Construction Technology and Management of Unilateral Support Formwork for 16M-High Concrete Outer Wall of Complex Deep Foundation Pit

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Abstract. Shanghai Grand Opera House, which is under construction in Shanghai, China, includes two relatively large opera halls, which are named as the large opera hall and the middle opera hall. Below the stages of these two opera halls are two deep stage pits where the mechanical equipment will be arranged after construction, therefore, the structure of these stage pits is designed to be basically hollow with only a small amount of floor slabs on the edges. For the most sections of the stage pits, the depth is 16m, and the arrangement of horizontal supports and lattice columns in the stage pits during the construction period is extremely complicated. To prevent the outer walls of the stage pits from leaking and further guarantee the quality of the structure, the unilateral support formwork, which is composed of multiple steel components as load bearing members, is applied to construct the 16m outer wall of the stage pits. In this paper, first, the specific working principle of the unilateral support formwork and numerical analysis of its construction steps are introduced. Then focus on explaining that through establishing detailed digital 3D models of the complex stage pits during construction period, the practical construction sequence and construction technologies are designed and formulated, meanwhile, the on-site staff can also be guided directly through digital 3D models, which guarantee the visualization of the complex technology and the convenience of on-site construction as well. The construction of the deep stage pits is currently in progress, and part of the outer wall has already been constructed successfully. The cost of the technology is certainly more than common construction methods, but it is still acceptable since most of the formwork members can be recycled and re-use, while the advantages are obvious. Finally, the main characteristics of the construction technology of the unilateral support formwork for 16m-high concrete outer wall is summarized and discussed, which can provide a reference for the construction of similar structures.

1. Introduction

For shear walls, columns and other vertical force-transmitting components of concrete structures, opposite pull screws formwork system is generally adopted to construct. But for some special cases, outer formwork systems may be applied to support the horizontal lateral pressure of concrete on one side during pouring, which is generally called unilateral support formwork. Since there are no holes on the surfaces, walls or columns constructed through unilateral support formwork system, always process excellent sealing property. Therefore, unilateral support formwork is usually applied to sections with high requirements for sealing property, such as outer wall of subway or basement [1,2]. Since the horizontal lateral pressure of concrete is relatively large, the structure of unilateral support
formwork system always requires high strength and rigidity, which usually result in high costs. Meanwhile, unilateral support formwork system is generally large in dimension, thus, it is difficult to apply to complex construction conditions and high walls, that actually is generally limited to walls less than 6m in height.

Shanghai Grand Opera House, which is under construction in Shanghai, China, includes two relatively large opera halls, which are named as the large opera hall and the middle opera hall. Below the stages of these two opera halls are two deep stage pits where the mechanical equipment will be arranged after construction, as shown in figure 1. For the most sections of the stage pits, the depth is 16m, and the arrangement of horizontal bracings and lattice columns in the stage pits during the construction period is extremely complicated. To prevent the outer walls of the stage pits from leaking and further guarantee the quality of the structure, the unilateral support formwork, which is composed of multiple steel components as load bearing members, is applied to construct the 16m outer wall of the stage pits. In this paper, first, the specific working principles of the unilateral support formwork and numerical analysis of its construction steps are introduced. Then focus on explaining that through establishing detailed digital 3D models of the complex stage pits during construction period, the practical construction sequences and construction technologies are designed and formulated, meanwhile, the on-site staff can also be guided directly through digital 3D models, which guarantee the visualization of the complex technology and the convenience of on-site construction as well. The construction of the deep stage pits is currently in progress, and part of the outer wall has already been constructed successfully. Finally, the main characteristics of the construction technology of the unilateral support formwork for 16m-high concrete outer wall is summarized and discussed, which can provide a reference for the construction of similar structures.

![Figure 1. Shape of Large and Middle opera hall](image)

2. Principle and construction process analysis

2.1. The principle of unilateral support formwork system

The common deep pit section of this project is shown in figure 2. There is a row of concrete piles surround the deep pit and a layer of concrete bracing left to brace the pit, which is named the second
concrete bracing. The construction target of the unilateral support formwork system is the concrete outer wall surrounding the deep foundation pit. The left wall in figure 2 is 10.2m high and the right wall is 16m high. In this project, the construction process of outer wall is divided into 6 steps, and the construction height of each step is 2.5m, 2.5m, 2.4m, 2.8m, 2.9m and 2.9m respectively.

**Figure 2.** Deep pit section

All components of the unilateral support formwork system are shown in figure 3. The existing components of different steps are different. The names and the types of the components are shown in table 1. In principle, the horizontal distance between main columns is 650mm, and the distance between main columns and the outer wall is 1000mm. The pile tie rod of step 1 to step 5 is connected to the flange of main column on one end, and the other end is connected to the steel bar planted in the concrete pile. The foundation slab tie rod is connected to mail column on one end and to embedded parts on the other end. The wall tie rod of step 2 to 6 is connected to the flange of main column on one end, and the other end is connected to the embedded parts which is in the outer wall that is constructed in last construction step.
Figure 3. All load-supporting components of the unilateral support formwork

Table 1. Component list

| Component          | Main Column   | Wall Tie Rod   | Pile Tie Rod | Foundation Slab Tie Rod |
|--------------------|--------------|----------------|--------------|-------------------------|
|                    | 18 # I Beam  | 16 # I Beam    | 14b# Channel Steel | 14b# Channel Steel      |

Adjustable support is arranged between concrete formwork and main column as shown in figure 4. Therefore, horizontal lateral pressure of the concrete is resisted by adjustable support and transferred to main column, then mail column transfers the load to wall tie rod and pile tie rod, and finally transfer the horizontal lateral pressure of the concrete to piles and the wall which completed in last construction step. In summary, the outer wall is constructed from the bottom to the top step by step.
2.2. Construction process
After the main column is fixed, install or remove unilateral support formwork components according to the construction steps, as follows:

Step 1: As shown in figure 5a. Install the step 1 pile tie rods and place the embedded parts of step 2 wall tie rods. After all the adjustable support and formwork are installed, pour the concrete of outer wall and the pouring height of step 1 is 2.5m.

Step 2: As shown in figure 5b. When the concrete strength is not less than 1.2MPa, the formwork, adjustable supports and pile tie rods of last step can be removed. And then install step 2 pile tie rods and wall tie rods, and place the embedded parts of step 3 wall tie rods. After all the adjustable support and formwork are installed and the strength of wall concrete, which was poured in last step, is not less than 75% of design strength, pour the concrete of outer wall and the pouring height of step 2 is 2.5m.

Step 3 – 6: Similar to previous steps, When the concrete strength is not less than 1.2MPa, remove formwork, adjustable supports and pile tie rods of previous step. Install the pile tie rods and wall tie rods of this step, and place the embedded parts of next step’s wall tie rods. But certain corrections need to be made according to the actual situation. For this project, in step 3, concrete bracing replacement and outer wall will be constructed simultaneously, as shown in figure 5c; Before step 4, remove the second concrete bracings in the deep pit; As shown in figure 5, only 4 steps will be enough to construct the left 10.2m-outter wall. The pouring height of step 3-6 are 2.4m, 2.8m, 2.9m and 2.9m respectively.
2.3. Construction process analysis

The construction process analysis for each step of unilateral support formwork system is introduced in this chapter, and the analysis software is Sap2000.

2.3.1. Load. According to *Code for construction of concrete structures* and *Load code for the design of building structures* [3,4], due to the reality that the outer wall is mainly constructed in spring and the temperature is relatively low, the horizontal lateral pressure of the concrete should be calculated according to equation (1), which is actually liquid pressure.
\[ F = \gamma_c H \]  

where:  
\( F \): horizontal lateral pressure.  
\( \gamma_c \): concrete density.  
\( H \): concrete height.

The construction joints on the outer wall between steps is shown in figure 6 to prevent water leakage. Therefore, the calculated height of horizontal lateral pressure of the concrete in each step is increased by 0.3m. The actual load of each step is shown in table 2.

![Figure 6. Joint between steps](image)

**Table 2. Nominal value of horizontal lateral pressure of the concrete**

| STEP | Height (m) | Horizontal lateral pressure (kN/m²) |  |  |
|------|------------|-------------------------------------|--|---|
|      |            | Top                                 | Bottom                    |
| 1    | 2.5        | 7.2                                 | 67.2                      |
| 2    | 2.5        | 7.2                                 | 67.2                      |
| 3    | 2.4        | 7.2                                 | 64.8                      |
| 4    | 2.8        | 7.2                                 | 74.4                      |
| 5    | 2.9        | 7.2                                 | 76.8                      |
| 6    | 2.9        | 0                                   | 69.6                      |

In the finite element model, the horizontal lateral pressure of the concrete is applied to the supports and then transferred to the main column. The joints between piles and pile tie rods are calculated as pinned restraints, and all the other joints are calculated as fixed restraints. The loads and the restraints of each step are shown in figure 7.
2.3.2. Calculation result. The deformation of the unilateral support formwork system is calculated through applying nominal value of the load. The deformed shape of each step is shown in figure 8, and the largest deformation value is shown in table 3.
The deformed shape of each step.

**Figure 8.** The deformed shape of each step.

**Table 3.** The largest deformation value of each step.

|       | STEP1 | STEP2 | STEP3 | STEP4 | STEP5 | STEP6 |
|-------|-------|-------|-------|-------|-------|-------|
| Value | 3.4mm | 4.9mm | 4.7mm | 6.2mm | 6.0mm | 5.3mm |

The largest deformation of all the steps is 6.2mm, which is small enough to satisfy the safety demand.
Horizontal lateral pressure of the concrete should be considered as permanent load and the partial factor for permanent load should take 1.35 according to *Load code for the design of building structures* [4]. Considering stabilities and strengths, the unilateral support formwork system’s stress ratio of all the steps is shown in figure 9. The largest stress ratio is 0.838 in step 4, and the section of it is at the joint between the main column and the wall tie rod. The strength is enough to satisfy the safety demand as well.

![Stress ratio of all the steps.](image)

**Figure 9.** Stress ratio of all the steps.

### 3. Detailed digital 3D models

The construction conditions of the deep pit are extremely complicated, and they are mainly reflected in three points:

1. The distribution of structural members such as walls, columns and beams are irregular, and there are a large number of concrete internal walls and outer walls staggered;
2. Part of the deep pit is located under the concrete trestle, making this part difficult to hoist and construct;
3. In addition to the second concrete bracing in the deep pit, there are also some first and third concrete supports that will not be removed temporarily.

As mentioned before, unilateral support formwork system is difficult to apply to complex construction conditions. In the deep pit of the project, it is not only difficult for workers to understand the construction process of unilateral support formwork system, but also that too many working drawings of different elevations pose challenges to the engineers and managers. Therefore, establishing a visualized 3D digital model of each construction step of the deep pit would greatly help the managers and workers to comprehend the entire construction methods, so as to analyzed the problems that may occur on site in advance and prepare solutions to ensure the construction convenience.
3D models of all the internal and outer walls which will be constructed is shown in figure 10, and it can be seen that the internal and outer walls, openings and beams are intricately arranged. The concrete trestle and the remaining bracings are shown in figure 11, and only by referring precise 3D model will it be possible to design and arrange unilateral support formwork system rationally and conclude the construction keys of different steps.

![Figure 10. 3D model of all the internal and outer walls](image)

![Figure 11. The concrete trestle and the remaining bracings](image)

As shown in figure 12, at the beginning of the construction of the outer wall, the remaining concrete bracing in the deep pit caused the length of the main column has to be different. The short main column will be connected up to 16m after the bracings are removed to construct the subsequent steps of outer wall.
4. Actual construction site

The construction of the outer wall in the deep pit is currently in progress, and the first step has been finished successfully, as shown in figure 13. The reinforcements and the components of step 2 are being installed, and the concrete wall of step 2 will be poured when the concrete strength of step 1 reaches 75% of the designed strength.

Figure 12. The remaining concrete bracings and short main column.

Figure 13. Actual construction site
5. Results and discussions

Technology: This construction method is technically feasible. The actual construction of most areas of the deep pit can be carried out in accordance with the principles listed in this paper, and the strength and deformation of the unilateral support formwork system can satisfy the safety requirements. However, there are usually many unexpected problems at the construction site. Such as in step 1, the waterproof rolls, which is laid outside of the outer wall, were laid one-meter-higher than the height which was set previously, therefore, the pile tie rods of step 1 were installed one-meter-higher, too. Fortunately, the height of step 1 is 2.5m and is relatively short, and the higher unilateral support formwork system could also satisfy the safety demand, and step 1 was already constructed successfully.

Cost: There is no doubt that the cost of unilateral support formwork system is higher than common opposite pull screws formwork system. In general, unilateral support formwork system is only suitable for projects with high quality requirements.

Construction management: As a special construction technology, there are many details that need to be focused on during the construction process. Such as if the main columns are positioned correctly at the internal corners and whether the adjustable supports are firmly fixed, etc. These details are the keys of ensuring construction quality.

6. Conclusions

This paper introduces a construction technology of unilateral support formwork system for 16m-high concrete outer wall of complex deep pit, including the construction principles and construction process analysis of the entire construction process. Through establishing 3D digital model of construction site, specific construction deployment was formulated and the visibility of the construction process was improved, so as to guarantee that the managers and workers could better understand the construction method. The construction of the outer wall is currently in progress, and step 1 of the construction has been successfully completed. Through theoretical analysis and practical construction, this unilateral support formwork system is technically guaranteed and is of great promotion value. However, during construction, it is necessary to focus on the construction quality of key points, and the cost of this construction technology is relatively high as well. So this construction method is generally suitable for projects with high quality requirements.

This construction method can provide a reference for similar projects. But since actual projects are generally special, it is necessary to formulate specific plans based on actual conditions.

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