Influence Analysis of Deep Excavation on the Nearby Undercrossing Road by Centrifuge Model Test

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ABSTRACT: An excavation with the depth of 32.7m will be constructed as a ventilation shaft in Shanghai metro Line 9. The excavation induced effect on a nearby undercrossing road in operation must be properly evaluated. A centrifuge model test was conducted to study the impact of deep excavation on this existing undercrossing. Detail simulation works are described in this paper. The excavation steps could be simulated in the no-stop state of centrifuge machine. And induced settlements of the undercrossing road in both parallel and vertical directions were analyzed. Protective partition cement soil piles were also simulated in the tests. Simulation test shows deep excavation has a great influence on undercrossing road and the partition pile can obviously deduce the influence.

Key words: Centrifuge model test; Deep excavation; Undercrossing road; Partition pile

1. Introduction

Deep excavation construction in urban area may lead to serious impact to surrounding structure. One ventilation shaft in the middle of Shanghai metro line 9 will be excavated. It has 24.922m in the length, 20.3 in the width and 32.727m in the depth respectively. Its retaining wall includes 1m thickness and 59m depth diaphragm wall and 9 layers of steel pipe struts. The undercrossing road with dual 6 lanes is only 3m away from one edge of this ventilation shaft excavation. For protecting the undercrossing, a row of Φ850 3 axial cement soil mixing pile is constructed between the excavation and the undercrossing, that we called partition pile. It has 40m in the depth and 10m beyond the excavation in the plain.

The ground surface of the project site is even with elevation between 3.48m to 5.42m. Main geological layers the excavation crosses are: ①$_1$ mixed filling, ②$_1$ silty clay, ③$_1$ clay and silty clay, ④soft clay, ⑤$_{1-1}$ clay, ⑤$_{1-2}$ silty clay, ⑥silty clay, ⑦$_{1-1}$ sandy silt, and etc.

Centrifuge model test is one effective way to analyze the effect on the surrounding environment by deep excavation. The main difficult problem is how to simulate the process of excavation. The drainage method is adopted to simulate the soil excavation in centrifuge (C.F.Leung, D.E.Ong and Y.K.Chow, 2006). In this method, a proper portion of soil in the excavation was removed at 1g and replaced by liquid with certain density. In the centrifuge model test, the excavation is simulated by gradually draining the liquid.

In this paper, a series of centrifuge model tests have been employed to investigate the behavior of the existing undercrossing due to nearby deep excavation. Also, the partition pile wall is simulated in this test. The parameters of the partition pile wall are discussed by the measured results of the tests. The study shows the partition pile is an effective measure to protect the undercrossing operation.

2. Centrifuge Model Test Design

2.1 Assumptions

For feasibility of the centrifuge model test, three assumptions are made in the test design period.

(1) Due to the symmetry of structure, semi-structure of the excavation is adopted and simulated.

(2) The soil distribution is simplified into three layers.

(3) Because of the restriction of the fabrication technology and operability, the struts are reduced into 5 layers. Software Tongji Qimstar is used to calculate the results of both the original and simplified supporting system and the results show that the simplification is acceptable.

2.2 Centrifuge Model Test Series

All the tests were conducted at 100g on the Geotechnical Centrifuge Machine in Tongji University. All the test parameters and results are presented in prototype scale. Four tests were carried out, namely, Tests 1, 2, 3 and 4 to observe different environment behaviors under different parameters of partition pile wall. Especially, Test 4 is an extra contrastive test with no soil excavation.

Table 1. Test parameters of Tests 1, 2, 3 and 4

Test Name	Soil excavation	Partition Piles	Depth of the Piles	Beyond Length
Test 1	Proceed	Designed	40m	10m
Test 2	Proceed	Designed	20m	5m
Test 3	Proceed	None	-	-
Test 4	None	None	-	-

2.3 Layout of the Model Box

A model box with the dimension of 700mm×700mm×900mm was used in the centrifuge model test. The plan view and a cross profile of the model box are show in Figure 1 and Figure 2.

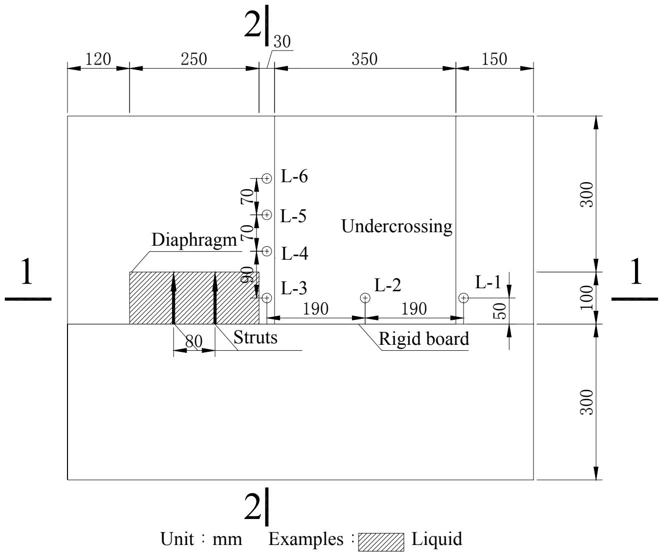

Fig. 1. Plan view of the model box and measuring points

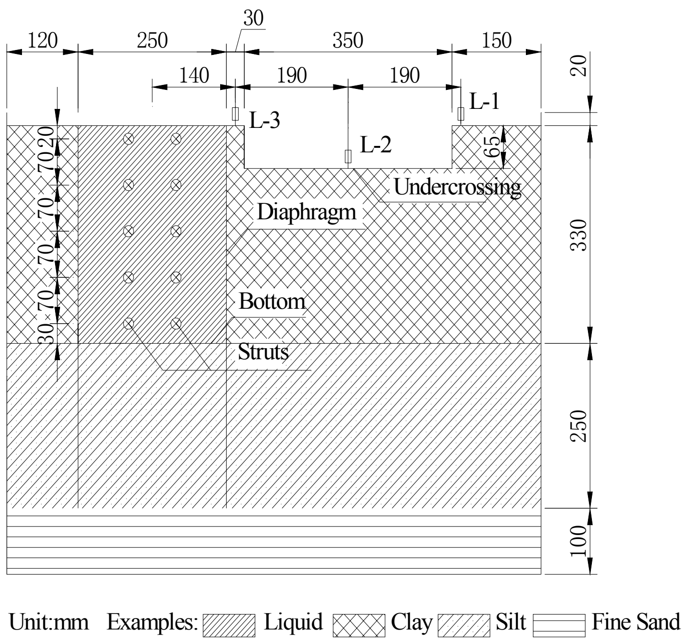

Fig. 2. Cross profile1-1

A rigid metal board was set in the model box to divide the model box into two sections. It can be found in the plan view (Fig.1) that the upper 900mm×400mm section was filled with soil and the lower 900mm×300mm section was arranged for the attachment such as the hydraulic valve and hydraulic locks.

2.4 Excavation Simulation Method

In this test, the soil excavation was simulated by draining the liquid in the room enclosed by the diaphragms and rigid board. Sodium silicate (Na_2SiO_3) was employed in this test. Sodium silicate is innocuous and the density of the liquid can be adjusted to satisfy that the lateral pressure provided by the liquid is the same as the original soil.

When the liquid level fell down to a certain height, the corresponding metal supporting struts in this layer were activated to prevent the diaphragm to move towards to the room.

The principal of the supporting device is shown in Figure 3.

All the transverse supporting struts were made of metal pipe. In the primary condition, all the struts contacted the diaphragm wall but could slide freely in the horizontal direction. When the liquid was drained into a certain height, hydraulic locks restrained the tails of the struts in the same layer and the struts were fixed instantaneously.

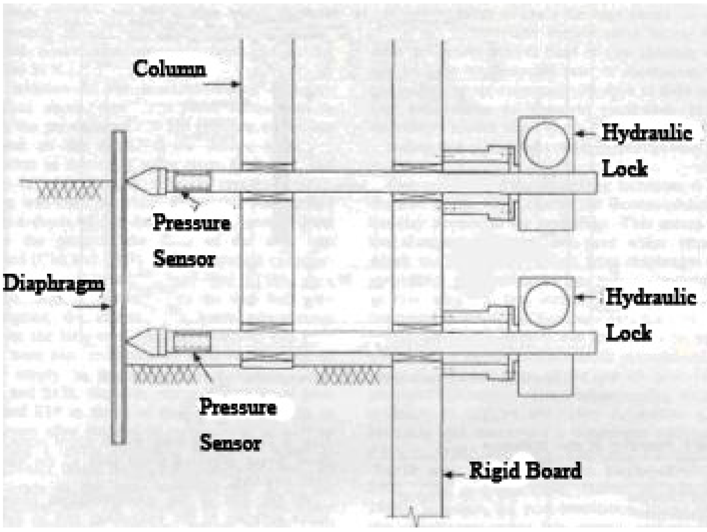

Fig. 3. Principal of the supporting system

2.5 Structure Model Fabrication

Aluminum plate was used to simulate the diaphragm wall and undercrossing structures. Steel pipe was used to simulate all the struts. According to the flexural rigidity similarity, the geometry parameters of models are shown in Table 2. It should be noted that different partition pile walls were used in different tests.

Table 2. Geometry parameters of models

	Short side length	Long side length	Depth	Thickness	Purlin	Struts
Diaphragm wall	100mm	250mm	600mm	10mm	8mm×10mm	Φ10×1mm

Undercrossing	Width	Length	Depth	Side wall thickness	Bottom plate thickness	
	343mm	300mm	65mm	4mm	8mm	
Partition pile wall	Width	Depth	Thickness			
	15/30mm	20/40mm	1mm			

2.6 Test Procedures

The soil of first two layers was obtained from project site and then remolded in the laboratory. The soil of third layer was bought from material market. It is believed that with the same consolidation degree, the property of the remolded soil is the same as the undisturbed soil. The water content of the remolded soils is controlled 105% as the undisturbed soil.

After devices such as the hydraulic valve and hydraulic locks were installed in the rigid board, the board was lifted and placed into the model box. Seams between the board and box were sealed up by polyurethane sealant.

Three layers of soil were filled into the model box, and all layers of soil were pre-consolidated in the centrifuge at 100g. According to previous test experience, the pre-consolidation time of these three layers were controlled in 30min, 90min and 180min respectively. Specimen test after the consolidation proved the controlled consolidation time reasonable.

In the process of soil filling, the diaphragm wall and undercrossing structures were installed. The bottom of the diaphragm structure was sealed by a rubber slab to prevent the leakage of the liquid in the excavation and also, the elasticity of the rubber slab met the requirement of normal bottom heave. The interface between the retaining wall and the rigid board was sealed by polyurethane sealant. Shearing deformation of the interface was permitted because of the elasticity of the sealant.

LVDT (Linear Variable Differential Transformer) was chosen to measure the settlement of points on the undercrossing model including both the top of the side wall and the center of the road (see Figure 1).

3. Result Analysis and Discussion

Figure 4 shows the acceleration-time history curve of the centrifuge.

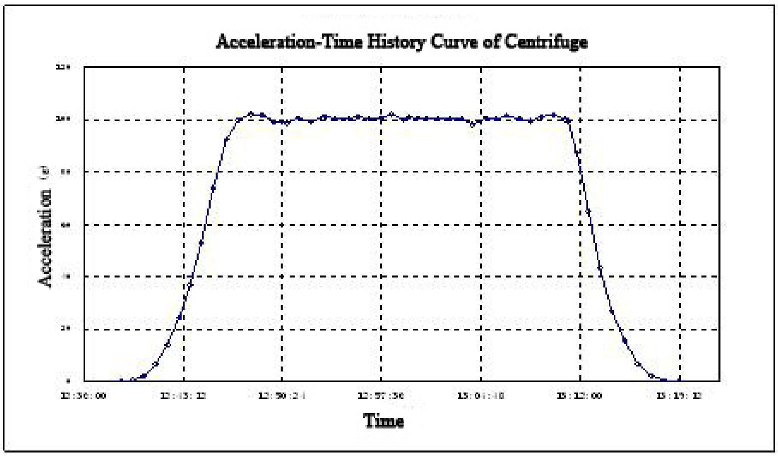

Fig. 4. Acceleration-time history curve of the centrifuge

The total test time is 41minutes which equals 5 months' excavation period in real project. Data from Test 1, 2 and 3 are compatible with each other, which prove the reliability of the excavation simulation system.

During the excavation process in centrifuge, the measured settlement of the undercrossing consists two parts. One part of the settlement is induced by the excavation, while the other part is caused by consolidation. To eliminate the influence of the second part, a comparative test, Test 4 was conducted. The results discussed in the following sections have been rectified from the influence of the consolidation. Data from Test 1, Test 2, Test 3 and site monitoring are analyzed here.

Figure 5, 6 and 7 show the settlement-time curves of the six measuring points in Test 3, 2 and 1 respectively. From Figure 5, 6 and 7, it can be found that the settlements of all the measuring points increase as the excavation proceeds. In some measuring points, the measured value fluctuates when the struts are constructed.

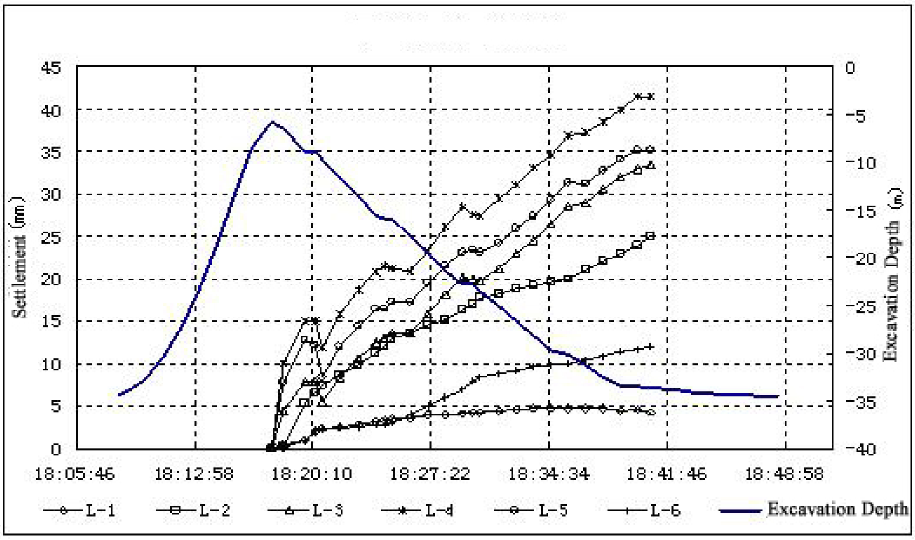

Fig. 5. Measured settlement of undercrossing for Test 3

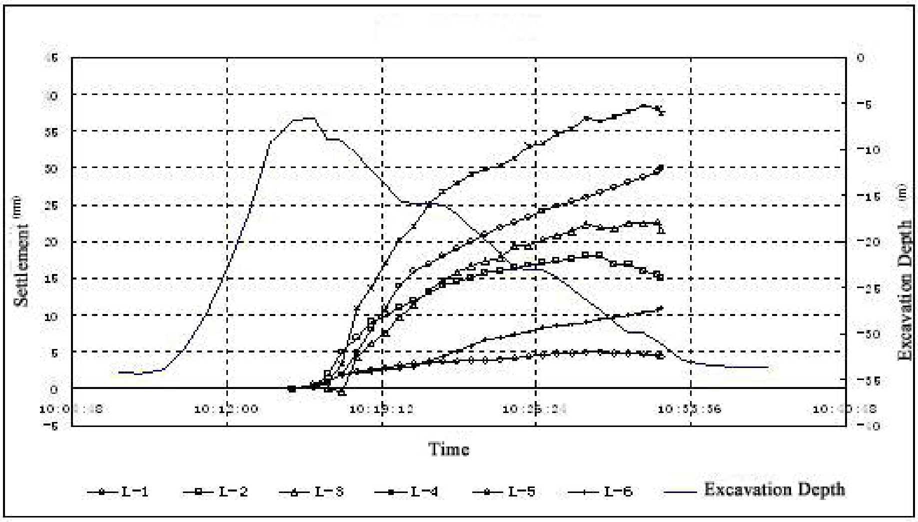

Fig. 6. Measured settlement of undercrossing for Test 2

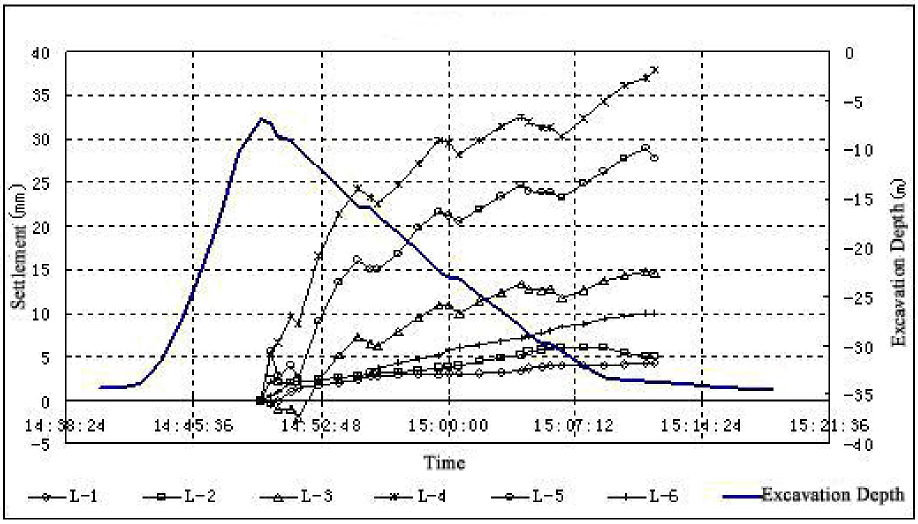

Fig. 7. Measured settlement of undercrossing for Test 1

In the following part, profile 1-1 (perpendicular to the road, see Figure 1) and profile 2-2 (parallel to the road, see Figure 1) are analyzed particularly.

(1) Profile 1-1 analysis (perpendicular to the road)

Figure 8 shows the comparisons between the settlement results of Test 1 and site monitoring in profile 1-1 in different phases of excavation. The parameters used of the shelter pile wall in real project are same to Test 1.

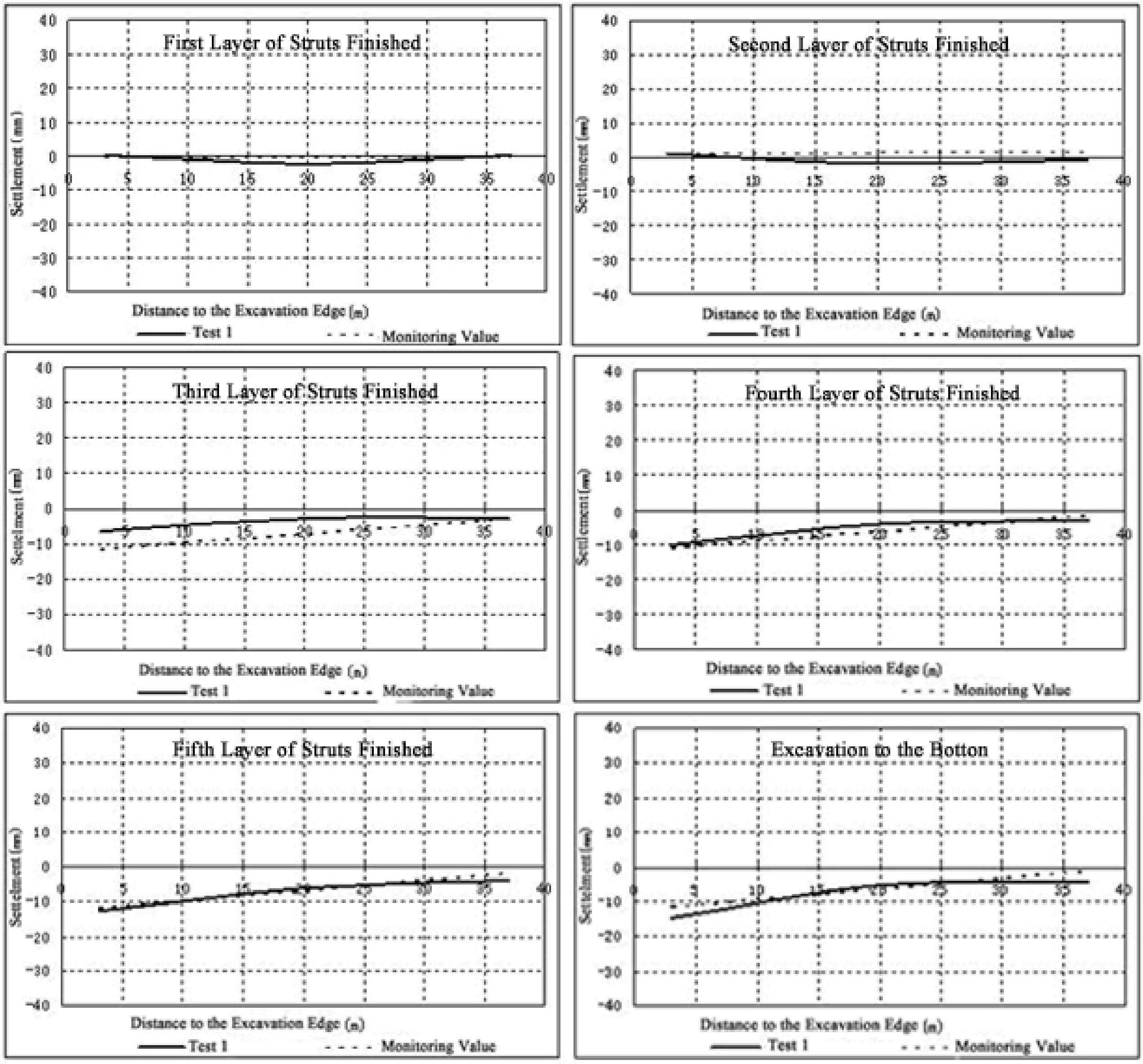

Fig. 8. Settlement comparison curves of undercrossing in profile 1-1 in the process of excavation

From Figure 8, the settlement trend reflected by the test which inclines toward the excavation is similar to the site monitoring result. Before the third layer of struts (-16m) is constructed, the settlement variation rate in monitoring is quicker than that in the test. After the fourth layer of soil is excavated, the settlement of monitoring is tend to be stable, while in the test, the settlement of the undercrossing keeps increasing and the final value is larger than the real project.

Figure 9 shows the comparisons between the settlements of Test 1, 2 and 3 in profile 1-1 in different phases of excavation.

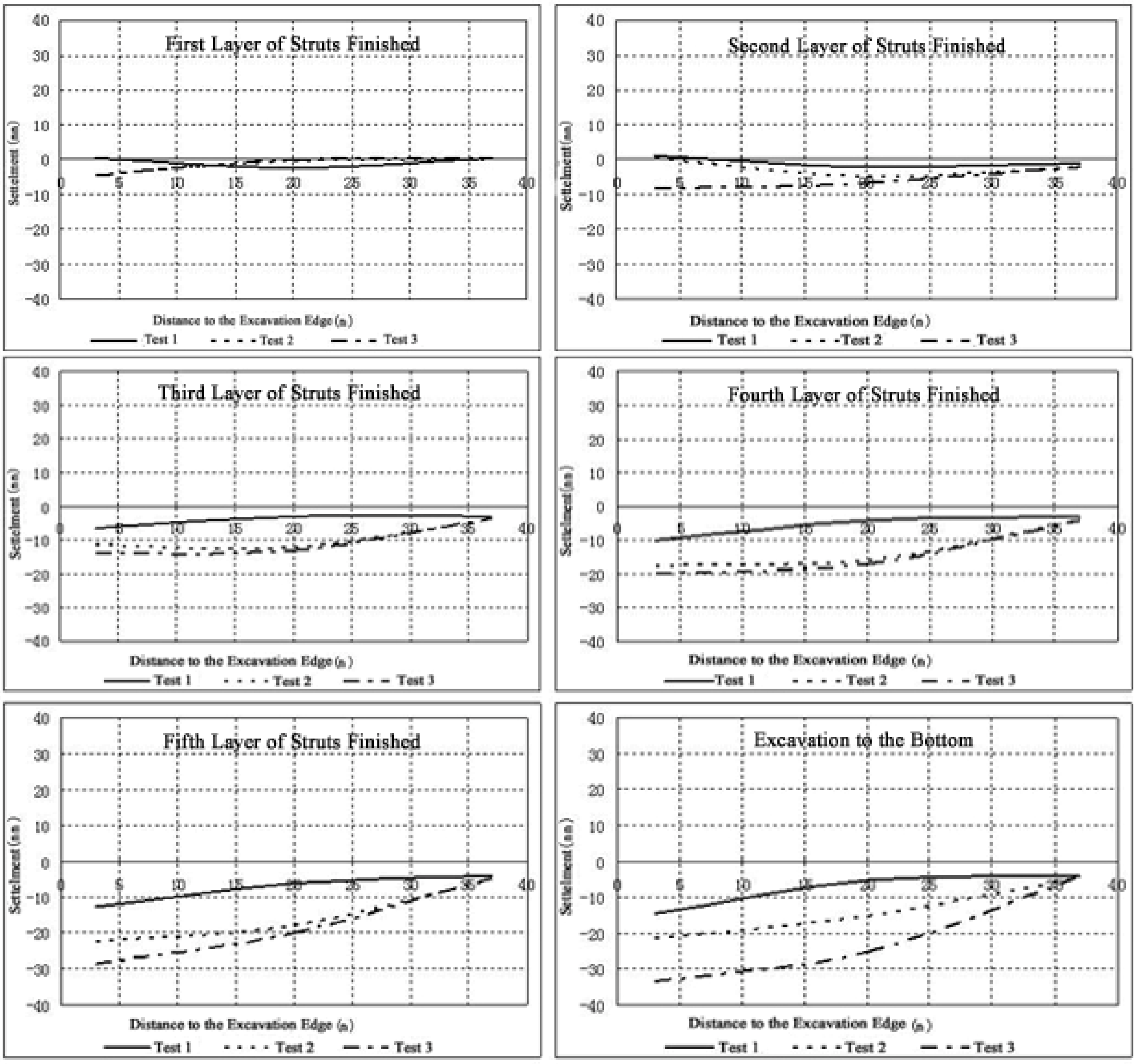

Fig. 9. Settlement comparison curves of undercrossing in profile 1-1 of Test 1, 2 and 3 in excavation

From Figure 9, the protective effect of the partition piles is obvious. Settlement value of the undercrossing in Test 1 is apparently less that the value in Test 2 and 3. Before the third layer of struts is constructed, the settlement value in Test 2 is less than Test 3, which means above this excavation depth, the influence of short partition piles is exerted. In the phase between the construction of third layer and fourth layer of struts, the results of Test 2 and 3 come to close. As excavation depth goes deeper, settlement in both Test 2 and 3 increases sharply. When the excavation is constructed to the bottom, the settlement value of Test 3 is nearly 3 times of Test 1 and the value of Test 2 is about 2 times of Test 1.

(2) Profile 2-2 analysis (parallel to the road)

Figure 10 shows the comparisons between the settlements of Test 1 and site monitoring in profile 2-2 in different phases of excavation.

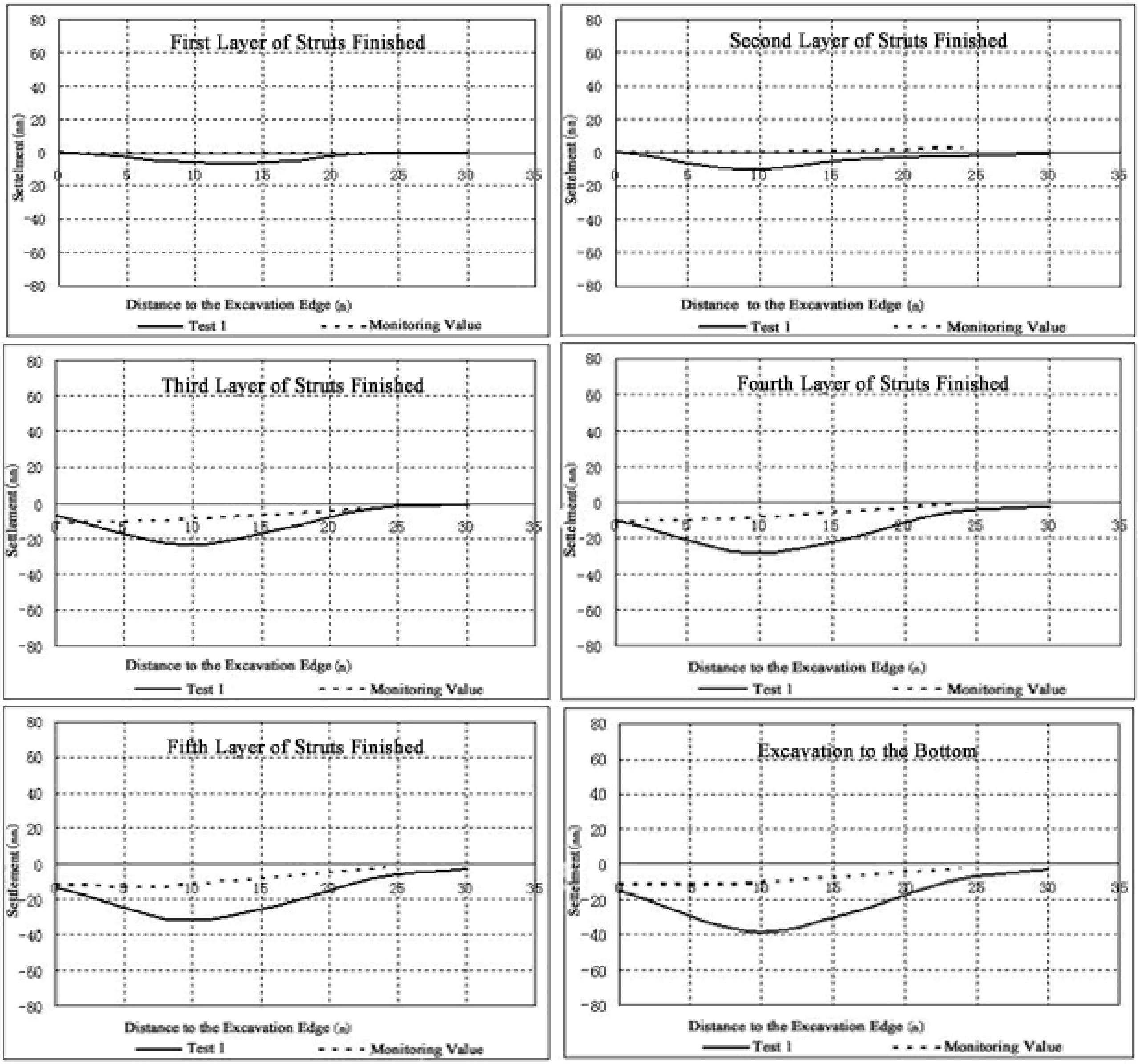

Fig. 10. Settlement comparison curves of undercrossing in profile 2-2 in the process of excavation

From Figure 10, it is found that in the real project, settlements of measuring points in 2-2 profile are close in the range of the excavation. Almost all the peak values appear in the middle axis of the excavation. In the centrifuge test, the maximum settlements appear a distance away from the axis of the excavation. The settlement troughs are in the shape of parabola. The reason of this phenomenon may be that friction exists between the rigid board and the soil.

Before the third layer of struts (-16m) is constructed, in the points near the excavation, the settlement of monitoring increases fast and is more serious than the settlement in the test. After the fourth layer of soil is excavated, the settlement of monitoring is tend to be stable, while in the test, the settlement of the undercrossing keeps increasing and the final value is nearly 3 times of the value in real project.

Figure 11 shows the comparisons between the settlements of Test 1, 2 and 3 in profile 2-2 in different phases of excavation.

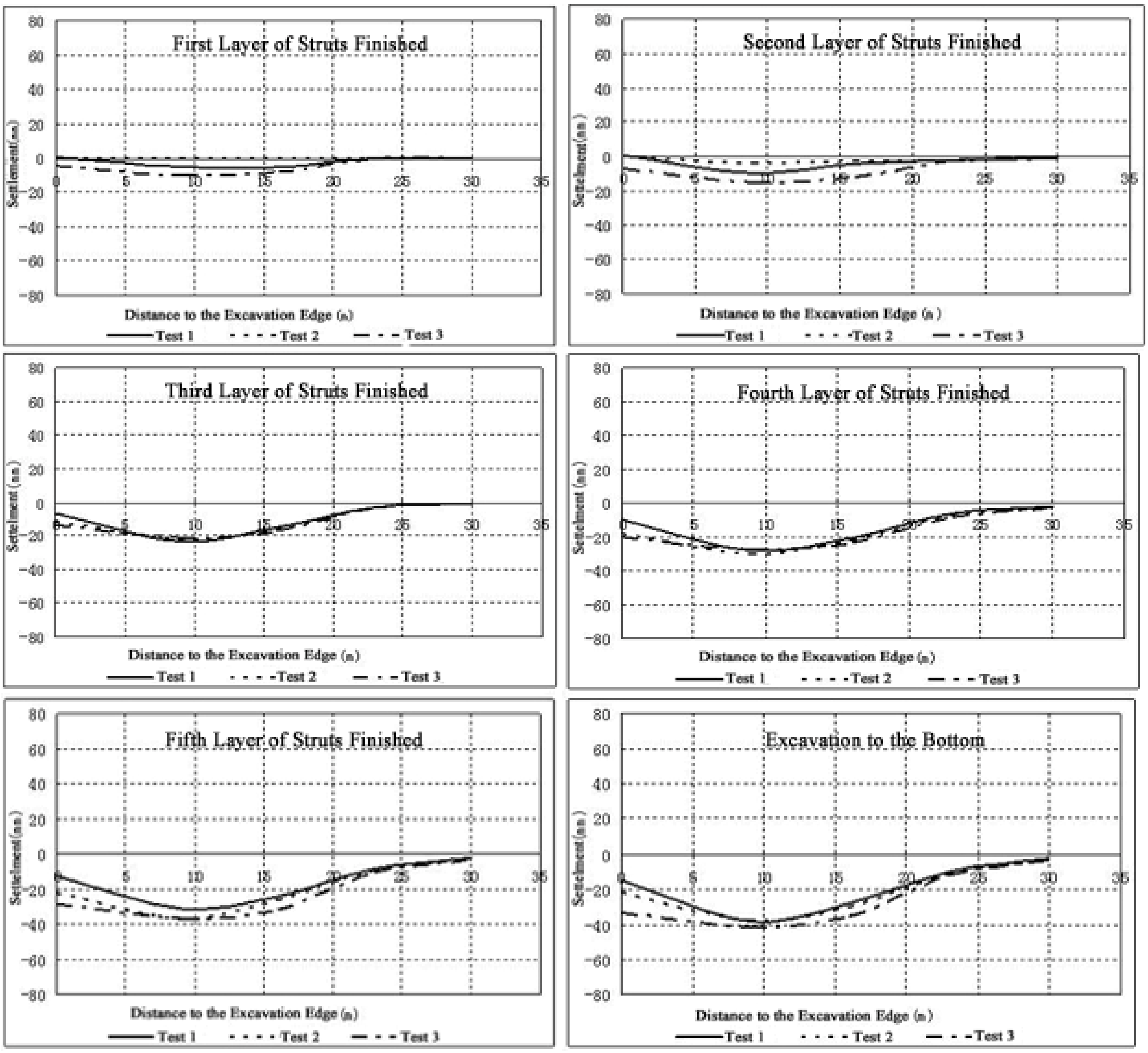

Fig. 11. Settlement comparison curves of undercrossing in profile 2-2 of Test 1, 2 and 3 in excavation

From Figure 11, as for the 2-2 profile, it can be found that in the range of the excavation (distance to the axis of excavation less than 10m), settlement value of Test 1 is smaller than Test 2 and value of Test 2 is smaller than Test 3. It is believed that in that range, the protective function of the shelter pile wall is effective. In the range beyond the excavation, settlements in three tests are close and tend to a convergence value as the distance goes farther. Increment of the length of the partition pile wall beyond a certain range is inefficient.

4. Conclusions

A series of centrifuge model tests have been conducted to investigate the performance of an undercrossing road near a deep excavation. Some main results that show useful to engineering practice are highlighted as follows.

(1) The deep excavation has an obviously influence on nearby undercrossing road. Centrifuge model test shows it's reliable and believable.

(2) The partition pile wall does have the function of protecting the undercrossing road. The length of the pile wall is relative longer; the protective effect is more obvious.

(3) The influence on the undercrossing is limited into a range along the parallel direction. Beyond the range of the excavation, the function of the partition pile wall is inefficient. It is suggested that the beyond length of the partition wall should be controlled in the half width of the excavation.

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