Foundation settlement prediction of immersed tunnel based on monitoring data

Bin Li 1,2,3,4,5*, zhijun Chen1,3,4,5, Zhao Liu1,3,4,5
1Tianjin Port Engineering Institute Ltd. of CCCC First Harbor Engineering Company Ltd., Tianjin, 30222, China;
2Key Laboratory of Ministry of Education for Geomechanics and Embankment Engineering, Hohai University, Nanjing, 210098, China;
3Key laboratory of port geotechnical engineering, ministry of communications, PRC Tianjin, 30222, China;
4Key laboratory of port geotechnical engineering of Tianjin, Tianjin, 30222, China;
5CCCC First Harbor Engineering Company Ltd., Tianjin, 30222, China;
*Corresponding author’s e-mail: lee_binbin@163.com

Abstract. Based on the actual project, through the simulation of the construction steps and the inversion analysis of the monitoring data, the settlement of immersed tube tunnel is predicted. Through analysis, it is found that the whole foundation soil layer of immersed tube tunnel appears rebound, the maximum rebound is 0.045m, and the maximum rebound appears on the surface of the foundation trough. As the depth of the soil deepens, the rebound decreases gradually. After the construction is completed, the vertical strain curves of the immersed tube model are all distributed in a saddle shape. After the immersed tube strain is stable, the strain variables of the immersed tube increase with time basically unchanged. 1000 days after the completion of backfilling, the maximum post-construction settlement is 0.0035m.

1. Introduction
A cross-sea passage project is a large-scale cross-sea passage connecting Hong Kong special administrative region, zhuhai city, guangdong province and Macao special administrative region. In order to accurately predict the settlement of immersed tube tunnel constructors and within a period of completion of construction, this paper simulates and analyzes the deformation characteristics of the foundation, and predicts the future settlement based on the measured data at the time of settlement.

Laboratory experiments were conducted on the density, cohesion and internal friction Angle of various types of soil.

Because of a soil layer contains multiple earth drilling, is one of soil density, cohesive force and Angle of internal friction of soil is the arithmetic mean of the sample results, poisson's ratio of reference is based on the site added after the engineering geological investigation report, written by deformation modulus value reference related information about the compression modulus and the modulus of resilience in the mathematical relationship between comprehensive tentatively. The modulus and density of backfill and immersed pipe are determined by reference to the selection of backfill parameters in relevant data. The value of poisson's ratio is determined by referring to JTG D70 and empirical value in highway tunnel design code, and the specific calculation parameters are shown in table 1.
Table 1. Physical parameters of soil

| Soil layer name | deformation modulus (MPa) | poisson's ratio | Cohesion(kPa) | internal friction Angle (°) | floating weight(kN/m²) |
|-----------------|---------------------------|----------------|--------------|-----------------------------|-----------------------|
| Silt            | 10                        | 0.430          | 7.2          | 19.9                        | 6.3                   |
| Silty clay      | 100                       | 0.400          | 54           | 30.0                        | 8.4                   |
| Clay sand       | 150                       | 0.296          | 50           | 18.5                        | 8.7                   |
| Clay sand inclusion | 200               | 0.300          | 18           | 38.3                        | 10.5                  |
| Coarse sand     | 130                       | 0.270          | 21           | 36.2                        | 10                   |
| Med-sand        | 160                       | 0.290          | 20           | 37.8                        | 10.3                  |
| Backfill soil   | 300                       | 0.25           |              |                             | 14                    |
| tube section    | 3000                      | 0.2            |              |                             | 0.01                  |

2. Numerical simulation of stress path of foundation soil

In order to better reflect the actual situation, the "life and death" unit is used to simulate the original consolidated soil, excavation and backfill of the foundation pit. The initial stress state is the dead weight stress of soil.

The boundary conditions of this model simulation are as follows:

1) The soil at the left and right boundary of the model is far away from the immersed pipe. Since construction factors have little influence on the stress and strain brought by the model, the horizontal displacement is not considered, so horizontal displacement constraint is applied to the left and right boundary;

2) Since the lower part of the model is strongly weathered granite, the elastic modulus is relatively large, and the deeper strata have little impact on the settlement, so the vertical displacement constraint is applied to the calculated depth boundary, regardless of its vertical displacement.

2.1. Model construction and mesh generation

According to the different materials of each part in the model, such as the original soil layer, immersed pipe, backfill and cushion, it is divided into different unit groups, and then grid generation is carried out for each unit group. In the mesh generation process of this model, in order to avoid the convergence of model calculation, the method of first dividing the line, then dividing the surface, and then manually adjusting the mesh density and shape in local areas was adopted. Among them, the mesh density of soil layer is mostly around 1 m, and the mesh density of immersed pipe and its vicinity is small, which can provide detailed data for analysing the interaction between tunnel pipe and foundation and the distribution of basement stress.

![Diagram of typical cross-section model of immersed tube tunnel](image-url)
As shown in figure. 1, the typical cross-section model grid diagram of immersed tube tunnel is shown. The construction steps of the tunnel are completely simulated by numerical calculation, that is, the whole construction process of gravel cushion, immersed tube sinking, pipe side backfilling, pipe top backfilling and backfilling after foundation pit excavation. Through the preliminary calculation, numerical simulation can be arbitrary point in the soil in the original soil, the excavation and backfill stress value of the three different working conditions, in turn, determine the stress path of the arbitrary location, and provide specific for indoor GDS triaxial test and unloading value, namely the original soil layer of test stress value of the first stage loading value, after the excavation unloading stress value is calculated by the test after the stress value of the corresponding backfill after stress value is calculated by the load test stage of stress value again.

2.2. The simulation analysis

As can be seen from the cloud map of relative displacement of section E after excavation, there is a certain rebound phenomenon in the soil after excavation, and the rebound deformation decreases gradually with the increase of depth. The maximum rebound deformation in contact with the excavation surface is 0.069m (the positive sign indicates the upward direction). At the bottom of the soil layer, there is no rebound phenomenon, and the relative displacement at the left and right interface of the cross section is negative, with slight recompression.

After excavation, the relative displacement on the excavation foundation groove is unequal and roughly arched. The rebound deformation is the largest at the center, and decreases symmetrically on both sides of the excavation slope foot. The rebound amount at the excavation slope foot is the smallest. There is a difference of 0.0024m between the rebound quantity at the center of the excavation bottom of section E and that at the foot of the excavation slope.

After backfilling and backfilling, the stress at each point on the bottom of the base trough is negative, and the soil mass is under downward pressure, and the stress value of the middle part is larger than that of the other parts.

According to the bottom of the back silting after excavation displacement curve and the bottom of the back silting after excavation stress graph, you can see that because of the immersed tube stiffness is very big, basic not happen flexural deformation, the settlement of basement each point is almost the same, and the basement of the additional stress is lesser, back silting after excavation are in saddle the underside of the displacement curve and stress curve distribution. In order to realize the stress path simulation test of soil under different working conditions, such as excavation, tunnel tube sinking, pipe jacking and so on, the stress values of different depth soil under different working conditions are obtained from the finite element numerical simulation results, and then the K0 consolidation test and stress path test are carried out on the soil samples.

E section construction completion after a period of time will be 15 m deep channel excavation, to unload again of foundation, the foundation in the channel excavation will happen again after springback phenomenon, if the amount of springback in the greater influence on the foundation of the tunnel, the numerical simulation of stress path foundation soil settlement result table query E cross section corresponding to different depth of soil and the stress value of the working condition of each stage according to the calculated value of GDS stress path triaxial test.

According to the data collected from the GDS triaxial test, the stress-strain diagram is drawn to obtain the compression modulus, rebound modulus, recompression modulus and rebound modulus corresponding to consolidation, excavation, backfill and excavation at each stage. The results can guide and adjust the parameters of numerical calculation.

Formed at different depth of silty sand layer with a certain point of stress path diagram and the stress strain curve and linear fitting these points stress strain curve of silty sand at different stages of modulus, which can represent different modulus of soil under the condition of different conditions, as the next step of numerical calculation parameters, numerical calculation, the numerical calculation and the result was compared with before the results of numerical calculation. The stress-strain curves corresponding
to each stage at different points of different soil layers were fitted, and the modulus values corresponding to different working conditions of each soil layer were summarized in table 2.

| The soil            | Compression modulus(consolidation) (MPa) | rebound modulus(excavation) (MPa) | recompression modulus (MPa) | Re-rebound modulus (MPa) |
|---------------------|------------------------------------------|-----------------------------------|-----------------------------|--------------------------|
| Coarse sand         | 12.17                                    | 171.42                            | 101.24                      | 136.27                   |
| Silty sand          | 25.53                                    | 145.69                            | 97.73                       | 108.13                   |
| Medium sand layer   | 30.80                                    | 187.96                            | 82.75                       | 124.78                   |
| Gravel sand         | 34.48                                    | 213.46                            | 98.85                       | 118.22                   |

Based on the above GDS triaxial stress path test data, in the numerical simulation calculation, the initial consolidation of the soil adopts the deformation modulus value, the first elastic modulus value is adopted in the excavation stage, the construction process adopts the recompression modulus value, and the later channel excavation adopts the elastic modulus value obtained from the later unloading.

3. The section simulation

Because soil deformation process is very complex, and its stress strain curve is not a simple linear deformation, this article through the GDS triaxial apparatus to E in situ soil of different depth section stress path simulation experiment was carried out, and get the modulus of resilience in the process of excavation unloading of soil, the soil and compression modulus, for the next step the stress path of numerical simulation provide strong variable parameters, so as to accurately calculate the deformation of soil. Numerical calculation of section E completely simulates the construction steps of the tunnel, that is, the whole construction process of gravel cushion, sinking pipe, pipe side backfilling, pipe top backfilling and backfilling shall be carried out after excavation of the foundation pit.

![Figure 2 relative displacement of excavated soil](image)

Figure 2 is displacement nephogram of the consolidation of soil after excavation, can be seen from the diagram, at the bottom of the immersed tube after excavation of vertical displacement are all positive, namely the soil as a whole appear rebound, maximum rebound amount is 0.045 m, the largest of rebound appeared in the groove surface, with soil depth deepening, the rebound amount decreases, does not rebound at the bottom of the soil layer is the most basic displacement.

After channel excavation, the maximum rebound amount of the base is 0.021m, and the difference of the rebound amount of the base is very small, and the average rebound amount is also 0.021m. The rebound law and law of foundation soil rebound when excavation close, just the rebound amount reduced, the discharge amount of about 30% of the amount of excavation unloading when the rebound amount is 50% of the initial rebound, due to the construction, after the completion of the foundation soil
consolidation degree has not yet reached the original state of degree of consolidation of soil, so the unloading again after rebound ratio is greater than the initial unloading ratio.

4. Comparative analysis of numerical calculation and monitoring data

The whole construction process of consolidation, excavation, backfilling and backsilting was simulated for the typical cross section E. The base course of section E does not contain clay layer, and from the top of the base groove bottom to the bottom is medium fine sand, coarse sand, medium sand and gravel sand. However, the difference between section E and other sections is that after the backfilling of section E, there is the process of channel excavation, so that the external load acting on the base can be unloaded again.

Figure 3 shows the vertical strain curves of each point at the bottom of section E after backfilling. As can be seen from the figure, the corresponding numerical calculation result curve is basically similar to the linearity of the monitoring data curve in both cases, and the monitoring data is lower than the calculation curve. After construction is completed, under the action of overlying water and backfilling soil, the vertical strain curves of the immersed tube model are all distributed in saddle shape. The strain values of the two sides of the immersed tube and part of the partition wall are negative and the deformation is downward.

![Figure 3 vertical strain of the bottom of section E after construction is completed](image)

In the process of 1000 days after the completion of backfilling construction, the displacement and settlement at the bottom of the base trough change curve with time. It can be seen from the curve that, after the completion of construction, the change of the base recompression amount is small, and the recompression amount is mainly completed in the loading process. After reaching the stable speed, the settlement amount increases slightly in the early stage, and then basically tends to be flat. 1000 days after completion, the maximum settlement after construction is 0.0035m. It can be seen that the post-construction settlement of section E is the smallest, which is caused by the natural base of section E.

5. Conclusion

(1) the whole soil layer appears rebound, the maximum rebound is 0.045m, and the maximum rebound occurs on the surface of the base trough. As the depth of the soil deepens, the rebound decreases gradually. After channel excavation, the maximum rebound of the base is 0.021m, and the difference of the rebound of the base is very small.

(2) after construction is completed, under the action of overlying water and backfilling soil, the vertical strain curves of the immersed tube model are all distributed in a saddle shape. The strain values of the two sides of the immersed tube and part of the partition wall are negative and the deformation is downward.

(3) 1000 days after the construction backfill is completed, the change in the base recompression is small, and the recompression is mainly completed during the loading process. After reaching the stable speed, the settlement increases slightly in the early stage, and then basically flattens out, and the maximum settlement after construction is 0.0035m.
Acknowledgments
This research was financially supported by the Science and technology and project of China Communications Construction Corporation (No. 2017-ZJKJ-PTJS08). Key Laboratory of Ministry of Education for Geomechanics and Embankment Engineering, Hohai University (No. 201708).

References
[1] Brand E. W. Brenner. R.P (1981) Softelay engineering, Elsevier Scientific Publishing Company, Amsterdam.
[2] Duncan. J. M. Chang. C.Y (1970) Nonlinear analysis of stress and strain in soils. J. Soil Mechanics of Foundation, 637–659, ASCE.
[3] Bose, N. B. and Soni, (1998) Parametric Study of abraded Cutby Finite Element Method. Puter and geoteelmies. 22: 1–7.
[4] J. M. Duncan, C. Y. Chang. (1970) Nonlinear Analysis of Stress-strain in Soils. Journal of the Soil Mechanics and Foundations Division. 5:1629-1653.
[5] D.C. Drucker, W. Prager. (1952) Soil Mechanics and Plastic Analysis or Limit Design. Quarterly of Applied Mathematics. 10(2):157-165.
[6] D.C. Drucker, R.E. Gibson, and D. J. Henkel. (1957) Soil Mechanics and Work-harding. Theories of Plasticity. 122: 338-346.
[7] K. H. Roscoe, A. N. Schofield, and C. P. Wroth. (1958) On the Yielding of Soils. Geotechnique. 8(1):22-53.