Experiment and Engineering Application Study on the Compression Properties of Foundation Soil in the Process of Reinforcing Existing Buildings with Composite Piled Foundation

Qiufeng Tang, Jianxing Tong, Ning Jia, and Shengbin Zhou

Abstract When an existing building has excessive settlement and has no convergence tendency due to foundation problems, the composite piled foundation is often used to partially underpin the upper load. However, considering that the compression properties of the foundation soil have changed greatly, the compressibility index provided by the initial survey report is no longer suitable for calculating the settlement of the reinforced foundation. In this paper, a consolidation test is designed to simulate the compression state of the foundation soil in the process of building construction, reinforcement, and settlement stability. The test results show that the recompression modulus E_{rs} of the soil sample is 2.5–3.5 times the compression modulus $E_{s1\text{-}2}$. In the engineering example, the recompression modulus is used to calculate the settlement of the reinforced foundation according to the settlement calculation method of the composite foundation with settlement-reducing piles, and the results are close to the actual settlement. In actual engineering, in the absence of supplementary survey, it is recommended to obtain the recompression modulus E_{rs} through simulated test or use 2.5–3.5 times the compression modulus $E_{s1\text{-}2}$ to calculate the settlement of the reinforced foundation.

Keywords Reinforcement of existing buildings · Consolidation test · The recompression modulus · Settlement calculation · Engineering application

---

Q. Tang · J. Tong (✉) · N. Jia · S. Zhou
State Key Laboratory of Building Safety and Built Environment, No. 30 North Third Ring East Road, Beijing, China
e-mail: tjxcabr@sina.com

Institute of Foundation Engineering, China Academy of Building Research, No. 30 North Third Ring East Road, Beijing, China

Beijing Engineering Technology Research Center of Foundation and City Underground Space Development and Utilization, No. 30 North Third Ring East Road, Beijing, China

S. Wang et al. (eds.), *Proceedings of the 2nd International Conference on Innovative Solutions in Hydropower Engineering and Civil Engineering*, Lecture Notes in Civil Engineering 235, https://doi.org/10.1007/978-981-99-1748-8_26

1 Introduction

In actual engineering, due to problems in survey, design, construction, use, and the surrounding environment, engineering accidents caused by the settlement of existing building foundations occur from time to time [1], such as excessive overall settlement, overall inclination, and local differential settlement, which results in failure of normal use, reduction of safety reserves, reduction of service life and even destruction [2–4].

When the settlement of the existing building is too large and there is no tendency to converge, adding new piles under the foundation is a relatively safe reinforcement solution. According to the proportion of the upper load underpinned by the new piles, it can be divided into the composite piled foundation reinforcement scheme and the piled foundation reinforcement scheme. The piles and the existing foundation in the composite piled foundation share the upper load together after reinforcement. Therefore, the composite piled foundation reinforcement scheme has lower pile bearing capacity of a single underpinning pile, smaller pile diameter, and greater pile spacing (generally greater than 6 times the pile diameter), and these mean less damage to the foundation, less disturbance to the foundation soil during reinforcement, and lower reinforcement costs. All things considered it is usually the first choice.

Considering the large settlement of the foundation before reinforcement, to make the total settlement meet the allowable value of foundation deformation and normal use requirements, the reinforcement design should calculate the settlement of the reinforced foundation. Literature [5] and [6] show that during the construction process, the physical and mechanical indexes such as soil void ratio and compressive modulus have changed significantly. In addition, the stress path of foundation soil is complicated during the reinforcement process. Therefore, the compressibility index provided by the initial survey report can no longer correctly reflect the real compressive properties of the soil, which will lead to large deviations in the calculation results.

Literature [7] analyzes the stress change under the foundation when the composite piled foundation is used to reinforce the existing building: (1) The foundation settlement problem generally occurs shortly after the building is completed, and the foundation soil has not yet been consolidated; (2) Before the piles are connected to the foundation, it is considered that the load shared by the soil between the piles remains unchanged; (3) After the piles are connected to the foundation, the piles begin to share the load, resulting in a decrease in the additional stress of the soil between the piles and an increase in the additional stress of the soil below the pile tip; (4) With the further consolidation of the foundation soil, the additional stress of the soil between the piles increases slightly [8–10], and finally remains stable. Considering that the soil stress at the pile tip is difficult to measure, and the settlement calculation is very complicated, it is not easy to compare the theory with practice, so this paper focuses on the compression properties of the soil between piles.

2 Consolidation Test

Two kinds of soil samples, silty soil and silty clay, were selected as the test objects, representing high compressibility soil and medium to low compressibility soil. Two kinds of consolidation tests were carried out for each soil sample, namely the standard consolidation test and the simulated consolidation test. The test load at each level is the sum of the self-weight stress and the additional stress at the corresponding depth.

The standard consolidation test is carried out according to the *Standard for Geotechnical Testing Method* [11]. The next level of load is loaded after the settlement of the soil sample under the current level of load is stable. The loading sequence of the simulated consolidation test is loading, holding, unloading, reloading, holding until stable. The loading time of each level is proportionally scaled according to Formula 1. Considering that the compression amount in the reloading stage of the simulated consolidation test is very small, the unloading range is slightly larger than the actual situation to reduce the test error.

$$\Delta t_{\text{sim}} = \frac{\Delta t_{\text{std}} \cdot t_1}{t_2} \tag{1}$$

In the formula, Δt_{std} is the average time required for the soil sample to reach settlement stability under each load in the standard consolidation test. In the test, it takes 6–8 h for silty soil and 3–4 h for silty clay t_1 is the time required for building construction and t_2 is the time required for building settlement stability, which are both determined according to engineering experience; Δt_{sim} is the average loading time of each level of load in the simulated consolidation test. It is estimated that it takes 40 min for silty soil and 1 h for silty clay in the test.

The test load is based on the measured data of a reinforcement project in Hainan province. The size of the foundation is about 70 m × 13 m, the pressure of the soil between the piles before and after reinforcement is 130 kPa and 78 kPa respectively. The main equipment and soil samples are shown in Fig. 1 and the test results are shown in Table 1.

According to the test results, the recompression modulus E_{rs} of the simulated test is 2.5–3.5 times the compression modulus $E_{\text{s1-2}}$ of the standard consolidation test under the test conditions.

3 Engineering Example

The engineering example is a reinforcement project in Hainan province. The project includes several buildings, each of which adopts shear wall structure, raft foundation, and composite foundation with cement-soil mixed piles. The characteristic values of bearing capacity of single pile, foundation soil and composite foundation are 300 kN, 130 kPa and 250–300 kPa respectively. The pile tip falls on the layer ④. The pile length is 15–18 m, the pile spacing is 1–1.2 m, the pile diameter is 500 mm, the pile

Fig. 1 The consolidation instrument and soil samples

Table 1 Test results

Soil sample	Sampling depth (m)	Recompression modulus E_{rs} (MPa)	Compression modulus $E_{s1\text{-}2}$ (MPa)	$E_{rs}/E_{s1\text{-}2}$
Silty soil	11	5.93	2.03	2.92
	15	6.41	2.30	2.79
	20	11.71	3.28	3.57
Silty clay	6	14.75	4.17	3.54
	13	14.36	5.68	2.53
	20	14.30	5.44	2.63

body strength is not less than 5.1 MPa, and the cushion thickness is 250 mm. The physical and mechanical indexes of each soil layer are shown in Table 2.

The settlement of each building after completion is too large and there is no convergence trend. The reason for the excessive settlement is that the foundation treatment method is improperly selected, the construction quality has serious defects, and the silty soil layer is thick. The test results of borehole sampling show that the cement-soil mixed piles in the silty soil layer are uneven, broken, and low in strength, and cannot effectively transfer the upper load to the deep layer.

The reinforcement scheme is to add piles under the foundation to partially underpin the upper load, forming a composite piled foundation with the existing composite foundation. The pile is a steel pipe with 8 mm wall thickness and C30 concrete poured inside. The parameters of the underpinning piles are shown in Table 3.

Table 2 The physical and mechanical indexes of each soil layer

Layer number	Soil layer	Average thickness (m)	Natural unit weight γ (kN m^{-3})	Compression modulus $_{s1\text{-}2}$ (MPa)	Limit shaft resistance (kPa)	Limit tip resistance (kPa)	Characteristic values of bearing capacity (kPa)
①	Fill	1.44	17.6	4.74		/	70
②	Middle sand	4.45	19.3	12.48	30	/	130
$②_1$	Fine sand	1.39	18.8	11.29	18	/	120
③	Silty soil	13.15	17.1	2.37	19	/	80
④	Gravel sand	5.39	20.7	13.92	116	2500	260
⑤	Silty clay	Unpenetrated	18.8	8.66	85	1200	280

Table 3 The parameters of the underpinning piles

Building No.	Pile diameter (mm)	Pile length (m)	Pile spacing (m)	Characteristic value of bearing capacity of single pile (kN)	Designed underpinning ratio (%)	Number of piles
A	299	18–19	1.8	300	44.2	280
B	299	18–19	1.9	300	35.9	204
C	245	14–15	1.9	250	37	195

There are two methods for settlement calculation of composite piled foundations in *Technical Code for Building Pile Foundations* [12]. One is that the settlement of the pile top, which is equal to the sum of the compression amount of the pile body and the compression amount of the soil under the pile tip, can be calculated as the settlement of the foundation. The other is that the settlement of the soil between the piles, which is equal to the settlement of the soil between the piles caused by the additional stress of the soil and the interaction between the pile and the soil, can be calculated to avoid the calculation of the plastic penetration amount of the pile tip.

The two calculation methods are mainly aimed at new buildings, but they are also applicable to the reinforcement of existing buildings with composite piled foundations in principle. In this project, the underpinning pile tip provides about 30% of the bearing capacity of a single pile, and the bearing layer is good, so the plastic penetration of the pile tip can be ignored, which means both calculation methods are applicable. However, according to the design idea of the simulated consolidation test in this paper, we can only choose the second calculation method.

The calculation parameters and results are shown in Table 4. The recompression modulus of layers ② and layer ③ is 3.5 times $E_{s1\text{-}2}$ considering the replacement and

Table 4 The calculation parameters and results

Building No.		A	B	C
Foundation size		About 70 m × 13 m	About 60 m × 13 m	About 50 m × 13 m
Press of the soil between the piles (kPa)		78	74	88
Calculation depth (m)	Layer ②	3	3	5
	Layer ③	15	15	9.3
	Layer ④	5.4	5.4	3.9
Recompression modulus E_{rs} (MPa)	Layer ②	43.68		
	Layer ③	8.30		
	Layer ④	41.76		
Calculated settlement value of the center point (mm)		51.3	48.5	38.0
Average measured settlement value (mm)		42.9	38.5	33.0

reinforcement effects of cement-soil mixed piles, and the recompression modulus of layer ④ is 3.0 times $E_{s1\text{-}2}$.

The calculated settlement of the reinforced foundation is 1.15–1.26 times of the average measured settlement, which means the results are relatively accurate and safe. If we adopt the compression modulus $E_{s1\text{-}2}$, the results will be far greater than the actual settlement, which will cause the reinforcement scheme to be too conservative.

On the other hand, it also proves that the second method can be applied to calculate the settlement of the reinforced foundation of the existing building reinforced by composite piled foundation.

4 Conclusion

Through consolidation tests and engineering examples, this paper studies the compression properties of foundation soil in the process of reinforcing the existing building with composite piled foundation, and the following conclusions can be drawn:

(1) In the simulated consolidation test, the recompression modulus of high compressibility soil and medium to low compressibility soil at different depths is 2.5–3.5 times the compression modulus $E_{s1\text{-}2}$ of the standard consolidation test.

(2) In the engineering example, the recompression modulus is used to calculate the settlement of the reinforced foundation according to the composite foundation with settlement-reducing piles settlement calculation method. The results

are close to the actual settlement, which prove the applicability of the test conclusion.

(3) In actual engineering, in the absence of supplementary survey, it is recommended to obtain the recompression modulus E_{rs} through simulated test or use 2.5–3.5 times the compression modulus $E_{s1\text{-}2}$ to calculate the settlement of the reinforced foundation.

References

1. (2012) Technical code for improvement of soil and foundation of existing buildings (JGJ123-2012). China Architecture & Building Press, Beijing
2. Gu BH (2015) Review of typical cases of geotechnical engineering. China Architecture & Building Press, Beijing
3. Sun XH, Tong JX, Yang XH, Luo PF, Du SW (2017) Application of micro-piles in reinforcement of soft soil area. Chin J Geotech Eng 39(S2):91–94
4. Sun XH, Tong JX, Yang XH, Sun XZ, Zhao ZP (2016) Research on engineering application of composite foundation with settlement-reducing piles in soft soil area. Build Sci 32(S2):206–209
5. Teng YJ et al (2012) Reconstruction and reinforcement technology of existing building foundation. China Architecture & Building Press, Beijing
6. Li QR (2008) Experimental study on redesign of soil and foundation for increasing storey on existing buildings. MA thesis, China Academy of Building Research
7. Tang QF, Tong JX, Jia N, Zhou SB (2021) Experimental study on the compression properties of the foundation soil of existing buildings considering the construction and reinforcement process. Build Struct 51(S1):1723–1727
8. Yan ML, Zhang DG (2001) Technology and engineering practice of composite foundation with CFG piles. China Water & Power Press, Beijing
9. Liu DL, Zheng G, Liu JL, Li JX (2006) Experimental study on comparison of behavior between rigid pile composite foundation and composite pile foundation. J Build Struct 27(4):121–128
10. Zhou F, Zai JM, Mei GX (2005) The composite ground and the composite pile foundation. Geotech Eng Tech 19(3):141–143, 151
11. (2019) Standard for geotechnical testing method (GB/T 50123-2019). China Planning Press, Beijing
12. (2008) Technical code for building pile foundations (JGJ94-2008). China Architecture & Building Press, Beijing