Analysis of the Influence of Differential Consolidation Settlement of Foundation on Redistribution of Internal Forces in Superstructure of Buildings

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Abstract. In order to explore the influence of differential settlement of foundation on the internal force and deformation of super-frame structure, the stress and deformation of the traditional fixed support model and the elastic support model under the local effect of the differential settlement of the two columns are compared. The model without considering the settlement of the structure (Model 1), the traditional fixed support model (Model 2), and the vertical elastic support model (Model 3) are respectively constructed for analysis. The left end of the frame column and A/1-2 beam are taken as an example, the axial force of the frame column in Model 3 significantly decreases from -817.8kN to -415.3kN compared with Model 1, with a reduction of 49%; the shear force at the left end of the lower A/1-2 beam increases from 42.3kN to 43.5kN with an increase of 3%; and the bending moment increases from -27.2kN·m to 152.7kN·m. Those indicate the shear force and bending moment of the beam directly connected with the subsidence column under the action of the elastic support model are smaller than that under the action of the fixed support model. It is hoped that these change rules can provide reference for the design and reinforcement of similar projects in the future.

Key words: Differential consolidation settlement; internal force redistribution; shear force; bending moment.

1. Introduction

Differential settlement of foundation results in redistribution of internal forces of superstructure [1], and some additional internal forces are generated by other components, resulting in structural cracking or collapse [2], which seriously endanger the safe use of buildings. Therefore, the study of the influence of the differential settlement of foundation on the stress and deformation of the columns on both sides of the upper frame can provide a reasonable basis for the structural design, reinforcement, and construction of the house.

At present, there are mainly three models for studying the influence of differential settlement of foundation on superstructure. The first is the vertical elastic support model, in which a spring is added at the bottom of each column of the building. The influence of differential foundation settlement on the superstructure can be simulated by adjusting the spring stiffness repeatedly. However, this method only considers the vertical effect, not the horizontal effect [3-4]. The second is the fixed support model, which...
is also the most common analysis model. Some displacement is applied to the support of the column base, and a fixed end can be added to the column base [5]. The third is a three-dimensional elastic support model, which simulates the vertical and lateral deformation of foundation with three-dimensional spring support, making up for the defects of the first two models [6].

In practice, the interaction between foundation stiffness and building superstructure should be considered. Therefore, the fixed support model and the vertical elastic support model are adopted to simulate the foundation so as to analyze the influence of differential settlement on the stress and deformation of the superstructure in local area.

2. Methods

2.1. Project Profile

An office complex with a 5-story frame structure is taken as an example in this study. The total height, length, and width of the project are 17m, 28m, and 14.1m respectively. All floors and roofs are cast-in-place reinforced concrete structure, which are with pile foundation and the height of each layer is 3.4m. The building has been in use for many years, and the foundations show significant differential settlement that the foundation is partially separated from the foundation floor and the wall is cracked in many places. The safety of the building is seriously affected by the cracking of some beams and columns and the creation of new cracks every day.

Figure 1 shows the floor plan of the 1-5 floors structure of the building. On-site monitoring is conducted, which includes the building's basic material performance, cracks, overall building tilt, and column settlement. For columns that can't be monitored internally, corresponding settlement values are obtained by longitudinal linear interpolation.

![Figure 1. Structure plan of 1-5 floors in a project (unit: mm)](image)

The 25 beams and columns of the frame are randomly selected as samples to test the compressive strength of concrete. The results show that the concrete strength of the extracted beams and columns meet the design requirements.

Part of the beam-column plates are randomly selected and the carbonization depth of the concrete is detected to be 6-15mm. Combined with the observation of the internal structure after cutting, no obvious corrosion is observed.
The length, width, strike, and position of cracks are recorded via the crack width meter. The results show that the main cracks are serious in longitudinal wall and light in transverse wall. Among them, A cross ③ and A cross ⑥ crack are the most serious, with the largest crack up to 7.5mm.

The suspension method is adopted to measure the overall tilt of the building. The results show that the overall tilt of the building to the east is small and meets the basic requirements.

According to the monitoring data, the settlement diagram of axis A and Axis D pillars are drawn, as shown in figure 2. Except the axis 1 and the axis 8 on both sides of the column, the settlement rate of the other columns along the X-axis coordinate direction is relatively close. Settlement rate = settlement difference \( \div \) X-axis column distance. The longitudinal differential settlement of the building is serious, while the transverse differential settlement is light.

![Figure 2. Statistical chart of settlement of axis A and Axis D](image)

2.2. Calculating Model

Structure Master of Midas Building is adopted and load is applied. The following three calculation models are established to reveal the influence of differential settlement on the stress and deformation of the superstructure in local scope:

- Model 1: a conventional design model that does not consider structural settlement.
- Model 2: the measured settlement value is directly applied to the base of each column, and the traditional fixed support model is adopted.
- Model 3: vertical elastic support model. The initial stiffness of each column spring is calculated, then the frame on both sides of the column bottom (namely axis and today axis) is made to produce 3cm settlement.

3. Results and discussion

3.1. Analysis of Variation of Axial Force Under Three Models

As shown in table 1 and figure 3, under the effect of Model 1, Model 2, and Model 3, when the structural column base settlement occurs on both sides, the axial force of the two column bases significantly decrease, while the axial force of the remaining column bases increase.

Compared with Model 1, when the settlement of the support on both sides of the column occurs, the axial force of the frame column (including ①×A and ⑧×A) of Model 2 significantly decreases from -817.8kN to -88.2kN, with a decrease of 89%. The axial force of ②×A and ⑦×A increase by 68% (from -1155.6kN to -1948.5kN). The increase in the remaining bars is within 5%. The axial force of the frame column of the B-axis of the middle frame column (①×B and ⑧×B) decrease from -974.5kN to
-235.1kN, with a reduction of 76%. The axial force of \( \text{②} \times \text{B} \) and \( \text{⑦} \times \text{B} \) increase by 61% (from -1323.1kN to -2127.6kN). The increase in the remaining bars is within 6%.

Compared with Model 1, the axial force of the frame column (including \( \text{①} \times \text{A} \) and \( \text{⑧} \times \text{A} \)) of Model 3 significantly decrease from -817.8kN to -415.3kN, with a decrease of 49%. The axial force of \( \text{②} \times \text{A} \) and \( \text{⑦} \times \text{A} \) increase by 23% (from -1155.6kN to 1418.5kN). The increase in the remaining bars is within 8.5%.

The axial force of the frame column of the B-axis of the middle frame column (\( \text{①} \times \text{B} \) and \( \text{⑧} \times \text{B} \)) decrease from -974.5kN to -503.7kN, with a reduction of 48%. The axial force of \( \text{②} \times \text{B} \) and \( \text{⑦} \times \text{B} \) increase by 22% (from -1323.1kN to -1615.8kN). The increase in the remaining bars is within 4%.

These data indicate that the spring simulated foundation may be closer to the actual settlement of the building than the fixed support method, and has less influence on the axial forces of both sides and adjacent columns. In practical engineering, the column adjacent to the settling column produces the largest axial force, and the further away from the settling column, the smaller the additional axial force.

Table 1. Comparison of axial force (kN) of each column base in axis A and axis B under three models.

|       | \( \text{①} \) | \( \text{②} \) | \( \text{③} \) | \( \text{④} \) | \( \text{⑤} \) | \( \text{⑥} \) | \( \text{⑦} \) | \( \text{⑧} \) |
|-------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|
| **A-axis** | Model 1 | -817.8 | -1155.6 | -1204.7 | -1206.3 | -1204.7 | -1155.6 | -817.8 |
|        | Model 2 | -88.2 | -1948.5 | -1263.5 | -1245.8 | -1263.5 | -1948.5 | -88.2 |
|        | Model 3 | -415.3 | -1418.5 | -1302.6 | -1284.9 | -1302.6 | -1418.5 | -415.3 |
| **B-axis** | Model 1 | -974.5 | -1323.1 | -1379.4 | -1379.4 | -1379.4 | -1323.1 | -974.5 |
|        | Model 2 | -235.1 | -2127.6 | -1452.0 | -1398.9 | -1452.0 | -2127.6 | -235.1 |
|        | Model 3 | -503.7 | -1615.8 | -1425.2 | -1384.5 | -1425.2 | -1615.8 | -503.7 |

Figure 3. Comparison of axial force (kN) of each column base in axis A (left) and axis B (right).

3.2. Change Analysis of Shear Force Under Three Models

The shear changes of the beams on both sides of the longitudinal axis A and B (the beams 1-2 and 7-8) are relatively significant. According to the principle of symmetry, only the shear of these beams is analyzed. Compared with Model 1, the shear force at the left end of A/1-2 beam under the action of Model 2 increases from 42.3kN to 107.5kN, with an increase of 154%. The shear force at the right end of A/1-2 beam increases from 40.8kN to 19.8.1kN, with an increase of 386%. The left end shear increase of B/1-2 beam is 156% (41.4kN to 106.0kN) and the right end shear increase is 365% (from 40.6kN to 188.7kN).

Compared with Model 1, the shear force at the left end of A/1-2 beam under the action of Model 3 increases from 42.3kN to 43.5kN, with an increase of 3%. The shear force at the right end of A/1-2 beam increases from 40.8kN to 123.5kN, with an increase of 203%. The left end shear increase of B/1-2 beam is 15% (from 41.4kN to 47.6kN) and the right end shear increase is 217% (from 40.6kN to 128.6kN), as shown in table 2 and figure 4.
On the transverse frame, the shear forces of each beam and column change little under the action of Model 1, Model 2, and Model 3.

When both sides settle, the settlement difference is generated along the longitudinal direction, which has great influence on the increase of shear force of frame beam and column, and there is no settlement difference between the transverse columns, so there is no impact generated by frame beams and columns. When traditional fixed support model and elastic support model are adopted for calculation, the influence of support settlement on shear force is different. When the same settlement occurs, the change of shear force caused by traditional fixed support is greater than that caused by elastic support.

Table 2. Shear force of frame 1-2 beams selected in three models (kN).

| A/1-2 beam | B/1-2 beam |
|------------|------------|
| Left end   | Right end  |
| Left end   | Right end  |
| Model 1    | 42.3       | 40.8       |
| Model 2    | 107.5      | 198.1      |
| Model 3    | 43.5       | 123.5      |

Figure 4. Shear force (kN) of beam 1-2 on Axis A and Axis B

3.3. Analysis of Bending Moment Variation under Three Models

The bending moments of the beams on both sides of the longitudinal A-axis and B-axis (1-2 beams and 7-8 beams) are more significant. According to the principle of symmetry, only the bending moment of this axis beam is analyzed. Compared with Model 1, Model 2 increases the bending moment of the left end of the A/1-2 beam from -27.2kN-m to 279.6kN-m; the mid-span bending moment decreases from 16.2kN-m to 9.1kN-m; the bending moment at the right end increases from -25.7kN-m to -346.0kN-m. B/1-2 beam left-end bending moment increases from -27.3kN-m to -275.6kN-m; mid-span bending moment increases from 16.8kN-m to 8.8kN-m; right-end bending moment increases from -27.1kN-m to -342.9kN-m.

Compared with Model 1, the Model 3 increases bending moment of the left end of the A/1-2 beam from -27.2kN-m to 152.7kN-m; the mid-bending moment increases from 16.2kN-m to 19.7kN-m; the bending moment at the right end increases from -25.7kN-m to -196.2kN-m. The bending moment at the left end of the B/1-2 beam increases from -27.3kN-m to 163.9kN-m; the bending moment at the mid-span increases from 16.8kN-m to 19.9kN-m; the bending moment at the right end increases from -27.1kN-m to 209.2kN-m, as shown in table 3 and figure 5.
On the transverse frame, the bending moments of each beam and column change little under Model 1, Model 2, and Model 3.

When both sides settle, the variation value of bending moment produced by traditional fixed support is greater than that produced by elastic support. In the three models, due to the settlement difference generated longitudinally, the bending moment values at the left and right ends of the beam adjacent to the settlement column change greatly, resulting in the change of the drawing direction of the bending moment. In the transverse aspect, there is no settlement difference, so the frame beam and column will generate little influence.

Table 3. Bending moment values (kN·m) of frame 1-2 under the three models

|       | A/1-2 beam | B/1-2 beam |
|-------|------------|------------|
|       | Left end   | Right end  | Left end   | Right end  | Right end  |
| Model 1 | -27.2      | 16.2       | -25.7      | -27.3      | 16.8       | -27.1      |
| Model 2 | 279.6      | 9.1        | -346.0     | -275.6     | 8.8        | -342.9     |
| Model 3 | 152.7      | 19.5       | -196.2     | 163.9      | 19.9       | -209.2     |

Figure 5. Maximum bending moment of selected beam-column (kN·m)

4. Conclusion
In this study, it mainly studies the deformation and stress characteristics of the superstructure caused by two kinds of support models (fixed support model and elastic support model) when both sides of the columns have differential settlement action in local scope. The results show that the differential settlement of the two columns has a great influence on the connecting beams, and the deformation of the two models is vertical subsidence deformation. Under the same settlement, the shear force and bending moment of the beam connected with the settlement column in the elastic support model are smaller than those in the fixed support model.

There are also some limitations in this study, such as the lack of comprehensive analysis of longitudinal and transverse columns, and the lack of stress analysis of beams and columns on each floor of the building. However, representative columns on both sides and adjacent columns are selected to analyze their stress conditions. The influence of uneven consolidation settlement on the redistribution of internal forces in the superstructure of buildings can be summarized in part, hoping to provide reference for the design and reinforcement of similar buildings.
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