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RECTIFICATION THEORY AND REINFORCEMENT PRACTICE BASED ON THE PRINCIPLE OF COUNTERFORCE CENTER

YANPENGA ZHU, KUIBIN YANG, JUN TAO, and XIULI WANG

School of Civil Engineering, Lanzhou University of Technology, Lanzhou, China

Like buildings with other types of foundations, buildings with pile foundations can tilt because of irrational designs, imperfections of foundation treatment, poor construction qualities, even the change of water environment during usage, etc. By studying and analyzing the causes for the inclination, this paper has proposed a theory of rectification and reinforcement for buildings with pile foundations based on the principle of counterforce center, which makes building be rectified by changing the counterforce center of pile foundation so that it can be in the same vertical line with the gravity center of upper structure. Then the calculation method was given. Combining with an engineering project, it has been proved that the principle of counterforce center is a good guidance for the rectification and reinforcement for buildings with pile foundations.

Keywords: Pile foundation, Building rectification, Foundation reinforcement, Pile supplement.

1 INTRODUCTION

Although the traditional conception believes that differential settlement and tilting rarely happens on structures with pile foundations, structures with pile foundations frequently tilt with the influence of many factors including design, construction, or use, etc. The inclination of the pile-foundation-structures brings a hidden trouble to the safe usage of structures and a threat to the safety of users' lives and properties.

Some scholars have made a conclusion from many engineering practices that one of the important reasons for the structures' inclination is that the center of gravity of upper structure and the centroid of foundation are not in the same vertical line (Gao 1991, Wen and Wei 2004, Wang *et al*. 2006). But these conclusions were not made from force perspective to illustrate inclination from its essential reason. Moreover, according to Technical Code for Improvement of Soil and Foundation of Existing Buildings (JGJ123 2012), the work for rectification is usually considered specifically in two methods: forced settlement and jacking. The principles of the two methods are stress-releasing principle (Liu 1990) or breaking soil structure and stress-transferring principle (Zhu *et al*. 2005). However, relating construction methods cannot satisfy the requirement of diverse types of structures, and especially they focus little on the method that can rectify pile-foundation-structures.

Through analysis about the tilting causes of pile-foundation-structures, this journal puts forward a new rectification and reinforcement theory based on the principle of counterforce

center. The theory was applied in a project, and the building in this project was rectified successfully.

2 THE RECTIFICATION THEORY BASED ON THE PRINCIPLE OF COUNTERFORCE CENTER OF PILE FOUNDATION

2.1 The Principle of Counterforce Center of Pile Foundation

The counterforce of pile foundation addressed in this paper is not actual bearing force. It is a hypothesis during force analysis. How much load that a single pile can actually bear is related to the ultimate bearing capacity, so the counterforce of pile foundation was calculated by assuming that every single pile bears the value of ultimate bearing capacity. Therefore, the ultimate bearing capacity was applied to calculate the counterforce of pile foundation.

The counterforce of pile foundation is the maximum stress set provided by all the single pile, whose direction is straight up, and the value is the sum of bearing capacity of all piles. The counterforce center is located at the point of bearing capacities' resultant force of all piles.

In projects, the counterforce center of pile foundation and the gravity center of upper structure sometimes are not in same vertical line, as shown in Figure 1. With the eccentric effect, the bearing stress of pile foundation would be nonuniform, and the more settlement would happen on the side bearing more. As a result, the whole structure would tilt. Moreover, the tilting of the whole structure causes more eccentric increment of upper loads, which leads to new moment increment increasing the tilt of whole structure in turn. Higher the structure is, more obvious the effect is (Lou *et al*. 2000).

To make pile foundation bear more loads from upper structure, the deformation of each pile should be made as much concerted with each other as possible, and the center of gravity of upper structure and the counterforce center of pile foundation should be kept as in one vertical line as possible. It is the basic principle to rectify tilting. According to the skewing degree between the counterforce center of pile foundation and the gravity center of upper structure, based on considering eccentric moment, the bearing loads on piles are rearranged. Then additional piles are added according to the rearranged bearing situation. Therefore, the gravity center of upper structure and counterforce center of pile foundation act on one vertical line and the structure is rectified.

2.2 The Calculation for Counterforce Center of Pile Foundation

The counterforce center is located at the point of action of bearing capacities' resultant force of all piles. Now how to locate the counterforce center of pile foundation is introduced by the example in Figure 2. The counterforce of a single pile is assumed to be the bearing capacity of the pile, which is calculated according to Eq. (1) from *Technical Code for Building Pile Foundations*.

$$Q_{uki} = u\sum q_{sik} l_i + q_{pk} A_P \tag{1}$$

where Q_{uki} is the standard value of single pile's bearing capacity, u is the perimeter of pile body, q_{sik} is the standard value of single pile's limited side friction in the ith layer, l_i is the length of single pile body buried in the ith layer, q_{pk} is the standard value of single pile's limited tip resistance, and A_P is the area of pile tip.

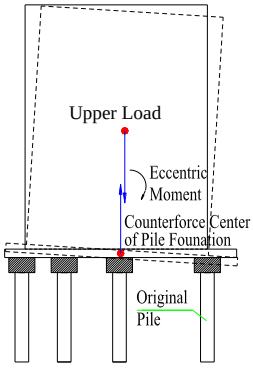

Figure 1. Diagram of inclined building.

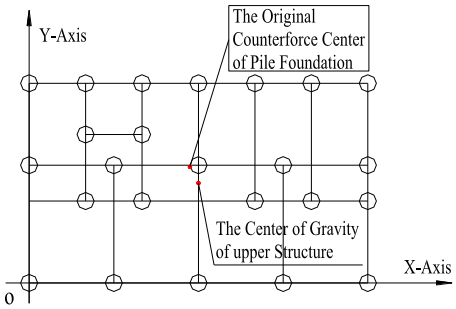

Figure 2. Layout plan of pile foundation.

After the calculation about the standard value of bearing capacity of a single pile, by establishing a rectangular plane coordinate system as a reference, the location of counterforce center of pile foundation can be calculated according to the principle of moment balance from Eq. (2):

$$X = \frac{\sum_{i=1}^{n} Q_{uki} x_i}{\sum_{i=1}^{n} Q_{uki}}, \quad Y = \frac{\sum_{i=1}^{n} Q_{uki} y_i}{\sum_{i=1}^{n} Q_{uki}} \tag{2}$$

where X and Y are the coordinate figures of the counterforce center in the rectangular plane coordinate system, x_i and y_i are the coordinate figures of the ith pile.

2.3 The Calculation for the Bearing Capacity of Pile Foundation Considering Additional Eccentric Moment

When the counterforce center of pile foundation and the center of gravity of upper structure are not in the same vertical line, eccentric effect would produce the additional moment, which results in that the bearing load is rearranged. Considering the nonuniformity of the bearing load on pile foundation brought by eccentric effect, the rearranged bearing capacity of piles is recalculated from Eq. (3).

$$N_i = \frac{G}{n} \pm \frac{G(X - X')y_i'}{\sum y_j'^2} \pm \frac{G(Y - Y')x_i'}{\sum x_j'^2} \tag{3}$$

where N_i is the eigenvalue of bearing capacity of a single pile considering additional moment, G is the total weight of the whole structure, n is the number of piles, X' and Y' are the coordinate figures of the gravity center of the upper structure in the rectangular plane coordinate system, x_i', x_j', y_i', y_j' are the distances of the ith and jth piles to the y-axis and x-axis, respectively.

2.4 The Calculation for Adding Piles

Comparing the standard value of bearing capacity of a single pile calculated from Eq. (1) and the bearing capacity of a single pile considering the additional eccentric effect calculated from Eq. (3), when the former is smaller than the double value of the latter, supplement for piles should be designed, which means adding one or several piles around the original pile to satisfy the requirement for bearing capacity. In the end, the center of gravity of upper structure and the counterforce center of pile foundation are in the same vertical line by this way. The number of additional piles is calculated from Eq. (4),

$$n = \frac{2N_i - Q_{uk}}{N} \tag{4}$$

where n is the number of addition piles around the original pile, Q_{uk} is the standard value of ultimate bearing capacity of original pile, N is the standard value of ultimate bearing capacity of new single pile added.

3 THE PRACTICE OF RECTIFICATION AND REINFORCEMENT BASED ON THE PRINCIPLE OF COUNTERFORCE CENTER

In recent years, the authors have made some rectification and reinforcement practices with the guidance of principles and technologies mentioned above, which proved to have a great effect. Hopefully the following example can provide any thought and reference for the future similar rectification and reinforcement engineering for pile-foundation structure.

3.1 Overview of the Project

With a total weight of 16,000 tons, the pile-foundation-building is 49.0m long, 13.0m wide, and 35.5m high. There are 1 floor underground and 12 floors on the ground of this frame-shear wall structure. The foundation type was bored concrete piles. The building started to tilt after 5 years from being built, shown in Figure 3 and Figure 4.

Figure 3. The tilting building.

Figure 4. The crack of the tilting building

The displacement measured from top to bottom of the building varies in the range of 225mm to 357mm. The whole building deformed and inclined to south, and the maximum gradient reached 12.75‰ beyond the allowable value for high-rise building required in *Code for Design of Building Foundation*, which threatens the safety of whole structure.

3.2 The Calculation for Rectification and Reinforcement Design Based on the Principle of Counterforce Center of Pile Foundation

The pile foundation was divided into two parts according to the tilting direction and settlement difference. The north part was induced settlement zone while the south was adjustment zone. The design integrated both rectification and reinforcement for the whole building by applying the new grout-steel pipe composite piles. By means of installing the bearing platforms on the top of the new grout-steel pipe composite piles, connected with original piles and bottom plate, the induced settlement was made by drilling the original bored concrete piles to fulfill rectification and reinforcement, shown in Figure 5.

The information of different layers is determined by geological survey materials. The vertical ultimate bearing capacity standard value of every single pile was calculated by Eq. (1). The calculated minimum bearing capacity standard value was 2054kN while the maximum bearing capacity standard value was 3081kN, and the total bearing capacity of pile foundation was 131466kN, which was smaller than the total weight of the building, 160000kN. So the original piles did not satisfy the requirement of bearing capacity. The counterforce center of pile foundation was at (-290.6, 980.9), calculated using Eq. (2). Obvious excursion happened comparing to the center of gravity (0, 0) of upper structure.

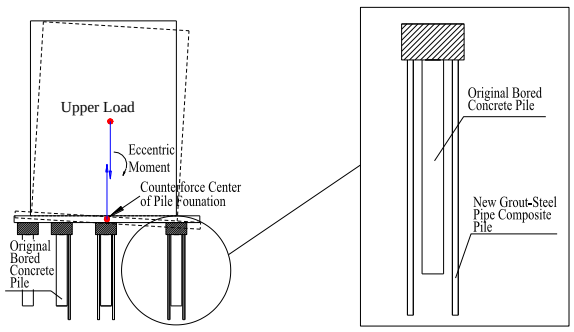

Figure 5. Figure of rectification.

The bearing capacity of every pile was calculated according to Eq. (3) considering the additional eccentric moment. The minimum counterforce of single pile was 2126.1kN appearing at northwest part, which was smaller than the actual bearing load of this pile, 2558.8kN. It did not satisfy the requirement of bearing capacity, and more piles need to be added to reinforce the foundation.

The selected pile type was grout-steel pipe composite pile, whose pile tip enters the intermediary weathered sandstone to the depth of 2m. The bearing capacity eigenvalue of single pile was 800kN. The amount of piles needing to be added was determined with Eq. (4). There would be 58 new grout-steel pipe composite piles and 36 bearing platforms being needed in total by the whole building through calculation. The arrangement for bearing platforms is shown in Figure 6. After adding new piles, the new counterforce center of foundation was calculated to be (-31.9, 37.5), with Eq. (2), which means the additional eccentric moment decreased a lot. So the rectification requirements were satisfied and the rectification is accomplished.

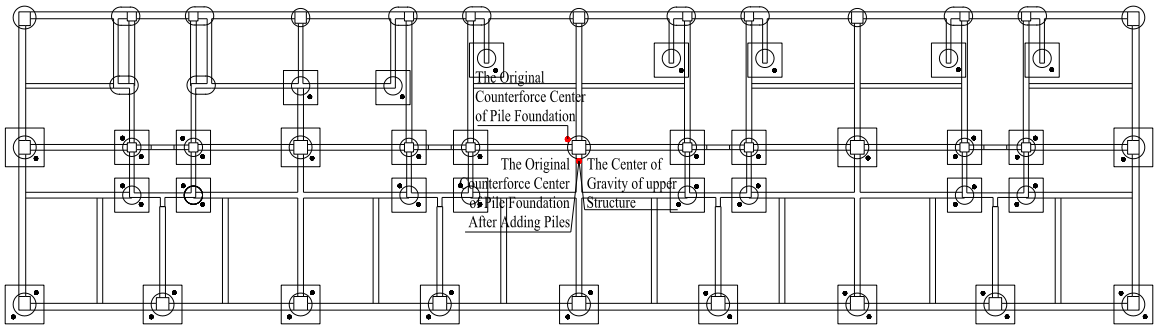

Figure 6. Plan of pile foundation after supplementary piles.

4 CONCLUSIONS

(1) Differential settlement of pile foundation would happen because of eccentric effect caused by that the gravity center of upper structure and the counterforce center of pile foundation are not in a vertical line, which is an important reason for the inclination of the whole structure.

(2) By decreasing the nonuniformity of additional pressure on foundation based on the thought of rectification and reinforcement applying the principle of counterforce center of pile foundation, the loads on pile foundation can be redistributed, which can be a good guidance for the rectification and reinforcement for buildings with pile foundation.

(3) In the practice of rectifying and reinforcing the buildings with pile foundations, firstly the eccentric distance between the counterforce center and the gravity center of upper structure is calculated. Then more piles are added according to the load redistributed considering the eccentric moment. In this way, the counterforce center of pile foundation and the gravity center of upper structure can be moved in the same vertical line so that the rectification of the structure is fulfilled.

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