Research on the monitoring method for vertical displacement of formwork support system

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Abstract. Vertical displacement is an important parameter in the safety monitoring of formwork support system, a numerical model is established to investigate the critical locations for vertical displacement monitoring. Considering the bearing capacity of every component of the system, the method to determine the alarm value for the monitoring is then studied. At last, the achievements are applied to an in-situ monitoring test, the result of which shows that the vertical displacement at the main beam is larger than the floor, which coincides with the numerical analysis, and proposed method for alarm value determination is applicable.

1. Introduction

Formwork support systems are frequently used as temporary structures to support the materials and form the fresh concrete into desired shape during construction. With the increasing number and scale of construction projects, formwork support systems are growing larger and larger in height and span, which may significantly raise the risk of collapse [1-3]. Thus, it is important to monitor the status of the formwork support system to ensure safety during concrete placement. At first, the monitoring was conducted with optical instrument [4], which is not efficient enough, so automatic devices were then applied. Moon et al. [5-6] studied the technology to collect monitoring data automatically using a wireless network, and then developed corresponding mobile devices. Huang et al.[7] proposed a method to determine the critical location and allowable value for the monitoring, however, only axial forces and lateral displacements were recommended to be monitored.

The vertical displacement, which is an integrated reflect of the deflection of slabs, beam members and the deformation of columns, is also an important parameter and should be monitored. With an actual formwork project as background, this article studies the critical locations for vertical displacement monitoring through numerical analysis, and then suggests an approach to determine the alarm value, finally, monitoring test is conducted to verify the proposed method.

2. Another section of your paper

The studied project is the cast-in-place concrete formwork for the construction of a basement located in Guangzhou, China. The formwork is to build the floor and beams of the basement. The floor is 6m high and 120mm thick. And the cross-sectional dimensions of the main beam and the secondary beam are 600mm×1100mm and 600mm×700mm respectively.

The formwork support system in this project, consisting of slabs, beam members, tubes and couplers, is 36m in length and 28m in width. The main parameters of the system are listed in table 1, and the properties of the materials are summarized as table 2.
### Table 1. Parameters of the formwork support system

| Type     | Height (mm) | Horizontal spacing (mm) | Beam member spacing (mm) | Vertical spacing (mm) |
|----------|-------------|-------------------------|--------------------------|-----------------------|
|          |             | Lengthwise              | Breadthwise              | Steel                 | Batten                | Steel | Batten |
| Floor    | 6000        | 1100                    | 1100                     | 1100                  | 380                   | 1800  |
| Main beam| 4900        | 1100                    | 400                      | 400                   | 380                   | 1800  |

### Table 2. Properties of materials

| Materials   | Strength (N/m²) | Young’s modulus (N/mm²) | Moment of inertia (mm⁴) | Cross section modulus (mm³) |
|-------------|-----------------|-------------------------|-------------------------|-----------------------------|
| Slab        | 15              | 1.00×10⁴                | -                       | -                           |
| Batten beam | 15              | 9.35×10⁵                | 3.03×10⁶                | 6.75×10⁴                    |
| Steel beam  | 205             | 2.06×10⁵                | 1.08×10⁵                | 4.49×10³                    |
| Tube        | 205             | 2.06×10⁵                | 2.16×10⁵                | 4.49×10³                    |

3. Layout of monitoring points

3.1. Numerical analysis

Commercial FEM software ANSYS is applied to conduct numerical analysis of the formwork support system. As shown in figure 1, 3-dimensional model of the formwork support system in the representative region is established. Beam188 unit is used to simulate the tubes and beam members, while the slabs are simulated by Shell181 unit.

![Figure 1. Numerical model of the formwork support system](image)

3.2. Critical location for vertical displacement monitoring

The vertical displacement of the entire formwork support system is shown in figure 2, it is clear that the maximum vertical displacement of the main beam (2.71mm) is much larger than that of the floor (1.69mm), which is because the load of the main beam is significantly greater than the floor. Thus, the main beam should be the focus of the vertical displacement monitoring.

However, on the main beam alone, the vertical displacement still varies. Since there are more columns under each crossing of the main and secondary beam, the place near the crossings appears to have smaller vertical displacement. Hence, the largest displacement of the main beam is observed at the midpoint between two neighbouring crossings, which implies that the midpoints are the critical location for monitoring.
The vertical displacement of the floor area is shown as figure 3. It can be seen that the displacement is not evenly distributed in the floor. On the top of the columns, the displacement is small, while in the middle of the region enclosed by four neighbouring columns, the displacement is relatively larger. In the area where the slab is not directly supported by the columns and the displacement is significant, there is a high risk of slab failure and concrete burst, thus these regions are also the critical locations for vertical displacement monitoring.

4. Determination of the Alarm Value
Slab, beam member, U-head and column are the major stressed members of the formwork support system, failure or buckling of any of them can lead to the overall collapse of the formwork support system. For example, the concrete will burst if the slabs or beam members are damaged, and the buckling of the columns will cause the instability of the formwork support system. Hence, to determine the alarm value of monitoring, the bearing capacities of every component should be considered [8].

If the only one single component is considered, the bearing capacity of the formwork support system is calculated as below.

Slab:
\[ q_{\text{slab}} = \frac{f_{\text{slab}} W_{\text{slab}}}{0.125 \times l_{\text{lab}}^2 b_{\text{lab}}} \]  
\[ (1) \]

Batten beam:
\[ q_{\text{batten}} = \frac{f_{\text{batten}} W_{\text{batten}}}{0.1 \times l_{\text{batten}}^2 b_{\text{batten}}} \]
\[ (2) \]

Steel beam:
\[ q_{\text{steel}} = \frac{f_{\text{steel}} W_{\text{steel}}}{1.1 \times 0.175 \times l_{\text{batten}}^2 l_{\text{steel}} b_{\text{steel}}} \]
\[ (3) \]

U-head:
\[ q_{\text{U-head}} = \frac{40000}{1.15 \times 1.1 \times b_{\text{batten}} l_{\text{batten}}} \]
\[ (4) \]

Column:
\[ q_{\text{column}} = \frac{f_{\text{ub}} A_{\text{sube}}}{l_{a} l_{b}} \]
\[ (5) \]

Where \( f_{\text{slab}}, f_{\text{batten}}, f_{\text{steel}} \) are the designed strength of the slab, batten beam and steel beam respectively, and \( W_{\text{slab}}, W_{\text{batten}}, W_{\text{steel}} \) are the section modulus of the slab, batten beam and steel beam respectively. \( l_{a} \) and \( l_{b} \) are the lengthwise and breadthwise horizontal spacing of columns.
To ensure the safety of every component, the maximum allowable load to the formwork support system is

\[ q_{\text{max}} = \min\{q_{\text{slab}}, q_{\text{batten}}, q_{\text{steel}}, q_{\text{U-head}}, q_{\text{column}}\} \]  

(6)

So the deflection or of each component under the maximum allowable load is

\[ w_{\text{slab}} = \frac{5q_{\text{max}}I_{\text{slab}}}{384EI_{\text{slab}}} \]  

(7)

Slab:

\[ w_{\text{batten}} = \frac{K_wq_{\text{max}}I_{\text{batten}}}{100EI_{\text{batten}}} \]  

(8)

Batten beam:

\[ w_{\text{steel}} = \frac{K_wq_{\text{max}}I_{\text{steel}}}{100EI_{\text{steel}}} \]  

(9)

Steel beam:

\[ \delta_{\text{column}} = \frac{q_{\text{max}}l_bH}{E_{\text{tube}}A_{\text{tube}}} \]  

(10)

Where \( K_w \) is the deflection coefficient suggested by the Chinese technical code [9]. So the alarm value for vertical displacement monitoring should be taken as the total vertical displacement of the formwork support system:

\[ d_{\text{alarm}} = w_{\text{slab}} + w_{\text{batten}} + w_{\text{steel}} + \delta_{\text{column}} \]  

(11)

5. Monitoring test

According to the proposed critical location of vertical displacement monitoring, 6 monitoring points were settled. As shown in figure 4, point 1, point 2 and point 3 were placed at the main beams, right on the midpoint of two neighbouring crossings. And point 4, point 5 and point 6 were placed at the middle of the floor, with no columns right beneath them. A displacement sensor was installed at each point to measure the displacement of the formwork support system.

Substituting the parameters of table 1 and table 2 into equation (1) ~ (5), the bearing capacities can be obtained: \( q_{\text{slab}} = 32\text{kN} \), \( q_{\text{batten}} = 64\text{kN} \), \( q_{\text{steel}} = 83\text{kN} \), \( q_{\text{U-head}} = 72\text{kN} \) and \( q_{\text{column}} = 40\text{kN} \), thus the maximum allowable load \( q_{\text{max}} \) is 32kN.

Substituting \( q_{\text{max}} \) in to equation (7) ~ (11), and the alarm value is calculated to be 11.0mm.

Figure 4. Layout of monitoring points

Figure 5. Vertical displacement of each point
The vertical displacement of each monitoring point during concrete displacement is shown in figure 5. The vertical displacements measured by all 3 points at the main beam are larger than that by the points at the floor area, which coincides with the numerical simulation and proves the validity of the proposed method for monitoring point arrangement. The measured displacements did not exceed the alarm value, which implied that the formwork support system was working well throughout the concrete placement.

6. Conclusions
In this paper, a method for vertical displacement monitoring of formwork support system is introduced. For formwork of main beams, the midpoint between two crossings is the critical location for monitoring, while for the floor area, the middle of the region enclosed by four neighbouring columns should be focused. The alarm value should be the displacement of the entire system under maximum allowable load. The result of the monitoring test has demonstrated the validity and applicability of the proposed monitoring method.

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