Study of the influencing factors of compressive characteristics for the foundation layer of undersea immersed tube tunnels

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Received 21 December 2014, www.cmnt.lv

Abstract

Shenjiamen undersea immersed tube tunnel in Zhoushan, Zhejiang was taken as prototype to establish a 1:10 scale model with 30m in vertical length. The formation process of sand grouted foundation layer in seawater environment was simulated in the experiment considering the interaction of gravels during the formation of foundation layer. Different construction factors were examined by incorporating different design boundary condition, back-silting condition and sand grout density. Results showed that in the boundary condition of one end fixed and the other free, the settlement at the free end of the tube increased significantly (approx. 3 times) and the timeframe for settlement to stable increased; back-silting increased the overall condensability of the foundation layer and leaded to non-uniform compression; the reduction of sand-water ratio of the grout reduce the compressive modulus of the foundation layer. Further settlement occurred when the load exceeded the limit which is detrimental towards the global stability of the foundation layer. Comparing the effects on the settlement of foundation layer or compressive modulus, the factor of one end fixed and one end free was most significant, followed by back-silting and reduced sand-water ratio.

Keywords: immersed tunnel; base layer; model test; compression feature; influencing factor

1 Introduction

The current construction methods of underground tunnel are mainly shield tunnelling method, shallow buried tunnelling method [1] and immersed tube method [2]. Immersed tube tunnel is a type of large underwater tunnel spanning over rivers and straits and is widely adapted in coastal cities worldwide [3-4]. Statistical analysis of the measured value of settlement from 19 domestic and international immersed tube tunnels showed that the average value of settlement during the construction of immersed tube tunnel was 52 mm and 55.9% of the total settlement [5]. Shao [6] pointed out that settlement during construction was mainly attributed to the adjustment of the foundation layer and the initial compression. Shao [7] proposed that the compressive behavior of the foundation layer of immersed tube tunnel is even worse than the original soil in the foundation and significant compressive deformation would occur under loading impose by the tunnel. Therefore, it is of interest to study the compressive characteristics of the foundation layer and the influencing factors.Model experiments are required to study the compressive characteristics of the foundation layer of immerse tube tunnel [8]. A series of model experiments on immersed tube tunnels were conducted by both domestic and international researchers [9-19] including large scale model experiments [9-10], 1:5 scale resemble model experiments [11-13], full size model experiments [14-17], same scale grouting model experiment [18] and 1:10 scale resemble model experiment [19] on a combination of Guangzhou Pearl River immersed tube tunnel, Guangzhou Bioisland-university town immersed tube tunnel, Guangzhou Zhoutou variable section immersed tube tunnel and Zhoushan Shenjiamen undersea immersed tube tunnel. Substantial conclusions were proposed regarding to the technics of grouting of foundation layer and sand injection as well as the effect of the construction and control parameters through the aforementioned researches but the compressive characteristics of the foundation layer in the water after grouting were not studied and the effect of different construction conditions on the compression of the foundation layer was not considered. It is, therefore, necessary to study the compressive characteristics of the foundation layer of immersed tube tunnel using model experiments and taking consideration of the effect of different construction conditions on the compression of the foundation layer. In this study, 1:10 scale model experiments were constructed to simulate the construction process of foundation layer using sand injection approach in seawater environment; the effect of different construction conditions on the settlement of

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foundation layer were simulated by different designed boundary conditions, back-silting conditions and grout density.

2 Model experiment

2.1 TEST SIMPLIFIED DESCRIPTION

This study is based on the undersea immersed tube tunnel project in Zhoushan City, Zhejiang Province which is currently under construction. Limited by space, details of the project and the design of the foundation layer can be found in [20]. The actual project is changed to be simple as is shown in the following when considering the operability of model test.

1) The length of the actual tube model was more than 70 meters. Only 30 meters was taken proportionally to reduce the building model, taking testing cost, operability and size effect of the tube length into consideration.

2) The perfusion cement slurry was used in the construction process of the actual tube's foundation layer. The model test used grouting mortar, taking into the reproducibility test, test compression, test cycles and practical reference value account.

3) Both the based groove depth and silt concentration in the actual project exist in-homogeneities. In order to simplify and manually facilitate the sludge concentration to compare conveniently, the model test are all considered on according to the uniform distribution.

4) In the actual project, beneath the soil were ripped-rock layers. Settlement was produced during construction. The model test object is only for the gravel base layers. It does not consider the soil, lying under a hard steel so as to avoid interference.

2.2 MODEL INTRODUCTION

A 30m portion of the tunnel was selected as the research object and the model was prepared at a scale of 1: 10 of the actual size. The main components of the model included water tank model and tube model which were both welded by steel plates with a thickness of 19mm. Figure 1 shows the photograph of the model. The entire model can be divided into the following five sections.

1) Water tank model. The size of the water tank was 3.6m (length)×1.6m (width)×0.5m (height) with a loop cycle water tank with a size of 0.5m (length)×0.3m (width)×0.3m (height) attached at one end. The water tank model was used as the main location of experiment to simulate the foundation trench of the seabed in the construction of immersed tube tunnel. The main purpose of the loop cycle water tank was to generate water cycle with the water tank and sand injection system without affecting the model experiment.

2) Tube model. The dimension of the tube model was 3m (length)×1.15m (width)×0.6m (height). As the tube was loaded via water injection during the experiment, three lengths of channel steel were connected at the center of the model as reinforcement to maintain the stability of the model. 17 holes were generated at the bottom of the model to enable sand injection. The location of the sand injection holes was determined according to individual sand tray tests. Figure 2 shows the individual sand tray tests and Figure 3 shows the results of the tests. The specific location of holes is given in Figure 4.

FIGURE 1 Schematic diagram of model experiment

3) Measuring system. Measuring system consisted of measuring shelf, dial test indicator, magnetic stand, steel ruler and measuring tape. The measuring shelf was welded by L-shape steel with a height of 85cm and a span width of 180cm; the dial test indicator had a measuring range of 0.3mm and an accuracy of 0.01mm; the steel rule had a length of 30cm; the measuring tape had a length of 2m. A total of four testing points for settlement were set up at each corner of the tube model. The point number and respective location is shown in Figure 4.

4) Control equipment. The control equipment consisted of lifting jacks, cushion blocks and portal frame. The lifting jacks had an initial height of 4.1cm, a lifting range of 0.7 cm and a maximum height of 4.8; the cushion blocks were 5.4cm in height, 12cm in length and 8cm in width; the portal frame had a height of 2.5m. A span width of 2m and a maximum lifting capacity of 1 tone.

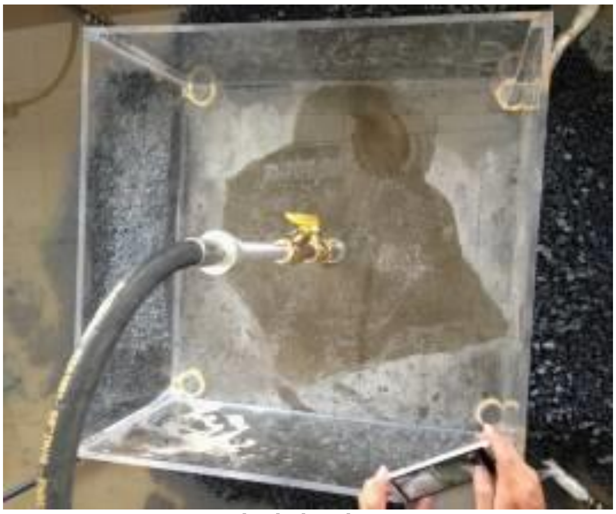

FIGURE 2 Individual sand tray tests

FIGURE 3 Single hole sand injection test result

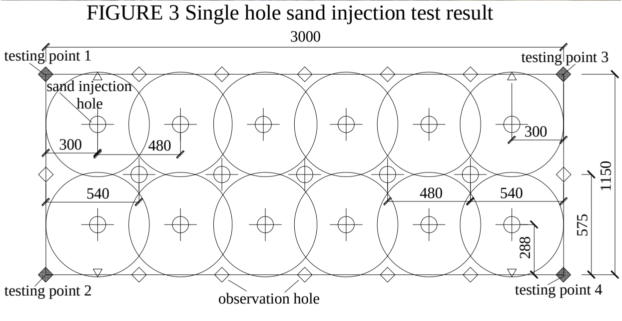

FIGURE 4 Demonstration of the location of injecting holes and observation holes (unit: mm)

5) Sand injection system. The sand injection system consisted of sand pump, water pump, injection tube and one way valves. The sand pump had a power of 1.5kW; the water pump had a power of 125w and a maximum flow rate of 35L/min; the injection tube had an inner diameter of 2.1cm and an outer diameter of 2.4cm; the one way valves had an inner diameter of 2.1cm.

2.3 TEST MATERIALS

Test materials include fine sand, gravel, saline water and silt. The grain size of the fine sand and gravel was determined by similarity relation. The composition of fine sand was: grain size between 0.6mm~0.3mm took 5.73% of the total weight, grain size between 0.3mm~0.15mm took 4.68% of the total weight and grain size below 0.15mm took 89.59% of the total weight; normal continuous grading gravel was used with a grain size between 16mm~5mm; industrial grade salt was used to configure the saline water with a density of 1.09g/ml; back-silting soil was taken from Shenjiamen harbor region as the silt.

2.4 CONFIGURATION OF EXPERIMENT

Four groups of experiments were conducted in the study. Experiment in base condition was first conducted, followed by three different conditions including one end free and the another fixed, back-silting, low density sand grout to enable comparison with the base condition.

Details of each condition are explained as follows:Condition 1: Compressed sand mixed with gravel layer. The foundation layer consisted of a gravel layer with a thickness of 5.74cm and a grouted sand layer with a thickness of 4.29cm. Condition 2: Compressed sand mixed with gravel layer when one end is fixed and the other is free. the foundation layer consisted of a gravel layer with a thickness of 5.30cm and a grouted sand layer with a thickness of 4.52cm, the A end of the tube model was lifted by lifting jack while the B was free. Condition 3: Mixed with large amounts of mud mixed sand and gravel layer compression. The foundation layer consisted of a gravel layer with a thickness of 5cm and a grouted sand layer with a thickness of 4.98cm with 15kg of silt evenly and manually was laid out between the two layers. Condition 4: Low concentrations of mixed sand gravel layer compression. The foundation layer consisted of a gravel layer with a thickness of 5.6cm and a grouted sand layer with a thickness of 4.17cm, and the density of sand grout was a half of that in other conditions with a sand-water mass ratio of 1:2.

The designed thicknesses of gravel layer and grouting layer for each condition were zoomed out by 1:10 of the action dimensions in Shenjiamen harbor undersea immersed tube tunnel project. The actual thickness was taken as the average value of point measurement. The prescribed spacing in the layer was fully grouted by sand.

Except for Condition 2, both ends of the model were free. In Conditions 1 to 3, the experimental sand-water ratio in volume was 3.4: 10 and in mass, 1:1. The applied load in the experiment was scaled at 1:10 of the calculated actual load which was taken as 3.5kPa at ultimate load. Simulating the actual construction process, gradation loading was used in the experiment at 1.5kPa, 2kPa, 2.5kPa and 3.5kPa.

2.5 EXPERIMENTAL PROCEDURE

Take Condition 3 as an example, the detailed experimental process was explained as follows:

1) Early-stage preparations. Gravels were laid at the bottom of the water tank model at designed thickness and the average thickness was measured; cushion blocks and lifting jacks were positioned; back-silting solutions were evenly poured and the back-silting layer was formed after curing; the tube model was lifted by portal frame and placed at the lifting jacks; the tube model was enclosed by gravels; the one way valves were shut and saline water at a density of 1.09g/ml was poured into the water tank.

FIGURE 5 Sand injection process

FIGURE 6 Loading process

2) Simulation sand injection. The sand pump was set up and the sand injection pipe was connected to the one way valve; sand and water was mixed according to the designed ratio and grout injection commenced; observe the expansion of sand tray surrounds the sand injecting holes and the overflow of grout in the nearby observation holes, as is shown in Figure 5; continue to the next hole when the previous one was fully filled until grout overflow occurred at all observation holes. The location of sand injection holes and observation holes is shown in Figure 4. The sand pump in this experiment was able to provide a pouring pressure of 20kg/cm^2.

3) Loading and measuring. The measuring shelf and dial test indicator were first put in position to record the initial reading; remove lifting jacks; the construction loading was simulated by pouring water in the tube model. Pouring stopped when the initial loading calculated from self-weight and buoyancy and record the reading of the dial test indicator; the loading remained constant and the reading was recorded at specific time and the intervals were 5min, 15min, 30min, 45min, 60min, 75min and 90min, respectively; when the readings at each measuring point became stable, continue load by pouring water, as is shown in Figure 6; loading continued and the measurement was recorded until all loading stages were completed.

4) Unloading. When the reading of settlement became stable at the final loading stage, unloading was then carried out; the tube model was lifted and the foundation layer was cleaned to prepare for the next experiment. Figure 7 shows the photograph of the foundation layer after unloading.

FIGURE 7 Condition of the foundation layer after unloading

3 Experimental data analysis

3.1 MEASURING RESULTS IN DIFFERENT CONDITIONS AND THE VARIATION TREND

The variations of measured settlement with time at measuring points for each condition was shown in Figure 8 to 23, in which Figure 8 to 11 show data in Condition 1, Figure 12 to 15 show data in Condition 2, Figure 16 to 19 show data in Condition 3, Figure 20 to 23 show data in Condition 4. Figure 24 to 27 show the variation of final settlement with loading. It is obvious from Figure 8 to 23 that the settlement of foundation layer increased with the increase of loading timeframe; the settlement increased dramatically and the rate of increase reduced until fully stable.

In Condition 1, the compression of four measuring points under single-stage load changed over time, which was shown in Figure 8 to Figure 11. As is shown in the picture, each measuring point reached stable compressive state at 45 min to 60 min with an average compressive modulus of 3.26MPa. The compressive modulus in A End (measuring points 1 and 2) was 3.06MPa and the number was 3.49MPa in B End (measuring points 3 and 4).

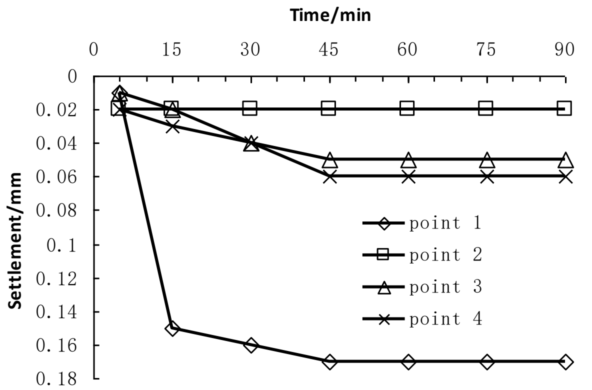

FIGURE 8 Variation of settlement at each point with time at 1.5kPa loading (condition 1)

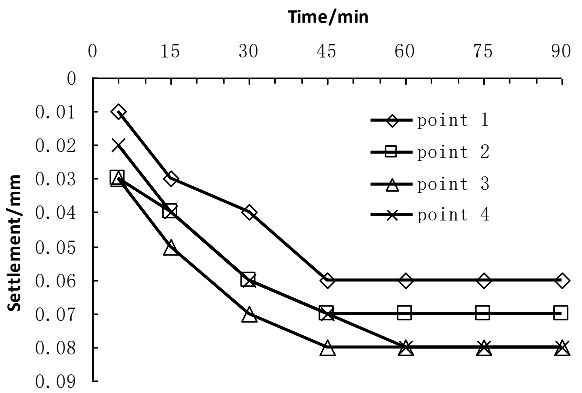

FIGURE 9 Variation of settlement at each point with time at 2kPa loading (condition 1)

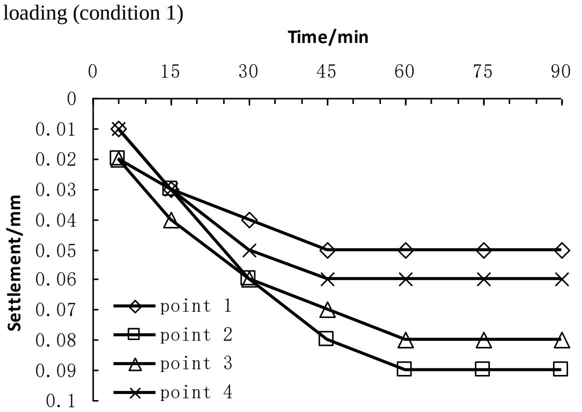

FIGURE 10 Variation of settlement at each point with time at 2.5kPa loading (condition 1)

The mechanism of the Sand and gravel interaction is shown in Figure 28. When sand tray is diffusing on gravel layer during the construction of the sand injection, the sand will penetrate and fill in the gravel pore under the pressure of the sand injection on one hand, at the same time, it will squeeze the gravel layer and increase the compactness of it. On the other hand, coarse surface of gravel will promote the diffusion resistance of the sand disc, while the resistance will counteract to the sand layer, which will increase the compactness of it. The process of the diffusing and filling sand tray on the gravel layer reduces the overall porosity of the base layer, in the mean time, it increases the compactness of the whole.

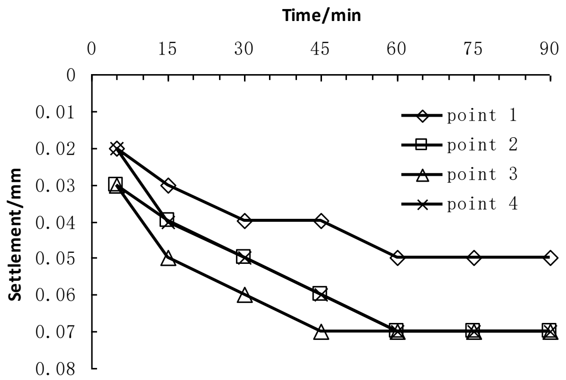

FIGURE 11 Variation of settlement at each point with time at 3.5kPa loading (condition 1)

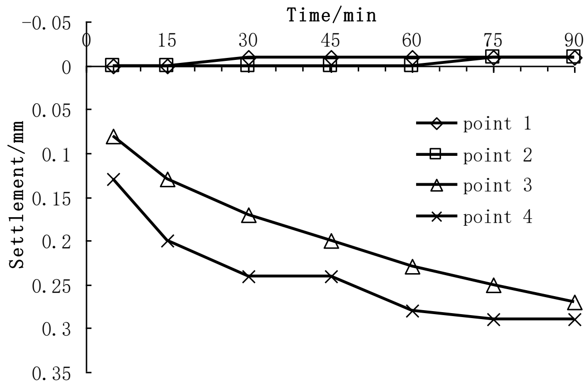

FIGURE 12 Variation of settlement at each point with time at 1.5kPa loading (condition 2)

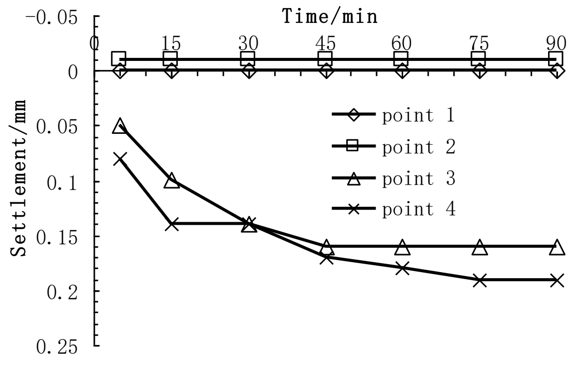

FIGURE 13 Variation of settlement at each point with time at 2kPa loading (condition 2)

The compression of four measuring points under single-stage load changes over time in Condition 2, which was shown in Figure 12 to Figure 15. As is shown in Figure 12 to 15, the settlement of the measuring points beside B in a single load is not the same level. Besides, the settlement of the fourth measuring point is greater than the settlement of third measuring points. Under the single-stage load, the 4th measuring point settling emerged an unusual phenomenon. It was at first sedimentation to transient stability, but then sedimentation continued until it was stable, shown specifically in Figure 12 and Figure 13; a side float behavior appeared under the single-stage load, specifically shown in Figure 12 and Figure 14. The reason may be in the initial stage, there is a certain unevenness because of the paved artificially gravel layer, causing the tube model to fall on the top of the large particle size gravel, leading to the transient stability. When the settlement of B side reached to a certain extent, a side appeared a slight floating phenomenon. The variation trend of measuring point in Condition 2 was discussed as follows: the stable timeframe for compression was obviously longer in B End (measuring points 3 and 4), especially in the initial stage which laid above 75 min but the stable timeframe reduced significantly at higher loading stage. Statistical results showed that the compressive modulus was 0.97MPa at B End.

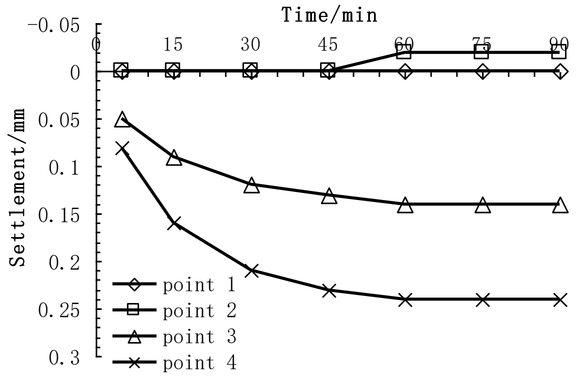

FIGURE 14 Variation of settlement at each point with time at 2.5kPa loading (condition 2)

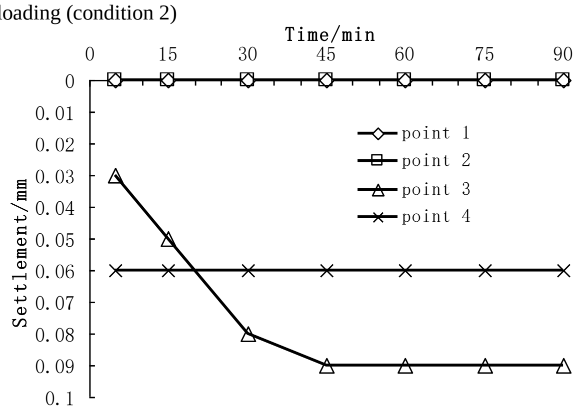

FIGURE 15 Variation of settlement at each point with time at 3.5kPa loading (condition 2)

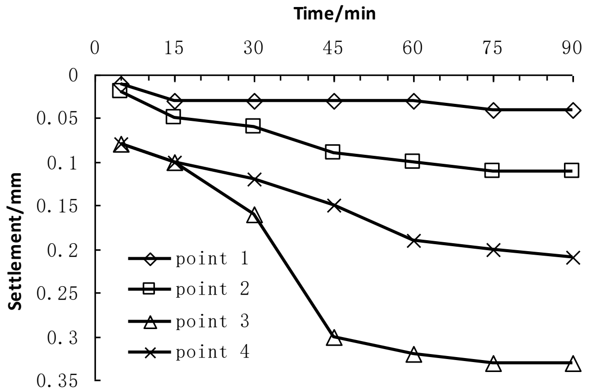

FIGURE 15 Variation of settlement at each point with time at 1.5kPa loading (condition 3)

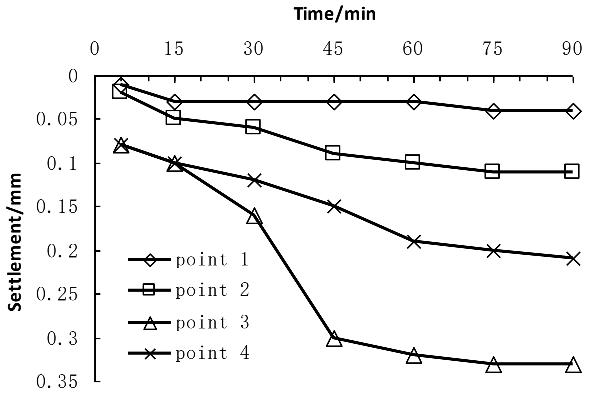

FIGURE 16 Variation of settlement at each point with time at 1.5kPa loading (condition 3)

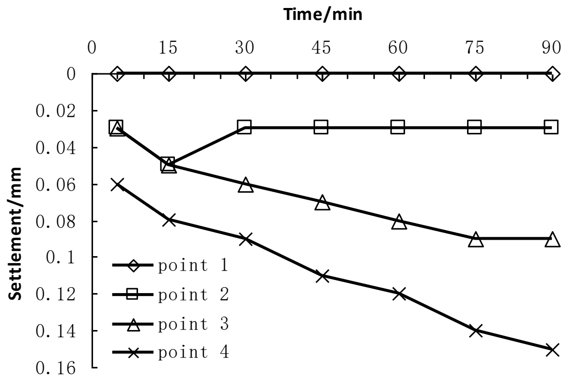

FIGURE 17 Variation of settlement at each point with time at 2kPa loading (condition 3)

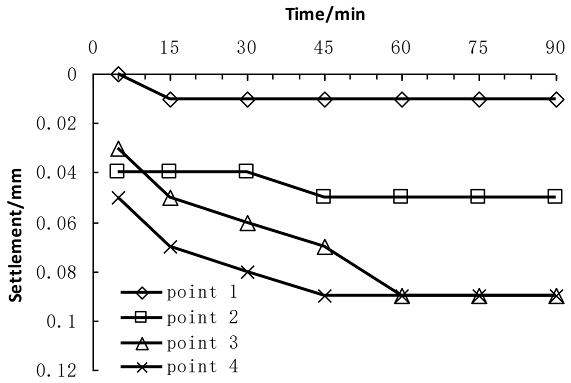

FIGURE 18 Variation of settlement at each point with time at 2.5kPa loading (condition 3)

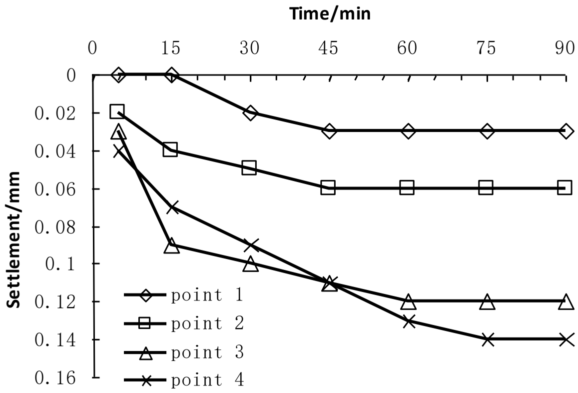

FIGURE 19 Variation of settlement at each point with time at 3.5kPa loading (condition 3)

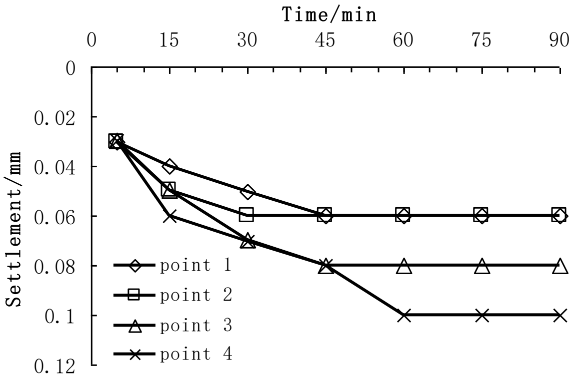

FIGURE 20 Variation of settlement at each point with time at 1.5kPa loading (condition 4)

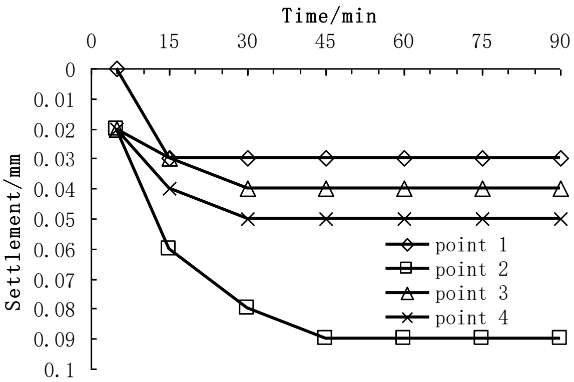

FIGURE 21 Variation of settlement at each point with time at 2kPa loading (condition 4)

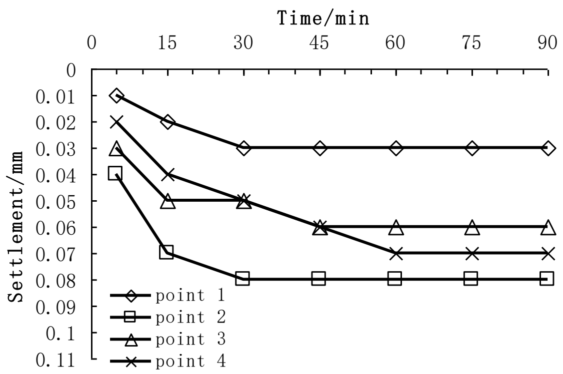

FIGURE 22 Variation of settlement at each point with time at 2.5kPa loading (condition 4)

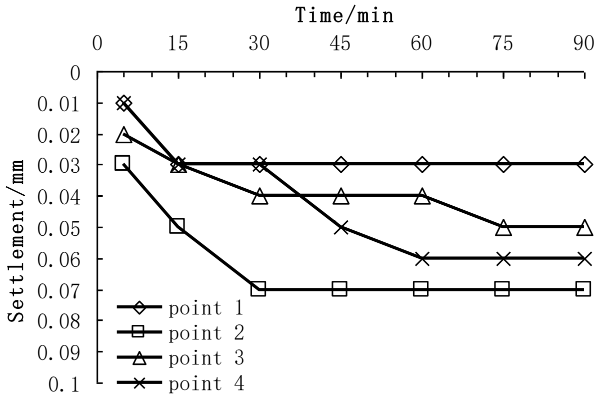

FIGURE 23 Variation of settlement at each point with time at 3.5kPa loading (condition 4)

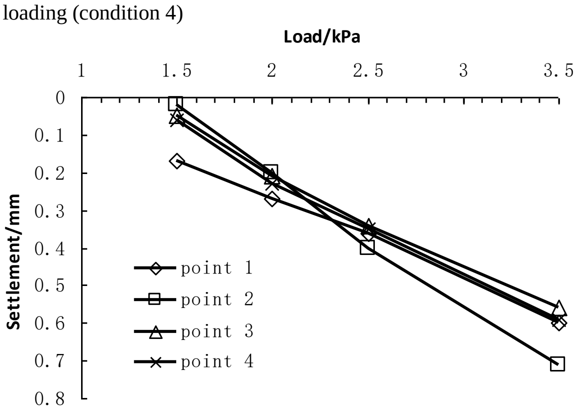

FIGURE 24 Variation of settlement with loading in condition 1

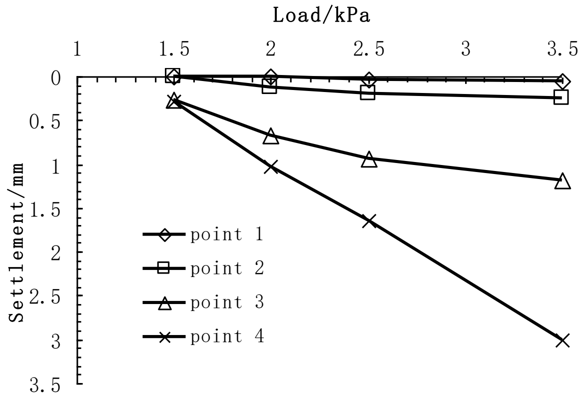

FIGURE 25 Variation of settlement with loading in condition 2

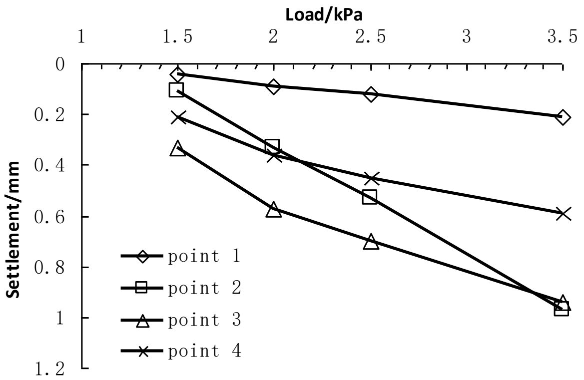

FIGURE 26 Variation of settlement with loading in condition 3

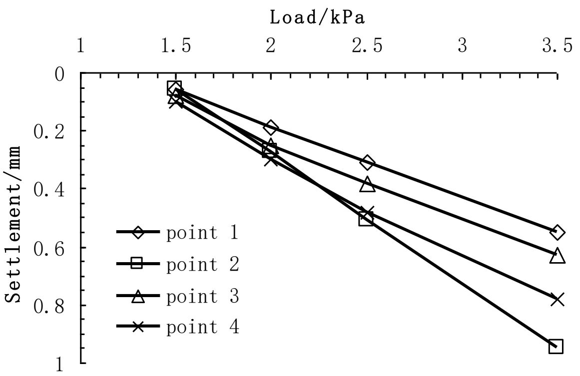

FIGURE 27 Variation of settlement with loading in condition 4

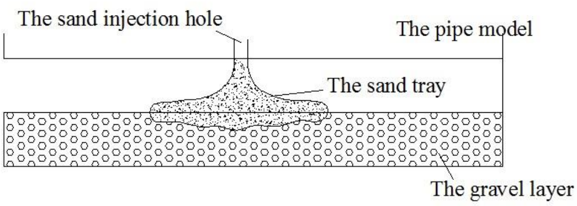

FIGURE 28 Interaction mechanism between sand and gravel

In back-silting condition (Condition 3), the compression of four measuring points under single-stage load changes over time are shown in Figure 16 to Figure 19. As is shown in Figure 16 to 19, the settlement of various measuring points under single-stage load varies, and there is no certain order of magnitude, particularly in Figure 18 and 19, the difference is obvious. Analysis of the reasons may be due to the base layer doped with silt layer, there is a certain unevenness. In the primary load, there are obvious differences in the stability of each measuring point compression. Under 2kPa, the second measuring point appeared a phenomenon, which was settlement at first, then float till stable finally. Analysis of the reasons may be the third and fouth test points larger settlement result in the second test point floating phenomenon. Each measuring point reached the compressive stable state at around 60 min and there was distinct difference in compression and stable timeframe for each measuring point with an average compressive modulus of 2.09MPa.

The compression of four measuring points under single-stage load changes over time in Condition 4 are shown in Figure 20 to Figure 23. As is shown in Figure 20 to 23, the difference of stable timeframe for compression for each measuring point under different loading in Condition 4 was significant. Large compression was witnessed after being stable for a period of time at some measuring points at 2.5kPa and 3.5kPa loading stages. The reason may be that the mass ratio of sand to water is relatively small. In theelastic stage, it can withstand a small load. As the load continued to increase, the plastic stage reached, the settlement continued to increase until stable. The overall average compressive modulus in Condition 4 was 2.99MPa, the average compression was 0.42mm for the loading stage of 1.5kPa~2.5kPa with an average compressive modulus of 2.33MPa; the average compression was 0.31mm for the loading stage of 2.5kPa~3.5kPa and the average compressive modulus of 3.15MPa.

3.2 COMPARISON OF DIFFERENT CONDITIONS

3.2.1 Comparison of Conditions 2 and 1

There were three main differences in Condition 2 compared with Condition 1: (1) the stable timeframe for compression was obviously extended at the settling end in each stage of loading; (2) the overall settlement at the settling end increased significantly where the average overall settlement in Condition 1 was 0.615mm and the number in Condition 2 reached as high as 2.1mm; (3) for the compressive modulus, The average compressive modulus at B End in Condition 1 was 3.49MPa and 0.97MPa in Condition 2, which was merely 27.8% of that in Condition 1.

The above phenomenon was mainly because that: A End was fixed in Condition 2. When subjected to impose loading, compressive force concentrated towards B End, resulting in large compressive force and settlement at B End (around 3 times). The settlement was steady and slow. Results from the experiment showed that when one end was fixed, the settlement at the other end would be magnified and the settlement timeframe was long.

For actual engineering, when one end is rigidly fixed and the other end is free, significant settlement will occur in the free end of the tube when grouting the tube which is disadvantage to the project.

3.2.2 Comparison of Conditions 3 to 1

Comparison showed that: (1) as is shown in Figure 24 and 26, in back-silting condition in Condition 3, the variation curve of settlement with time for each measuring point scattered compared with Condition 1 with no back-silting, suggesting that the existence of back-silting affected the uniformity of local compression; (2) from the aspect of settlement, the settlement in back-silting condition was above 0.9mm for points 2 and 3 but the maximum settlement was only 0.7mm in non-back-silting condition, suggesting that back-silting leaded to increased settlement of the foundation layer; (3) the average compressive modulus in back-silting condition was 2.09MPa which was smaller than 3.26MPa as in non-back-silting condition. The compressive modulus in Condition 3 was 64.1% of that in Condition 1.

Results from the tests showed that back-silting affected the compression of foundation layer on two aspects: back-silting increased the global condensability, reduced the compressive modulus and increased the settlement; meanwhile back-silting increased the global non-uniformity and the local difference of settlement in foundation layer was magnified.

The author thinks that the mechanism of the the silting influence is shown in Figure 29. As the silting layer is affected by the injection of sand, the silting appears unknown permeability, crowding and transferring, making the underwater situation more complex. A similar lubricant back silting up can be thought, resulting in the sand in the upper loads being more easy to embed and fill the pole of the gravel sand. Then it leads to deeper range. So the existence of the back silting increases the whole presence of plastic cushion, extends the sand overlapped time, increases the overlap volume sand and leads to the increase of the settlement stability time and settlement. At the same time, because of the effect of the silting, uneven regional compression is also increased magnification.

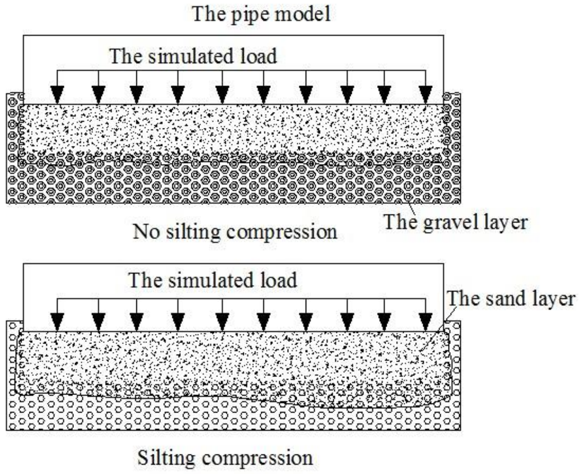

FIGURE 29 Silting influence schematic

Pan et al. [21] stated that silt located between sand foundation and soil in the foundation trench is the main cause to the large settlement of the tube section. Results from the study showed that silt between the gravel layer and sand layer caused relatively large settlement of the foundation layer.

3.2.3 Comparison of Conditions 4 and 1

There were three distinct differences between the two conditions: (1) during the compression process, when the loading was large, the data in Condition 1 did not vary after a stable state was reached but significant compression was witnessed in Condition 4 after a period of time in the stable state; (2) the compression varied linearly with the increase of load for both Conditions 1 and 4 but the points were more concentrated in Condition 1 and for Condition 4, the variation curves were similar in small loading but became scattered with the increase of loading; (3) the average compressive modulus in Condition 4 (2.99MPa) was smaller than that in Condition 1 (3.26MPa). The compressive modulus in Condition 4 was 91.7% of that in Condition 1.

The comparison suggested that sand-water ratio affect significantly the compressive characteristics and stability ofthe foundation layer. When the sand-water ratio was mall and the density of the sand grout was low, the upper limit of pressure to maintain the initial compressive capacity of the formed foundation layer was low. When the construction load exceeded the limit, local infiltration and crushing of sand layer towards gravel layer would occur and result in a large displacement. A new balance would be formed in time. The compression of points 3 and 4 in 2.5kPa and 3.5kPa loading stages with time explained clearly this phenomenon. However, the stable-variation-stable process affects significantly the global stability of the foundation layer and may lead to non-uniformed settlement which should be avoided during construction. It is recommended that the sand-water ratio be optimized through experiment.

3.3 MODEL TEST APPLICATION EXAMPLES

By 1:10 size shrinking model test, which was made four more later. Two of the compression layer were only gravel and two were sand. The test showed that the average compressive modulus of gravel layer is 0.67MPa and the sand layer is 0.8MPa.

The paper analyzed the settlement data of Shenjiamen tube tunnel. E1 pipe joints was chosen to calculate which was not affected by connector. Both of the end of the pipe were semi-soft and semi-rigid joints. The total thickness of the E1 pipe base layer turned out to be 1m (the thickness of grouting layers is 40cm and gravel layers is 60cm) and the average settlement of base layer was 24.33mm. The average construction load was 45.95kPa.

Method 1: The interactions between the gravel and sand mixed was ignored, calculating the sum of the settlement:

$$S = S_1 + S_2 \quad (1)$$

$$S_1 = Ph_1/E_1 \quad (2)$$

$$S_2 = Ph_2/E_2 \quad (3)$$

In the formula: S was a gravel base layer of the total settlement, S_1 was sand layer sedimentation, and S_2 was the layer of gravel sedimentation; h_1 was sand thickness values 40cm, h_2 was gravel layer thickness values 60cm; P was the total load of the upper part of base layer, taking 45.95kPa; E_1, E_2 respectively were sand and gravel layer compression modulus, taking 0.67MPa and 0.8MPa.

The total settlement of the base layer calculated was 64mm.

Method 2: Considering the interaction between the gravel layer of gravel mixed and taking into account the impact of the construction process and silt back, the summation method is used and the stratified settlement was as follows:

$$S = PH / E_{\text{complex}} \quad (4)$$

In the formula: E complex was a base layer of a composite compression modulus equivalent, taking

3.41MPa. *H* was the total thickness of the base layer, taking 1m.

The total settlement of the base layer calculated was 13.5mm.

Method 3: Considering the interaction between the gravel layer of gravel mixed and taking into account the impact of the construction process and silting back, Elastic mechanics calculations were used and results were as follows:

$$s = \omega \frac{(1/\ \mu^2)b}{E_{back\ silting}} p \tag{5}$$

In the formula: ω was affected by the settlement coefficient, taking 1.68; *b* was the width of the rectangle load, taking 1.15m; μ was Poisson's ratio, taking 0.35; *P* was the upper total load of the base layer; *E* back silting was the overall compressive modulus, taking 2.335MPa.

The calculated total settlement of the base layer was 33mm.

Method 4: Considering the interaction between the gravel layer of gravel mixed and taking into account the impact of the construction process and silt back, the summation method is used and the stratified settlement was as follows:

$$S = PH / E_{back\ silting} \tag{6}$$

In the formula: $E_{back\ silting}$ was the overall compressive modulus, taking 2.335MPa; *H* is the total thickness of the base layer, taking 1m.

The calculated total settlement of the base layer was 19.7mm.

TABLE 1 The settlement calculation method base layer shenjiamen comparison immersed tube tunnel

	Method 1	Method 2	Method 3	Method 4
The type of method	hierarchical summation	hierarchical summation	Elastic	hierarchical summation
Base layer compression modulus *E*（MPa）	0.67(sand)/ 0.8(gravel)	3.41	2.335	2.335
The total settlement of the base layer (mm)	64	13.5	33	19.7
The actual base layer average settlement (mm)	24.33			
Comparison of theoretical and practical	Too large	Too small	Too large	Match
Reason	Gravel mixed are not considered	The effect of siltation was not considered	Assuming the foundation for the elastic foundation is inconsistent with the actual	Using hierarchical summation method, and taking into account the compression preliminary soil

The base layer of Shenjiamen immersed tube tunnel was treated by grouting measured settlement (see Table 1), the resulting sedimentation method 4 was more consistent compared with the measured settlement. In all, this article has some reliability test results.

3.4 DISCUSSION ON FURTHER STUDY

This article did not consider the effect of underlying soil layer. Using a plate instead of soil, but also did not consider deposition of gravel between layers and underlying soil layer. The base layer compression characteristics obtained with the actual circumstances has differences.

The data of every condition obtained in this article was formed in the same material dimensions and perfusion pressure, which you can compare with each other. Not only the density of the base layer during the compression and after the compression is measured, but the base layer modulus of resilient is measured after unloading during the test. It leads to the test results reduce compared with other tests.

The selection of test materials and simulation technology mainly takes into account the aspects of feasibility. The differences exist between the model and the actual project which the model relys on, leading to the results that it can not be compared with the actual project.

Further research is recommended to study on the basis of this article.

4 Conclusions

1) Compared with the condition that two ends are free, in the condition that one end is fixed and the other is free, the settling end is more likely to settle (with 3 times of the amount of settlement). The compressive modulus was only 27.8% and the time for settlement to stable was extended obviously.

2) Compared with non-back-silting condition, back-silting increased the global condensability of the foundation layer, reduced the compressive modulus (64.1%) and increased the amount of settlement; moreover it increased the overall non-uniformity and magnified the local difference of settlement in the foundation layer.

3) The condensability of the foundation layer formed by low density sand grout was higher, which

reduced the compressive modulus. When the load exceeded the limit, further settlement would occur in the foundation layer which is detrimental towards the global stability of the foundation layer.

4) On the whole, the compression performance of the immersed tube tunnel's base layer is poor. Great compressive deformation was produced under load. Comparing the effect on the settlement of foundation layer or compressive modulus, the factor of one end fixed and one end free was most significant, followed by back-silting and reduced sand-water ratio. These factors should be considered during the design and construction of immersed tube tunnel.

Acknowledgements

This work was financially supported by The Chinese National Natural Science Foundation (51178428), Zhejiang Provincial Natural Science Foundation of China under Grant No. LZ12E08001, The Young Academic Leaders Academic Climbing of Zhejiang Province Colleges of China (pd2013454).

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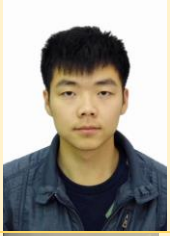

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