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Comparative Analysis of Different Combined Retaining Measures for Deep Foundation Pit of High-rise Buildings

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Abstract: With the rapid economic development, deep foundation pit engineering of high-rise buildings is becoming more and more popular in urban areas of China. Taking the deep foundation pit engineering of a high-rise building as an example, this paper establishes ABAQUS finite element models to compare two composite retaining measures, namely the segmented combination of pile-anchor and soil nail wall, i.e. applying different measures to different places, and the staged combination of pile-anchor and soil nail wall, i.e. applying different measures to the upper and lower parts at the same place, and to analyze the horizontal displacement and vertical displacement of slope crest. The results show that: The staged combination does a better job than the segmented combination in controlling slope crest horizontal/vertical displacement, and the deep soil displacement.

Keywords: D*eep foundation pit, Pile-anchor retaining, Soil nail wall, Optimal combination*

1. Introduction

As high-rise buildings spring up across China, deep foundation pit engineering is increasingly common and complex. It is not sufficient to maintain foundation pit safety or meet design requirements with a single retaining measure. This gives rise to combined retaining structures in which multiple measures are flexibly integrated to retain a single deep foundation pit according to the soil properties, surrounding environment conditions and the depth of the foundation pit. As an economic and reasonable way to retain deep foundation pits, a combined retaining structure applies different measures to different places or even to the upper and lower parts at the same place. So far, researchers have made fruitful achievements on the combined retaining of deep foundation pit. In light of the characteristics of deep foundation pit engineering, Du [1] introduces the construction plan and specific construction technologies of combined retaining of deep foundation pit which retains the upper part with soil nail wall and retains the lower part with pile-anchor. Citing a deep foundation pit in Handan as an example, Si [2] carries out whole process simulation of the excavation of such two models as pile-anchor retaining and soil nail wall retaining in strict accordance with actual construction conditions on FLAC3D finite difference software, and discloses the laws of coordination and interaction between the soil nail wall and the pile-anchor, two parts of the combined retaining structure, through comparative analysis of the simulation results.

Chen and Liu [3] establish a three-dimensional numerical model of deep foundation to study the impact of foundation excavation for a subway station nearby under construction. Targeted at a deep foundation pit engineering in Shijiazhuang, Zhang, et al. [4] monitor the slope crest horizontal displacement of the deep foundation pit retained by segmented combination of pile-anchor and soil nail wall and carry out comparative data analysis, which reveals that the pile-anchor method has a better retaining effect than soil nail wall method, and with either method, the displacement is greatly affected by spatial locations.

Song, et al. [6] investigated the failure modes for geocell flexible retaining wall under different height-width ratios and soil strengths. Song, et al. [7] investigated the failure mode of the retaining wall with lengthening geocell layers as reinforcements. Li, et al. [8] explore surrounding rock activity law and stress distribution of gob-side entry retaining with hard roof.

Over the years, the combination of pile-anchor and soil nail wall has been extensively applied to deep foundation pits, and many experts and scholars have carried out numerical simulation and basic monitoring of the combined retaining measure [9, 10]. However, little research has been done on comparative analysis of the following two retaining measures: the segmented combination of pile-anchor and soil nail wall and the staged combination of pile-anchor and soil nail wall.

In the context of practical engineering and with the aid of ABAQUS finite element simulation software, this paper makes a comparative analysis of slope crest horizontal/vertical displacements and deep soil displacements between these two combined retaining measures, i.e. the segmented combination of pile-anchor and soil nail wall and the staged combination of pile-anchor and soil nail wall, so as to provide reference for the engineering application of the two combined retaining measures.

2. Project Overview

2.1 Geological Conditions

The project is located in Shijiazhuang, Hebei Province. A previous exploration drilling shows that, apart from miscellaneous fill, the main soil layer in the 40.0m depth range of the drilling is made up of the alluvial clayey soil formed in Quaternary period, as well as some silt, sandy soil and gravelly soil. According to lithology and physical and mechanical properties, the soil layer can be divided into 9 engineering geological layers and 4 engineering geological sub-layers. See Table 2.1 for parameters of the soil layer within the excavation range of the foundation pit.

2.2 Foundation Pit Retaining Conditions

The foundation pit is a Grade 1 foundation pit. It is about 80m long from east to west and about 120m long from north to south. The base elevation is -10.35m. The excavation depth is about 10.0m. New suction line, suction well, and cable conduit are added to the northern section to the west of the foundation pit. The suction line is 1.7m away, and the east wall of the suction well is 1.3m away from the edge of the foundation of the new building. To facilitate construction and control displacement, the 30m long northern section of the west side of the foundation pit is retained by the pile-anchor method, while the other sections are retained by soil nail wall. For the pile-anchor retaining structure, the pile diameter is 600m, the pile spacing is 1.5m, and the embedded depth is 3.5m. Two anchor bars are laid at a horizontal spacing of 1.5m. The top beam is 700m wide and 500mm tall. For the soil nail wall retaining structure, 100mm-diamter soil nails are placed at a horizontal spacing of 1.2m, a vertical spacing of 1.5m, and a dig angle of 10°. The surface layer is sprayed with fine aggregate concrete. Figures 2.1 and 2.2 are shows details on the layout.

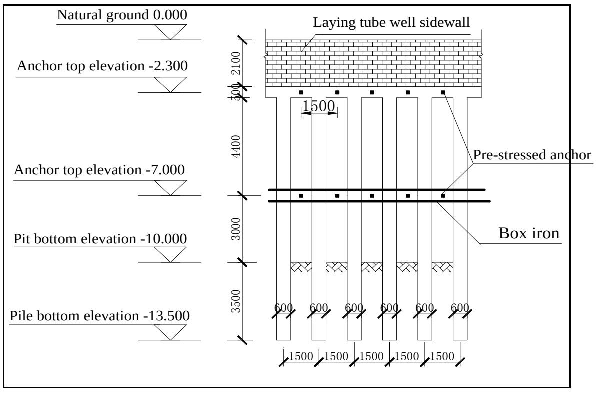

***Figure 2.1**: Front view Map of Pile-anchor Retaining Structure*

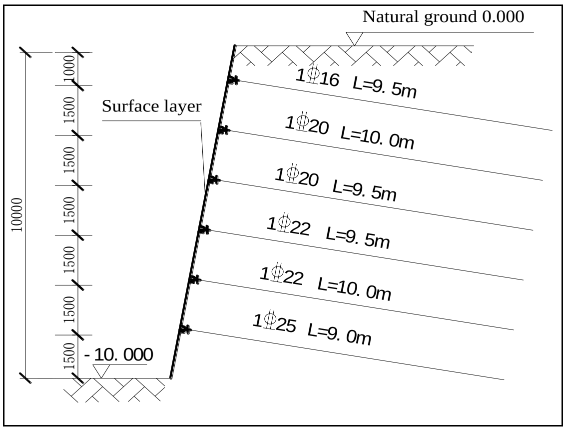

***Figure 2.2**: Profile Map of Soil Nail Wall*

***Table 2.1** Parameters of the Retaining Soil Layer of the Foundation Pit*

Layer No.	Name of Soil	Layer Thickness h (m)	Specific Weight γ (kN/m^3)	Engineering Geological Features
1	Msicellaneous fill	0.70	19.0	Mostly silty clay, the soil has a small amount of plant roots on the top, and contains brick fragments and stones.
2	Clayey soil	1.90	19.5	Yellowish brown, plastic~hard plastic, the soil is homogeneous, containing a small amount of ginger stone, and traces of iron manganese oxides. Thin layers of silt are seen in local areas.
3	Silt	4.60	19.1	Brownish yellow, slightly wet~wet, slightly dense~medium dense, the soil is non-homogeneous, containing chunks of silty clay in local areas, and traces of rusts and ginger stones.
4	Silt	2.70	19.3	Brownish yellow, slightly wet~wet, medium dense~desnse, the soil is non-homogeneous and scattered, containing traces of sheet micas and pores, and a few amount of sand particles in local areas.
5	Fine sand	1.10	18.5	Greyish white, slightly dense, slighty wet, the sand is pure, easy to sort and excellently rounded, which mainly contains quartz-feldspars and traces of mica flakes.
6	Silt	1.20	19.3	Brownish yellow, slightly wet~wet, medium dense~desnse, the soil is non-homogeneous and scattered, containing chunks of silty clay in local areas, a lot of sand particles, and traces of rusts and sheet micas.
7	Medium sand	2.60	18.5	Greyish white, medium dense, slighty wet, the sand is rather pure, easy to sort and excellently rounded, which mainly contains quartz-feldspars and traces of mica flakes. Thin layers of fine sand are seen in local areas.

3. Calculation Model

According to the aforementioned engineering geological conditions and foundation pit retaining parameters, the author establishes finite element model 1 for segmented combination of pile-anchor and soil nail wall (type 1 retaining). In order to eliminate the boundary effect, the length and width of the model are five times those of the foundation pit. After giving full consideration of the existing soil layer data (excluding pebble bed), the author sets the depth of the model at 30m. Thus, the overall dimensions of the model are 620m×365m×30m. With the purpose of simulating the entire foundation pit in strict accordance with the actual working conditions, the author sets up a 3D model first, divides the soil into different layers, and carries out grading. Compared with those models which only analyzes 1/4 of the foundation pit or overlooks sloping, the construction of this model is much more difficult.

For the four sides of the model, horizontal displacement constraints are set in the X and Y directions. For the base of the model, constraints are set in the X, Y and Z directions. The load is the dead weight of soil, and the constitutive relation of the soil is described with the Mohr-Coulomb model. The structured grid is generated by sweeping technology and the job is generated and submitted for analysis. According to pre-set steps, the author carries out stress balance, piling, excavation, soil nailing till reaching the maximum depth of 11.35m. See Figure 3.1 for the complete model. See Figure 3.2 for the part of the model simulating the foundation pit.

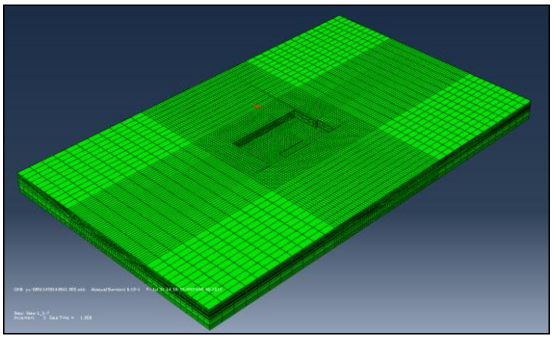

***Figure 3.1**: The Complete Model*

The above retaining method is combines pile-anchor and soil nail wall in horizontal segment. Based on this method, the author alters the design by combining pile-anchor and soil nail wall in the vertical direction. In other words, the author develops another combined retaining method which uses soil nail wall to retain the upper part of the foundation pit, and uses pile-anchor to retain the lower part of the foundation pit. In order to compare the bearing properties of these two retaining measures, the author establishes finite element model 2 (type 2 retaining) for the same foundation pit to simulate the staged combination of pile-anchor and soil nail wall. See Figure 3.3 for the profile map of the retaining structure.

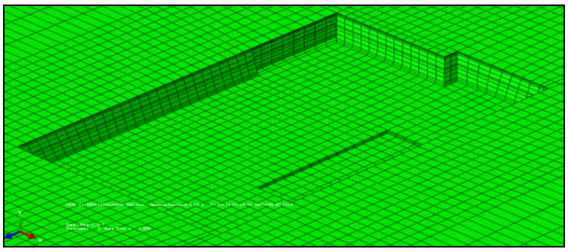

***Figure 3.2**: The Part of the Model Simulating the Foundation Pit*

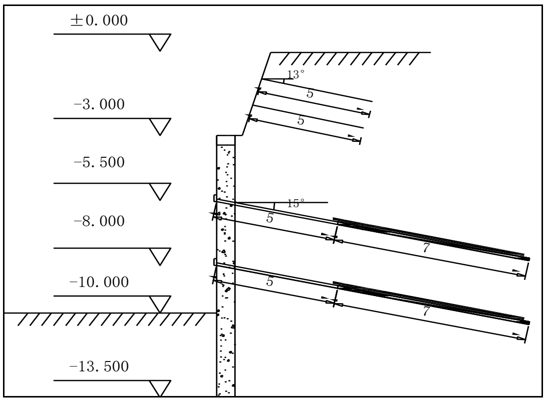

***Figure 3.3**: Profile Map of Staged Combination of Pile-anchor and Soil Nail Wall*

4. Analysis of Calculation Results

4.1 Comparison between Simulated Results and Measured Results of Segmented Combination of Pile-anchor and Soil Nail Wall

The monitoring points on the west side of the foundation pit is arranged according to the Technical Code for Monitoring of Building Foundation Pit Engineering.[5] See Figure 4.1. Among them, S2, S3 and S4 monitoring points are located in the section retained by pile-anchor, while S23, S24, S25 and S1 are located in the section retained by soil nail wall. See Figure 4.2 for the simulated results and measured results of cumulative horizontal displacement and see Figure 4.3 for the simulated results and measured results of cumulative vertical displacement of S1, S2, S3, S4, S23, S24, and S25 on the west of the foundation pit.

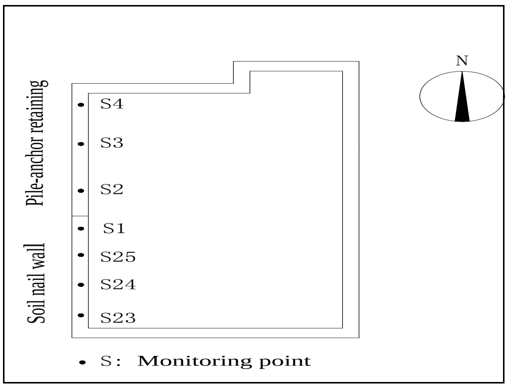

***Figure 4.1:** Layout of Foundation Pit Monitoring Points*

Figure 4.2*: Photos of Segmented Combination of Pile-anchor and Soil Nail Wall*

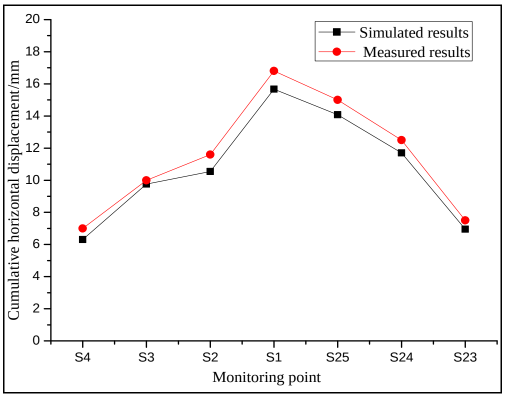

Figure 4.3*: Simulated Results and Measured Results of Cumulative Horizontal Displacement of Each Monitoring Point*

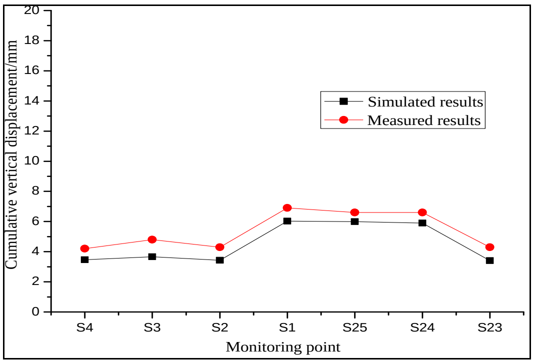

Figure 4.4*: Simulated Results and Measured Results of Cumulative Vertical Displacement of Each Monitoring Point*

According to Figure 4.3 and Figure 4.4, the simulated results of the cumulative horizontal and vertical displacements at each monitoring point are changing in the same trend with the measured results. Besides, the maximum horizontal cumulative difference between the simulated results and the measured results appears at S1, which is 1.2mm, while the maximum vertical cumulative difference appears at S3, which is 1.1mm. Hence, the models can accurately reflect the actual conditions of the foundation pit. In the meantime, the data show that, in the middle of the west side of the foundation pit, S3/S2 in the pile-anchor retaining section has a much smaller displacement than S1/S25 in the soil nail wall retaining section, indicating that the displacement of the foundation pit, especially the horizontal displacement, is greatly affected by spatial locations.

4.2 Comparison between Segmented Combination of Pile-anchor and Soil Nail Wall and Staged Combination of Pile-anchor and Soil Nail Wall

4.2.1 Analysis of Slope Crest Horizontal/Vertical Displacements of the Two Retaining Measures

On the numerical models of the segmented combination of pile-anchor and soil nail wall and the staged combination of pile-anchor and soil nail wall, the author gathers the simulated results of slope crest horizontal/vertical displacement at the calculation points corresponding to the measurement points (S1, S2, S3, S4, S23, S24 and S25), and obtains the displacement curves based on the statistics as shown in Figure 4.5 and Figure 4.6.

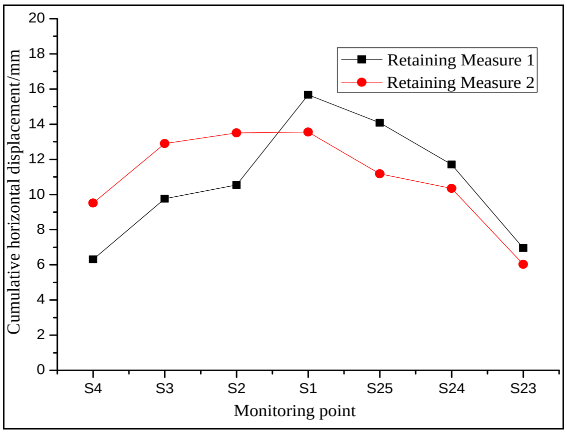

Figure 4.5*: Comparison between Horizontal Displacement Curves of the Two Retaining Measures*

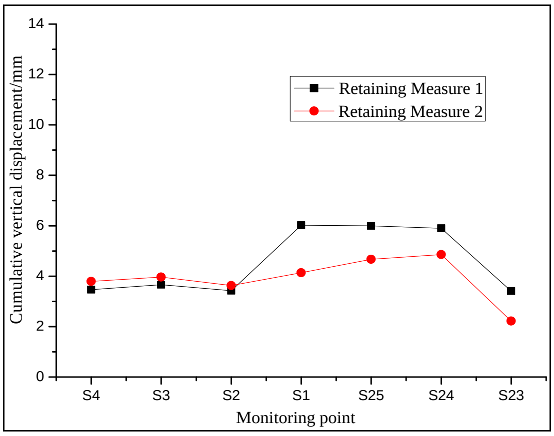

Figure 4.6*: Comparison between Vertical Displacement Curves of the Two Retaining Measures*

In order to analyze the quantitative relationship between the slope crest horizontal/vertical displacements of the two retaining measures, the author prepares Table 4.1 and Table 4.2 on the basis of Figure 4.5 and Figure 4.6.

Table 4.1: *Results and Difference of Slope Crest Horizontal Displacements of the Two Retaining Measures (mm)*

	S4	S3	S2	S1	S25	S24	S23
Type 1 Retaining	6.3	9.8	10.5	15.7	14.1	11.7	7.0
Type 2 Retaining	9.5	12.9	13.5	13.6	11.2	10.3	6.0
Displacement difference of the two retaining measures	-50.8	-31.6	-28.6	13.4	20.6	12.0	14.3

Table 4.2: *Results and Difference of Slope Crest Vertical Displacements of the Two Retaining Measures (mm)*

	S4	S3	S2	S1	S25	S24	S23
Type 1 Retaining	3.5	3.7	3.4	6.0	5.9	5.8	3.4
Type 2 Retaining	3.8	4.0	3.6	4.1	4.7	4.9	2.2
Displacement difference of the two retaining measures	-8.6	-8.1	-5.9	31.7	20.3	15.5	35.3

According to Figure 4.5, Figure 4.6, Table 4.1 and Table 4.2:

(1) For both segmented combination of pile-anchor and soil nail wall and staged combination of pile-anchor and soil nail wall, the maximum slope crest cumulative horizontal displacements appear at S1, which are 15.7mm and 13.6mm respectively, while the minimum displacements appear at S23, which are 7.0mm and 6.0mm respectively; Besides, the horizontal displacement of the foundation pit is greatly affected by spatial locations, i.e. the slope crest horizontal displacement increases as the distance to corners of the foundation pit widens.

(2) For the segmented combination of pile-anchor and soil nail wall, the maximum slope crest vertical displacement appears at S1, which is 6.0mm, while the minimum result appears at S23, which is 3.4mm; for the staged combination of pile-anchor and soil nail wall, the maximum slope crest vertical displacement appears at S24, which is 4.9mm, while the minimum result appears at S23, which is 2.2mm. Besides, the slope crest vertical displacement gradually reduces from the middle to the corners of the foundation pit.

(3) The two retaining measures differ on horizontal/vertical slope crest displacement. In comparison with the staged combination of pile-anchor and soil nail wall, the pile-anchor retaining section of segmented combination of pile-anchor and soil nail wall is 28.6%~50.8% smaller in slope crest horizontal displacement, and 5.9%~8.6% smaller in slope crest vertical displacement, while the soil nail wall retaining section of the segmented combination is 13.4%~20.6% greater in slope crest horizontal displacement, and 15.5%~35.35 greater in slope crest vertical displacement.

4.2.2 Analysis of Deep Soil Horizontal Displacements of the Two Retaining Measures

Figures 4.7 to 4.10 are drawn based on the locations of S2, S3, S1 and S25, and on the simulated results of horizontal displacements of segmented combination of pile-anchor and soil nail wall and staged combination of pile-anchor and soil nail wall.

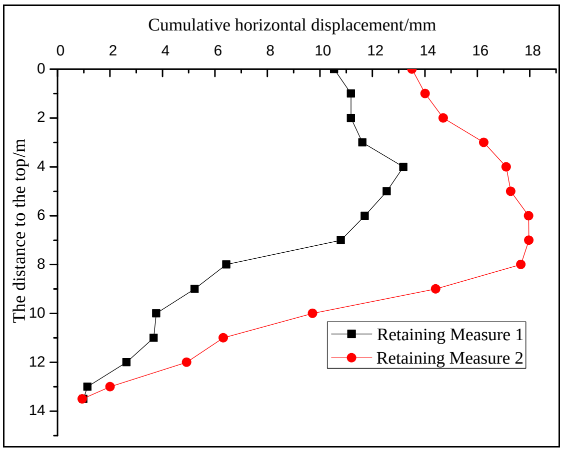

Figure 4.7*: Deep Soil Horizontal Displacement at S2*

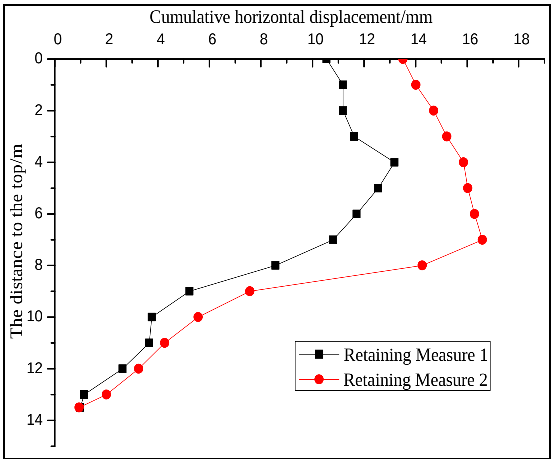

Figure 4.8: *Deep Soil Horizontal Displacement at S3*

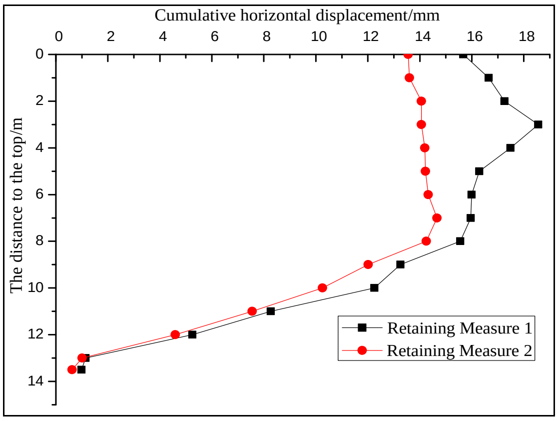

Figure 4.9*: Deep Soil Horizontal Displacement at S1*

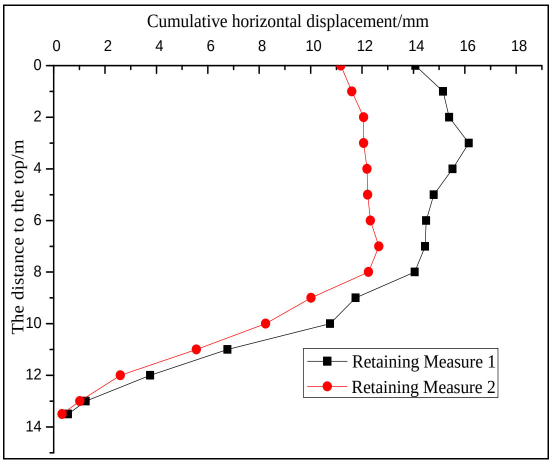

***Figure 4.10** Deep Soil Horizontal Displacement at S25*

According to Figures 4.7 to 4.10:

(1) For pile-anchor retaining, the maximum deep soil horizontal displacement appears at 0.4H (H stands for the excavation depth of the foundation pit); for soil nail wall retaining, the maximum horizontal displacement appears at 0.3H; for staged combination of pile-anchor and soil nail wall, the maximum value appears at 0.8H.

(2) The two retaining measures also differ on deep soil displacement and the difference above the excavation surface is greater than that below the excavation surface. In comparison with the staged combination of pile-anchor and soil nail wall, the pile-anchor retaining section of segmented combination of pile-anchor and soil nail wall is 34.5%~42.8% smaller in maximum deep soil horizontal displacement, while the soil nail wall retaining section of the segmented combination is 32.0%~33.9% greater in maximum deep soil horizontal displacement.

5. Conclusion

The author draws the following conclusions after comparing the simulated results and measures results of segmented combination of pile-anchor and soil nail wall, and carrying out comparative analysis of the simulated results of segmented combination of pile-anchor and soil nail wall and staged combination of pile-anchor and soil nail wall:

(1) The numerical models for segmented combination of pile-anchor and soil nail wall are reasonable and effective because they can accurately reflect the actual conditions of the foundation pit.

(2) In terms of simulated results, segmented combination of pile-anchor and soil nail wall and staged combination of pile-anchor and soil nail wall are in good agreement with each other. The latter both reflect the actual conditions of the foundation pit, and demonstrate that the displacement of the foundation pit is greatly affected by spatial locations.

(3) The two retaining measures differ on displacement. In comparison with the staged combination of pile-anchor and soil nail wall, the pile-anchor retaining section of segmented combination of pile-anchor and soil nail wall is 28.6%~50.8% smaller in slope crest horizontal displacement, 5.9%~8.6% smaller in slope crest vertical displacement, and 34.5%~42.8% smaller in maximum deep soil horizontal displacement; while the soil nail wall retaining section of the segmented combination is 13.4%~20.6% greater in slope crest horizontal displacement, 15.5%~35.35 greater in slope crest vertical displacement, and 32.0%~33.9% greater in maximum deep soil horizontal displacement.

(4) The bearing properties of staged combination of pile-anchor and soil nail wall fall between those of soil nail wall retaining and those of pile-anchor retaining. Generally speaking, staged combination of pile-anchor and soil nail wall is slightly better than segmented combination of pile-anchor and soil nail wall.

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