Analysis of internal force and displacement of foundation pit pile anchor supporting structure based on soil frost heaving

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Abstract: In order to study the influence of soil frost heaving on the internal force and displacement of foundation pit supporting structure in seasonal frozen soil area in Northwest China, the field test of pile anchor supporting structure for deep foundation pit is carried out to monitor the change of internal force and displacement of supporting pile in winter. The interaction relationship between soil frost heaving and internal force and displacement of supporting pile is analyzed combined with temperature change conditions. The results show that: Under the condition of natural frost heaving in winter, the frost heaving effect is the most significant at 0.5 m of the upper part of the supporting pile, and the reinforcement stress value on both sides of the pile body is the largest. The change rate of bending moment of supporting pile above 3.25m is higher than that of the embedded section and the maximum bending moment is at 0.5m, while the blot has a certain constraint on the bending moment deformation. The displacement of supporting pile increases in proportion to the freezing time, and the final increase is 157.7% of the initial value. It can be seen that soil frost heaving has great influence on the internal force and deformation of the upper structure of the retaining pile. The research results can provide reference for the construction of foundation pit support engineering in similar areas in winter.

1. Introduction
In Northwest China, seasonal frozen soil is the main area, with long winter time and large temperature difference between day and night. However, the freezing time in seasonal frozen soil area is relatively short, which is easy to be ignored in construction. The damage of side wall of foundation pit caused by soil frost heaving in winter often occurs[1-3]. In the pile anchor supporting structure of deep foundation pit, the change of internal force of supporting pile plays a decisive role in the overall safety of the supporting structure [4-5], and the frost heaving of soil has a direct impact on the change of internal force of pile body. Therefore, it is of practical significance to study the interaction law between soil frost heaving and pile internal force for foundation pit support engineering in seasonal frozen area.

Dahu Rui et al. [6] revealed the interaction mechanism of water and heat in the process of soil frost heaving by field tests; Zhang Yuan [7] based on a practical project in Lanzhou, applied finite element software to study the deformation law of soil nailing support under freeze-thaw action; Zhang Zhihao [8] through monitoring a deep foundation pit project in Beijing, summarized the frost heaving factors affecting the pile anchor supporting structure and proposed relevant treatment measures; Zhao Yankai [9] summarized the limitations of soil nailing support method in seasonal frozen soil area, and improved the support method to ensure the stability of deep foundation pit; Zhou Yansheng [10] studied the
deformation law of foundation pit with the change of frost heaving time and temperature with the help of numerical simulation; Sun Chao et al. [11] used numerical simulation to analyze the distribution law of horizontal frost heaving force of retaining piles under different soil negative temperature conditions.

It can be seen that many scholars have carried out relevant research on the interaction between soil frost heaving and deformation of foundation pit supporting structure. However, due to the distinct regional characteristics of foundation pit engineering, the problems encountered in foundation pit construction in different regions are different. Therefore, taking Xining area as an example, through the field test, this paper studies the influence of soil frost heaving on the internal force and deformation of pile anchor supporting structure in Northwest seasonal frozen soil area, so as to provide reference for foundation pit construction in winter in similar areas.

2. Overview of field test
An field test of pile-anchor support structure for deep foundation pits was conducted in a site in Chengbei District, Xining City. The test site was distributed with a large thickness of loess, with uniform, loose and under consolidated soil. The size of the foundation pit is: length × width × height (2×2×3m), which is supported on the south side of the foundation pit. The construction conditions are shown in Table 1. Two supporting piles Z1 and Z2 in the middle of the foundation pit are selected, and the reinforcement strain gauge and resistance strain gauge are respectively arranged at the corresponding positions at different depths of the retaining side (D side) and the free side (L side). For the pile body above 3.25m, the spacing is 500mm; for the pile body below 3.25m, the reinforcement strain gauge and resistance strain gauge are arranged at the interval of 750mm and 650mm. A total of 14 measuring points are arranged. See Fig. 1 for the specific location of each monitoring point. The internal force of the pile is monitored by the comprehensive tester (JMZX-7000) and the resistance strain gauge (JMYJ-2002). The excavation work of the foundation pit was completed on November 11 (Fig. 2). The monitoring data started from November 12 to December 29.

| Working condition | Construction content                                                                 |
|-------------------|--------------------------------------------------------------------------------------|
| 1                 | Four reinforcement cages of supporting piles are bound, and steel strain gauges and resistance strain gauges are respectively arranged at the retaining side and the free side. Excavate the pile hole with the depth of 4m, the hole diameter of 200mm and the pile spacing of 500mm, and complete the pouring of supporting pile and crown beam. When the foundation pit is excavated to 1m, the first row of anchor rods are arranged at 0.5m. The anchor rods are all HRB400 reinforcement stress, a total of 3, the total length is 4m, the inclination angle is 15°, and the anchor section is 2.5m. Apply 20kN of prestress after solidification. Excavate the foundation pit to 2.8m, arrange the second row of anchor rods at 2m, the total length is 3m, the inclination angle is 15°, the anchoring section is 1.5m, and the construction process is the same as the first row of anchor rods. The foundation pit was excavated to 3m from the base, and the relevant test data were monitored. |
3. The effect of soil frost heave on the stress of supporting piles

3.1. Analysis of temperature change process

Temperature change leads to heat exchange between soil and the outside world. When the temperature drops to the crystallization point of water in soil, the soil begins to frost heave. The analysis of temperature change in the test is the basis for studying the influence of soil frost heaving on the internal force and deformation of pile anchor supporting structure in winter. During the whole test period, the temperature presents two stages of "decline and steady fluctuation", which shows a downward trend as a whole. In the "descent" phase, the freezing phenomenon of the soil in the foundation pit gradually increased, and the temperature fluctuated steadily within a certain range after December 2, and the freezing effect of the soil was further enhanced.
3.2. Analysis of stress change of supporting pile reinforcement

It can be seen from Figure 4 that the values of reinforcement stress at D and L sides of Z1 retaining pile show an overall increasing trend during the test period. The maximum stress value is located at 0.5 m of the upper part of the pile body, and its change rate is significantly higher than that of other depths of reinforcement stress, and the stress change of embedded section pile body is relatively stable. In the middle of the test, the lowest temperature dropped to -13°C, and the average temperature was below 0°C. According to the geological survey report, the maximum freezing depth in this area was 1.32m. The soil at 0.5 m undergoes vertical and vertical frost heaving, and the internal stress of the supporting pile increases. With the increase of the exposure time of the foundation pit, the prestress of the anchor rod gradually dissipates, which leads to the increase of the pile stress. However, due to the joint action of the anchor rod and the crown beam, the stress of the supporting pile at this place eventually shrinks.

![D side reinforcement stress distribution diagram](image1)

![L side reinforcement stress distribution diagram](image2)

Fig. 4 Stress change curve of Z₁ support pile body

It can be seen from Figure 5 that the maximum stress of reinforcement in both sides of Z2 supporting pile is located at 0.5m, and the stress change rate is also the largest, which is basically consistent with the stress change rule of Z1 supporting pile at 0.5m. The stress distribution of reinforcement in D side of Z2 supporting pile is more dispersed than that in L side. The overall stress form of 3.25m above is more complex.
The comparative analysis of Z1 and Z2 supporting piles can be obtained. The stress change of the upper reinforcement of the two supporting piles is more obvious than that of the embedded section, and the maximum value is located at 0.5 m of the upper part of the supporting pile, which indicates that the frost expansion effect on the upper part of the supporting pile is more significant than that in other parts. Therefore, more attention should be paid to the deformation of the upper part of the supporting structure during the construction of the foundation pit in winter in this area, so as to take relevant measures in time.

4. The influence of soil frost heave on the bending moment of supporting piles

According to the steel bar strain measured in the field test, combined with the bending deformation and stress-strain analysis of beam in material mechanics, the pile bending moment is calculated by the pile bending moment calculation formula [12]. According to the bending moment diagram of pile shaft in Fig. 6, the bending moment distribution of Z1 and Z2 supporting piles is basically the same, and the bending moment of supporting pile is mainly negative bending moment. The bending moment at each measuring point of the two supporting piles increases with time. The bending moment of the pile body above 3.25m is larger than that of the embedded section, and the bending moment at 2m is relatively small. The reason is that the second row of anchor bolts are set at 2m of the pile body, which has a certain constraint on the deformation of the supporting pile, so the bending moment at 2m is small. Relatively speaking, because the soil at 0.5m of the first row of bolts experienced vertical and vertical frost heaving, its temperature change is more significant. As the temperature decreases, the liquid water in the soil gradually freezes into solid water, and ice crystals fill the internal gaps of the soil to increase the volume of the soil, resulting in a larger increase in the bending moment of the pile. In addition, the maximum bending moments of the two supporting piles both appear at 0.5m, and there is more than one inverted bending point, most of which are located in the upper middle of the supporting piles.

Generally speaking, the bending moment change rate of the supporting pile above 3.25m is large, and the bending moment near the pile bottom tends to 0, and the maximum bending moment is about 6000N \cdot m, which are all located on the upper part of the supporting pile. Therefore, in order to ensure the safety of the supporting structure, more attention should be paid to the bending moment variation of the middle and upper part of the retaining pile during the construction of the foundation pit in the seasonal frozen area in winter.
Fig. 6 Bending moment curve of pile body

5. Displacement change of supporting pile

During the experiment, the temperature dropped greatly and the lowest temperature dropped to -14 °C. It can be seen from Figure 7 that the displacement of the soil behind the pile increases in a positive proportion with time, from the initial value of 2.79mm to 4.4mm, increasing by about 57.7%. In the early stage of foundation pit excavation, the soil pressure outside the pile decreases to 0, and the soil support behind the pile weakens and the slope effect is obvious. At this time, the ground temperature is affected significantly by the temperature drop, which causes the free water in the soil to freeze into ice. Therefore, the displacement growth rate from November 15 to November 18 is relatively large. In the middle stage of frost heaving, the temperature continues to decrease, and the unfrozen water moves to the freezing front in large area, which leads to the aggravation of frost heaving, which is the main reason for the larger growth rate of soil displacement in this stage. In the later period of frost heave, the temperature rises, the effect of local soil frost heave weakens, and the soil displacement slightly shrinks from 4.19mm to 4.14mm. It can be seen that in the winter monitoring process, the displacement of the soil behind the pile is mainly increased, and it is greatly affected by low temperature. Therefore, the monitoring and early warning of the displacement should be strengthened when the construction continues at low temperature in winter.

Fig. 7 Displacement curve of soil behind pile
6. Conclusion

(1) Under the action of soil frost heaving, the stress value of reinforcement at 0.5m of supporting pile is the largest than that of other parts; and due to the influence of temperature, moisture and other factors, the stress distribution of adjacent two supporting piles is different. It can be seen that frost heaving has a certain effect on the stress of the supporting pile, and the stress on the upper part of the pile is the main force. Therefore, during construction in winter, close attention should be paid to the changes in the force on the upper structure of the foundation pit support to achieve real-time warning and timely processing.

(2) The bending moment of Z1 and Z2 retaining piles has the same trend with the pile depth. The bending moment at the middle and upper parts of the pile changes significantly, and the bending moment tends to be stable with the increase of depth. The maximum bending moment is located at the upper part of the supporting pile, and the deformation of the upper part of the supporting structure increases with the increase of frost heaving times, which should be paid attention to in the construction, and the bolt has a certain restraint effect on the bending moment variation of the pile body.

(3) The displacement of the soil behind the retaining pile is positively correlated with the temperature change, and the displacement increases with the duration of frost heaving, and finally increases by 57.7%, which is a threat to the overall safety of the supporting structure. In winter, attention should be paid to its change to avoid local damage of supporting structure caused by sudden increase of displacement.

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