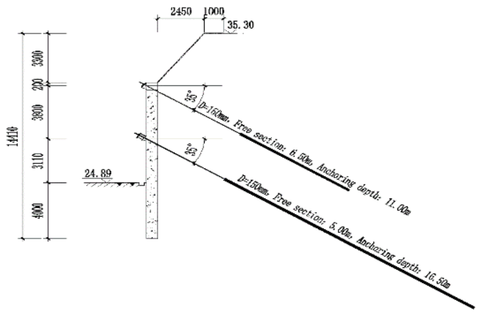
2.2 Supporting scheme for the foundation pit

According to the environmental conditions and the geological and hydrological investigation reports, the project supporting scheme mainly adopted the form of pile-anchor support combining with soil nailing wall as shown in Figure 2.

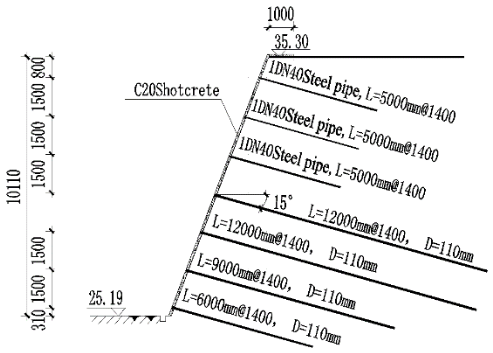
3. THREE DIMENSIONAL NUMERICAL MODEL OF FOUNDATION PIT

3.1 Scope of foundation pit model

Based on the stratigraphic section presented in the investigation report, the analysis model was established by using MIDAS/GTS software. According to the experience from project practices, the width of the affecting scope of foundation pit excavation was 3-4 times of the excavation depth, and the depth is 2-4 times of the excavation depth (Wu and Fu, 2009; Xu, 2007, Dai,2008).



（a）Pile-anchor support diagram



（b）Soil nailing wall diagram

Figure 2 Main foundation pit supporting forms

As the length-width ratio of foundation pit was about 6:1, the model size was designed as 700m×280m×60m. Solid elements were used in the stratum soil part and buildings. The soil constitutive law of the soils was based on the Mohr-Coulomb model. Elastic model of solid elements were used in the surrounding buildings. The particular modeling assistant of anchor bolt and retaining pile unit in MIDAS/GTS could help the pile unit and anchor unit better combined with the soil. After division, the number of cells was 491411, and the number of nodes was 88162. The 3D finite element model of the foundation pit was shown as Figure 3.

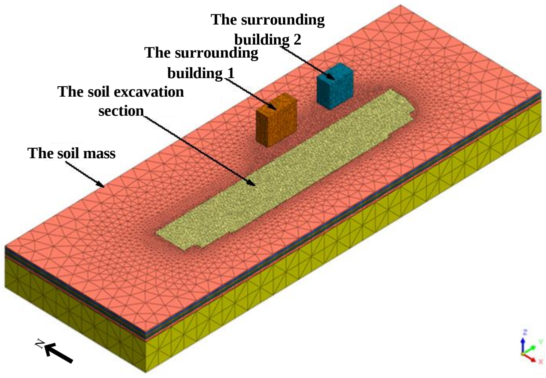


Figure 3 Stratigraphic model diagram

3.2 Mechanical parameters of foundation pit model

During the numerical simulation, the soil was divided into six floors according to the real situation of the stratum. According to the results of drilling, in situ test and laboratory soil test, the soil properties were given in Table 1 and the physical mechanical parameters of other units were shown as Table 2:

3.3 Steps of foundation pit model excavation

Based on the layering of the soil, the simulation of the foundation pit excavation can be divided into eight steps. Step 1: excavated the first layer to 1.5m; step 2: excavated the second layer to 3.3m; step 3: sprayed concrete on the excavation surface, put in soil nails and slope-protection piles; step 4: put in the first anchor bolt and applied prestress; step 5: excavated the third layer to 5.3m; step 6: excavated the forth layer to 7.3m; step 7: put in the second anchor bolt and applied prestress; step 8: excavate the fifth layer into 10.3m.

Table 1 Physical mechanical parameters of soil in different areas

Number	The stratum	E	*v*	*r*	Saturated unit weight	*C*	*Φ*
1	Backfill soil	10000	0.35	18	19	5	25
2	Clay	14000	0.4	18	18	27	10
3	Gravel soil	18000	0.35	20	20	4	32
4	Silty clay	20000	0.3	18	18	19.8	5.1
5	Silty-fine sand	26500	0.3	19.8	19.8	7	30
6	Weatheredrock	39700	0.3	20.8	20.8	20	12

Table 2 Physical mechanical parameters of steel and concrete

Number	Materials	E/(KN/m^2)	*v*	*r*(KN/m^3)	Saturated unit weight
1	Steel	2e9	0.3	78.5	
2	Concrete	2e7	0.2	25	25

4. NUMERICAL SIMULATION ANALYSIS ON FOUNDATION PIT

4.1 Analysis on the X-axis displacement nephogram of the foundation pit

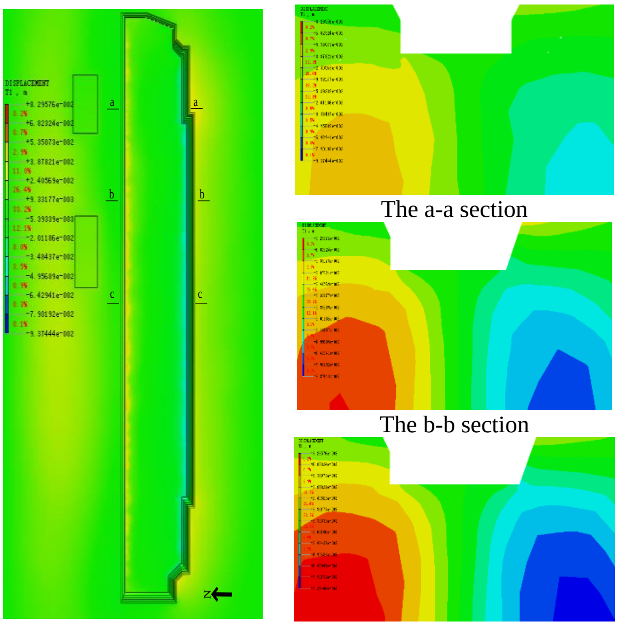
As the foundation pit was a long and narrow foundation pit with approximate length-width of 6:1, considering the influence of foundation pit size effect on the foundation pit deformation, the positions with length-width ratios of 1:1, 2:1 and 3:1 were chosen at the upper foundation pit as the a-a, b-b and c-c sections. Due to the limited space, only the displacement nephogram when excavated at the bottom of the foundation pit was presented, as shown in Figure 4.

As shown in Figure 4, due to the complicated long and narrow foundation pit, different positions had different displacement values. Through the analysis on the influence of excavation depth on the slope top, slope bottom and internal displacement, the displacement changes at the positions with different length-width ratios were studied in particular.

4.1.1 Influences of excavation depth on slope top displacement changes

Based on the displacement nephogram in the X-axis direction, the changing relationship between the slope top displacement values at different section positions at two sides of the foundation pit and the excavation depth of the foundation pit was shown as Figure 5.

With the increase of the excavation depth in the foundation pit, at the same side and same excavation depth, the slope top displacement deformation increased with the increase of the length-width ratio. After the excavation was accomplished, the slope top displacement at the two sides of the foundation pit had a small change at a-a section. Obviously, the squeezing of the soil from the two sides limited the foundation pit displacement; the change was obvious at b-b position especially before the anchor bolt construction, with the maximum values reaching 11mm and 24mm respectively; c-c section, which was located at the middle of the long edge, had the biggest displacement values of 14mm and 31mm respectively. In conclusion, the displacement deformation value within a-a section position was small; from a-a to b-b, the displacement increased gradually; from b-b to c-c, the increase of the displacement was relatively slow and finally stabilizes.



The vertical view of foundation pit

The a-a section

The b-b section

The c-c section

Figure 4 X-axis direction displacement nephogram when excavated at the bottom of foundation pit

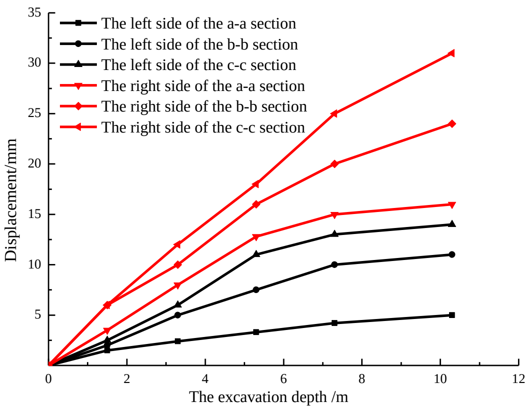


Figure 5 Changing diagram of excavation depth and slope top displacement

The left side of the foundation pit was supported by the pile-anchor . When excavating the first two layers of soil, the foundation pit was in a cantilever state, and the displacement increased with the excavation depth. When excavating the third layer of soil with anchor bolt, the increase of displacement slowed down, which showed that the application of anchor bolt could restrain the slope top soil displacement and made the slope top more stable; the right side of the foundation pit was the soil nailing wall support. At the soil nailing wall side, the soil at the slope top position increased with the excavation depth, almost in a linear growing relationship. The maximum displacement was 31mm at the slope top, which was close to the alert value of 35mm and required special attention during the construction(Shi and Liu,2003;Tian,1998;Guo,2012).

4.1.2 Influences of excavation depth on slope bottom displacement changes

In the first three steps of excavation, the changes at the left side and right side of the slope bottom in the foundation pit were small. The size effect was not obvious. When excavating to the depth of 7.3m and 10.3m, the change at the slope bottom was obvious. The displacements at different slope bottom section positions were shown as Figure 6.

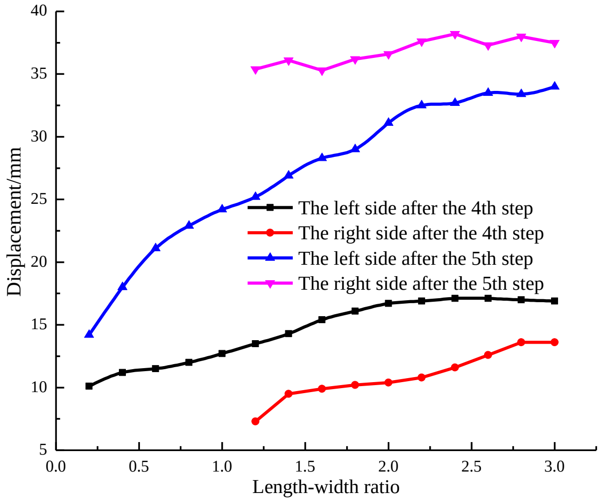


Figure 6 Changing diagram of different section positions displacement at slope bottom

After the excavation, the maximum slope bottom displacements at two sides were 14mm and 18mm at a-a section, 24mm and 27mm at b-b section, and 33mm and 40mm at c-c section, respectively. Apparently, the slope bottom at the middle of the long edge in the foundation pit had the maxim deformation, which exceeded the alert value of 35mm and required special observation during the construction.

After the 4th step, the displacement of left pile-anchor support was larger than the right soil nailing wall supporting surface, almost 5mm larger on average. The reason was that, before applying anchor bolt, the left sail had no support and restriction from the anchor bolt, while the right soil nailing wall produced supporting effect immediately after construction; after the 5th step, the displacement of the right soil nailing wall supporting surface was larger than the left pile-anchor supporting surface. The maximum difference reached 10mm. It showed that, with the increase of excavation depth, the soil thickness behind the soil nailing wall increased continuously, and the supporting effect of the soil nailing wall which played a passive supporting role was obviously weakened. According to the comparative analysis on the displacement differences between pile-anchor support side and soil nailing wall support side, the pile-anchor support was more stable than the soil nailing wall support.

4.1.3 Influence of excavation depth on internal displacement changes

Based on the displacement nephogram in the X-axis direction, the changing relationship between the internal displacement at different section positions at the two sides of the foundation pit and the excavation depth of the foundation pit was shown as Figure 7.

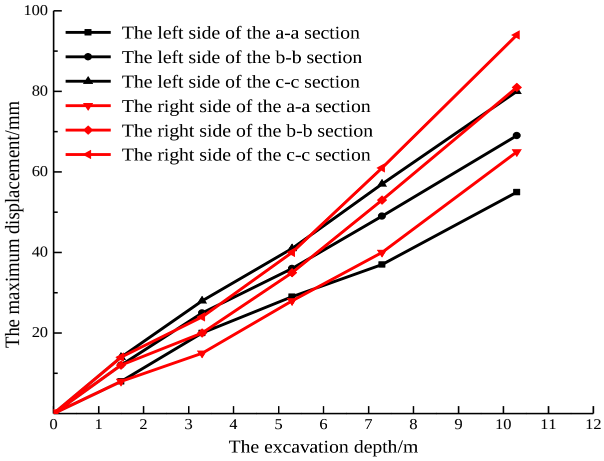


Figure 7 Analysis diagram of the influences of excavation depth on the internal displacement in the foundation pit

After the excavation, the maximum slope bottom displacements at two sides were 55mm and 65mm at a-a section, 69mm and 81mm at b-b section, and 80mm and 94mm at c-c section, respectively.

The left side of the foundation pit was the pile-anchor support form. After the excavation, the internal deformation at the pile-anchor support side was less than the other side. After the second anchor bolt construction, the pile-anchor supporting effect was obvious. The tendency of displacement increase slowed down and the soil deformation was restricted by the prestressed anchor bolt; the right side of the foundation pit was the soil nailing wall support form. With the increase of the excavation depth, the internal deformation at the soil nailing wall support side became larger. If the depth kept on increasing, the soil nailing wall would not be able to satisfy the stability requirements of the foundation pit.

4.2 Analysis on the Y-axis displacement nephogram

As the foundation pit Y-axis direction was too long, the analysis only considered the positions near the slope, and grabbed the screenshots of the two side slope positions. The displacement changes at the two sides of the foundation pit in the Y-axis direction were studied in particular when the excavations reached 1.5m, 3.3m, 5.3m, 7.3m and 10.3m. But due to the limited space, only the displacement nephogram when excavated to the bottom was presented. The Y-axis foundation pit slope displacement diagram when the excavation reached the bottom is shown as Figure 8.

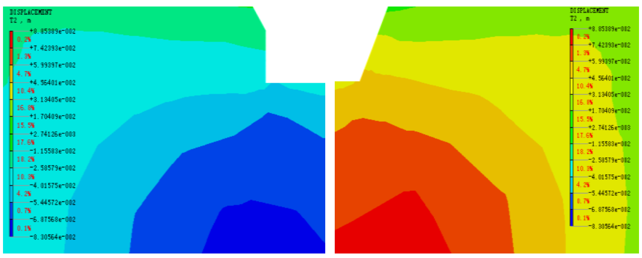


Figure 8 Y-axis foundation pit slope displacement diagram when the excavation reaches the bottom

In the foundation pit excavation Step 1 and Step 2, the slopes at the two sides of the foundation pit were soil nailing support, the slopes were the same and the deformation at the two sides of the foundation pit was also similar. For Step 3 and steps after that, the left side of Y-axis was pile-anchor support, and the right side was soil nailing wall support. Due to the differences on the supporting effects, the deforion of the two sides was also different (as shown in Figure 9). According to Figure 11:

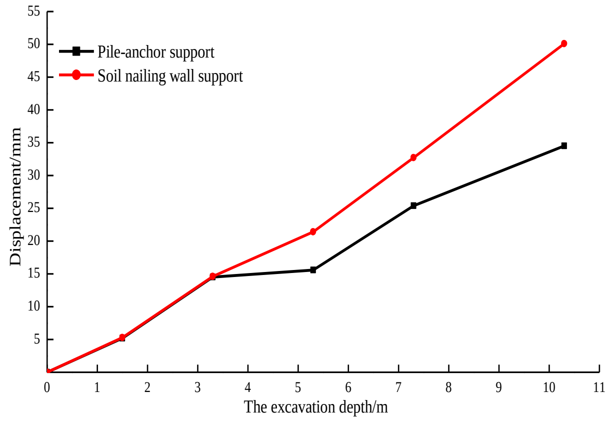


Figure 9 Changing diagram of the slope bottom displacement with the excavation depth of the foundation pit in the Y-axis direction

According to Figure 9:

(1) Both of the first two steps of excavation at two sides were soil nailing wall support. So the deformation at the slope bottom of the foundation pit was basically the same.

(2) After the 3rd step, the deformation speed of the pile-anchor support side at the slope bottom decreased and the deformation speed of the soil nailing wall support kept the same. The deformation at the soil nailing wall support side was larger than the deformation at the pile-anchor support side, and the pile-anchor support was more stable than the soil nailing wall support.

(3) The slope bottom displacement in the Y-axis direction of the foundation pit was larger than that in the X-axis direction. The Y-axis direction side slope was short slope, where stress was more concentrated and the squeezing from the two sides was obvious. So the deformation was larger than that of long slope. The maximum deformation at the soil nailing wall was 48mm, which was higher than the alert value of 35mm and needed to be reinforced during the construction.

4.3 Analysis on the Z-axis displacement nephogram

The deformation in the Z-axis direction of the foundation pit was less influenced by the size effect of the foundation pit. The displacement changes at the foundation pit bottom in the Z-axis direction were studied in particular when the excavations reached 1.5m, 3.3m, 5.3m, 7.3m and 10.3m. The Z-axis deformation diagram when excavated to the bottom was shown as Figure 10.

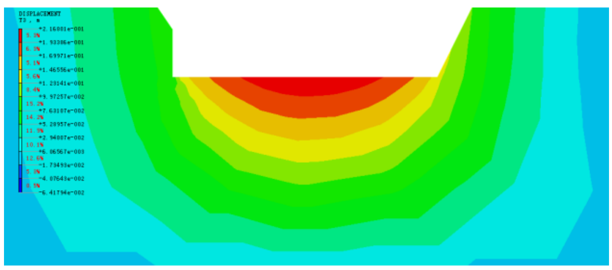


Figure 10 Z-axis direction deformation nephogram when excavated to the bottom of the foundation pit

(1) The basement upheaval increased with the excavation depth, and had a minimum deformation at the slope bottom. The supporting structure and slope position had certain restriction on the soil upheaval. The deformation at the middle position of the foundation pit tended to be stable and reached the maximum value of 212.7mm.

(2) The increase rate of the basement upheaval was fastest within 10m to the slope bottom, and the increase rate slowed down when the distance was more than 10m. simulation well represented the lateral displacement of the slope top of the foundation pit.

(3) All the measured pile top subsidence values were smaller than the simulated deformation value. The differences were about 3mm on average. The numerical simulation results well represented the subsidence and deformation of the pile top.

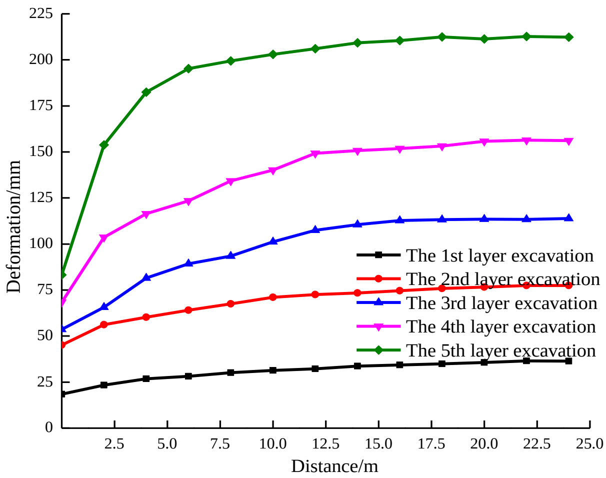


Figure 11 Relationship between the basement upheaval deformation and its distance to the slope bottom

5. COMPARISON BETWEEN IN-SITU MONITORING AND SIMULATED RESULTS

5.1 Layout of monitoring points

There were totally 32 monitoring points: 7 points in the surrounding buildings near the foundation pit, 18 points around the slope top of the foundation pit, and 7 points at the upper supporting piles. The layout of the monitoring points was shown as Figure 12.

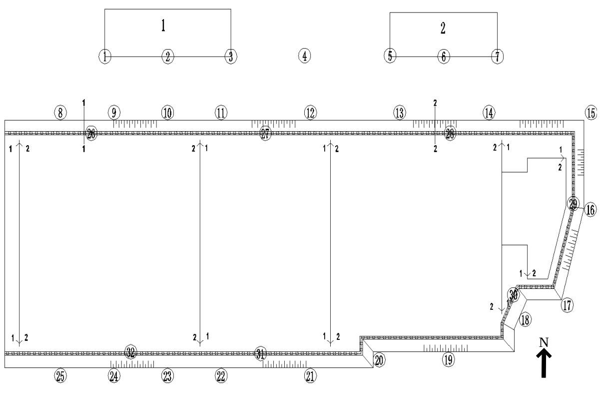


Figure 12 Layout of the monitoring points

5.2 Monitoring values

Based on the continuous monitoring of the displacements at each monitoring points, the values of each points were summarized and shown as Figure 13, 14 and 15.

5.3 Comparative analysis on the measured values at monitoring spots and the simulated values

The comparison diagram between the measured values and the simulated values was shown in Figure 16.

According to Figure 16:

(1) All the measured subsidence values of the surrounding buildings were smaller than the simulated deformation values. The minimum difference was 1mm. The maximum difference was 6mm. The numerical simulated results well represented the subsidence and deformation of the foundation pit.

(2) The monitoring values at 8#, 11#, 14#, 18# and 23# measuring points were 1.7mm, 0.6mm, 1.6mm, 4.8mm and 0.7mm higher than the simulated values respectively, all of which were smaller than the alert value of 35mm. This showed that the stability of the foundation pit was good during the process of excavation and backfill. No collapse of slope would occur. The numerical

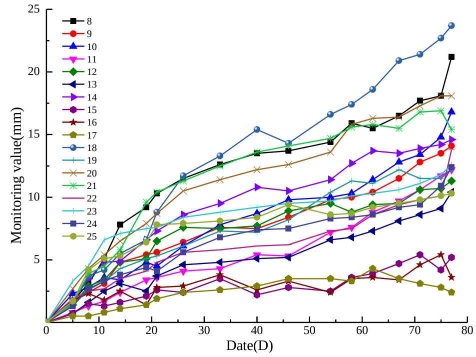


Figure 13 The measured lateral displacement values of the slope top

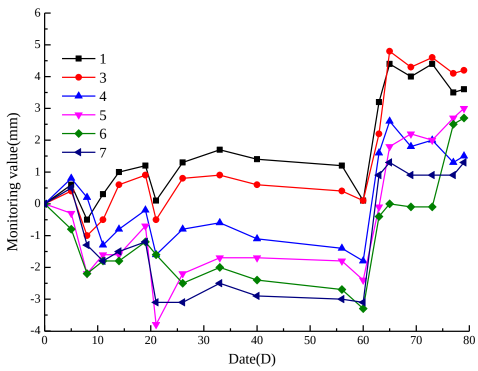


Figure 14 The measured subsidence values of the surrounding buildings

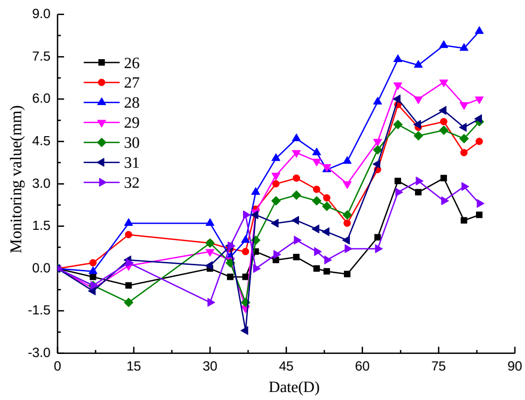


Figure 15 The measured subsidence values of the pile top

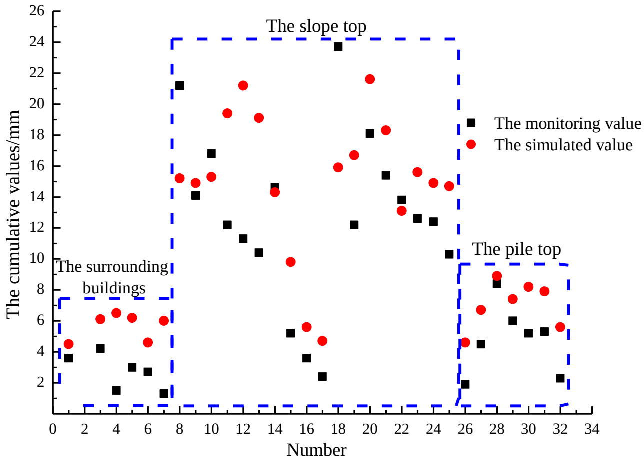


Figure 16 The comparison diagram between the monitoring values and the simulated values

6. CONCLUSION

This paper adopted MIDAS software to conduct its numerical simulation on the long and narrow foundation pit. Based on the excavation order and support schemes of the in-situ construction, The displacement deformation in the X-axis, Y-axis and Z-axis directions were analysed. For X-axis, the displacement deformation value was small at the positions with the length-width ratios less than 1:1, and increased with ratios from 1:1 to 2:1. When the ratios reach from 2:1 to 3:1, the increase of the displacement deformation slowed down and tended to be stable; for Y-axis, the maximum displacement of the slope bottom was 48mm. The slope stress was concentrated with obvious squeezing force from the two sides; for Z-axis, the basement upheaval within 10m away from the slope bottom had the fastest increase rate. The increase rate of the basement upheaval and deformation slowed down gradually after 10m.

The main supporting forms of foundation pit were pile-anchor support and soil nailing wall support. Before excavating the first two layers of soil with application of anchor bolt support, the displacement of pile-anchor support surface was, on average, 5mm larger than that of the soil nailing wall support, which showed the quick effect of soil nailing wall support. However, after the anchor bolt construction and started the excavation of the third layer of soil, the displacement of soil nailing wall support surface was, on average, 10mm larger than that of the pile-anchor support, which showed the positive support advantage of pile-anchor. As a result, the support design required a comprehensive consideration and took the best combination of supporting methods.

Totally 32 monitoring points were set in the foundation pit for monitoring: 7 points in the surrounding buildings near the foundation pit, 18 points around the slope top of the foundation pit, and 7 points at the upper supporting piles. According to the comparison of measured values and simulated values, the simulated values were basically larger than the measured value, and the data were approximately identical. This showed that MIDAS software could accurately reflect the changing of the long and narrow foundation pit displacement with the excavation depth. Hence, the adoption of MIDAS for numerical simulation analysis and in-situ point monitoring could provide an effective method for the long and narrow deep foundation pit project.

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