Research on the Influence of Variable Stiffness Levelling Piles on Differential Settlement of High-rise Buildings

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Abstract: Due to the differential settlement of the piled raft foundation of high-rise buildings and super high-rise buildings, secondary stresses will be generated in the superstructure, and variable stiffness leveling can solve this problem. However, different methods of laying piles may cause large differences in the amount of piles used and the bearing capacity of the foundation. In order to explore the effects of different combinations on differential settlement and internal forces, this article studies the upper structure and foundation as a whole, using finite element software ABAQUS, calculation and analysis of piled raft foundations under self-weight and lateral loads. The effects of different pile lengths, different pile diameters, dense piles, and different pile lengths and different pile diameters on the different settlements and internal forces are analyzed. The research found that the variable pile length form has the best effect on the control of differential settlement, followed by the variable pile pitch type, and the effect of the variable pile diameter, the combination of variable pile length and variable pile diameter is poor. The research results can guide the design unit's design of pile distribution, and maximize the economy and safety.

1. Preface
Forty years since the reform and opening up, China’s economy has continued to develop and the process of urbanization has accelerated. Tall and super high-rise buildings can use land efficiently, enhance the image of the city, and promote economic development, making more and more cities construct high-rise and super high-rise buildings. Table 1 shows the number of super high-rise buildings in cities in China from 2013 to 2018. Because the load of the superstructure of high-rise and super high-rise buildings is much larger than that of existing ordinary buildings, the high-rise and super-high-rise buildings have relatively high requirements for settlement deformation and bearing performance. At present, the pile foundation as a deep foundation form is being widely used in high-rise and super high-rise building foundations [1]. But a new problem arises: differential settlement of the foundation. The dish-shaped differential settlement problem caused by the traditional design method of piled raft (box) foundation of high-rise buildings and the differential settlement problem of the main podium [2]. "Technical Specifications for Building Pile Foundations" [3] proposed a new concept of variable stiffness leveling design. The basic idea of this concept is to consider the joint action of the foundation, foundation and superstructure, and adjust the distribution of the supporting stiffness of the pile and soil, the dominant factor that affects the settlement and deformation field.
Table 1. Statistics of the number of super high-rise buildings in each city.

| Ranking | City     | Quantity | Ranking | City     | Quantity |
|---------|----------|----------|---------|----------|----------|
| 1       | Tianjin  | 20       | 6       | Wuhan    | 7        |
| 2       | Shenzhen | 15       | 6       | Shenyang | 7        |
| 3       | Wu Xi    | 9        | 6       | Guiyang  | 7        |
| 4       | Guangzhou| 8        | 10      | Chongqing| 6        |
| 4       | Dalian   | 8        | 10      | Kunming  | 6        |
| 6       | Shanghai | 7        |         |          |          |

Variable stiffness leveling is to adjust the stiffness distribution of the foundation and base, so that the load of the superstructure and the reaction force of the foundation are coordinated with each other, and the settlement of the foundation will tend to be uniform, so that the internal forces of the superstructure and the foundation are kept within a reasonable range. There are many methods for leveling the stiffness of a piled raft foundation, such as variable pile length, variable pile diameter, variable pile spacing, combination of variable pile length and variable pile diameter, combination of variable pile length and variable pile distance, variable pile diameter and variable The combination of pile spacing and the combination of variable pile length, variable pile diameter, and variable pile spacing. Can be expressed by a general equilibrium equation [4]:

$$ [K_b + K_r + K_s]\{\mu_0\} = \{Q\} + \{S_b\} \quad (1) $$

Where: $[K_b]$ is equivalent boundary stiffness matrix of superstructure; $[K_r]$ is base stiffness matrix; $[K_s]$ is foundation stiffness matrix; $[\mu_0]$ is displacement vector of base node; $[Q]$ is load vector of base part node; $\{S_b\}$ is equivalent node load vector of superstructure.

It can be seen from equation (1) that the settlement of the foundation is directly related to the stiffness of the superstructure, foundation, and foundation. To reduce the differential settlement of the foundation, it is necessary to increase the stiffness of the above three. Among them, the effect of increasing the stiffness of the superstructure on reducing the differential settlement of the foundation is not obvious, and the effect of increasing the stiffness of the foundation on reducing the differential settlement of the foundation is also not good, and it will also increase the cost. Therefore, only by adjusting the foundation stiffness $K_r$ can the differential settlement of the foundation be effectively reduced.

In the research field of variable stiffness leveling of piled raft foundations, Liu Jinli [5] proposed the concept and method of optimal design for joint variable stiffness leveling to adjust the pile length on the basis of maintaining the same amount of raw materials to reduce the differential settlement of the foundation. Franke et al. [6] broke through the traditional design method and used unequal pile-length combed pile foundations (internally strong and weakly outside the pile) to reduce uneven settlement and prevent the building from tilting, and achieved good results. Basuony et al. [7] used model tests to analyze the bearing and settlement properties of single piles, raft foundations, and piled raft foundations in sandy soils. At the same time, the slenderness ratio of the piles, the relative stiffness of the rafts, and the rafts were analyzed. Effect of thickness on load bearing and settlement properties. Ghalesari et al. [8] designed an optimal pile length and pile position layout scheme through specific examples, and pointed out that the economic and practical design of the pile raft foundation was carried out by optimizing the pile length and pile position. Abdarbo et al. [9] studied the effects of piles with different pile lengths and diameters on the working performance of group piles through model tests.

In order to explore the effects of different combination methods on differential settlement and internal force, this article studies the superstructure and foundation as a whole, and analyzes the variable pile length, variable pile diameter, combination of variable pile length and variable pile diameter, and centrally-distributed piles.

2 ABAQUS finite element analysis method and model of pile foundation

With the continuous development of computer technology and the emergence and promotion of
commercial finite element software, numerical simulation analysis methods are becoming more and more popular with scholars. For the study of pile-soil interaction, you only need to set relevant parameters and establish corresponding models according to the research needs, and you can calculate the results that are more realistic and basically consistent with the field test, which greatly reduces the time and cost of scientific research. To achieve a more satisfactory result, ABAQUS can be used to analyze a variety of mechanical model problems, whether linear or more complex non-linear problems. ABAQUS can be divided into ABAQUS / Standard (implicit method) and ABAQUS / Explicit (explicit method) two modules, of which ABAQUS / Standard is a standard general analysis module, which can be used to analyze static, dynamic, and stress-coupled analysis problems. ABAQUS / Explicit is mainly used to simulate and analyze relatively short-term transient dynamic problems, such as earthquakes, explosions, and shocks. The study of pile-soil interaction in group pile foundations in this paper mainly involves static problems, that is, to simulate the working state of group pile foundations under static load, so the ABAQUS / Standard module can be used. Numerical simulation of pile-soil interaction can be completed through ABAQUS / CAE (pretreatment) and ABAQUS / VIEWER (posttreatment).

2.1 Introduction to computational models
The model of this example is: 12-story frame-core tube superstructure with a height of 3m, the core tube shear wall thickness is 250mm, the beam section size is 250mm × 600mm, and the column section size is 600mm × 600mm. The raft is 0.6m thick and its plane size is 26.4m × 26.4m. The pile is a reinforced concrete pile with a diameter of 600mm and a length of 19m. Concrete material parameters in the model: Poisson's ratio is 0.2, density is 2500Kg/m$^3$, and elastic modulus is 30GPa. The layout of the pile is shown in figure 1. Modeling with ABAQUS finite element software, taking a range of 132m × 132m × 53m of ground soil. The constitutive model of the foundation soil is Mohr-Coulomb's elastoplastic model. At the same time, a horizontal acceleration of 0.05g was applied to the superstructure to simulate earthquake loads. See table 2 for material parameters.

| Name of the soil | Thickness (m) | Elastic modulus E(MPa) | Poisson’s ratio $\mu$ | Cohesion C(kPa) | Friction angle $\Phi$ (°) | density $\rho$ (Kg/m$^3$) |
|-----------------|---------------|------------------------|-----------------------|-----------------|--------------------------|--------------------------|
| Silty clay      | 53            | 31.5                   | 0.3                   | 30.0            | 20.0                     | 1800                     |

Figure 1. Layout plan of the piles.

2.2 Model mesh and boundary conditions
In this model, beam elements are used to simulate the beams and columns in the superstructure, shell elements are used to simulate the shear walls of the floor slab and the core tube, and the pile raft foundation and soil are simulated by solid elements. Considering the interaction, the superstructure is rigidly connected to the raft, and the coefficient of friction between pile and soil is 0.3. The side of the soil is restrained laterally, and it can slide freely vertically. The bottom surface is completely restrained
in three directions. As shown in figures 2 and 3.

3 Study on the influence of different forms of piles

3.1 Research on the influence of different pile length on differential settlement

Change the pile length of No. 1 ~ 4 pile to 29m, and other parameters are not changed, that is, change the pile length to adjust the foundation stiffness distribution. Through finite element calculation, the OX axis settlement distribution of the cent line of the raft is shown in figure 4 and the axial force distribution of No. 1 to 4 center piles is shown in table 3.

It can be seen from figure 4 that, compared with the uniformly-distributed piles, the variable pile length reduces the differential settlement of the foundation. When the piles are evenly distributed, the differential settlement of the raft is 22.6mm. When the length of the central pile is 29m, the differential settlement of the foundation is 14.6mm, which is 8mm less than that of the uniform pile. At the same time, it can be seen from table 3 that the axial force of the top of the center pile at the same location increases. This is because the stiffness of the foundation is adjusted by increasing the length of the center pile, and the internal force distribution of the foundation is also changed. Axial force at the top of the pile increases.

3.2 Research on the influence of different pile diameters on differential settlement

Take the diameter of the center pile (No. 1 ~ 4 piles) as 0.8m, and other parameters remain unchanged. Adjust the level of stiffness by increasing the diameter of the center pile. By finite element calculation, the OX axis settlement distribution of the centerline of the raft is shown in figure 5 and the axial force
distribution of No. 1 to 4 center piles is shown in table 4.

![Figure 5. OX axis settlement map of the raft.](image)

**Table 4.** Axial force of the center piles’ top (KN).

| Form of piles         | NO. 1 | NO. 2 | NO. 3 | NO. 4 |
|-----------------------|-------|-------|-------|-------|
| Evenly distributed piles | 1294  | 1362  | 1292  | 1219  |
| Different pile’s diameter | 1534  | 1609  | 1545  | 1470  |

As can be seen from the figure, compared to uniformly-stacked piles, the differential settlement of the rafts is reduced by the form of piles with varying center-piled diameters, and the differentially-settlement of the uniformly-rafted rafts is 22.6mm. When the diameter of the central pile is 1.2m, the differential settlement of the raft is 20.1mm, which is 2.5mm less than that of a uniform pile. As can be seen from the table, the axial force of the top of the pile in the form of a variable center pile diameter is larger than the top axial force of the uniformly piled pile. This is due to the increase of the center pile diameter and the readjustment of the stiffness of the foundation. The internal force of the foundation is reduced, the raft settlement at the center pile is reduced, and the axial force at the top of the pile is increased.

3.3 Research on the influence of different pile spacing on differential settlement

By increasing the number of piles under the core tube, the pile spacing is reduced. Add four piles at the lower part of the core tube, as shown in figure 6, the remaining parameters remain unchanged. By finite element calculation, the OX axis settlement distribution of the centerline of the raft is shown in figure 7 and the axial force distribution of No. 1 to 4 center piles is shown in table 5.

![Figure 6. Layout plan of piles.](image)  
![Figure 7. OX axis settlement map of the raft.](image)
Table 5. Axial force of the center piles' top (KN).

| Form of piles                  | NO. | 1   | 2   | 3   | 4   |
|-------------------------------|-----|-----|-----|-----|-----|
| Evenly distributed piles      | 1   | 1294| 1362| 1292| 1219|
| Dense piles                   | 2   | 1112| 1235| 1195| 1039|

From the results, it can be seen that compared with uniformly piled piles, the differential settlement of the piled piles in the form of reduced pile spacing is reduced, and the differential settlement of the uniformly piled raft is 22.6mm. The differential settlement of the pile foundation in the form of dense piles is 18.3mm, which is 4.3mm smaller than that of uniform piles. It can be seen from the table that the axial force of the central pile and the uniformly-distributed pile in the form of a dense pile are reduced. This is due to the addition of four piles in the center of the raft to share the upper load.

3.4 Research on the influence of different settlement of different pile length and pile diameter combinations

The central piles (No. 1 ~ 4 piles) are 24m long and 1.0m diameter. Adjust the stiffness of the foundation by changing the pile length and diameter. By finite element calculation, the OX axis settlement distribution of the centerline of the raft is shown in figure 8 and the axial force distribution of No. 1 to 4 center piles is shown in table 6.

![Figure 8. OX axis settlement map of the raft.](image)

Table 6. Axial force of the center piles’ top (KN).

| Form of piles                              | NO. |
|-------------------------------------------|-----|
| Evenly distributed piles                  | 1   |
|                                           | 2   |
|                                           | 3   |
|                                           | 4   |
| Different pile lengths and different pile diameters | 1477|
|                                           | 1541|
|                                           | 1483|
|                                           | 1405|

As can be seen from the figure, compared with the uniformly piled piles, the piled piles with different pile lengths and different pile diameters reduce the differential settlement of the raft. The differential settlement of the uniformly piled raft is 22.6mm. When the central pile length is 24m and the pile diameter is 1.0m, the differential settlement is 21mm, which is 2.5mm less than the uniform pile distribution. As can be seen from the table, the stiffness of the foundation is adjusted by the form of piles with different combinations of pile lengths and diameters. The internal force of the foundation also changes.

4 Conclusion

According to the calculation results, it can be found that the average settlement of the variable pile length, variable pile diameter, compacted pile, combined pile length and variable pile diameter in the form of pile piles is reduced compared to uniform pile piles, but the reduction is not significant enough. Although the above pile-laying forms do not have a good effect on reducing the average settlement,
the differential settlement of pile-raft rafts with reduced pile length, variable pile diameter, dense pile, and combination of variable pile length and variable pile diameter has been reduced, which has achieved relatively good result. In addition, among these several types of piles, the variable pile length has the best control effect on differential settlement, followed by the variable pile spacing type, variable pile diameter, and the combination of variable pile length, and variable pile diameter. The effect of the pile form is relatively poor. In terms of material usage, the material used for the variable pile length and variable diameter pile form is much less than the other two types of pile forms. Among them, the variable pile length form has a better effect on reducing differential settlement than the variable pile distance, and the amount of material And less. Therefore, under certain conditions, the material used in the form of variable pile length is more economical, and the optimal design effect of the foundation is also better. At the same time, in actual engineering, which form of piles to be used needs to be considered in combination with specific site conditions and construction difficulty, as well as economic applicability, etc.

5. References

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