Numerical Simulation and Analysis of Thermal Stress on Restressed Assembly Steel Struts System in Foundation Excavation

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Abstract. When using horizontal internal bracing system in large span deep foundation pit, the influence of temperature effect on bracing system must be considered. Based on the long-term thermal stress monitoring of a project in the west of Hangzhou, this paper studied the influence of Angle brace temperature effect on the foundation pit enclosure structure after excavation to the bottom by using three-dimensional finite element model. When the strut temperature rises, the strut axial force increases. The longer the length is, the higher the axial force rises. The horizontal displacement of the surrounding wall and soil will be in the external direction of the pit, which is conducive to the stability of the surrounding system. The second layer struts are more affected by the temperature effect than the first layer struts, and the combined action of the two struts makes the surrounding wall produce greater displacement. The pouring of the bottom plate makes the strut subject to the temperature effect to generate greater axial force, the second layer struts change more violently, and at the same time reduces the displacement and deformation of the retaining structure. When the temperature drops, the strut axial force decreases and the horizontal displacement of the retaining structure to the pit increases, which is not conducive to the stability of the system. At this time, the reinforcement of the nearby soil body can be considered to reduce the deformation of the soil body and the retaining wall.

1. Introduction

Deep and large foundation pits in soft soil often use the retaining wall combined with the internal strut and strut form for excavation work. Due to the thermal expansion and contraction of the strut material, the temperature change in the environment, such as the temperature difference between day and night and the seasonal temperature difference, will cause the expansion and contraction of the strut, and the strut system connected with the strut will constrain the deformation of the strut, thereby generating thermal stress. Thermal stress will change the axial force of the strut and create additional stress on the
enclosure structure. In the foundation pit engineering, the long strut is often made of concrete or steel pipe and steel. The steel composite strut has the advantages of small weight, high rigidity and reusability [1], which has been widely used in foundation pit engineering. However, regardless of the concrete material or the steel, as the length of the strut increases, the thermal stress caused by the change in the ambient temperature increases accordingly. This additional stress effect is particularly pronounced for steel composite struts.

Regarding the influence of thermal stress on the strut, Zheng Gang et al [2] proposed a simplified calculation method for the strut structure considering the single-layer horizontal strut temperature effect by using the elastic resistance method. Wu Ming et al [3], Ai Zhiyong et al [4] Liu Chang [5] proposed a simplified analysis method that considers the effects of multi-layer horizontal strut temperatures. Lu Peiyi et al. [6], Zhang Liming et al. [7] studied the influence of horizontal strut temperature field changes on the foundation pit retaining structure through two-dimensional finite element numerical simulation. Peng Quanmin et al [8] used the space rod unit coordination model to establish a three-dimensional finite element model to analyze the internal forces and deformations of the concrete strut structure under the action of water and soil pressure load and temperature change. Xiang Yan [9] analysed the influence of thermal stress on the axial force of the inner strut rod and the deformation of the strut structure by monitoring the stress and deformation of the retaining structure.

Most of the above studies are to calculate the influence of temperature variation on the horizontal axial force. But there are few studies on the three-dimensional stress analysis for horizontal Angle brace and the existence of strut length variation.

In this paper, the long-term thermal stress monitoring of large-scale foundation pit steel strut angle braces in a soft soil site in Hangzhou is carried out to establish a finite element model. The comparative monitoring data is used to analyse the temperature effect on the strut axial force under different working conditions after foundation pit excavation. And the impact on the foundation pit retaining structure.

2. Thermal stress of the slender rod

For the elongated rod, when the overall temperature of the rod changes, there will be axial expansion deformation, thermal expansion and cold contraction. When there is a constraint on both ends of the rod to restrict the free deformation of the rod, an axial force is generated inside the rod under the action of thermal stress.

As shown in Figure 1 below, an axial length of an elongated rod of $L$ is constrained by springs $k_1$ and $k_2$, and the coefficient of linear expansion is $\alpha$. Considering only the axial deformation of the slender rod, the influence of temperature changes on the axial force of the slender rod is now analysed.

![Figure 1. A slender rod with two ends axially bound by springs](image)

When the temperature is $T$, the system is in equilibrium. When the temperature rises by $\Delta T$, assuming that the displacements of the two springs after rebalancing of the system are $x_1$ and $x_2$ after the system is rebalanced. The state after the balance is as shown in Figure 2 below.
Figure 2. Force analysis of the system after temperature rise

At this time, the axial force inside the slender rod

\[ N = k_1x_1 = k_2x_2 \]  \hspace{1cm} (1)

The slender rod expansion displacement is

\[ \Delta L = x_1 + x_2 \]  \hspace{1cm} (2)

Compared with the deformation without springs, internal force of the slender rod with restraint is the result of the axial deformation of the spring slender rod.

\[ \alpha\Delta TL - (x_1 + x_2) = \frac{NL}{AE} \]  \hspace{1cm} (3)

Then there is

\[ \alpha\Delta TL - (x_1 + x_2) = \frac{k_1x_1L}{AE} = \frac{k_2x_2L}{AE} \]  \hspace{1cm} (4)

With \( k_1 = k_2 = k \), then

\[ N = kx_1 = kx_2 \]  \hspace{1cm} (5)

Brought into (4), can be solved

\[ x_1 = \frac{\alpha\Delta TLAE}{2AE + Lk} \]  \hspace{1cm} (6)

Axial force

\[ f_N = \frac{\alpha\Delta TLAE}{2AE + L} \]  \hspace{1cm} (7)

When \( k \to \infty \), that is, the axial force is the largest when both ends are consolidated

\[ F_N = \alpha\Delta TAE \]  \hspace{1cm} (8)
The displacement at both ends is

$$x_1 = x_2 = \frac{\alpha \Delta T AE}{2AE} + k$$

Then there is

$$f_N = F_N \beta', \beta' = \frac{1}{\frac{2AE}{kL} + 1}$$

Where, $\beta$ is the axial force coefficient that varies only with the slender rod characteristics ($A$, $E$, $L$) and the axial constraint ($k$). Commonly used H-shaped steel H400×400×13×21 as strut, Q345 steel, the material property of single root is the cross-sectional area $A=0.02195m^2$, the elastic modulus $E=206GPa$, the linear expansion coefficient is $\alpha=1.2\times10^{-5}$, according to the monitoring The data shows that the surface temperature of summer steel is 25°C in the morning, up to 50°C in the afternoon, and the maximum temperature difference between day and night is 25°C ($\Delta T=25°C$). The strut of this type of steel can be $F_N=1356.5kN$ according to formula (10).

At the same time, we can get the axial force variation curve of this type of steel under different axial constraints as shown in Figure 3.

**Figure 3.** The Curve of Strut Length-Constraint Conditions-Axis Force under Thermal stress

It can be seen from Figure 3 that under the action of thermal stress, the axial force of the steel beam member increases with the axial constraint and the strut length, and the shorter the strut length, the greater the influence of the equivalent axial constraint. As long as the axial constraint level is determined, the axial force and displacement generated by the thermal stress can be obtained. When the axial constraint is infinite, it is equivalent to the fixed end, and the axial force coefficient $\beta$ is approximately equal to 1.

3. **Engineering background**

The proposed project is located in the Xihu Science and Technology Park in Xihu District, Hangzhou. The main soil layer in the foundation pit is a typical muddy soil in the west of Hangzhou. The soil quality is poor. The physical and mechanical indexes of the soil are shown in Table 1.
Table 1. Physical and mechanical parameters of soils

| Soil layer         | Severe (kN/m$^3$) | Compression modulus $E$ (MPa) | Cohesion $C$ (kPa) | Internal friction angle $\phi$ ($^\circ$) |
|--------------------|-------------------|-------------------------------|--------------------|----------------------------------------|
| 1-1 miscellaneous fill | 18.0              | -                             | 5.0                | 9.0                                    |
| 1-2 silty clay     | 18.4              | 4.913                         | 19.5               | 12.0                                   |
| 3 silty clay       | 17.0              | 2.662                         | 14.4               | 9.0                                    |
| 4-1 silty clay     | 19.2              | 5.743                         | 26.5               | 13.5                                   |
| 4-2 silty clay     | 18.4              | 4.514                         | 20.8               | 13.4                                   |
| 5-1 silty clay     | 17.4              | 3.014                         | 14.2               | 10.5                                   |
| 6 clay 1           | 18.8              | 5.221                         | 42.0               | 15.0                                   |
| 7-1 clay 2         | 17.6              | 4.295                         | 36.4               | 10.7                                   |
| 7-2 silty clay     | 19.2              | 5.849                         | 39.4               | 13.8                                   |

The foundation pit is about 300m long and 160m wide. The general excavation depth of the foundation pit is about 12.00m. The two-way restressed steel combined strut + SMW method pile is used as the retaining structure. The depth of the retaining wall is 22m and embedded in the bottom of the pit is 14m. The foundation pit profile and typical section view are shown in Figure 4 and Figure 5.

![Figure 4. General situation of foundation excavation site](image1)

![Figure 5. Typical profile of foundation pit engineering](image2)
The medium-sized steel strut standard rods of this project are made of H400×400×13×21 steel, Q345b; the columns and beams are all made of H350×350×12×19 steel, Q235b; all members are connected with 10.9 M24x8.0 high-strength bolts. The bolt material is 20MnTiB and the construction pre-tension is 250kN. This paper mainly analyses the horizontal angle brace of the southwest corner of the foundation pit project. There are two layers struts in the area. Prestressing is applied to each strut erection. The basic conditions of the main strut are as follows:

| Strut number | Length (m) | Number of steel bars | Total cross-sectional area (m²) | Total pre-stress (kN) |
|--------------|------------|----------------------|-------------------------------|----------------------|
| A3           | 39.55      | 4                    | 0.0878                        | 1200                 |
| A4           | 57.25      | 4                    | 0.0878                        | 1500                 |
| A5           | 82.10      | 4                    | 0.0878                        | 1800                 |
| A6           | 91.65      | 4                    | 0.0878                        | 1800                 |
| A7           | 86.85      | 4                    | 0.0878                        | 2000                 |
| D3           | 36.55      | 4                    | 0.0878                        | 1500                 |
| D4           | 53.85      | 4                    | 0.0878                        | 1800                 |
| D5           | 79.10      | 5                    | 0.10975                       | 1800                 |
| D6           | 89.45      | 5                    | 0.10975                       | 1800                 |
| D7           | 84.90      | 5                    | 0.10975                       | 2000                 |

4. Project site monitoring

4.1. Monitoring instruments
Temperature monitoring projects include axial force monitoring, profile surface temperature and temperature monitoring. The instruments used in the monitoring are listed below. The axial force gauge is welded on the web of the strut steel, and the data can be read at any time, and the axial force variation of the strut is obtained by the frequency change of the axial force meter. Temperature and profile surface temperatures are obtained by multiple measurements per day.

| Project                        | Instrument                                    | Range                |
|--------------------------------|-----------------------------------------------|----------------------|
| Steel axial force              | Vibrating wire surface strain gauge            | -                    |
| Section steel surface Temperature | Infrared thermometer                           | -18°C ~275°C         |
| Air temperature                | Kerosene thermometer                           | -30°C ~100°C         |

4.2. Typical monitoring results in different periods
Figure 6-8 below shows the axial force change-temperature curve of the same steel in the A4 strut at different times. The axial force in the figure is based on the 5 o'clock axial force on July 23.

The first layer struts was erected in July and the second layer struts were not erected.
Figure 6. Typical axial force change-surface temperature-temperature curve of A4 strut in July.

The second layer struts were erected in October, after the foundation pit was excavated.

Figure 7. Typical axial force change-surface temperature curve of A4 strut in Oct.

In November, the strut floor was poured to reach strength, and the second layer struts were removed.
Figure 8. Typical axial force change-surface temperature-temperature curve of A4 strut in Nov.

Comparing the axial force change and temperature change in Figure 6~8, it can be seen that the temperature rises and falls on the upper and lower surfaces of the profile steel with the air temperature rise and fall, and the lift range is greater than the air temperature change range. Among them, the average surface temperature of the steel in July was the highest, and the temperature difference between the upper and lower surfaces of the steel was also the largest. The temperature difference between day and night was the largest at the end of November. With the change of the surface temperature of the section steel, the change of the axial force value is: the axial force increases continuously when the temperature rises, and the axial force decreases continuously when the temperature is lowered.

5. Three-dimensional finite element simulation

5.1. Basic situation of the model

5.1.1. Model size and unit type. This paper uses the general finite element software Abaqus modeling. In order to analyze the influence of thermal stress on different lengths of strut and considering the spatial effect, the representative southwest corner area of the project is selected to be simulated. Since the lengths of A1-A2 and D1-D2 are short, the model mainly analyzes the thermal stress of struts such as A3-A7 and D3-D7.

The model simplifies the surrounding environment of the study area as shown in Figure 9. Soil body range of 50m outside the retaining wall is calculated as the site boundary. The model is 185m long and 175m wide, and the horizontal direction is constraint around boundary. The depth of the model is 34m, which is about 12m below the retaining wall, and it is fixed at the bottom of the model.
In the model, the soil, the retaining wall, the crown beam, the bottom plate, etc. adopt C3D8R eight-node three-dimensional solid element, the strut adopts S4R four-node shell element, and the column and beam are simulated by B31 beam element. Among them, the surrounding wall is equal to the SMW method pile cement-soil mixing wall by equal stiffness and other materials. The basic control size of the model mesh is 1m×1m, and the mesh model is shown in Figure 7.

In the model, the retaining wall and the soil are integrated and modeled without relative displacement. The bottom plate and the soil and the retaining wall in the pit are also combined and modeled, with no relative displacement. The triangular pier members strut the foundation pit retaining structure are connected by *Tie contact, the column beam and the strut are combined and modeled, and the column and the soil and the bottom plate in the pit are connected by *Embedded. The model changes the state of the strut or the bottom plate by the removal and activation of the element to change the operating conditions, and the thermal stress is applied by changing the temperature field to the first layer struts and the second layer struts.

5.1.2. Selection of material parameters. During the excavation of the foundation pit, it is actually the unloading process of the soil. When the soil excavation is completed, the temperature field changes to the thermal stress generated by the strut and then acts on the retaining structure and the soil, which is equivalent to a loading process. At this time, most of the soil is still within the yield plane and the whole system is in a linear range. On the unloading modulus of soil, based on the indoor test to simulate the stress path during excavation of foundation pit, Liu Guobin et al [10], Yuan Jing et al [11], Xu Zhonghua
et al [12], Wang Weidong et al [13] obtained the variation of vertical and horizontal unloading modulus with the depth of overlying soil, and got the method to determine the parameters of small strain hardening model of soil. We can get the unloading modulus of the soil after excavation of the foundation pit is about 5~9 times of the compressive modulus of the soil. When considering the excavation of the foundation pit, the strut temperature rises to the loading process of the soil, in the model. The unloading modulus of each soil layer is 8 times of the compressive modulus, as shown in Table 4. The soil is analyzed by the Mohr-Coulomb elastoplastic constitutive model. The $c$ and $\phi$ of the soil are the geological survey data in Table 1.

| Soil layer         | Thickness (m) | Severe (kN/m$^3$) | Poisson ratio $\nu$ | Unloading modulus $E_{ref}$(MPa) |
|--------------------|---------------|-------------------|---------------------|---------------------------------|
| 1-1 miscellaneous fill | 0.9           | 18.0              | 0.35                | 21.29                           |
| 1-2 silty clay     | 1.1           | 18.4              | 0.4                 | 39.30                           |
| 3 silty clay       | 1.4           | 17.0              | 0.48                | 21.29                           |
| 4-1 silty clay     | 1.8           | 19.2              | 0.4                 | 45.94                           |
| 4-2 silty clay     | 5.4           | 18.4              | 0.4                 | 36.11                           |
| 5-1 silty clay     | 4.4           | 17.4              | 0.48                | 24.11                           |
| 6 clay 1           | 6.1           | 18.8              | 0.45                | 41.77                           |
| 7-1 clay 2         | 6.4           | 17.6              | 0.4                 | 34.36                           |
| 7-2 silty clay     | 6.5           | 19.2              | 0.4                 | 46.79                           |

The concrete material in the model includes triangular pier, crown beam and bottom plate with elastic modulus of 30GPa, weight of 18kN/m$^3$, Poisson's ratio of 0.25, and retaining wall thickness of 0.85m. SMW cement-soil mixing wall is used, and the elastic modulus of profile steel is 206GPa. The elastic modulus of cement soil is 300Ma. According to the research of Zheng Gang and Chen Huiping [14], the interpolated steel can significantly improve the bending stiffness of cement soil wall, simplifying the surrounding wall as a homogeneous material, with a comprehensive elastic modulus of 10GPa and a gravity of 19kN/m$^3$, Poisson's ratio 0.25; the elastic modulus parameter of the strut steel material is 150MPa, which is obtained by the field pressure test of the strut. Since the strut is composed of several steel sections, the elastic modulus is slightly lower than the theoretical elastic modulus of the steel, and the steel weight is 78500kN/m$^3$. Poisson The coefficient of linear expansion is 1.2e-5, which is 0.2. Because the linear expansion coefficient of steel is bigger and the influence of temperature stress is bigger than that of concrete and soil, only the temperature stress of strut steel is considered in the model.

5.1.3. Simulation conditions

| Project            | First layer struts       | Second layer struts       | Bottom plate     |
|--------------------|--------------------------|---------------------------|-----------------|
| Working condition 1| Heating up 30°C           | Unerected                 | no              |
| Working condition 2| Heating up 30°C           | Heating up 25°C           | no              |
| Working condition 3| Heating up 30°C           | Heating up 25°C           | Pouring completed|
| Working condition 4| Heating up 30°C           | tear down                 | Pouring completed|

Table 5 shows the four operating conditions simulated in the finite element model. The working conditions from the first condition to the fourth working condition are based on the fact that the foundation pit has been excavated to the bottom of the pit and the strut and the foundation pit retaining structure and the soil have reached equilibrium, and then the temperature field stress is applied to the strut temperature field. After the road strut is erected, the excavation is carried out to the bottom of the pit. The working condition does not exist. The pouring completion refers to the pouring of the bottom
plate and the design strength is reached. In the actual project, the working condition 3 does not exist, and the second layer struts have been completely removed when the bottom plate reaches the design strength. Working condition 1 and working condition 3 mainly play a comparative analysis role.

5.2. Comparison of calculation results and monitoring data

Figure 11 is the axial force generated by the main strut in the first layer struts to increase the temperature by 30°C under different working conditions. As can be seen from the figure, the erection of the second layer struts reduces the axial force of the first layer struts, and the casting of the bottom plate also increases the axial force of the temperature change. When the casting of the bottom plate reaches the design strength, the second pass is removed. After the strut, the temperature changes the axial force to the maximum.

![Figure 11. Axial force of A3 - A7 strut under different conditions](image)

![Figure 12. Axial force of D3~ D7 strut under different conditions](image)
Figure 12 is the axial force generated by the main struts in the second layer struts at a temperature rise of 25°C under different working conditions. Comparing Figure 11, we can get that the temperature change axial force of the second layer struts under the same working condition is greater than the first layer struts, and when the bottom plate is poured, the temperature change axial force of the second layer struts is increased, when the bottom plate reaches the strength, the axial force of the second layer struts change more severely with temperature. Therefore, the second layer struts should be removed in time after the bottom plate is poured to reduce the adverse effect of temperature changes on the foundation pit.

Figure 13 and Figure 14 are the overall displacement cloud diagram of the foundation pit and the displacement cloud diagram of the foundation pit retaining structure and soil. It can be seen from the cloud map that the foundation pit retaining structure and the soil body mainly move horizontally outside the pit when the temperature rises. Comparing Figure 11, it can be obtained that when the first and second layer struts are simultaneously heated, the displacement of the longest strut A6 end is the largest; the maximum displacement of the retaining structure and the soil is concentrated near the end of the A5–A7 end, with The horizontal and vertical distances from the A6 strut end are increased and decreased.

Figure 13. Displacement nephogram of angle brace model under working condition ii

Figure 14. Displacement nephogram of soil and retaining wall under working condition ii

Figure 15 and Figure 16 are the whole displacement cloud diagram of the foundation pit under the working condition and the displacement cloud diagram of the foundation pit retaining structure and the soil. The comparison shows that when the first layer struts are heated after the casting of the bottom
plate reaches the design strength, the displacement of the end of the longest strut A6 is still the largest; the maximum displacement of the retaining structure and the soil is concentrated near the end of the A5-A7 end, with the increase in the horizontal and vertical distance of the A6 strut end is rapidly reduced. Comparing Figure 13 with Figure 14, it can be seen that as the casting of the bottom plate and the removal of the second layer struts, the displacement of the foundation pit retaining structure caused by the strut thermal stress is reduced.

![Displacement nephogram of angle brace model under working condition iv](image1)

**Figure 15.** Displacement nephogram of angle brace model under working condition iv

![Displacement nephogram of soil and retaining wall under working condition iv](image2)

**Figure 16.** Displacement nephogram of soil and retaining wall under working condition iv

Based on the axial force and displacement diagrams of Figure 11 to Figure 16, it can be seen that when the strut temperature is constant, the axial force generated by the thermal stress increases with the constraint of the envelope structure and the soil as a whole (the pouring of the bottom plate). The increase of the strut axial force under the action of thermal stress is accompanied by the decrease of the displacement of the retaining structure. When the strut is increased, the axial force generated by the temperature change of the second layer struts are larger, and the axial force generated by the temperature change of the first layer struts are reduced, and the displacement of the retaining structure is increased by the joint of the two struts, and the bottom plate is second. The increase in the axial force of the road strut is greater. According to the deformation of the foundation pit system during the heating process and the axial force combined with the thermal stress monitoring data, we can analyze the reduction of the strut axial force during the cooling process, and the horizontal displacement of the soil and the retaining structure into the pit.
Figure 17 shows the calculated values of the axial force and the measured values of the field under different temperature differences. From the figure we can see that for the longer struts A6 and A7, the two are closer together at larger temperature differences. For a slightly shorter strut A3–A5, the degree of fit is poor. For the case of small temperature difference, since each strut is composed of multiple long steels, the relative displacement between the steels weakens the influence of thermal stress on the total axial force, which is expressed as a linear relationship under large temperature difference; Instead of a plurality of sections, a section of steel with the same total cross-sectional area is used, and there is no relative displacement between the sections, so the overall performance is a linear relationship between the axial force value and the temperature difference. Although there are some differences between the model and the measured results, it is verified that the effect of the strut length and the surrounding environmental constraints on the strut axial force under the thermal stress is consistent with the influence law of the spring-bound elongated rod.

6. Conclusion

Based on the monitoring of engineering site, this paper analyzes the temperature axial force of different lengths of steel under different working conditions under the girders of large span foundation pits. The effects of axial stress generated by thermal stress on the length of the steel and the structure of the retaining structure and soil constraints were verified by finite element simulation. The main conclusions are as follows:

(1) Based on the linear thermal expansion theory of one-dimensional members, the relationship between axial force and length of equivalent strut members and equivalent constraints is obtained.

(2) The change of the strut axial force under the effect of temperature:

When the temperature rises, the axial force increases, the axial force decreases, and the axial force generated after the second layer struts were erected is greater than the first layer struts, and the first layer struts axial force generated by the thermal stress are lower than when the second layer struts are not installed; After pouring the bottom plate, the axial forces of the two struts are increased, and the second layer struts are increased by more than the first layer struts.

(3) Changes in the displacement of the envelope structure:

Under the effect of strut temperature, the retaining structure mainly produces horizontal displacement, and moves outside the pit when heating, and moves inside the pit when cooling, and the maximum
displacement change is concentrated near the top of the first longest strut retaining wall, with the
distance from the strut decreasing; When the second layer struts are erected, the increased thermal stress
will increase the maximum displacement of the retaining structure; When the foundation pit is poured,
the displacement change of the envelope structure is reduced.
(4) After the foundation pit is poured into the bottom plate, the influence of the thermal stress
increases as the overall strut of the foundation pit increases.
(5) The thermal stress of the long strut in the foundation pit should be fully considered, and if
necessary, the soil near the long strut should be reinforced.

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