A Study on the Settlement of Gravel cushion and DCM Piled Compound Foundation

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Abstract. The DCM pile is applied in immersed tunnel foundation improvement first time at home in the mega project of Shenzhong Link with improved ground areas over 700000 m\(^3\). The compound foundation composed of gravel cushion and DCM piled foundation settlement law is not definite. To explore this law loading plate test in place on site is carried out and the test results show: (1) under the first order of load effect the settlement amount of the compound foundation accounts for over 60\% of the total settlement, the modulus of compression of the gravel cushion is 1.5MPa being approximately 10\%~20\% of normal modulus of compression; (2) under other loading effects the final deformation of compound foundation settlement curve shows stable state with the modulus of compression of the gravel cushion in range of 4.5~12MPa which is equivalent to the normal value. The numerical analysis for purpose of the testing shows that the gravel cushion settlement accounts for larger proportion being 58.57\% of the total settlement and the gravel cushion thickness, density, residual layers fallen in DCM dredging, all may be factors affecting settlement. Hence it is suggested to enhance study on the workmanship of the tunnel bed formation in order to improve the bed rigidity and anti-deformation ability.

1. Introduction

Shenzhong Link is the mega project which uses deep cement mixing(DCM) piled foundation at sea as immersed tunnel(IMT) foundation improvement measure first time in China and in this project the total areas improved with DCM has exceeded 700000 m\(^3\) in large scale and the improved area included deep thick soft ground in sand collecting pit under west island ramp, the soft silty clay stratum under middle tunnel section. According to the design requirement the DCM improved depth shall extend down to top surface of totally weathered rock by penetrating various types of stratum and the construction technique and control is highly demanded[1-4].

Scholars at home and abroad have done a lot of research on the settlement mechanism of immersed tunnel[5-12]. Controlling the differential settlement between soft foundations is the most important task in the design of immersed tunnel. The DCM method used as IMT soft ground improvement technique was first time used in Busan-Geojedo IMT in which the DCM pile diameter is 1m and four piles form a group with overlapping 10cm and diameter of 1.9m and the replacement rate is 40\% with
local replacement of 61%[13]. In the Shenzhong Link DCM is extensively used at sea in China as the IMT foundation improvement means. The design of compound foundation consisted of gravel cushion and flaky stone level adjusting layer and DCM outside the island and in island rotary jet grouting pile is applied in west island ramp section and single DCM pile is the laid out with single pile diameter of 1.3m, overlapping 0.3m, clustered four piles with diameter 2.3m and single pile is arranged at spacing of 3m longitudinally. The piles under the immersed tunnel and backfill protection has three kinds of transverse spacing respectively as 3m, 4m, 5m subject to the size of loading and overall replacing rate is in range of 41%~47.4% and arrangement is shown in figure 1.

DCM is often used in the treatment of wharf, bank slope, seawall and soft foundation. Its mechanism of force and deformation is relatively clear[14-18]. As the foundation treatment scheme of immersed tunnel, DCM must form composite foundation with gravel cushion at the bottom of the IMT. In addition, the foundation works is hidden and covered, especially the under water foundation and quality problems may occur [19-20]. Shenzhong Link as important as the State key construction project in “the thirteenth five-year plan” and as well as the mega project attracting high attention at home and abroad cannot afford tiny risk of works quality and deformation. In spite of the fact that many scholars at home and abroad have conducted many studies on the mechanical deformation characteristics of the gravel cushion[21-25], the reference materials on the study on settlement features of the compound foundation consisted of DCM and gravel cushion are rare[26-27]. Therefore, in the earlier stages of construction drawing joint design and construction under water loading plate testing carried out to investigate the settlement of DCM compound foundation at sea environment was highly necessarily important.

To solve the problem of unclear settlement law of DCM compound foundation loading plate test was carried out on site to investigate the settlement feature of DCM and gravel cushion compound foundation and the test results were analyzed and sorted out. According to the test results 3D numerical reverse analysis of the loading plate test was also conducted to further explore the settlement feature of the DCM compound foundation so as to provide feasible support to the design solution.

2. Test scheme and method

2.1. Test scheme
In place loading plate testing was carried out to test the bearing capacity of compound foundation improved with DCM under the west island ramp section in Shenzhong link and the test had to be carried out after DCM reached age of at least 60 hours. Two tests on bearing capacity of the compound foundation were carried out and the specific test parameters are shown in following table.

### Table 1. DCM test scheme.

| Test SN. | Pile quantity layout | Bearing areas ($m^2$) | Target bearing capacity (kPa) | Max. test bearing (kN) | Cement addition required ($kg/m^3$) |
|---------|----------------------|-----------------------|------------------------------|------------------------|-----------------------------------|
| A1      | 4 piles, 3mx4m layout | 48                    | 158.6kPa                     | $\geq$7612.8           | Cement addition with tested area as per 320kg/m³ |
| A2      | 4 piles, 3mx3m layout | 36                    | 211.1kPa                     | $\geq$7612.8           |                                                   |

2.2. Test system formation

(1) loading plate

The loading piece concrete block with the specific tonnage requirement for the loading piece is: the total loading on the compound foundation shall be no less than 761.3 tons and loads are added at least at 4 levels. Loading piece for the caisson must follow the requirements of 8m ($L$) × 6m ($W$). The loading pieces shall keep stability subject to wave loading effect and it is not preferred that the loading piece appears above water surface.

(2) Compression bearing plate

The pressure plate shall have base in size of 6m×8m and shall be formed with welded molded steel and steel plate. Test table holding instrument and the displacement limiting device between loading pieces shall be placed on the pressure bearing plate.

(3) Hanging frame and reference plate

The hanging frame is installed at sides of the loading block for hanging reference plate system. The net spacing between the reference plate and the bearing plate is 6.0m and shall meet 3 times plate width required by the specification. The hydrostatic water level shall be installed as the reference point on the reference plate.

(4) Soil pressure box installation and pile top level confirmation
Settlement testing points of group A1 and A2 and locations of soil pressure box embedment are shown in figures 3 and 4 respectively. After the pile litter is removed the soil pressure boxes in A1 and A2 tested areas are embedded as per the drawing. The soil pressure boxes T1~T7 have their respective embedment levels of -17.65m, -17.97m, -17.93m, -17.88m, -17.99m, -17.88m and -17.54m while the soil pressure boxes T8~T14 have their respective embedment levels as -17.69m, -17.72m, -17.73m, -17.52m, -17.82m, -17.81m and -17.76m. The vertical level of the soil pressure boxes on top of DCM are taken as the pile top level of DCM in that the place.

2.3. Test flow
Test flow is shown as follows:
(1) Loading block positioning.
(2) Loading system installation in the test.
(3) Reference plate, loading plate touch the gravel cushion.
(4) Loading in 4 levels.
(5) Unloading in 3 levels.
(6) remove testing system.

3. Test analysis
3.1. Test results
The settlement amounts measured at four corner points in group A1 are shown in table 2. The average value is taken to plot load-settlement curve diagram as shown in figure 5.

| Loading level | load (kPa) | J3   | J4   | J5   | J6   | 平均 |
|---------------|------------|------|------|------|------|------|
| Step 1        | 47.1       | 61.1 | 44.7 | 12.9 | 47.8 | 41.6 |
| Step 2        | 84.2       | 73.1 | 53.8 | 15.9 | 56.2 | 49.8 |
| Step 3        | 121.2      | 83.9 | 66.3 | 21.7 | 63.8 | 58.9 |
| Step 4        | 158.3      | 92.8 | 76.8 | 25.7 | 68.4 | 65.9 |
| Unloading step 4 | 121.2 | 92.7 | 76.4 | 25.8 | 68.3 | 65.8 |
| Unloading step 3 | 84.2 | 92.2 | 75.2 | 25.3 | 67.6 | 65.1 |
| Unloading step 2 | 47.1 | 91.9 | 73.6 | 25.5 | 67  | 64.5 |
| Unloading step 1 | 0    | 89.9 | 69.9 | 27.7 | 62.3 | 62.5 |
Figure 5. Group A1 Test Loading/Unloading-Settlement Curves.

In test A1 under the step 1 load of 47.1kPa the settlement is 41.6mm, and under step 2 load (37.1kPa) the settlement is 8.2mm under that single step load, under step 3 load of (37.1kPa) the settlement is 9.2mm under that single step, under step 4 load of 37.1kPa the settlement is 7.0mm of that single step load. In test A1 under the actions of total load of 158.3kPa, the total settlement is 65.9mm, of which the settlement under step 1 accounts for 63.13% of the total settlement. In process of unloading the rebounding of settlement under various respective loading steps is comparatively small and rebounding amounts under from step 4 loading throughout to loading step 1 are respectively 0.13mm, 0.72mm, 0.58mm, 2.05mm and the total rebounding amount is 3.48mm and the rebounding under the final step loading accounts for 58.91% of the total rebounding.

The compression modulus at the four corner points back calculated based on the test results are shown in table 3.

| Load step kPa | NE J3 | NW J4 | SWJ5 | SEJ6 |
|---------------|-------|-------|------|------|
| 0~47.1        | 1.2   | 1.5   | 6.5  | 0.5  |
| 47.1~158.3    | 9.5   | 9.5   | 40.0 | 12.0 |

The settlement at the four corner points in test A1 are shown in table 4 and its average value is taken to plot the load-settlement curve as shown in figure 6.

| Load step (kPa) | J3 | J4 | J5 | J6 | 平均 |
|-----------------|----|----|----|----|------|
| Step 1          | 62.8 | 52  | 50.3 | 78.6 | 78.7   | 64.9 |
| Step 2          | 112.3 | 63.6 | 55.8 | 103.7 | 114.5 | 84.4 |
| Step 3          | 161.7 | 72.2 | 62.1 | 116.3 | 133.5 | 96.0 |
| Step 4          | 211.1 | 84.9 | 68.3 | 125.2 | 152.2 | 107.7 |
| Unloading step 4 | 161.7 | 84.9 | 68.3 | 125.2 | 152.2 | 107.7 |
| Unloading step 3 | 112.2 | 85.0 | 67.9 | 125.2 | 152.1 | 107.6 |
| Unloading step 2 | 62.8 | 84.9 | 67.3 | 125.0 | 150.6 | 107.0 |
| Unloading step 1 | 0 | 83.6 | 66.1 | 124.6 | 149.4 | 105.9 |
In test group A2, under load one of 62.8kPa the settlement is 64.9mm; under load step two (49.4kPa) single step settlement is 19.5mm; under load step three (49.4kPa) single step settlement is 11.6mm; under load step four (49.4kPa) single step settlement is 11.6mm. In test group A2, under actions of total loads of 211.1kPa the total settlement is 107.7mm. The settlement under step one load accounts for 60.26% of the total load. In unloading process the settlement rebounding under various respective loading is relatively small and the rebounding amounts for each loading step from step four throughout step one are 0.0mm, 0.10mm, 0.60mm, 1.03mm respectively and the total rebounding is 1.7mm and the rebounding of last step accounts for 60.59% of the total rebounding.

The compression modulus of the four corner points back calculated based on the test data are shown in table 5.

| Load step kPa | NEJ3 | NWJ4 | SWJ5 | SEJ6 |
|---------------|------|------|------|------|
| 0~62.8        | 1.9  | 1.85 | 1.45 | 1.45 |
| 62.8~211.1    | 12   | 30   | 4.50 | 4.50 |

3.2. Test results analysis

The rest results indicate that the settlement values of the four corner points of gravel cushion are considerably different. The gravel cushion compression under action of the step one loading is relatively and is caused by high hardship of under water construction by cause analysis and mainly by the following two problems:

(1) Problem of sunken residue on pile top

After completion of final dredging of foundation trench in test area sea sweeping measurement is carried out in the area under test. On basis of the divers exploration the average residue layer thickness after dredging can be calculated to be approximately 46cm and this residue fallen blocks were formed during grab dredging.

Since DCM has reached strength of or over 60 or days when the grab dredged the surface layer of DCM the levels of DCM became uneven with different sizes of residual pieces which called for close attention. In the given test pile residuals are cleaned and removed by diver work and the all the pile waste within tested area was removed except for large pile waste in local places. But for the dredging
operation with grabs below tunnel bottom the constructor shall make sure the feasibility of construction method of reducing and removing fallen waste pieces.

(2) Gravel cushion thickness uneven and added filling process

After the soil box is embedded stones are filled with dredging at sea and gravel cushion is leveled under water by hand. In test group A1 the gravel cushion has average thickness about 58cm and 103cm in group A2.

The above gravel cushion thickness exceeds greatly the test design thickness of 30cm which indicates the hardship of underwater leveling and the large difference between accuracy by manual leveling and by leveling vessel.

After manual placement and leveling firstly place the step one load for 2 hrs and observe the level degree of the loading block and carry out commissioning of relevant testing equipment installed. During this process uneven sign of the gravel cushion was found both in test A1 and A2 and filling was added in both tests.

Since no surcharge was carried out after supplementary filling measuring work was carried out directly in test A1 and the modulus and thickness of the gravel cushion may be different within loading plate area which further affected level degree of the test.

4. In place test value back analysis

4.1. Style and spacing

soil layer and structure parameters shown as below:

| Soil stratum | Structure model | Saturation and unit weight kN/m³ | c' kPa | phi' o | Stress index m | Eoed MPa | E50 MPa | Eur MPa | vur |
|--------------|----------------|---------------------------------|--------|--------|----------------|----------|---------|---------|-----|
| 21- silt     | HS             | 15.23                           | 6.69   | 8.04   | 1.00           | 1.57     | 1.57    | 4.71    | 0.2 |
| 22- silt     | HS             | 15.72                           | 8.01   | 9.17   | 1.00           | 1.64     | 1.64    | 4.92    | 0.2 |
| 224- silty   | HS             | 19.25                           | 9.80   | 22.00  | 0.5            | 10.00    | 10.00   | 30.00   | 0.2 |
| 23- silty    | HS             | 14.33                           | 6.63   | 11.17  | 1.00           | 2.33     | 2.33    | 6.99    | 0.2 |
| 36- medium   | HS             | 21.10                           | 9.00   | 28.20  | 0.5            | 8.40     | 8.40    | 25.20   | 0.2 |
| 37- coarse   | HS             | 20.90                           | 7.40   | 28.40  | 0.5            | 10.29    | 10.29   | 30.87   | 0.2 |
| 61-21-       | HS             | 20.30                           | 18.00  | 23.90  | 0.00           | 50.00    | 50.00   | 125.00  | 0.2 |
| sandy soil   |                |                                 |        |        |                |          |         |         |     |
| like high    |                |                                 |        |        |                |          |         |         |     |
| weathered    |                |                                 |        |        |                |          |         |         |     |
| granite      |                |                                 |        |        |                |          |         |         |     |
| flaky stone  |                |                                 |        |        |                |          |         |         |     |
| gravel       |                |                                 |        |        |                |          |         |         |     |
| cushion      |                |                                 |        |        |                |          |         |         |     |
| backfilled   |                |                                 |        |        |                |          |         |         |     |
| crushed      |                |                                 |        |        |                |          |         |         |     |
| stone        |                |                                 |        |        |                |          |         |         |     |
| DCM pile     | M-C            | 22                              | 500    | 30     | 160            | 34500    | 34500   | 50.00   | 0.2 |
| IMT structure| M-C            | 26.023                          | 34500  | 0.1    | 67             |          |         |         |     |
By the site test results the modeled gravel cushion is divided into four areas at average and by back analysis of site test results the modulus of the bed in the four areas in tests A1 and A2 are shown in table 3 and table 5.

Considering the set up of actual model and grid division the pile body is equivalent to round pile with pile diameter of 2.43m.

In loading case of A1 the top level of pile No.19 is -17.65m, -18m of pile No.11, -17.9m of pile 10 and -17.55m of pile 18. The average thickness of the gravel cushion is 60mm.

In loading case of test A2, the top level of pile No. 23 is -17.6m, -17.7m of pile No.15, -17.7m of pile No.14 and -17.8m of pile No.22. the average thickness of gravel cushion is 1000mm.

The calculation software used is plaxis3d and the pile body is simulated with real pile unit. The simulated water level takes design average water level of +0.52m. The simulated soil is draining material and pile is non-multiple hole material and the loading plate is equivalent to one rigid plate. The 3D model of loading cases in test A1 and A2 are shown in following figure.

![Computational model](image)

(a) loading case of A1. (b) loading case of A2.

Figure 7. computational model.

4.2. Comparison of settlement

The results comparison between loading case numerical value back analysis and site in place test settlement in A1.

![Load vs Settlement](image)

(a) NE corner. (b) NW corner.
Figure 8. The numerical back analysis and experimental comparison results of A1 working condition.

The results comparison between numerical value back analysis and site in place settlement:

Figure 9. The numerical back analysis and experimental comparison results of A2 working condition.

The comparison results between in place test and numerical calculation show that under different conditions of initial starting loading and subsequent loaded gravel cushion modulus the settlement law distribution in test and numerical simulation match well. In addition, with the increase of external loading the pile settlement accounts for larger proportion of the total settlement value. With the abnormal data eliminated under the maximum loading effect the settlement value of the gravel cushion accounts of about 58.57% of total settlement. Hence corresponding measures shall be taken to improve stiffness of the gravel cushion and reduce the overall settlement of the compound foundation.
5. Conclusion
In this paper such method as site testing and numerical calculation are applied in analysis of load-settlement variation law of IMT of gravel cushion and DCM compound foundation condition.

(1) The site test results show that under various loads steps in test A1 and A2 DCM compound foundation is featured with rapid occurrence of settlement and rapid convergence and the foundation deformation is stable and settlement curve varies in non-linear way. Under the step 1 load the corresponding settlement value is relatively large accounting for more than 60%. Through cause analysis this sign is caused mainly by uneven bed thickness placed manually and uneven modulus.

(2) Because construction deviations under the action of step one load the gravel cushion compression modulus obtained by back analysis in A1 are 0.5, 1.2, 1.8, 6.5MPa respectively and in A2 are 1.45, 1.45, 1.85, 1.9MPa. After eliminating abnormal data of 6.5MPa, the average is around 1.5MPa. During the loading process of step one the modulus of the gravel cushion is approximately 10%–20% of normal one.

(3) Under the actions of loads of other steps. the gravel cushion modulus obtained by back analysis in test A1 are respectively 9.5, 9.5, 40 and 12MPa while in test A2 are 12, 30,4.5 and 4.5MPa and most modulus are distributed in range of 4.5–12MPa, which is essentially consistent with the gravel cushion compression modulus of HZMB immersed tunnel[7]. Modulus 30–40MPa is basically assumed to be the rebounding recompression modulus of the gravel cushion.

(4) The results comparison between in place test and numerical calculation show that the considering the difference of gravel cushion modulus between initial loading and subsequent loading, the settlement law distribution trend shown in site test and numerical simulation match properly and the bearing capacity of DCM pile body meets design requirement. In addition, with the increase of external load the large proportion of settlement of piles occurred. By eliminating abnormal data the settlement value of the gravel cushion un maximum loading accounts for about 58.57% of the total settlement. Hence the solution must be found to the problem that lower initial modulus of surface bed appeared in sediment removal at pile top . Study on gravel cushion formation workmanship (vibration and compaction, leveling or preloading of drop pipe) shall be intensified to improve the stiffness and anti-deformation of the gravel cushion.

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References
[1] Wang Y.N, Xiong G. (2007) Application and current situation analysis of immersed tunnel technology. J. Modern tunnel technology, (04): 1-4.
[2] Li Y, Hans D. (2017) Technical difficulties and innovations of immersed tube tunnel of Hong Kong-Zhuhai-Macao Bridge. J.Southern Energy Construction, 4(02): 1-16.
[3] Xu G.P, Huang Q.F. (2018) Overall design of Shenzhen-Zhongshan River-Crossing Corridor Project.J. Tunnel Construction (English and Chinese), 38 (04): 627-637.
[4] Feng H.B, Su C.X. (2019) Research and analysis of foundation treatment methods for immersed tunnel.J. Modern tunnel technology, 56(01): 33-38.
[5] Schmid B, Grantz W.C. (1979) settlement of immersed tunnels. J. Journal of Geotechnical & Geoenvironmental Engineering, 105(9):1031-1047.
[6] Brand E. W. &Brenner R.P (1981) Softelay engineering, Elserier Scientifie Publishing Com Pomy, Amsterdam, 36-42.
[7] Grantz W C. (2001) Immersed tunnels settlement. Part1: nature of settlements.J. Tunnelling & Underground Space Technology, 16(3): 195-201.
[8] Grantz W C. (2001) Immersed tunnels settlement. Part2: case histories.J. Tunnelling & Underground Space Technology, 16(3): 203-210.
[9] Li J, Li F.Q, Li B.(2002) Computational analysis of settlement control of immersed tunnel.J. Journal of Zhengzhou University (Engineering Edition), (03): 94-97.
[10] Zhong H.H, Li S.G, Liu X.S, Zhou J, Cui J.H, Feng K.(2007) Review of immersed tunnel.J. Municipal Technology, (06): 490-494.
[11] Xu G.P, Su Q.K, Li Z.X, Liu H.Z. (2015) Key Technologies for Design of Overseas Extra-Long Immersed Tunnel.J. Highway, 60 (04): 1-7.
[12] Su Z.X, Chen S.Z, Chen Y, Su C.(2018) Discussion on Longitudinal Static Calculation of Immersed Tube Tunnel.J. Tunnel Construction (English and Chinese), 38(05): 790-796.
[13] Zhang Z.G, Fu B.Y, Liu X.D, Liu Y.P, Liu H.Z.(2018) Hong Kong-Zhuhai-Macao Bridge Immersed tunnel foundation bed type selection and general design. J. China Harbour Construction, 38(1):0034-05. (in Chinese).
[14] Leroueil S and Vaughan P R. (1990) The general and congruent effects of structure in natural soils and soft rocks. J. Geotechnique, 40(3):467-488.
[15] Gens A and Nova R. (1993) Conceptual bases for a constitutive model for bonded soils and weak rocks. C. Proc. 1st. Int. Conf. Hard soils and soft Rocks. 485-494.
[16] Huang J T and Airey D W. (1998) Properties of artificially cemented carbonate sand. J. Journal of Geotechnical Engineering, ASCE. 124(6):492-499.
[17] Kiyono Kasama, Hidetoshi Ochina and Noriyuki Yasufuku. (2001) On the stress-strain behavior of lightly cements clay based on an extended critical state concept. Soils and Foundations. 40(5):37-47.
[18] Wang C, Xu Y.F, Dong P. (2014) Working characteristics of concrete-cored deep cement mixing piles under embankments. J. Journal of Zhejiang University-SCIENCE A (Applied Physics & Engineering), Vol.15 (6), pp.419-431.
[19] Yu Huajin. (1999) Analysis of Construction Quality Problems of Cement Mixing Piles. J. Zhejiang Water Conservancy Science and Technology, (A07): 33-34.
[20] Chen F, Li H.T. (2015) Study on Construction Technology of Deep Cement-soil Mixing Pile in Huanghua Port Area. J. Journal of Geotechnical Engineering, 37 (s1): 156-160.
[21] Wei G, Wei X.J. (2012) Study on Long-term Settlement and Stress Behavior of Submarine Immersed Tube Tunnel. J. Municipal Technology, 30 (1): 61-63.
[22] Chen J.F, Zhou W.X.(2013) Foundation treatment and application of immersed tunnel in Dalian Bay cross-sea project. A. [C]: China Highway Magazine:7.
[23] Xu G.P, Li Y, FU B.Y, et al.(2015) Simplified calculation method for allowable longitudinal differential settlement of immersed tube tunnel. J. Highway, (4):22-27.
[24] Wang Y.(2015) Experimental study on deformation characteristics of gravel cushion of deep immersed tunnel foundation. J. Geotechnical Mechanics, 36(12): 3387-3392.
[25] Liu Y.P, Xu X.W, Wei H.B, Song J.W.(2018) Load test technology for deep water foundation of Hong Kong-Zhuhai-Macao Bridge. J. Geotechnical Mechanics, 39 (S2): 480-485.
[26] Hao Y.L, Wang L.Z, Chen Y.M.(2001) Settlement analysis and control of deep soft soil cement mixing pile composite foundation. J. Journal of Geotechnical Engineering, 23 (3): 345-349.
[27] Li X.J.(2003) Technical Research and Engineering Practice of Cement Mixing Pile Composite Foundation .D. Tianjin University.