Impact Analysis of Support Structure of Unsymmetrical Loading Deep Foundation Pit Adjoining Highway

Donglin Wang* and Lei Wang

School of Civil Engineering, Anhui Jianzhu University, Hefei, Anhui, 230601, China

Abstract: The air shaft deep foundation pit 6 is influenced by subgrade unbalance loading of highway 312, specifically its deep horizontal displacement of supporting piles and subgrade settlement of expressway 312 under unsymmetrical load effect. This paper carries out construction monitoring and numerical simulation analysis and gives a detailed study on the influenced factors of support structure deformation. Calculation results show that subgrade unsymmetrical load has a great influence on deep horizontal deformation of supporting piles. The maximum horizontal displacement at the bias side is about three times more than non-bias side's; when the distance of subgrade to foundation pit is the same as the depth of excavation, the influence of subgrade on pit can be ignored; as the cohesion and internal friction angle increases, the horizontal displacement of fender piles decreases. However, enlarging the embedded depth of supporting piles has no significant influence on the stability of foundation pit.

Keywords: Unsymmetrical loaded foundation pit, *in-situ* monitoring, numerical simulation, horizontal displacement.

1. INTRODUCTION

In the process of the excavation of deep foundation pit, soil stress changes, thus ground surface settlement, building settlement and the surrounding pipeline deformation comes into being [1-3]. Deep foundation pits of subway station are generally located at the crowded urban central areas, the construction is faced with various challenges as the surrounding geology and environmental conditions are complex, as well as the adjacent buildings. Recently, with the increase of excavation depth, the poor design or construction management result in frequent foundation pit accidents, which gives rise to huge economic losses [4, 5].

The studies on deep excavation under extreme bias conditions are very rare at home and abroad. Lin Gang *et al*. had research on the supporting structure characteristics of deep excavation under the action of unbalanced surcharges by using PLAXIS software [6]; Yao Aijun and Zhang Xindong analyzed the deformation of deep excavation retaining structure under asymmetric load [7]; Tang Wenpeng made some comments and suggestions on the design of asymmetric bias pit [8]; Shi Yufeng *et al*. studied the deformation and internal forces of bias subway deep excavation retaining structure under dynamic load of trains [9]; Zhang Guoliang studied the stability and deformation characteristics of subway deep excavation projects close to the railway station [10].

The air shaft deep foundation pit 6 is taken as a project case, the air shaft 6 is influenced by the extreme bias pressure of subgrade of national highway 312, and the effect of this bias load for excavation can not be ignored. This paper carries out constructive monitoring on the support structure deformation during its excavation and subgrade deformation close to national highway 312, simulating analyzes the supporting pile deformation by using finite element analysis. According to software Midas with the actual excavation conditions, and makes detailed analysis on the influenced factors of support structure deformation.

2. PROJECT PROFILE

The air shaft deep foundation pit 6 is supported by bored piles and inner support is protected with shotcrete between piles. Excavation depth is 26.22m. Pile length 45m, using 1200@1500 bored piles. 8 braces are set for vertical pit. The first is concrete and the rest are steel, in which the concrete support adopts C30 concrete, 800mm × 1000mm in size. Steel support adopts Q235 steel tubes, diameter is 609mm, thickness is 16mm. Installation location of those supports are as follows: the first concrete support is at -0.5m, the first steel support is at -3.8m, the second steel support is at -7m, the third steel support at -10m, the fourth steel support at -13m, the fifth steel support at -16.5m, the sixth steel support at -19.5m, the second steel support at -22.9m, supporting prestress is exerted to all these steel supports, they are shown in Table **1**.

3. MONITORING RESULT ANALYSIS

3.1. Assignment of Monitoring Points

Site conditions and monitoring standards are taken into consideration comprehensively, and the assignment of foundation pit monitoring points is shown in Fig. (**1**).

*Address correspondence to this author at the School of Civil Engineering, Anhui Jianzhu University, 292 Ziyun Road, Hefei City, Anhui Province, China; Tel: 13695698055; E-mail: wdlvip@126.com

1874-1495/15

Table 1. Supporting axial force.

Steel Timbering	Designed Support Axial Force (KN/m)	Pre-applied Axial Force (KN/m)	Support Interval (m)	Pre-applied Axial Force Calculation (KN)
The first steel support	397	240	3	720
The second steel support	386	230	3	690
The third steel support	618	370	3	1110
The fourth steel support	713	430	3	1290
The fifth steel support	1142	685	2	1370
The sixth steel support	1404	845	2	1690
The seventh steel support	1028	620	2	1240

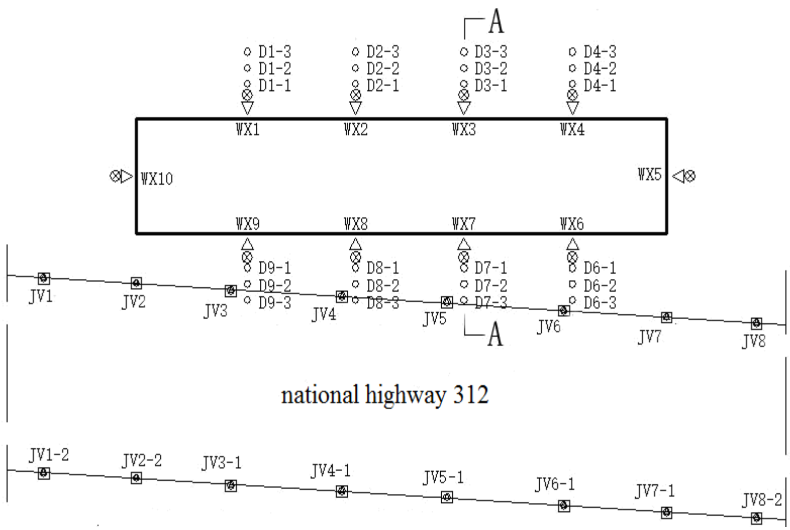


Fig. (1). Plan layout of monitoring points.

3.2. Monitoring Results of Deep Horizontal Displacement of Supporting Piles

Monitoring results of deep horizontal displacement of supporting piles is an important guarantee to reflect the stability of foundation pits and is one of the main monitoring projects in the process of excavation. Air shaft foundation pit 6 covers 10 supporting pile deep horizontal displacement measuring points.

Fig. (**2**) shows the monitoring results of deep horizontal displacement of supporting piles when excavating to the bottom. It can be seen from the figure, when excavating to the bottom, the monitoring points (wx1, wx2, wx3, wx4) at the north side of foundation pit are basically within the deformation limit (30mm), supporting piles at the side are stable; the deformation of measuring points (wx6, wx7, wx8, wx9) at the south side of foundation pit surpass the warning value, the maximum deformation surpasses 60mm. Bias pressure undertaken by the south side of excavation results that the supporting piles on the north side of foundation pit has a moving tendency towards the outside of pit. The subgrade bias pressure has significant influence on supporting piles of foundation pit.

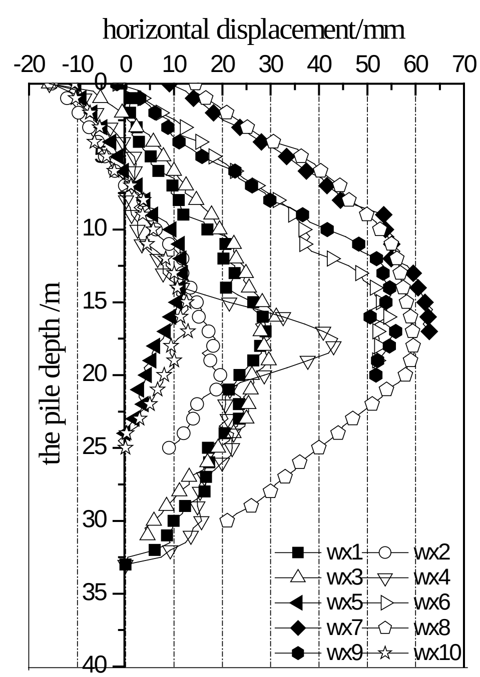


Fig. (2). The value of horizontal displacement of supporting piles.

3.3. Monitoring of Subgrade Settlement of National Highway 312

National highway 312 is close to air shaft 6, with the excavation of foundation pit, the subgrade settlement grows. Too large subgrade settlement not only leads to instability of the pit, but also has impact on the road performance and security, so it is essential to monitor the subgrade settlement of national highway 312.

Subgrade settlement sites on highway 312 are dotted on both sides of the road shoulder, 16 in total. Figs. (**3** and **4**) are duration curves of the north side of subgrade (next to foundation pit) and south side of subgrde (far away from foundation pit) settlements of highway 312 respectively. We can see from the figures, subgrde deformation trends on both sides of state highway 312 reach consensus, increases with the increasing depth of excavation, and settled amount of subgrade close to foundation pit is greater than the amount that is far away from foundation pit. The maximum settlement amounts of every measuring point when excavating to the bottom of the pit are converted into the Fig. (**5**), it shows whether on the north side or south side of subgrades, the sites of the maximum settlements locate near the long edge midpoint of foundation pit, and the final settlement deformation exceeds the limit (30mm). Although the settled amount surpasses specification limits. The pavement structure is not damaged when observing the road.

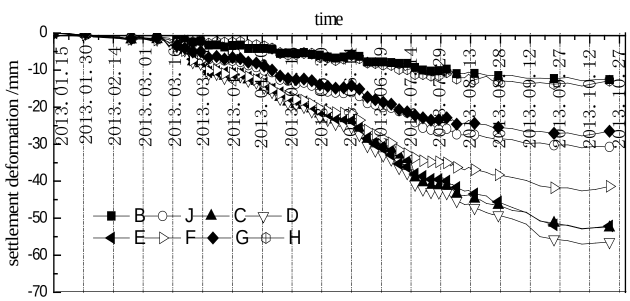


Fig. (3). Duration curve of the north side of subgrade (next to foundation pit) settlement.

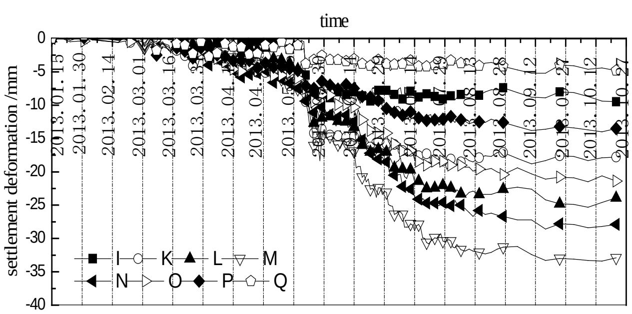


Fig. (4). Duration curve of the south side of subgrade (far away from foundation pit) settlement.

4. NUMERICAL SIMULATION

4.1. Finite Element Model

According to the actual situation of the project, the two-dimensional numerical simulation analysis are conducted by using Midas. Considering the impact area of the excavation, the model dimensions are: 200m in length and 100m in width. Soil parameters of the model are based on Table **2**. The soil is simulated by using a two-dimensional plane strain element, supporting piles are simulated using beam elements, concrete support and steel support are simulated by truss elements. Displacement constraints are applied to the left and right sides of the model in the horizontal direction, and to the bottom of the model in the vertical direction. Considering the non-bias side is influenced by the construction load, thus 20kpa ground overload is taken into account within the depth of foundation pit around the pit, 30kpa static vehicle load is considered in national highway 312.

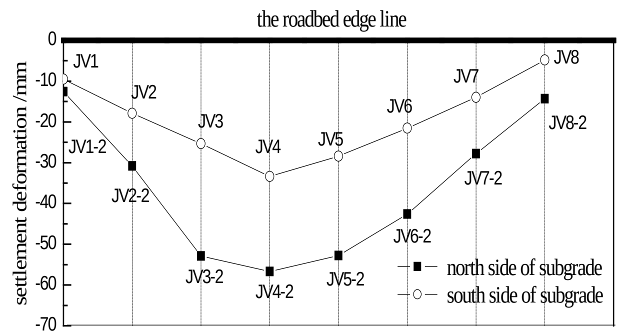


Fig. (5). The curve of subgrade maximum subsidence.

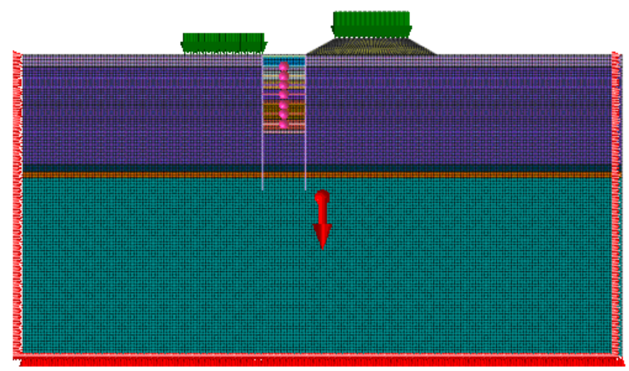


Fig. (6). Finite element model.

4.2. Construction Process and Load Step Setting

According to the project's engineering geological investigation reports, hydrological data and geotechnical experiment results, the mechanical parameters adopted in calculation process are in Table **2**.

4.3. Computation Process Simulation

Calculation process is as follows: first, the gravitational field is applied to calculate the initial stress of soil, and reset its initial displacement; then the construction of bored piles; then simulating soil excavation process, every time when completing the excavation, the reactions of soil and supporting structures are calculated. The first step excavate to 5.2m, and add the first steel support at 3.8m below the top of the pile; the second step excavate to 8.4m, and add the second steel support at 7m below the top of the pile at the top of the pile; the third step excavate to 11.4m, and add the third steel support at 10m below the top of the pile at the top of the pile; the fourth step excavate to 14.9m, and add the fourth steel support at 13m below the top of the pile at the top of the pile; the fifth step excavate to 16.92m, and add the

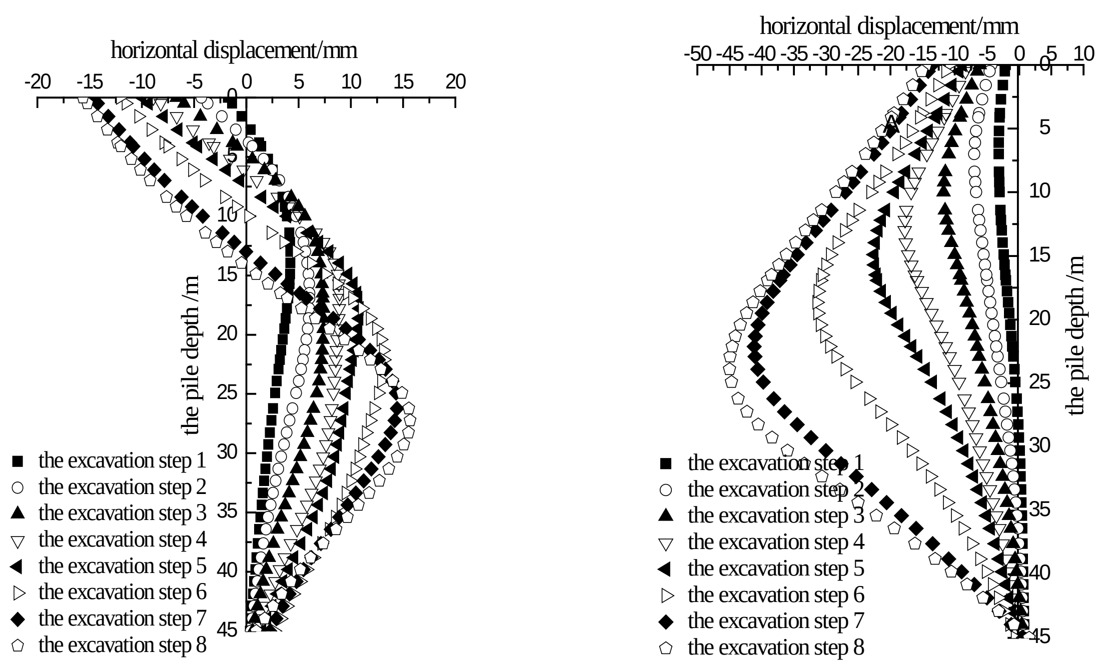
Table 2. Physical and mechanics parameters.

Layer	Name	Layer Thickness (m)	Natural Density	Compression Modulus E_s	Internal Friction Angle (^{o})	Cohesion c
1	Artificial filled soil	5.4	1.9	18.5	12	25
2	Expansive soil(clay)	4.11	1.98	10	13	40
3	Expansive soil(clay)	32.3	2.0	12	15.9	45
4	Expansive soil(clay)	2.4	2.07	12	16.5	42
5	weathered siltstone	2.0	1.97	18	16	20
6	Intense weathered siltstone	59.2	2.0	30	20	30

fifth steel support at 16.5m below the top of the pile at the top of the pile; the sixth step excavate to 21.32m, and add the sixth steel support at 19.5m below the top of the pile at the top of the pile; seventh step excavate to 24.92m, and add the seventh steel support at 22.9m below the top of the pile at the top of the pile; the eighth step, excavate to 26.22m. Numerical calculation model is shown in Fig. (**6**).

4.4. Contrastive Analysis of Numerical Simulation Results and Monitoring Data

Fig. (**7**) is the numerical simulation diagram of horizontal displacement of deep foundation pit piles, we can see from the figure, the deformation rule of envelope pile on bias side is similar to the deformation rule of the general foundation pit; but because of the subgrade on bias side, the top of



(**a**) The non-biased side. (**b**) The biased side.

Fig. (7). The curve of horizontal displacement of supporting piles.

Table 3. Result comparison of supporting piles maximum horizontal displacement

Maximum Horizontal Displacement		Step 1	Step 2	Step 3	Step 4	Step 5	Step 6	Step 7	Step 8
The biased side(WX7)	Simulation value	3.16	6.95	11.71	17.76	22.52	31.42	41.15	44.98
	monitoring value	4.92	10.22	24.32	26.89	40.90	52.15	57.25	63.45
The non-biased side (WX3)	Simulation value	4.22	6.05	7.39	8.92	10.82	13.15	14.33	15.69
	monitoring value	4.08	4.72	9.57	11.95	19.05	23.06	28.20	31.16

fender piles on the non-bias side "drift" outside the pit, which is different from the structure of general foundation pit.

Through comparative analysis of Table **3**, we can see that the deformation rule of simulation results and the actual monitoring results are consistent. When excavating to the bottom of the pit, the simulation results show that the maximum horizontal displacement of the bias side is 44.98mm, and the non-bias side is 15.69mm. For the reason that vehicle dynamic loading of Hening highway roadbed, over-excavation and timbering untimely is not taken into account, the simulation results are smaller than monitoring structure, the numerical simulation results can reflect the actual deformation to a certain extent. The final deformation of envelope on the bias side is three times more than the non-bias deformation, and the bias side suppresses the limits while the non-bias side is not.

5. FACTOR ANALYSIS OF SUPPORTING PILE DEFORMATION

On the basis of the air shaft foundation pit 6 project, the following analyses are taken on the influence factors of the deformation of bias deep excavation supporting pile:

(1) The impact of subgrade bias pressure on envelope pile deformation;

(2) The impact of the distance of subgrade on pile deformation;

(3) The impact of soil parameters on pile deformation;

(4) The impact of envelope pile embedded depth on its deformation.

5.1. Contrastive Analysis of Numerical Simulation Results and Monitoring Data

This paper only lists the maximum horizontal displacement of fender piles when excavating to the bottom of the pit, which are shown in Fig. (**8**).

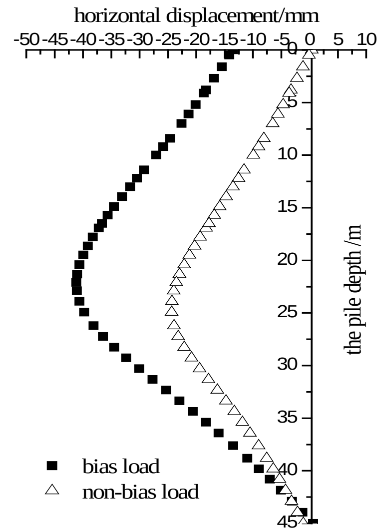
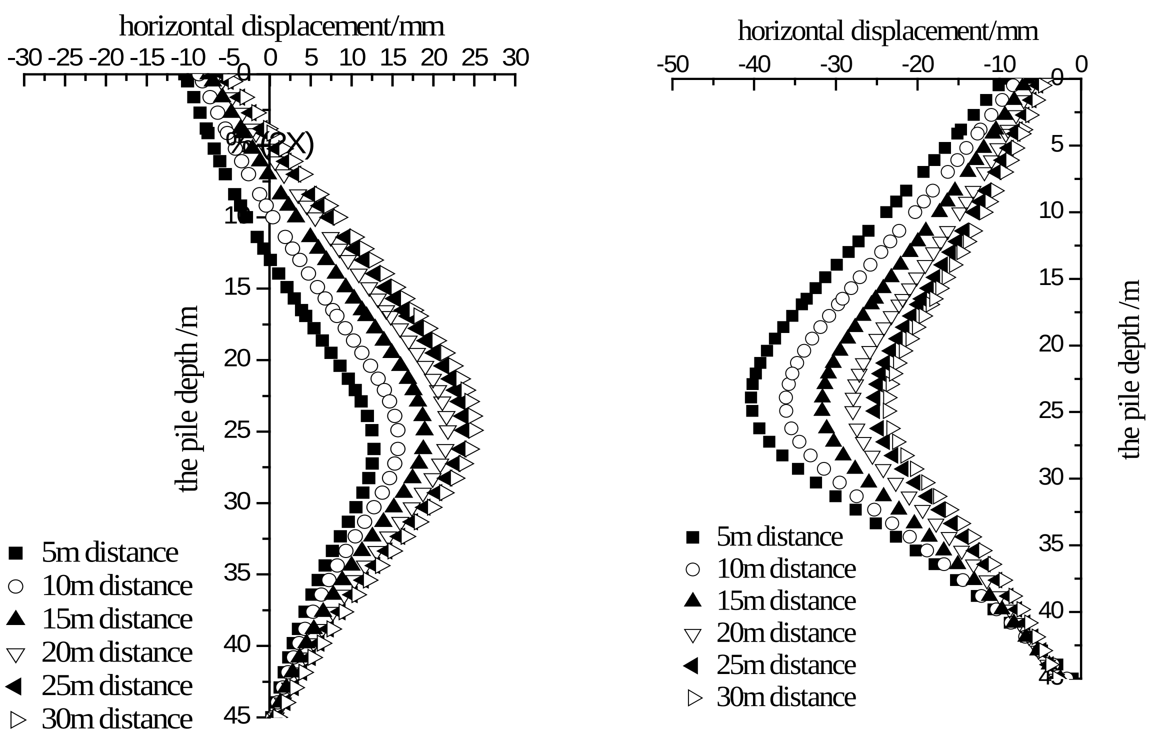


Fig. (8). Influence curve of bias load on supporting pile deformation.

Changes of supporting pile horizontal displacement values caused by bias pressure are in Table **4** below. Comparative analysis on supporting structure of foundation pit under bias and non-bias pressure conditions illustrate, the impact of subgrade bias pressure on the stability of foundation pit can not be ignored. Due to subgrade bias load,



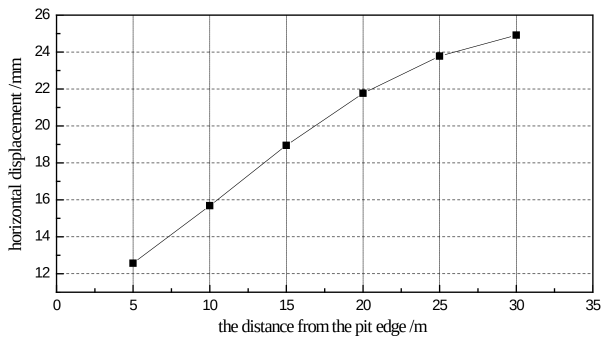
(**a**) The non-biased side. (**b**) The biased side.

Fig. (9). Influence curve of distance of subgrade on supporting pile deformation.

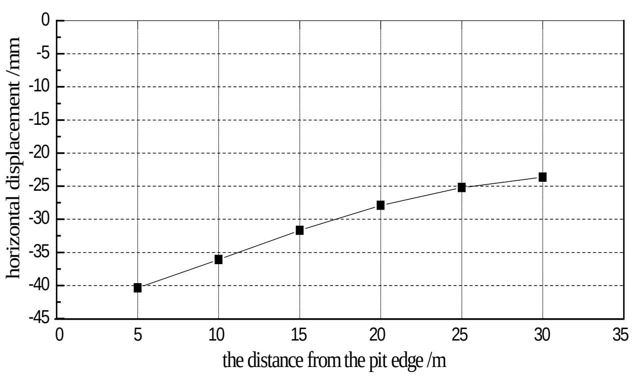
Table 4. Result comparison of supporting pile horizontal displacement.

Unbalance Loading Condition	Maximum Displacement of The Piles(Mm)	Position of Maximum Displacement(M)
Biased	44.98	21
Non-biased	24.35	24

the deformation of bias side may surpass the limit value, while the non-bias side does not. Roadbed bias can cause the supporting pile instability on bias side, resulting in the destruction of the whole pit, so it is essential to take measures to strengthen the pit.



(**a**) The non-biased side.



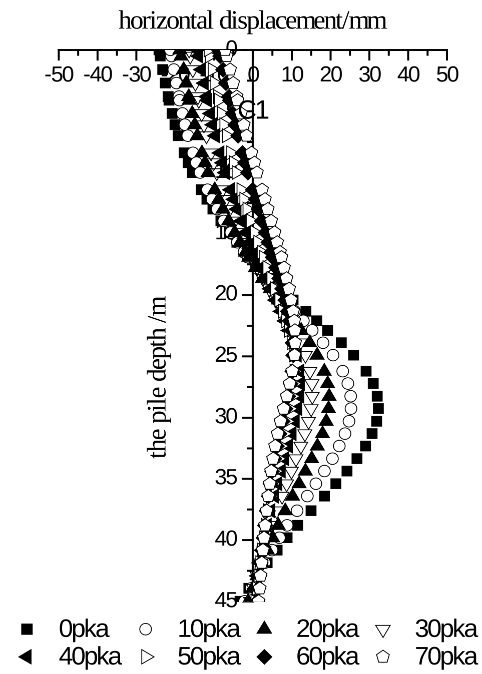
(**b**) The biased side.

Fig. (10). The influence of distance from foundation pit on the maximum horizontal displacement of piles.

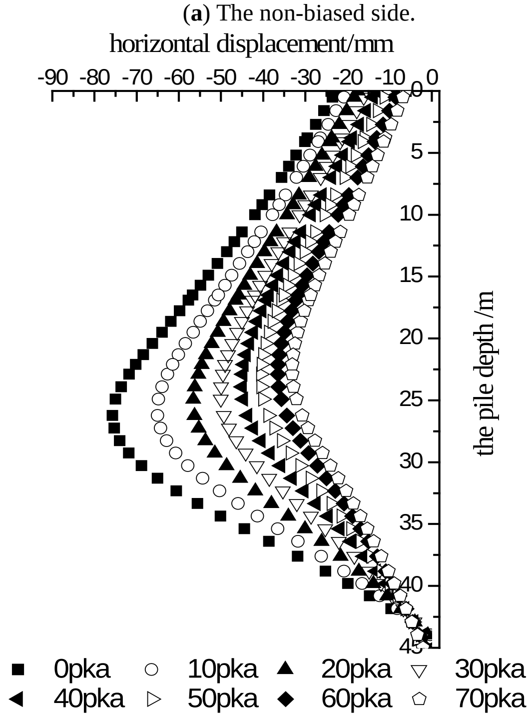
5.2. Contrastive Analysis of Numerical Simulation Results and Monitoring Data

6 distances of subgrade to excavation margin are adopted to research the impact of the distance of subgrade on foundation pit, they are 5m, 10m, 15m, 20m, 25m, and 30m respectively. Supporting pile deformation is shown in Fig. (**9**).

We can see from Figs. (**9** and **10**), as the space between bias side subgrade and foundation pit increases constantly, the maximum horizontal displacement of the non-bias side of the envelope pile also increases, while the bias side decreases. The main reason is that, as the distance of subgrade on the bias side gets farther, the effect of subgrade on foundation pit reduces continuously. When the distances are 25m and 30m, their maximum horizontal displacements of the retaining structures are basically the same, indicating that when the distance is about 25m, the effect of roadbed on envelope can be basically ignored.



(**a**) The non-biased side.

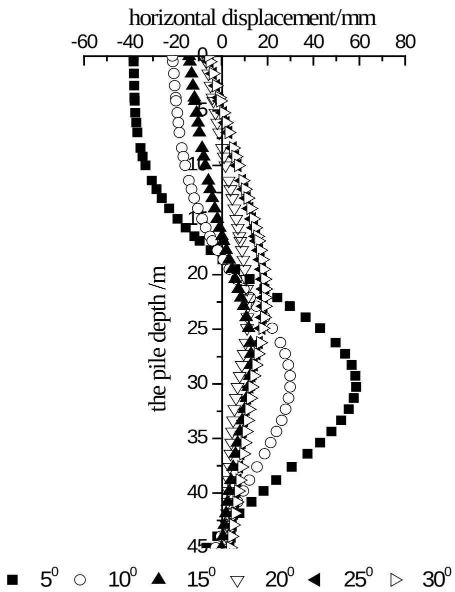


(**b**) The biased side.

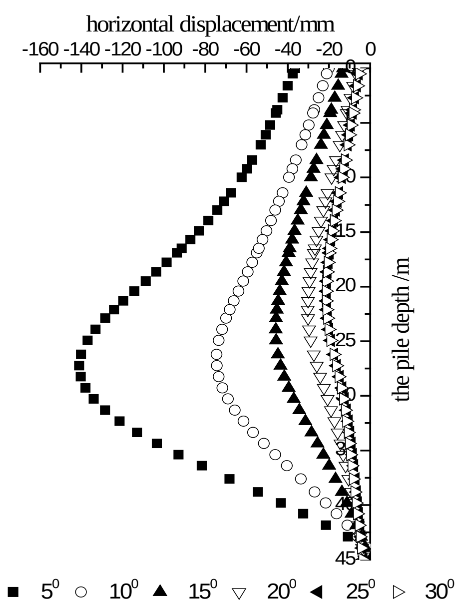
Fig. (11). Influence curve of cohesion on supporting pile deformation.

5.3. Influence of Soil Parameters on Supporting Pile Deformation

The excavation part is located in the third layer of soil, so only the properties of third layer soil is changed, its cohesion are 0kpa, 10kpa, 20kpa, 30kpa, 40kpa, 50kpa, 60kpa and 70kpa, internal friction angles are 50, 100, 150, 200, 250, 300 , calculate respectively, the final maximum horizontal displacements of envelope piles are in Figs. (**11** and **12**).



(**a**) the non-biased side.

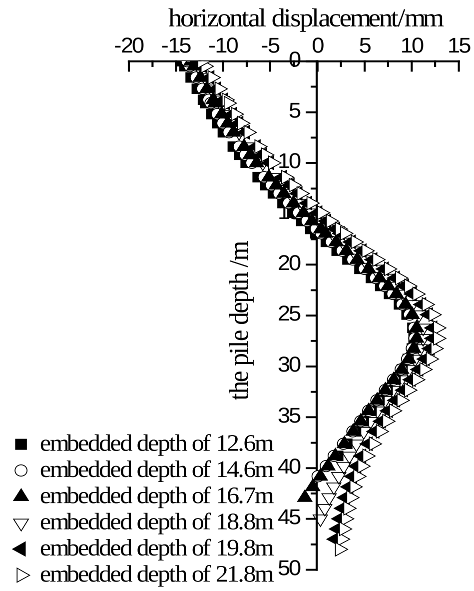


(**b**) The biased side.

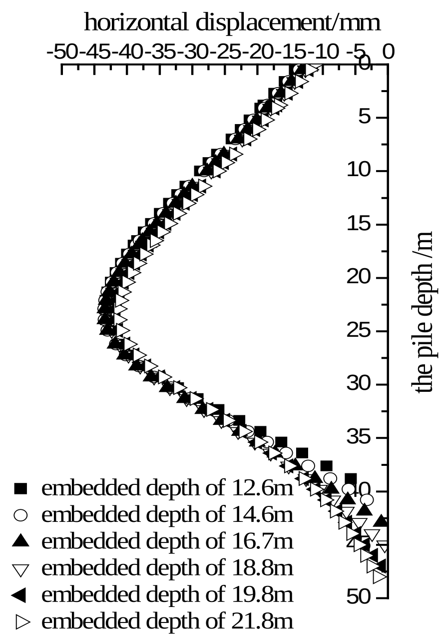
Fig. (12). Influence curve of internal friction angle on fender pile deformation.

5.4. Influence of Supporting Pile Embedded Depth on its Deformation

In order to make contrast easier, on the basis of the original model, this one is modified, and considering mesh generation and other reasons, six embedded depths of the envelope pile are chosen to study its impact on fender pile deformation, they are 12.6m, 14.6m, 16.7m, 18.8m (original embedded depth), 19.8m and 21.8m. The final envelope pile deformation is shown in Fig. (**13**).



(**a**) the non-biased side.



(**b**) The biased side.

Fig. (13). Influence curve of fender pile embedded depth on its deformation.

We can see from Fig. (**13**), as the embedded depth of envelope piles increases continually, the maximum horizontal displacement on the bias side of the supporting pile decreases, however, the deformation on the non-bias side influenced by the supporting piles on the bias side moves to the inside of pit gradually. Although the embedded depth of supporting pile can enhance the stability of the pit, but not significantly.

CONCLUSION

Air shaft deep foundation pit 6 at Hefei subway station is studied in this paper to analyze the excavation and its adjacent national highway 312's monitoring data, conduct a simulation study on deformation rule of its supporting structure by using numerical simulation software Midas, and explore various factors that effects the deformation of supporting piles. Conclusions are educed as follows:

(1) Under the bias load effect of national highway 312, the supporting piles at bias side of air shaft foundation pit 6 presents a "spoon-shaped" deformation and with the increasing depth of excavation, the maximum horizontal displacement of piles increases gradually, while the position of the maximum horizontal displacement moves down continuously; the top of the non-bias side distorts toward the outside of foundation pit and expands as the depth of excavation increases, but the deformation of the lower part of piles is still towards the inside of foundation pit.

(2) The factors of air shaft deep foundation pit 6's supporting pile deformation are studied, the results show, subgrade unsymmetrical pressure has a great influence on deep horizontal deformation of supporting piles, the maximum horizontal displacement at the bias side is about three times more than non-bias side's; when the distance of subgrade to foundation pit is the same as the depth of excavation, the influence of subgrade on pit can be ignored; deformation of supporting piles is reduced gradually as the cohesion and internal friction angle increase, stability of building envelope gets enhanced continuously; deformation of supporting piles will reduce gradually as its embedded depth increases, but the trend is not particularly significant.

CONFLICT OF INTEREST

The authors confirm that this article content has no conflict of interest.

ACKNOWLEDGEMENTS

This work is supported by National Science Foundation of China (No. 51474004) and the Anhui Province Natural Science Foundation (No. 1308085QE85, 1408085QE96).

REFERENCES

[1] L. Jian-guo, and C. Liang-kui, "Pit support technology development and engineering practice in Beijing", *Rock and Soil Mechanics*, vol. 30, no. 4, pp. 13-17, 2009.

[2] C. Min-hua, C. Zeng-xin, and Z. Chang-sheng, "Application of FLAC in analysis of foundation excavation", *Chinese Journal of Geotechnical Engineering*, vol. 28, no. 3, pp. 1437-1440, 2006.

[3] L. Ji-guo, and Z. Ya-wu, "Application of FLAC3D to simulation of foundation excavation and support", *Rock and Soil Mechanics*, vol. 27, no. 3, pp. 505-508, 2006.

[4] W. Xiao-wang, F. Jian-fei, and D. Xue-wei, "Monitoring and stability analysis on a tunnel foundation pit", *Analysis and Research*, vol. 4, no. 3, pp. 122-127, 2009.

[5] L. Guobin, and W. Weidong, *Handbook for Foundation Pit Excavation Engineering*, China Architecture and Building Press: Beijing, 2009.

[6] L. Gang, X. Chang-jie, and C. Yuan-qiang, "Research on characters of retaining structures for deep foundation pit excavation under unbalanced heaped load", *Rock and Soil Mechanics*, vol. 08, pp. 2592-2598, 2010.

[7] Y. Ai-jun, and Z. Xin-dong, "Influence of asymmetric load on supporting deformation for deep foundation pit", *Rock and Soil Mechanics*, vol. S2, pp. 378-382, 2011.

[8] T. Wen-peng, "Discussion on the design of the asymmetric bias foundation pit", *Human Communication Science and Technology*, vol. 02, pp. 136-139, 2008.

[9] S. Yu-feng, Y. Jun-sheng, B. Wei, and Z. Xue-min, "Analysis of field testing for deformation and internl force of unsymmetrical loaded foundation pits enclosure structure close to railway", *Chinese Journal of Rock Mechanics and Engineering*, vol. 04, pp. 826-833, 2011.

[10] Z. Guo-liang, "Study on the stability and deformation characteristics of deep foundation pit near existing line". *Central South University*, 2012.

Received: September 17, 2014 Revised: December 17, 2014 Accepted: December 23, 2014