

Article

Improving the Performance of Piled Raft Foundations Using Deformation Adjustors: A Case Study

Rui Zhu ¹, Feng Zhou ^{1,*}, Zhihui Wan ¹ , Shengjun Deng ^{1,2} , Xin Dong ¹, Zekun Zhou ³ and Wei Xing ¹

¹ College of Transportation Engineering, Nanjing Tech University, Nanjing 211816, China

² Research Center of Coastal and Urban Geotechnical Engineering, Zhejiang University, Hangzhou 310058, China

³ China Railway 19th Bureau Mining Investment Co., Ltd., Beijing 100161, China

* Correspondence: zhoulfeng@njtech.edu.cn; Tel.: +86-139-1384-4622

Abstract: Complicated soil conditions are direct difficulties for high-rise building projects. A new device called a deformation adjustor, which is used to optimize the stiffness distribution in the piled raft system, has achieved good results for this challenge. This paper presents a case study on the application of deformation adjustors to improve the performance of a piled raft foundation. This case study describes the preliminary design of pile-raft foundations with deformation adjustors, followed by numerical analysis. Based on the numerical study, the potential savings are demonstrated due to the good performance of soil bearing capacity. Comparing the numerical results with the monitoring results in raft settlements, earth pressures, deformation amount of deformation adjustors, pile top reactions, and load-sharing ratios between soils and piles, the accuracy of the design schemes with an aided numerical analysis is verified. Through a long-term monitoring, soils below the raft carried 63% of the total applied loads, while the piles bear 37% of the loads. This case study proved that a piled raft foundation with deformation adjustors was an effective and economical design scheme, which can make full use of the soil bearing capacity. It is of great significance to facilitate the design and construction of piled raft foundations in complicated soil conditions.

Keywords: end-bearing piles; composite foundation; piled raft foundation; deformation adjustors; numerical analysis; differential settlement



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1. Introduction

The mechanism and design theory considering the utilization of soil below the raft to bear a part of the total applied load in piled raft foundation has been a research hotspot for more than half a century [1,2]. A large number of theoretical studies, experimental studies, and numerical studies have carried out in-depth explorations of the bearing characteristics of a piled raft foundation [3–5], and different optimized design methods for a composite pile foundation on soft clay subjected to vertical loads have been reported in the literature [6–9]. All of the above-mentioned works require that the pile foundation be close to its ultimate bearing capacity, thereby enforcing the pile tip piercing downward to achieve the compatible deformation between piles and soil [10].

In some cases, a cushion with a finite thickness may be laid on the top of the pile to make the pile top penetrate into the cushion so that the soil between the piles can work better [11–13]. However, it is still difficult to use for end bearing piles due to the limited role of the cushion. As the stiffness of pile and soil varies significantly, the differential deformation between pile and soil is large and cannot be easily coordinated, which is one of the major concerns in the end bearing pile foundation [14]. To solve this issue and to realize the pile-soil interaction, Zhou et al. [15] developed an optimization device called a deformation adjustor, which is placed between the top of the piles and the raft. This technique is able to accomplish the optimization of load distribution between soils and

piles in complicated soil conditions. In recent years, this technique has been applied in more than twenty high-rise building projects in China [16–18].

Accordingly, this paper presents a case study on applying deformation adjusters to improve the performance of piled raft foundations in complicated soil conditions. In the original design of piled raft foundations, the majority of the total applied loads were carried by piles, while piles were prevented from being installed to the required depth due to the number of large boulders. Consequently, this technique (using deformation adjusters) was used for such a challenging project. The design scheme of a piled raft foundation with deformation adjusters in this case was presented briefly. Then, the numerical results were compared with the monitoring results for raft settlements, earth pressures, deformation amount of deformation adjusters, pile top reactions, and load-sharing ratios between soils and piles during and after construction, which proved that a piled raft foundation with deformation adjusters was an effective and economical design scheme in complicated soil conditions. Through this study, we expect to provide a reference for improving the performance of piled raft foundations.

2. Project Information and Site Conditions

The project is located in Xiamen, China, and was for the construction of two high-rise residential buildings (building A and building B) with a total construction area of 38,000 m². The case described herein focuses on the piled raft system of building A with a height of 120 m, as shown in Figure 1.

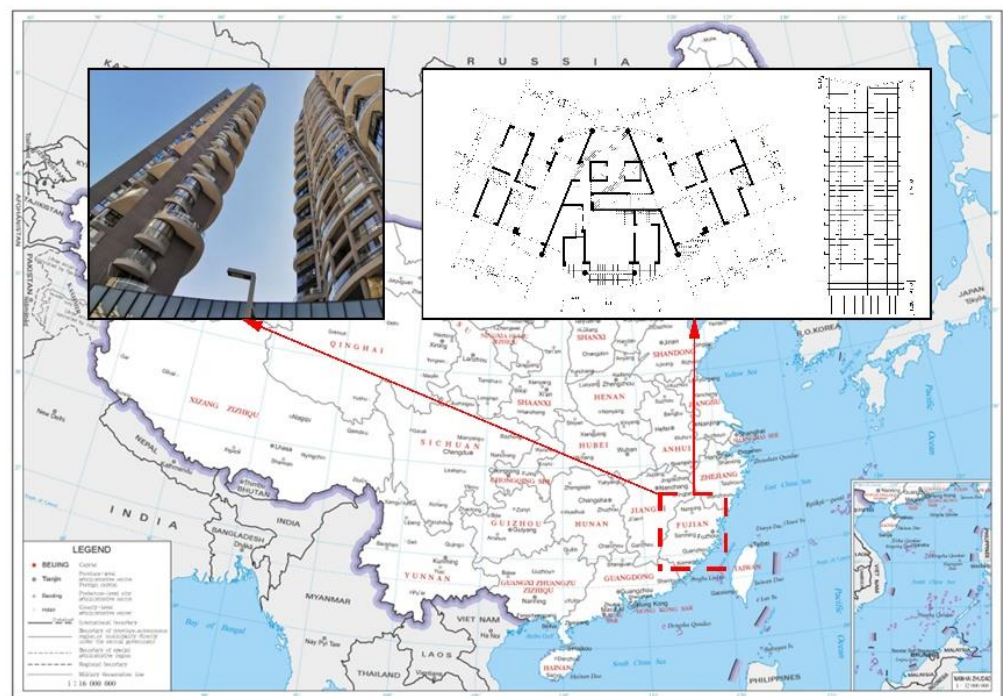


Figure 1. Project Information.

The site exploration was conducted in 2006. It was found that the soil conditions were complicated, mainly consisting of residual soil and weathered granite. Specifically, the unit weight, cohesion, internal friction angle, and deformation modulus of residual soil were 18.6 kN/m³, 18 kPa, 28°, and 35 MPa, while those of weathered granite were 19.5–23.5 kN/m³, 40–45 kPa, 27–30°, and 60–120 MPa, respectively. Similarly, characteristic values of the subgrade bearing capacity, skin resistance, and tip resistance for residual soil and weathered granite were 280, 100, and 1200 kPa and 400–3000, 150–800, and 1500–10,000 kPa, respectively. Soils of the site experienced highly uneven weathering and spheroidal weathering, leading to the formation of various sizes of boulders, which mainly appeared in completely and strongly weathered granite layers, as indicated in

Figure 2. Additionally, the distribution of the soil layer is highly uneven with regards to depth, resulting in the different soil characteristics in the same depth. Accordingly, the complicated soil conditions bring about severe challenge to the design and construction of piled raft foundations.

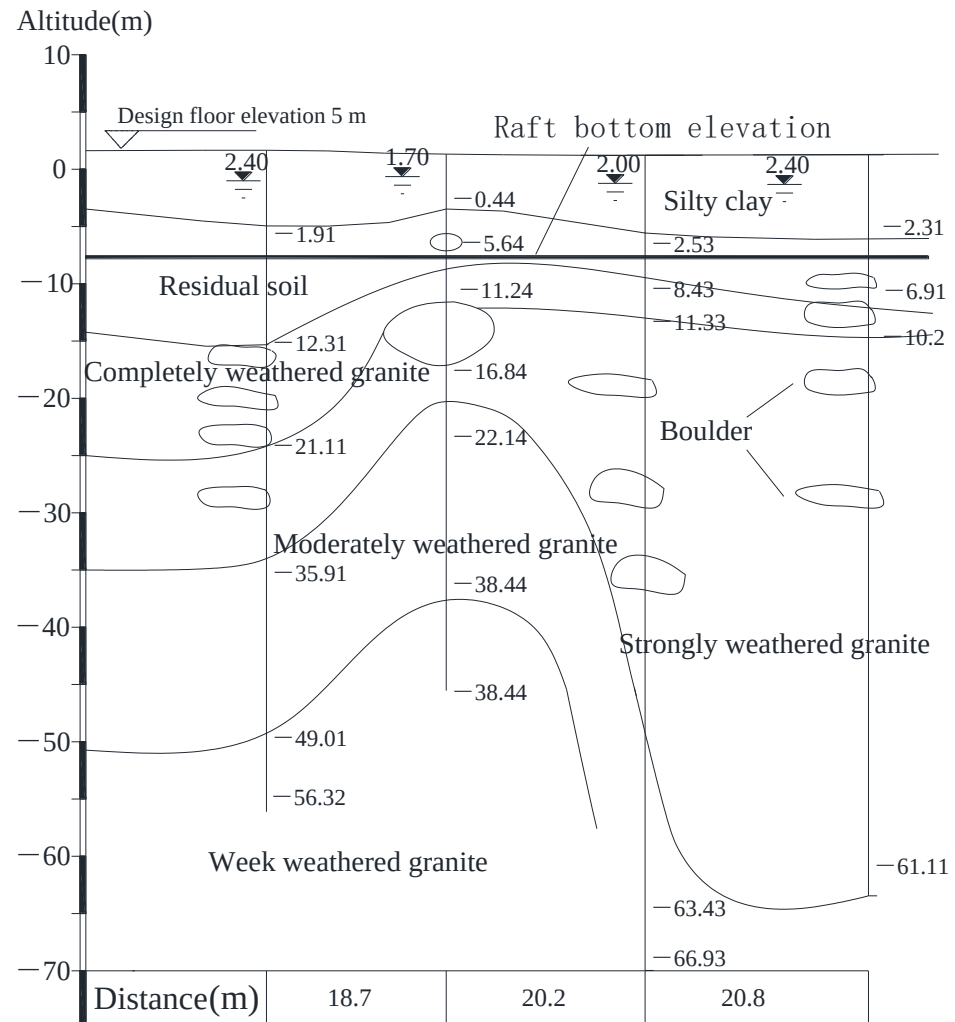


Figure 2. Typical geological section.

3. Preliminary Design Scheme

3.1. Design Concept

A deformation adjuster is a device used to adjust the bearing stiffness between two contacting objects. The overall stiffness of piled raft foundations is adjusted through the large deformation of deformation adjusters placed between the top of the piles and rafts. The schematic diagram of its mechanical model is shown in Figure 3. It can be seen that the placement of deformation adjusters is equivalent to installing springs with a specific stiffness on the top of the piles. The stiffness of the deformation adjuster is generally much lower than the stiffness of the pile. Accordingly, the applied load is partly transferred to the soils below the raft with the deformation of deformation adjusters, which significantly reduces the requirement for the bearing capacity of piles. It would save a lot of money and time for the project.

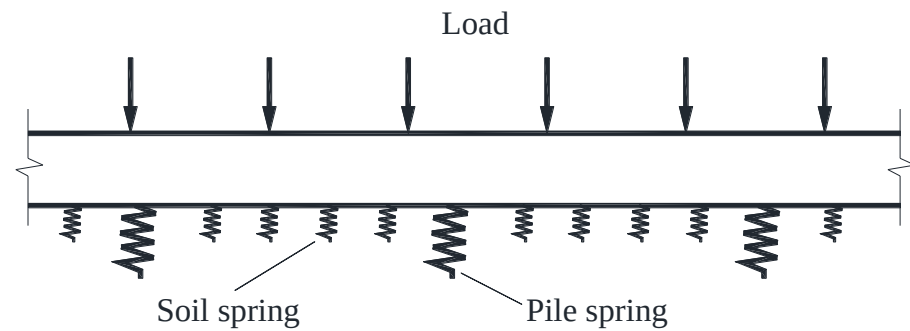


Figure 3. Mechanical model of piled raft foundations with deformation adjustors.

3.2. Parameters of the Building

The raft of building A has a width of 20.8 m, a length of 44.5 m, and an L-shaped plane close to the rectangle. The diameter (R_0) of the equivalent circular raft is 35 m. The superstructure load was approximately 524,700 kN. The area of building A was 960 m², and the corresponding earth pressure was 546 kPa.

3.3. Soil Bearing Capacity

The soil ultimate bearing capacity provided by the geotechnical report was 280 kPa, which was derived from laboratory tests. However, the residual soil and weathered granite are easily disturbed. The soil ultimate bearing capacity will be reduced after the disturbance. Thus, the value provided by the geotechnical report is underestimated. According to local engineering specifications, the bearing capacity was approximately 480 kPa. To confirm this value, a static plate load test, a standard penetration test, a pressure meter test, and a deep screw plate test were conducted. The test results indicated that the allowable bearing capacity was above 480 kPa, with a safety factor of 2.

3.4. Preliminary Design Scheme

The design scheme adopted a 2.5 m thick raft supported on hand-dug piles. The piles were 1 m in diameter, 12 m long, and the average center-to-center spacing of piles was four times the pile diameter. The pile tip was located at −18 m YSL, indicating that most of the piles were borne on the highly weathered granite layer. As such, the foundation should be designed as a piled raft with end-bearing piles. The design procedures are described in detail in [18] for piled raft foundations with deformation adjustors. The main parameters for this project were calculated as per [19,20], as listed in Table 1.

Table 1. Design parameters.

Quantity	Meaning	Value
P_{pr} (kN)	Loads applied to the piled raft	660,000
q_t (kN)	Allowable axial bearing capacity of a single pile	4200
R_r (kPa)	Allowable raft bearing capacity	450
A (m ²)	Gross raft area	960
η	Group stiffness efficiency factor	1.0
k_r (kN/mm)	Stiffness of the raft alone	8912
ξ	Load-sharing ratio of soils	0.62
n_a	Number of deformation adjustors per pile	1
k_{Pa} (kN/mm)	Overall stiffness of a single pile with deformation adjustors	7268
k_a (kN/mm)	Stiffness of a deformation adjustor	120
n	Pile number	60
S_t (mm)	Calculated total settlement of the building	64
S_d (mm)	Calculated differential settlement of the building	16

Besides, the calculation value of the pile number is equal to 53. Considering some special needs of the superstructure configuration, the pile number, $n = 60$, was used for the design scheme. The pile arrangement is presented in Figure 4.

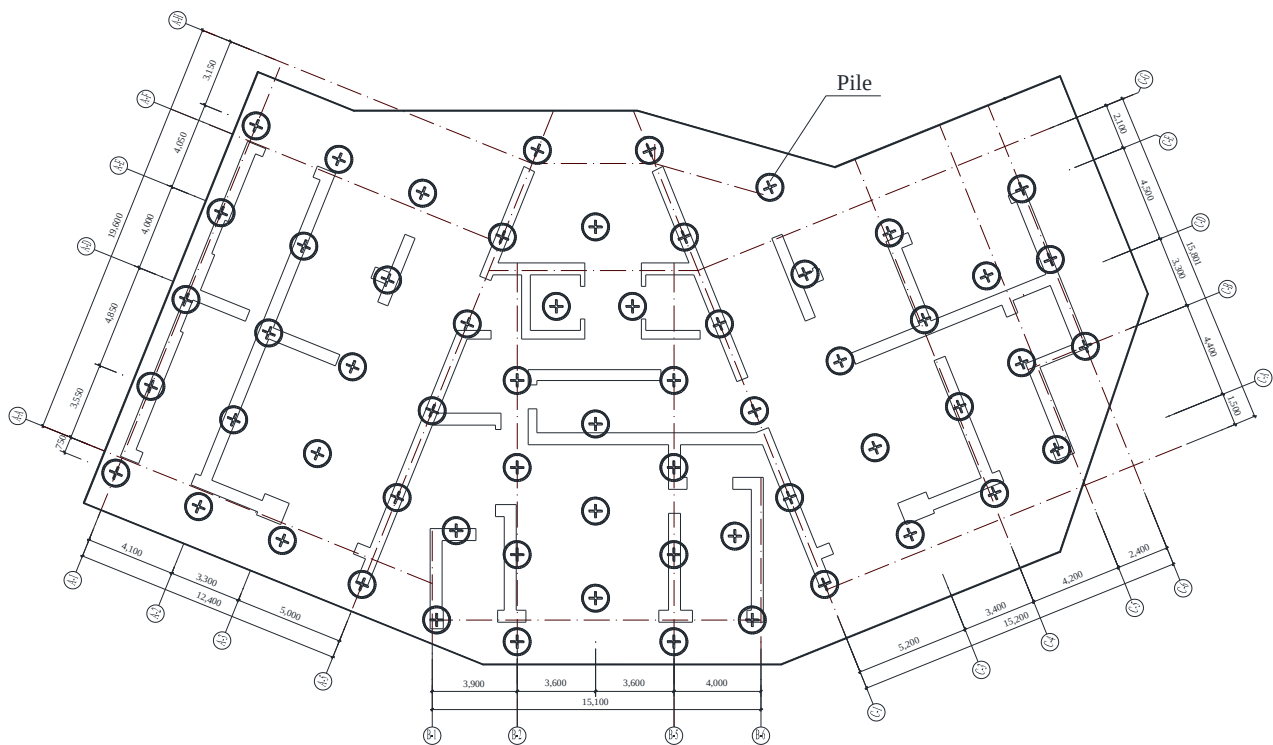


Figure 4. Plan of pile arrangement.

4. Description of the Numerical Study

4.1. Geometric Configuration of the Model

In this paper, the numerical analysis was carried out using the *ABAQUS* [21]. To be in correspondence with the construction, the three-dimensional numerical model of the piled raft foundation was simulated as it had been in the construction in both its configuration and dimensions. Figure 5 presents the basic configuration of the model. The size of model is 120 m in the x direction, 60 m in the y direction, and 40 m in the z direction. The piles are 1 m in radius and 12 m in depth. Respectively, a raft which had a thickness of 2.5 m was arranged on the pile-soil system to enable the system to support the applied load. To simulate the deformation adjusters on the pile heads in the construction, an analysis was performed on them with a simulation where two rigid plates are the top and bottom of the deformation adjuster and a spring with a length of 30 mm was between the two plates. For simplicity, the rigid plate had zero thickness. The cross-sectional geometry of the numerical deformation adjuster was identical to that of the pile ($2R = 1$ m). The boundary was given according to different conditions: $x = 0$, $y = 0$, and $z = 0$ on the upper and lower surfaces of the model, while $x = 0$ and $y = 0$ on the surface around the model. The whole model has 54,820 units and 111,728 nodes. In this paper, the model was simulated without taking advantage of the symmetry due to the irregular geometry of the piled raft foundation in the project. Additionally, the soil and the piled raft foundation are modeled with finite elements. The pile mass, raft mass and soil mass were discretized using continuum solid elements, mainly 8-noded hexahedral elements with reduced integration.

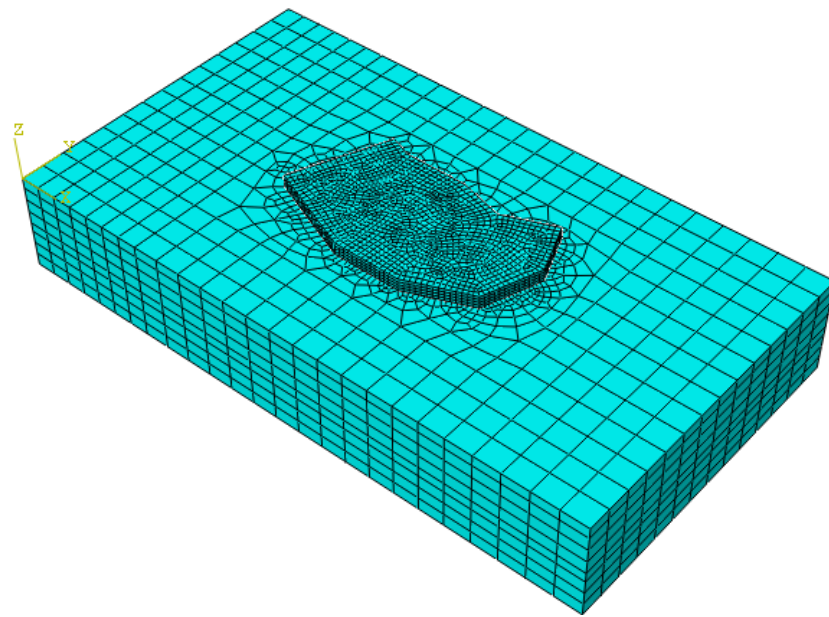


Figure 5. Typical finite element mesh.

4.2. Material Property

Actually, the soil is a multiphase medium. For simplicity, it was simulated as a one-phase media in this paper. The Mohr–Coulomb plasticity model was used to model the soil plasticity [22]. The pile and raft were simulated as elastic materials, and the properties of them were in accordance with the parameters in the construction. All of the model parameters are shown in Table 2. The validity of the model parameters in the program based on the analysis of the two static load tests, and the comparison of P - S curve between numerical results and static load test results was shown in Figure 6. As we can see, all of the three curves matched well. Hence, the conclusion was reached that the model parameters in the program are reasonable.

In addition, the contact between the structure and the soil was simulated as perfectly rough and no relative motion would appear between the finite elements nodes. Duplicated nodes were used to form a zero-thickness interface between the pile and the soil, the pile and the plate, the soil and the raft, and the plate and the raft.

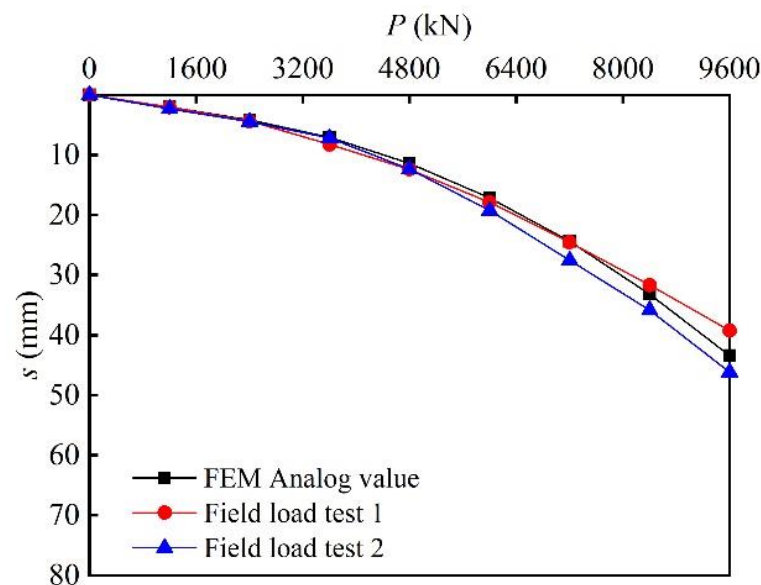


Figure 6. P - s curve.

Table 2. Model parameters.

Material	Model	Elastic Modulus (MPa)	Cohesion (kPa)	Internal Friction Angle	Poisson's Ratio	Unit Weight (kN/m ³)
Pile	Linear elasticity	30,000	-	-	0.2	25
Raft	Linear elasticity	30,000	-	-	0.2	25
⑥Residual soil	Mohr–Coulomb plasticity	35	18	28	0.3	18.6
⑦Completely weathered granite		60	40	27	0.3	19.5
⑧Strongly weathered granite		500	45	30	0.25	20.5

4.3. Numerical Analysis Scheme

In order to further analyze the influence of the stiffness of the deformation adjusters on the load-sharing ratio, and whether the stiffness of 12,000 kN/m in the preliminary design scheme is reasonable, numerical analysis was conducted for studying the bearing characteristics of the piled raft foundations with different stiffnesses of the deformation adjusters, which is equal to spring stiffness, as shown in Table 3.

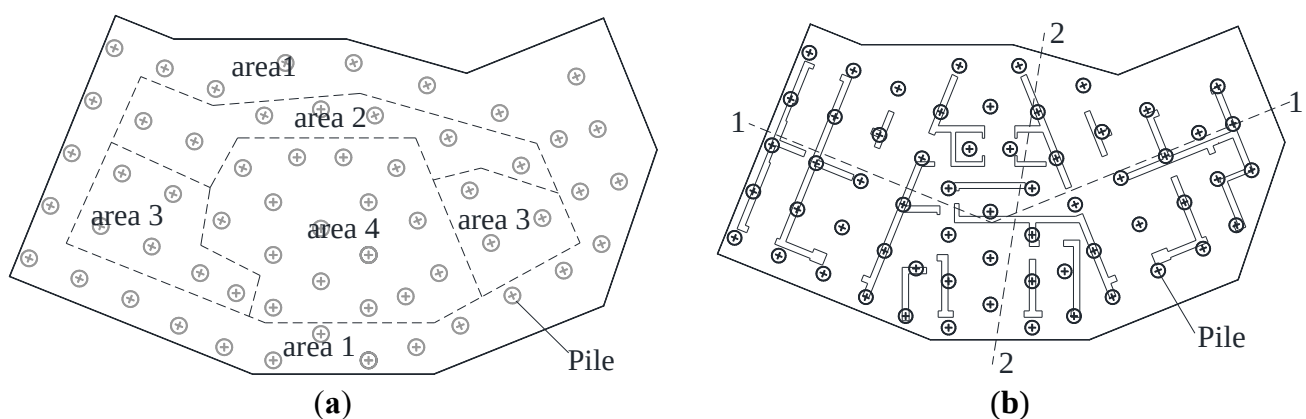
Table 3. Different stiffness of deformation adjusters.

Adjuster Number	DA-0	DA-5	DA-12	DA-20	DA-30	DA-mix
Stiffness(kN/m)	0	50,000	120,000	200,000	300,000	Table 4

Table 4. The mixed stiffness of deformation adjustor.

Aera	1	2	3	4
Stiffness (kN/m)	50,000	100,000	200,000	300,000

The above schemes were only for the case where the deformation adjusters were a single stiffness. Actually, deformation adjusters with different stiffness could be placed on different areas to make full use of the soil bearing capacity, as shown in Figure 7a and Table 4. To limit the length of the article, the author selected path 1-1' and path 2-2' for the analysis, as shown in Figure 7b.

**Figure 7.** Numerical analysis scheme: deformation adjusters in different regions (a), direction of the path (b).

5. Numerical Results

5.1. Analysis of Settlement

The raft settlement distribution variation along path 1 and path 2 is shown in Figures 8 and 9, respectively. The stiffness of the deformation adjusters had a great influence on the raft settlement. The overall settlement and differential settlement significantly increased as the

stiffness of the deformation adjusters was reduced. When the stiffness of the deformation adjusters was 120,000 kN/m, the maximum settlement and differential settlement were 41 mm and 17 mm, respectively, which was consistent with the range proposed by [23]. It indicated that 120,000 kN/m was the reasonable stiffness of the deformation adjusters. Besides, the differential settlement could be controlled nearly to zero as the deformation adjusters of different stiffness were placed in different areas.

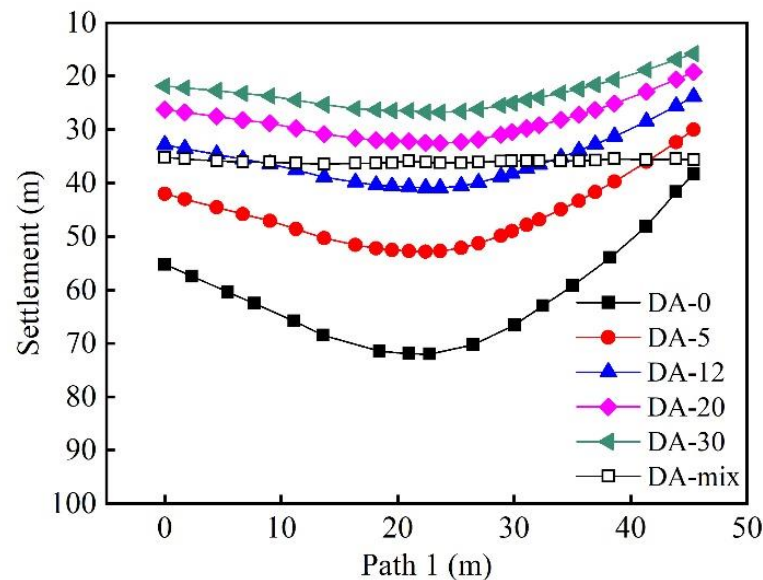


Figure 8. Curve of raft settlement along path 1.

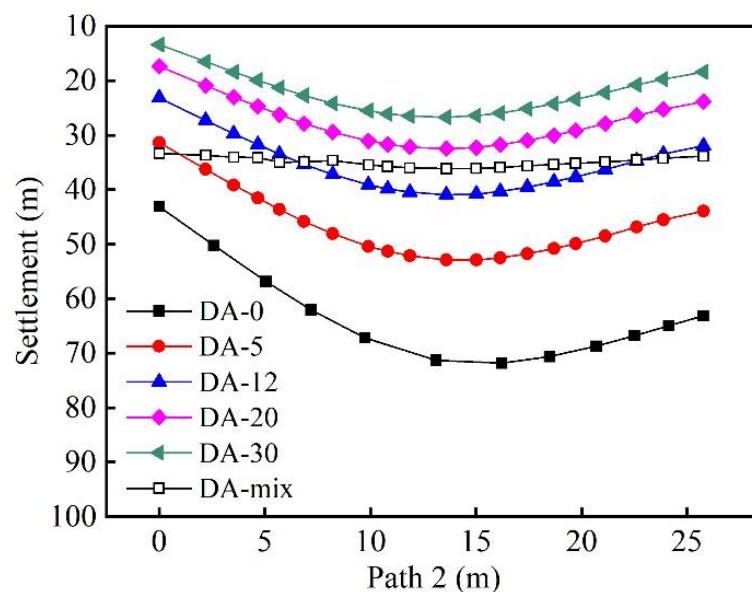


Figure 9. Curve of raft settlement along path 2.

5.2. Analysis of Earth Pressure

The earth pressure distribution below the raft along path 1 and path 2 are presented in Figures 10 and 11, respectively. The distributed load on soil gradually increased as the stiffness of the deformation adjusters reduced. When the stiffness of the deformation adjusters was zero, the average earth pressure below the raft was 602 kPa, which was greater than the actual soil bearing capacity. If 12,000 kN/m was chosen as the stiffness of the deformation adjusters, the average earth pressure below the raft was only 377 kPa, indicating that the deformation adjusters have a significant effect on promoting the pile-soil

interaction. Additionally, the earth pressure distribution below the raft was more uniform in the scheme of deformation adjusters with different stiffness placed in different areas than that with a single stiffness, which is the main reason that the differential settlement was close to zero. Comparing the earth pressure distribution in Figures 10 and 11, it is found that when the earth pressure is small, the earth pressure below the raft showed characteristics of partial stiffness along the direction of the short side and somewhat showed flexibility along the direction of the long side due to the uneven distribution of the upper load. This distinction should be taken into account in the design of the raft.

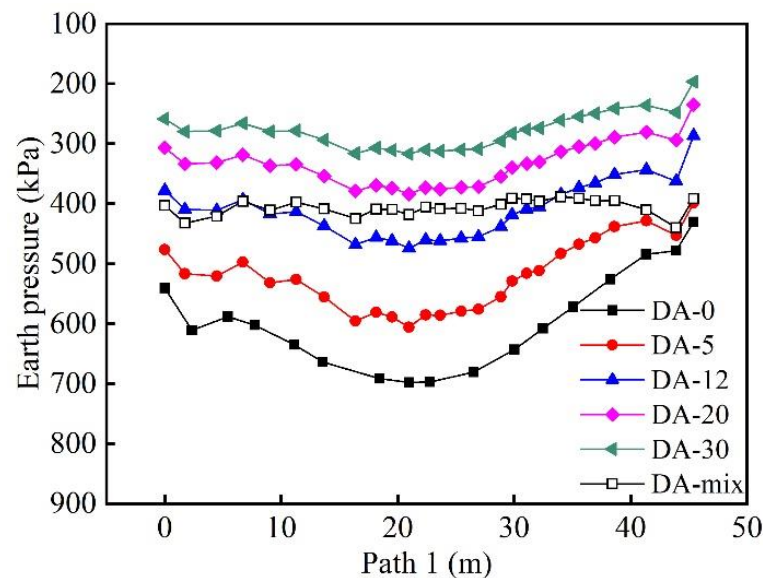


Figure 10. Curve of earth pressure along path 1.

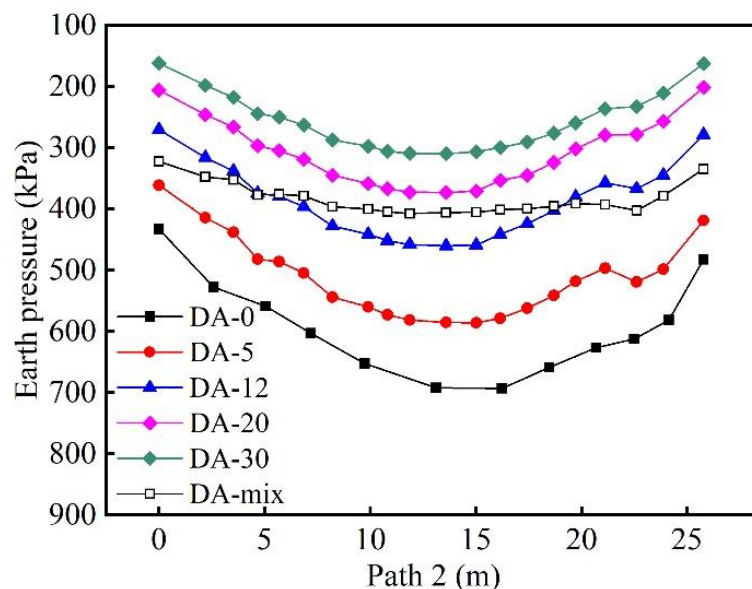


Figure 11. Curve of earth pressure along path 2.

5.3. Analysis of Deformation Amount of Deformation Adjustors

Figure 12 shows the curve of deformation amount of deformation adjustors variation with the percentage of load applied. As shown in Figure 12, the deformation amount of deformation adjustors was smaller as the stiffness of deformation adjustors was larger. When the stiffness of deformation adjustors was 12,000 kN/m, the deformation amount of the deformation adjustors was 32.52 mm after the load was applied, whereas

it was 33.66 mm in the scheme of deformation adjusters with different stiffness placed in different areas.

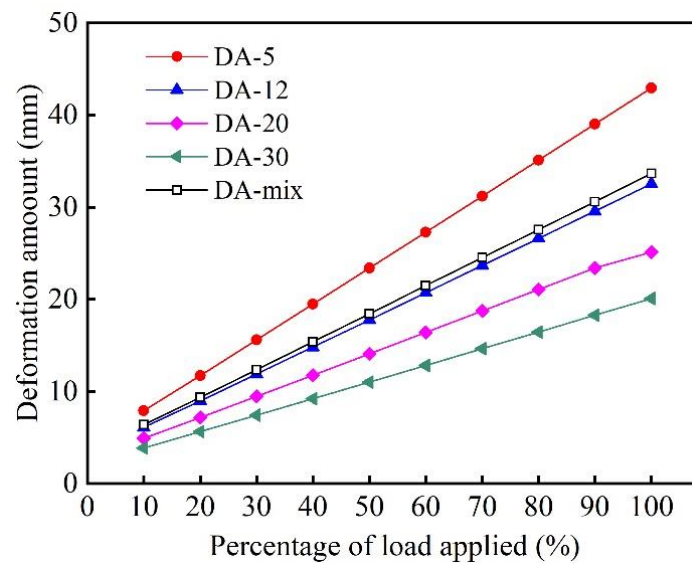


Figure 12. Curve of deformation amount of deformation adjusters variation with percentage of load applied.

5.4. Analysis of Pile Top Reaction

Figure 13 presented the curve of the pile top reaction variation with the percentage of the load applied. As shown in Figure 13, the pile top reactions increased significantly as the stiffness of deformation adjusters became larger. The average pile top reaction was 4057 kN, as the stiffness of the deformation adjusters was 120,000 kN/m, which was slightly smaller than the pile allowance bearing capacity. Additionally, in the scheme of deformation adjusters with different stiffness placed in different areas, the pile top reaction could be calculated by the deformation amount of deformation adjusters and the stiffness of deformation adjusters. Accordingly, the maximum and minimum pile top reactions were 10,098 kN and 1683 kN, respectively, which were higher than the pile allowance bearing capacity. When the deformation adjusters were adopted, the pile top reactions would be significantly different. The stiffness 120,000 kN/m was the relatively reasonable value on the basis of satisfying the design condition.

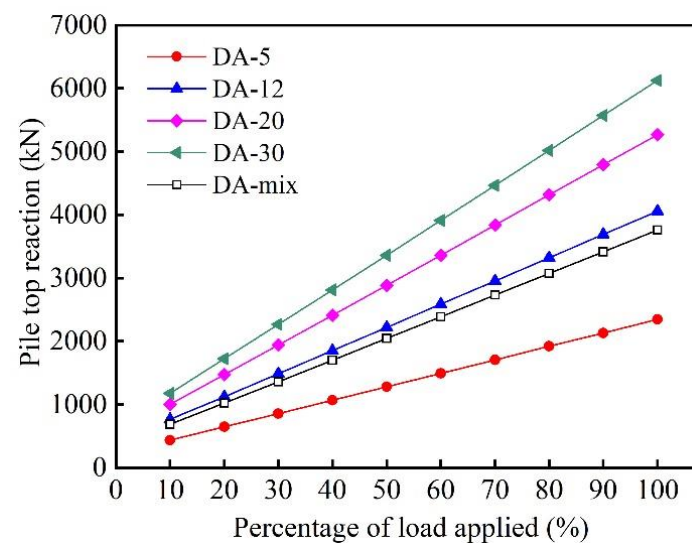


Figure 13. Curve of pile top reaction variation with percentage of load applied.

5.5. Analysis of Load-Sharing Ratio between Soil and Pile

Figure 14 is the curve of the load-sharing ratio of soil variation with the percentage of load applied. As shown in Figure 14, the load-sharing ratio of soil decreased and tended to be stable as the percentage of the load applied increased. This is because the raft, soil, and deformation adjusters were deformed and coordinated in the process of the load applied. When the stiffness of the deformation adjusters was 120,000 kN/m, the load-sharing ratio of soil was up to 59.76%. The conclusion that was reached was that the deformation adjusters could effectively change the load-sharing ratio between soil and piles, and that they made full use of the soil bearing capacity.

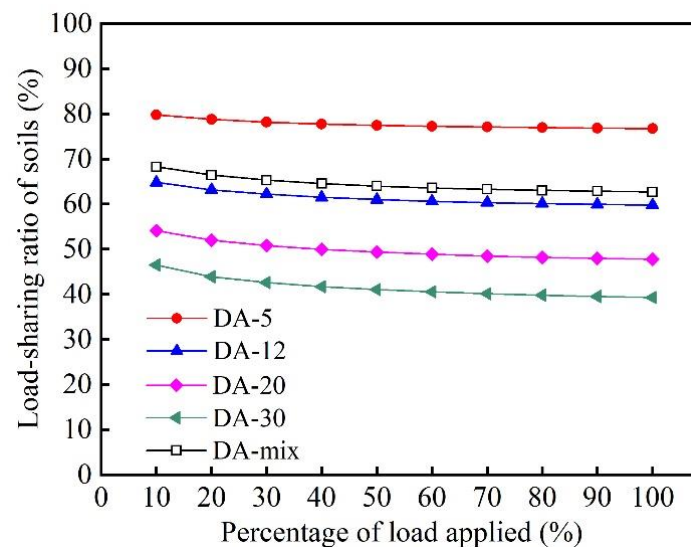


Figure 14. Curve of load-sharing ratio of soils variation with percentage of load applied.

Figure 15 presented the curve of the load-sharing ratio of soil variation with stiffness of deformation adjusters. When the stiffness of the deformation adjusters is zero, the foundation is equivalent to the natural ground, and the superstructure load was all carried by soil. With the stiffness of the deformation adjuster increasing, the decreasing trend of the load-sharing ratio of soil gradually slows down and tends to be stable. The foundation will show the characteristics of a conventional pile foundation, as the stiffness of the deformation adjusters was close to the stiffness of the piles.

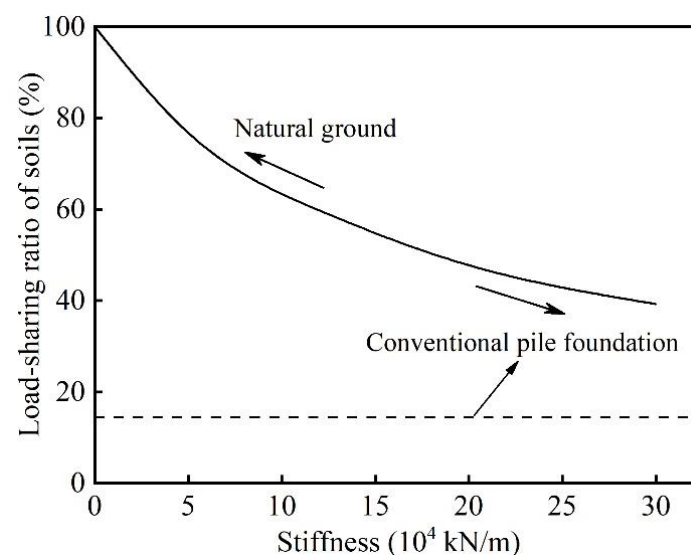


Figure 15. Curve of load-sharing ratio of soils variation with stiffness of deformation adjusters.

The essence of the deformation adjuster placed on the top of piles was an optimization of practical engineering. The deformation adjusters with different stiffness determine the difference in the load-sharing ratio of soil, resulting in different total settlements and differential settlements.

5.6. Determination of Design Scheme

Based on the above analysis, the average settlements and differential settlements of the building were all in the reasonable range when the piled raft foundation with deformation adjusters (120,000 kN/m) was adopted. The average earth pressure is 377.2 kPa and the average pile top reaction is 4057 kN. This scheme not only took full advantage of the soil bearing capacity, but also greatly reduced the project cost. The numerical analysis was also proven to be an effective method for assisting in the design of the piled raft foundation with deformation adjusters.

Additionally, deformation adjusters with different stiffness in four areas had a better effect on achieving pile-soil interaction in the numerical analysis. The differential settlement would be smaller and the distribution of the earth pressure under the raft would be more uniform. However, this scheme was more complex in the process of design and construction and had not ever been used in practical engineering. Thus, it is not adopted for the time being.

6. Monitoring Measurement

The project completed the construction of the two-story cushion and the main structure at the end of December 2010 and December 2011, respectively. During and after construction, a comprehensive monitoring of settlements, earth pressures, deformation amount of deformation adjusters, pile top reactions, steel bar stress, and load-sharing ratios between soils and piles was carried out. The monitoring measurement lasted for seventeen months from January 2011 to May 2012 and the monitoring points were arranged, as shown in Figure 16.

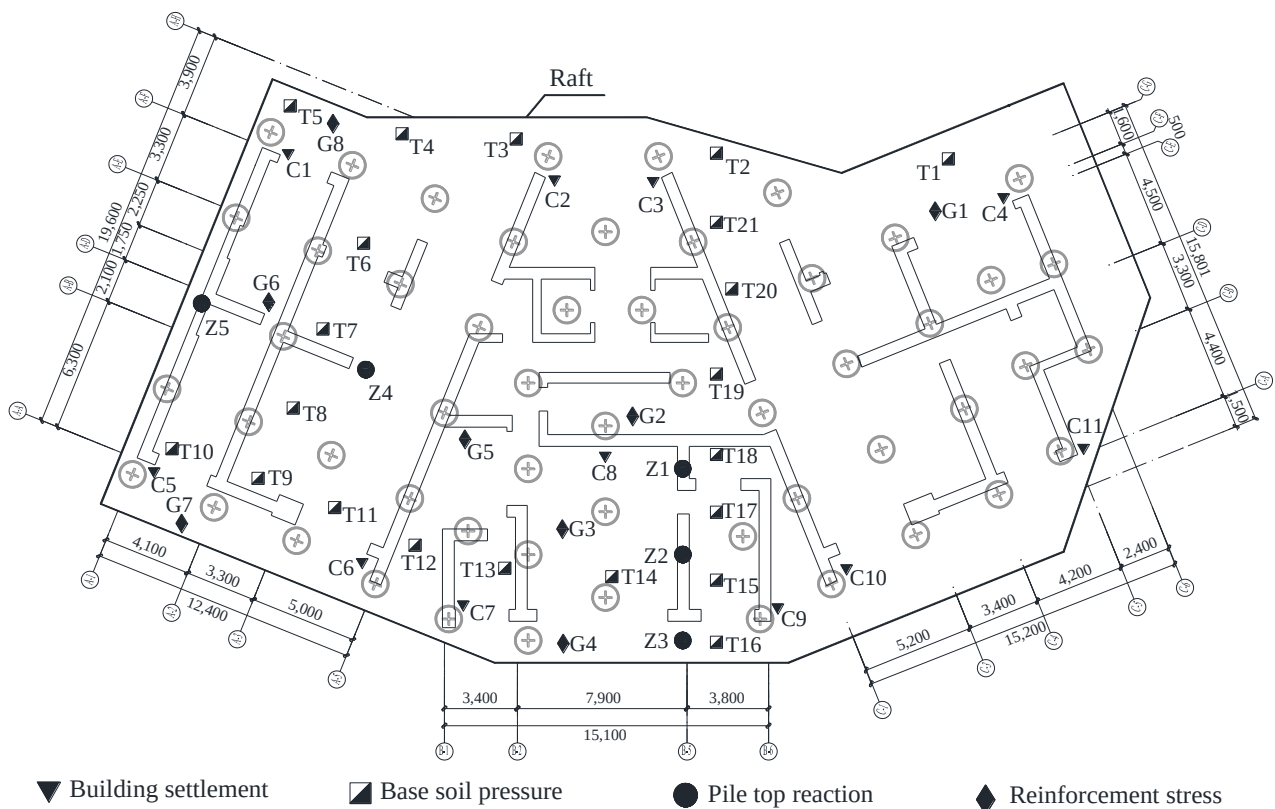


Figure 16. Arrangement of monitoring points.

6.1. Analysis of Settlements

Eleven monitoring points were arranged on the raft during construction and seven monitoring points were still active after construction. Figure 17 presents the curve of the building settlements variation with time. The maximum settlements were measured at C8 and C3, while the minimum settlement was at C11. Such a difference of settlement distribution may be attributed to the fact that the raft was irregular and that some monitoring points might be located at the elevator shaft or the raft corner. The average settlement and differential settlement were 24.5 mm and 4.2 mm after construction, and then, half a year later, the average settlement and differential settlement were 25.4 mm and 5.1 mm, respectively. The measured values were significantly lower than the calculated values listed in Table 2 and the numbers in [20], which were less than 200 mm for the total settlement and less than 0.001 R_0 for the differential settlement.

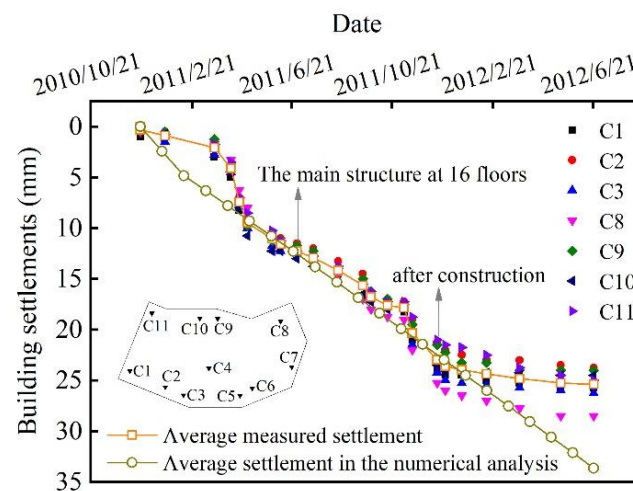


Figure 17. Curve of building settlements variation with time.

6.2. Analysis of Earth Pressure

During construction, 21 earth pressure cells were installed between the raft and the soil, 11 of which remained at work after construction. Figure 18 shows the curve of earth pressure variation with time. It was seen that the earth pressure increased significantly over time during construction. The maximum and minimum earth pressure were up to 433 kPa and 152 kPa, respectively. After construction, the average earth pressure tended to be stable and had a value of about 315 kPa, which was less than the value in the numerical analysis. Considering that the load applied was about 80% of the design value, the above results are relatively reasonable.

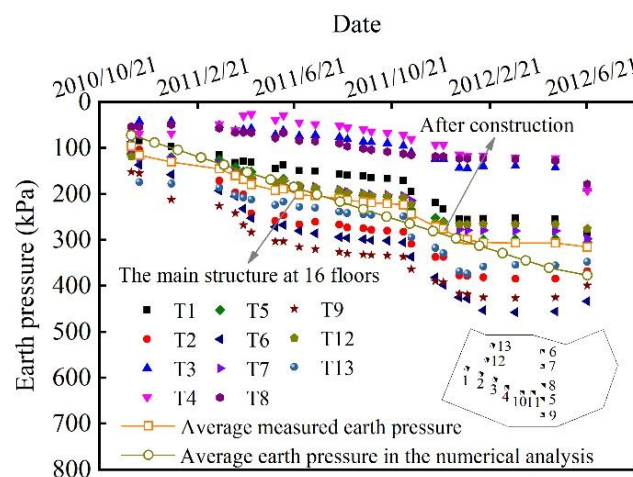
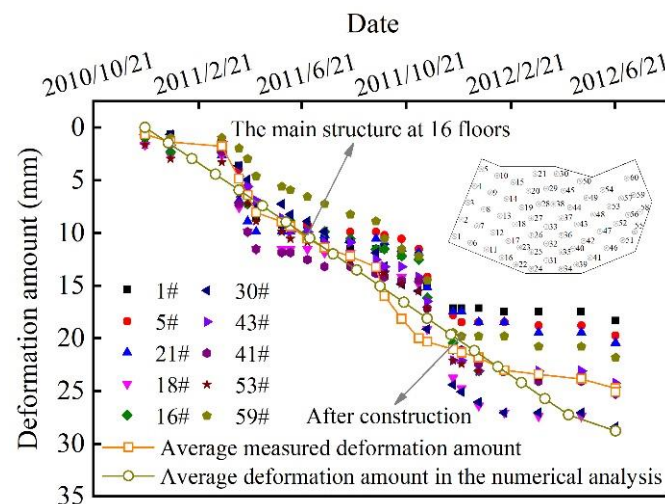


Figure 18. Curve of earth pressure variation with time.

6.3. Analysis of Deformation Amount of Deformation Adjustors

In this project, 60 deformation adjustors with monitoring sensors (1#–60#) were placed on the top of the piles, and 54 monitoring sensors were still active after construction. The deformation amount of the deformation adjustors was obtained by subtracting the pile top settlement measured from the building or raft settlement. Figure 19 shows the curve of deformation amount of deformation adjustor variation with time. As shown in Figure 19, the deformation amount increased relatively linearly with the load applied during construction, which was consistent with numerical results. After construction, the deformation amount gradually became stable. The maximum deformation amount was up to 26.1 mm and the average deformation amount was approximately 25.8 mm.



during construction and was up to 3246 kN after construction, which was consistent with the numerical results. However, the pile top reactions were unequal in different monitoring points. The possible reason for such a phenomenon was that each monitoring point had a different soil sharing area, leading to various measured pile top reactions. Additionally, the pile top reaction became stable and decreased slightly at 3120 kN until the termination of the monitoring in June 2012, while the pile top reaction still increased in linear in the numerical analysis. This is because the decoration load and live load had not been applied, leading to the applied load being smaller than the design value. In the numerical analysis, the load, which was consistent with the design value, was applied linearly. Consequently, the measurements were reasonable, which also indicated that the load distribution between soils and piles was further adjusted over time.

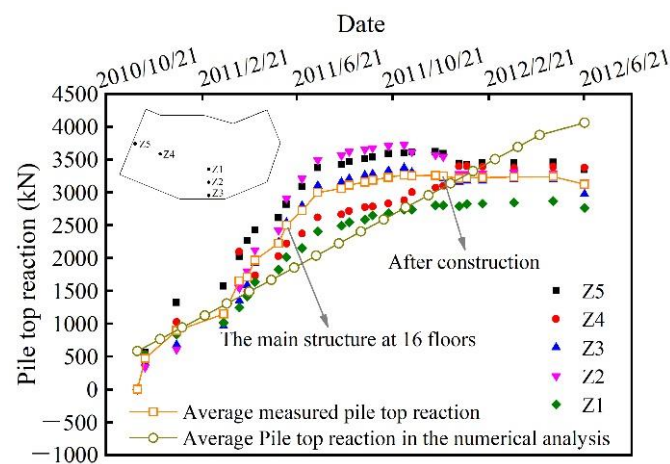


Figure 21. Curve of pile top reaction variation with time.

The average pile top reaction can be approximately calculated according to its stiffness and deformation amount. Figure 22 presented the curve of measured and calculated average pile top reaction variation with time. Since the average deformation amount of the deformation adjustor was obtained from 54 piles and the measured average pile top reaction was only obtained by five piles, the calculated average pile top reaction is significantly smaller than the measured value. However, it still indicated that the trends of measured average pile top reaction variation with time were basically in line with the calculated average pile top reaction.

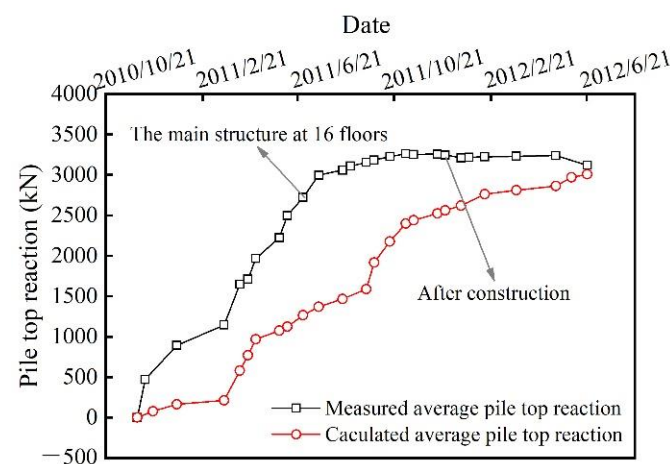


Figure 22. Curve of measured and calculated average pile top reaction variation with time.

6.5. Analysis of Steel Bar Stress

In this project, eight bar stress meters were installed within the raft in order to measure the stress distribution in the raft. Figure 23 presented the curve of steel bar stress variation with time. As shown in Figure 23, the steel bar stress significantly improved with the increase of load applied prior to the 16th floor of the main structure. Since then, the steel bar stress tended to be stable until the completion of the construction. The maximum steel bar stress was at G2, followed by G5, and then G7. This is because G2 was located in the core tube, where the structure was more rigid, and the load was concentrated. G5 and G7 were located on the edge of a shear wall and in the edge area of the raft with a small load, respectively. After construction, the maximum steel bar stress was 108.5 MPa, which did not reach the 1/3 of the design value. It was consistent with the facts written in the literature stating that the measured stress of most steel bars within the raft was low. After the field observation, there was no cracking or water seepage on the raft surface, indicating that the design concept of piled raft foundations with deformation adjusters was successful.

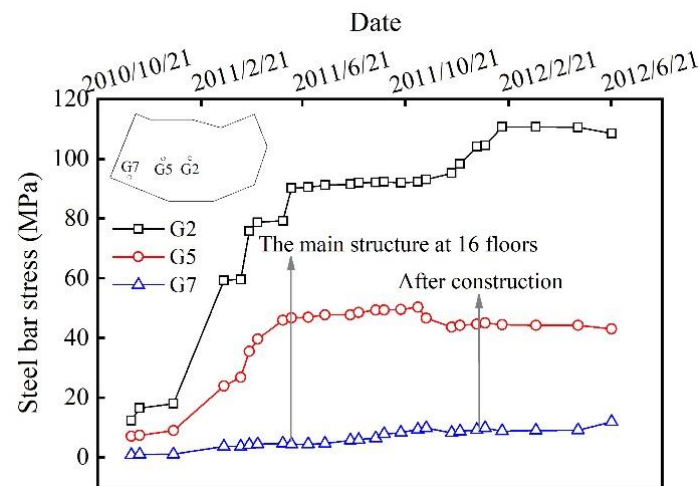


Figure 23. Curve of steel bar stress variation with time.

6.6. Analysis of Load-Sharing Ratio between Soils and Piles

In this project, the soil bearing capacity has significant utilization potential. Thus, the soil was designed to have an allowable bearing capacity of 353 kPa for supporting 62% of the superstructure load, whereas the piles were designed to bear 38% of the applied loads. The load-sharing ratio between soils and piles can be derived from the measured average earth pressure and the measured average pile top reaction directly. Figure 24 presented the curve of the load-sharing ratio of soil variation with time. As shown in Figure 24, the load-sharing ratio of soils varied with time but fluctuated around the design value. After construction, the load-sharing ratio gradually became stable. The measured value indicated that the load-sharing ratio of soils was 63%, which is slightly higher than the design value and numerical results. The application of deformation adjusters put the end-bearing piles and soils into play synchronously, which was essentially different from friction piles.

In addition, the numerical results showed that the load-sharing ratio of soils was high in the beginning of construction, and then gradually reduced to the design value with load applied, which was not exactly the same with measured results. This is because the raft and soil were in contact first, and soils deformed earlier than the deformation adjusters, leading to soil carrying more load in the beginning. As the deformation adjusters worked, the load-sharing ratio between soil and piles gradually stabilized.

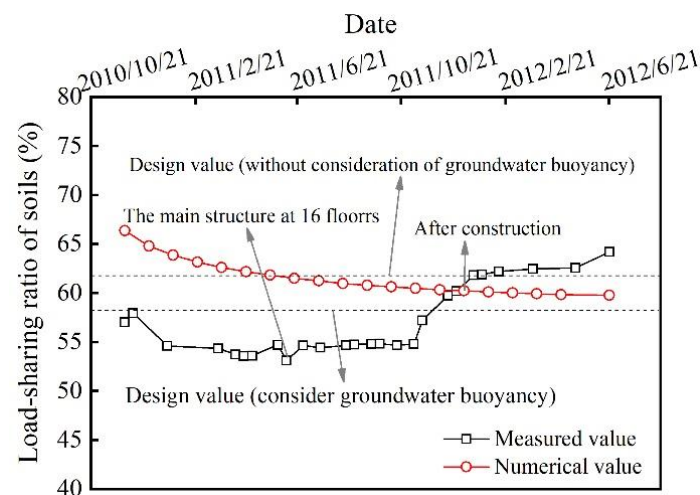


Figure 24. Curve of load-sharing ratio of soil variation with time.

7. Conclusions

(a) The pile-raft foundation with deformation adjusters was used successfully in complicated soil conditions. The deformation adjusters solved the challenges caused by abundant boulders and made the piled raft foundation into a coordinated deformation.

(b) As an application of deformation adjusters with different stiffness, the differential settlement of the building could be well controlled. The earth pressure distribution is also more uniform. However, the difference of pile top reactions was large, and the design scheme was more complex. It still needs to be tested and studied later.

(c) Deformation adjusters helped to adjust the stiffness difference so that soils and piles would jointly bear superstructure loads. In this case study, the soil was capable of supporting 63% of superstructure loads, whereas piles carried 37% of the loads.

(d) The piled raft foundations with deformation adjusters have been successfully applied to more than 20 projects, showing a better performance than conventional piled raft foundations in challenging conditions. However, the stiffness of current deformation adjusters cannot be changed after installation. Further studies are encouraged to carry out investigations on the active control technology of stiffness during the working period of deformation adjusters.

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References

1. Wu, J.T.; El Naggar, M.H.; Zhao, S.; Wen, M.J.; Wang, K.H. Beam-unequal length piles-soil coupled vibrating system considering pile-soil-pile interaction. *J. Bridge Eng.* **2021**, *26*, 04021086. [\[CrossRef\]](#)
2. Zhang, Y.P.; Wu, W.B.; Zhang, H.K.; El Naggar, M.H.; Wang, K.H.; Jiang, G.H.; Mei, G.X. A novel soil-pile interaction model for vertical pile settlement prediction. *Appl. Math. Model.* **2021**, *99*, 478–496. [\[CrossRef\]](#)
3. Ko, J.Y.; Cho, J.Y.; Jeong, S.S. Closure: Analysis of load sharing characteristics for a piled raft foundation. *Geotech. and Eng.* **2018**, *16*, 99–102.
4. Mayne, P.W.; Poulos, H.G. Approximate displacement influence factors for elastic shallow foundations. *J. Geotech. Geoenvironmental Eng.* **1999**, *125*, 453–460. [\[CrossRef\]](#)
5. Randolph, M.F. Design methods for pile groups and piled rafts. In Proceedings of the 13th International Conference of Soil Mechanics and Foundation Engineering, New Delhi, India, 1 January 1994; Taylor & Francis: Leiden, The Netherlands, 1994; Volume 5, pp. 61–82.
6. Randolph, M.F.; Wroth, C.P. Analysis of deformation of vertically loaded piles. *J. Geotech. Eng.* **1978**, *104*, 1465–1488. [\[CrossRef\]](#)
7. Reul, O.; Randolph, M.F. Design strategies for piled raft subjected to nonuniform vertical loading. *J. Geotech. Geoenvironmental Eng.* **2004**, *130*, 1–13. [\[CrossRef\]](#)
8. Mandolini, A.; Russo, G.; Viggiani, C. Pile foundations: Experimental investigations, analysis and design. In Proceedings of the 16th International Conference on Soil Mechanics and Geotechnical Engineering, Osaka, Japan, 12–16 September 2005; Balkema: New York, NY, USA, 2005; Volume 1, pp. 177–213.
9. Lee, S.H.; Chung, C.K. An experimental study of the interaction of vertically loaded pile groups in sand. *Can. Geotech. J.* **2005**, *42*, 1485–1493. [\[CrossRef\]](#)
10. Fleming, K.; Weltman, A.; Elson, K. *Piling Engineering*; Taylor & Francis: New York, NY, USA, 2009.
11. Liang, F.Y.; Chen, L.Z.; Shi, X.G. Numerical analysis of composite piled raft with cushion subjected to vertical load. *Comput. Geotech.* **2003**, *30*, 443–453. [\[CrossRef\]](#)
12. Sharma, V.J.; Vasanvala, S.A.; Solanki, C.H. Behaviour of cushioned composite piled raft foundation under lateral forces. *Indian Geotech. J.* **2015**, *45*, 89–97. [\[CrossRef\]](#)
13. Liu, H.K.; Xia, T.D. Pile-soil stress analysis of geogrid-reinforced pile-supported embankments with piles arranged in triangle. *J. Cent. South Univ.* **2014**, *45*, 3957–3963.
14. Poulos, H.; Mattes, N. Settlement and load distribution analysis of pile groups. *Aust. Geomech. J.* **1971**, *1*, 18–28.
15. Zhou, F.; Lin, C.; Wang, X.D.; Cheng, J.Y. Application of deformation adjusters in piled raft foundations. *Proc. Inst. Civ. Eng. Geotech. Eng.* **2016**, *169*, 527–540. [\[CrossRef\]](#)
16. Zai, J.M. *Theory and Practice of Composite Pile Foundation*; Intellectual Property Publishing House: Beijing, China, 2004.
17. Zhou, F.; Qu, W.; Guo, T.X.; Lin, S.Z. Engineering practice of composite end-bearing pile foundation based on settlement control. *Chin. J. Rock Mech. Eng.* **2015**, *5*, 1071–1079.
18. Zhou, F.; Lin, C.; Zhang, F.; Lin, S.Z.; Wang, X.D. Design and field monitoring of pile-raft foundations with deformation adjusters. *J. Perform. Constr. Facil.* **2016**, *30*, 04016057. [\[CrossRef\]](#)
19. CDC. *Technical Code for Design of Building Foundation (GB 50007)*; China Building Industry Press: Beijing, China, 2002.
20. CDC. *Technical Code for Building Pile Foundations (JGJ 94)*; China Building Industry Press: Beijing, China, 2008.
21. Hibbitt, H.; Karlsson, B.; Sorensen, P. *ABAQUS. Theory Manual, Verion. 6.12*; SIMULIA: Providence, RI, USA, 2012.
22. Tradigo, F.; Pisanò, F.; Prisco, C.D. On the use of embedded pile elements for the numerical analysis of disconnected piled rafts. *Comput. Geotech.* **2016**, *72*, 89–99. [\[CrossRef\]](#)
23. Bjerrum, L. Allowable settlement of structures. In Proceedings of the 3rd European Conference on Soil Mechanics and Foundation Engineering, Weisbaden, Germany, 1963; Volume 2, pp. 135–137.