Study on large-scale in-situ pressurization test of steel composite support

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Abstract. The reinforced concrete support as the horizontal internal support of the foundation pit engineering has the optimal effect in limiting the displacement of the surrounding structure, but the engineering cost is high, and the environmental impact is large when it is removed. In some of the foundation pits that meet the requirements, steel supports are used as internal support, which has the characteristics of economy, efficiency and green environmental protection. The restressed steel composite support is connected by high-strength bolts, which has a high strength and a wide application range than the traditional steel support joints. Through the normal axial compression test, the unconstrained axial compression test and unrestrained eccentric compression test were carried out on the composite support of section steel, the influence of steel composite support on the displacement of retaining structure under different loads is explored, and the deformation performance of steel composite support is also explored. The test shows that the displacement of the retaining structure changes linearly with the applied load, and most of it is elastic deformation, and the displacement of the retaining structure on both sides of the support has obvious side-angle effect; The test applied load far exceeds the total prestress value of the composite support of the steel, and the compression deformation of the composite steel support exhibits elastic deformation; The test results show that the steel composite support has strong adaptive stability and large safety redundancy value.

1. Introduction
In recent years, with the rapid development of the country's economy and society, the development of underground space has become bigger and bigger, thus a series of various foundation pits have emerged as the times require, and the foundation pits develop rapidly in depth and area. In the soft soil foundation pit, the support form of the row pile combined with the horizontal inner support is generally adopted, for example, the bored pile is combined with the reinforced concrete support. However, this type of support will cause greater environmental problems, and the architectural concept of "four sections and one environmental protection" has gradually been deeply rooted in people's mind [1]. The green support
technology of foundation pit engineering has been paid more and more attention by experts in geotechnical engineering. The steel support as the horizontal support of the foundation pit has the characteristics of material recycling and recycling, in line with the concept of green construction. Steel support has been widely used in foundation pit engineering, especially in subway foundation pit engineering. The traditional steel support includes steel pipe support and steel support. The steel pipe support and the support pile are welded by weld joints, hard to ensure the construction quality, node strength is low, and the support stiffness of the single steel is limited. so the subway foundation pit collapse also occurred frequently, for example, the adoption steel pipe support of Hangzhou xianghu lake stand large-area collapse accident [2], the subway foundation pit with steel supporting Singapore Nicoll Highway foundation pit in subway along the length direction of continuous damage, eventually led to the collapse of the entire support system [3-5], the consequences of the collapse of the foundation pit are very serious, causing huge economic losses while causing casualties. The restressed steel composite support combines multiple steel sections into one truss support, and the joints are connected by high-strength bolts effectively solves the main problems of the traditional steel support. It is easy to install and dismantle, and the steel can be recycled, and has the characteristics of economy, high efficiency, environmental protection, etc. At the same time, restressing force can be applied to each support, which has a good effect on limiting the displacement of the retaining structure. The composite support of steel sections has been gradually promoted and used in China, domestic experts and scholars have also studied this. According to the analysis of foundation pit monitoring results, Li Ying [6] concluded that restressed steel composite support can be applied to soft soil foundation pit. Liu Faqian [7] made a preliminary analysis of stability of steel composite support, and Liu Xing Wang [8] analyzed the influence of beam on support beam in vertical plane and horizontal plane, and proposed requirements on beam stiffness and strength.

At this stage, the research on the steel composite support is still insufficient, and the practical engineering application is more and more. The design of foundation pit retaining structure has also changed from strength control to deformation control, and the deformation requirements are more and more strict. Therefore, it is necessary to conduct further experimental research on the steel composite support, and analyse the force deformation performance of the steel composite support and the influence of the steel composite support on the displacement of the retaining structure under pressure.

2. Large-scale in-situ pressurization test of steel composite support

2.1. Engineering background

The proposed project is located in the Xihu Science and Technology Park in Xihu District, Hangzhou, with convenient transportation. The total land area of the project is 81,907 m², and the total construction area of the project is 254,965 m², of which the underground construction area is 84,585 m², and the basement area is near the whole distribution. The second floor underground, the elevation of the floor board is about -7.00m (yellow sea elevation), the excavation depth is about 11.0m, and the foundation pit length × width: 300 × 160m. The topography of the site belongs to the gulf-fluvial and lacustrine sedimentary plain, and the topography is flat and open; the regional stability is better. The alluvial phase fume silt, sand gravel and silty clay are mainly distributed in the area of foundation pits; and the silt soil and cohesive soil of the new alluvial sea, river and lake phases are typical soft soil foundation pits, the main stratum structure of the site and the physical and mechanical parameters of the soil layer are shown in Table 1. The foundation pit retaining structure of this project adopts SMW process pile and composite steel support, and the basement junction of the first and second floors in the pit is treated with bored pile plus support.
Figure 1. Foundation pit overview.

Table 1. Soil physical and mechanical indicators.

| Geotechnical number | Geotechnical name     | State                  | Thickness H/m | Soil heavy g/(kN/m³) | Compression modulus E/MPa | Cohesive force c/kPa | Internal friction angle φ/(°) |
|---------------------|-----------------------|------------------------|---------------|----------------------|--------------------------|----------------------|-------------------------------|
| ①-1                | Miscellaneous fill    | Loose                  | 1.30–9.20     | -                    | -                        | -                    | -                             |
| ①-2                | Silty clay            | Soft plasticity        | 0.20–3.40     | 18.38                | 4.913                    | 36                   | 14.5                          |
| ③                  | Muddy clay            | Flow molding           | 0.90–7.50     | 16.97                | 2.662                    | 8.1                  | 2.6                           |
| ④-1                | Silty clay            | Hard plasticity        | 0.50–5.60     | 19.19                | 5.743                    | 36.9                 | 12.4                          |
| ④-2                | Silty clay            | Soft plasticity        | 0.60–8.00     | 18.39                | 4.514                    | 23.1                 | 11.3                          |
| ⑤-1                | Muddy clay            | Flow molding           | 1.20–13.80    | 17.44                | 3.014                    | 11.8                 | 4.4                           |
| ⑥                  | clay                  | Hard plasticity        | 3.40–13.20    | 18.79                | 5.221                    | 42.1                 | 13.6                          |
| ⑦-1                | clay                  | Soft plasticity        | 0.50–10.0     | 17.56                | 4.295                    | 36.4                 | 10.7                          |
| ⑦-2                | Silty clay            | Hard plasticity        | 0.50–9.50     | 19.2                 | 5.849                    | 39.4                 | 13.8                          |

2.2. Test overview

The project steel composite support system adopts H350×350×12×19 steel stud, Q235b for steel and E43 for welding rod; H400×400×13×21 is used for internal support standard parts, except as noted, Q345B is used for steel, and E50 is used for welding rod; coping beam, support beam and enclosing purlin all adopt cast-in-place concrete structure, and the concrete strength grade is C30. The steel members are connected by 10.9 grade M24×8.0 high-strength bolts, and the bolt material is 20MnTiB. The steel support pressure test uses a hydraulic jack to pressurize the steel composite support step by step.

In the foundation pit construction, after the steel composite support is installed and meets the design requirements, restressing is required to the steel composite support to achieve the purpose of limiting
the displacement of the retaining structure. The compression position of section steel supports is different in different regions, the shorter angle supports are D1, D2, and the pressurization position is at the end. Generally, the section steel composite support pressurization position is located at the middle of the support. When the jack is restressed to the design value, the force retaining box is placed to maintain the prestress applied, and then the jack is returned oil and the jack is withdrawn.

When carrying out the steel support pressure test, put the jack and removes the bolt of the force retaining box, pressurize the jack until all the pressure box slides down, then jack oil return to 0 MPa, and place the steel gasket on the back of the jack, so that there is no gap between the front and the rear. At this time, the support is in a state of complete pressure relief. The two ends of the jack only contact with the steel support, and there is no pressure. In this state, the jack starts to pressurize step by step.

![Image](image_url)

(a) Axial compression test  
(b) Eccentric compression test

Figure 2. Pressure test site real shot diagram.

In-situ pressure test of section steel composite support and the same support carries out three sets of pressurization tests: under normal conditions, the axial compression test, the unconstrained axial compression test, that is, all the high-strength bolts on the composite steel support are subjected to the pressure test, to unconstrained the eccentric compression test.

3. Steel compression test and field measurement analysis

The foundation pit is equipped with two sections of steel composite support, and the second type steel support is tested by the pressure test to facilitate the setting up of jacks and various types of test equipment. Three consecutive in-situ pressure tests are carried out on the same support: under normal circumstances, the axial compression test, the unconstrained axial compression test and the unconstrained eccentric pressure test. A dial indicator is set up at the supporting structure at both ends of the support to monitor the displacement of the retaining structure. At the same time, a dial indicator is set up along the length of the section steel to monitor the lateral and vertical displacement of the section steel during pressurization, and a displacement gauge is set up at the pressure of the jack to monitor the elongation of the pressurized jack. The specific installation method of the dial gauge is as follows: two test points are arranged on the southeast end of the pressurized steel composite support, and a and dare respectively from west to east. The measuring points a and d are placed on the enclosing purlin on the left and right sides of the concrete triangle, and the layout of the measuring point is shown in Figure 3. At the same time, the other end of the steel support, namely the northwest end, has two measuring points, from south to north, respectively e and f. The e measuring point and the f measuring point are arranged on enclosing purlin on the left and right sides of the concrete triangle, and the arrangement is the same as the a and d measuring points. The dial gauge is arranged along the reasonable distance of the profiled steel strut to monitor the vertical and lateral displacement of the strut during the pressurization process. The stability of the support in and out of the plane can be discussed. This paper has limited space and is not discussed here.
Each support of the gusset is subjected to a pressure test, and each support data is monitored and analysed. The D6 support with stable working conditions was analysed during the experiment. The D support is located at the second support of the southwest corner of the foundation pit, the D support is located below the A support, and the D6 support corresponds to the A6 support, the specific position is shown in Fig. 1. The D6 support is assembled from five supports with a total length of 89.45m and a total prestress of 1800kN.

3.1. Displacement of retaining structure
Three-pressurization test displacement change of retaining structure is shown in the figure below. The horizontal axis represents the load applied by the jack, and the vertical axis represents the displacement change of the retaining structure.

![Image 3: Survey point layout.](image3)

**Figure 3.** Survey point layout.

![Image 4: Axial compression retaining structure displacement.](image4)

**Figure 4.** Axial compression retaining structure displacement.
Figure 5. Unconstrained the displacement of axis pressurized retaining structure.

Figure 6. Unconstrained the displacement of the eccentric pressurized retaining structure.

Figure 7. D measuring point retaining structure displacement hysteresis line.
From Fig. 4 to Fig. 6, it can be seen that the displacement of the retaining structure changes linearly with the applied load, and the larger the load is, the larger the displacement will be. Under the condition of the same applied load, the unconstrained axial compression is compared with the normal axial compression, the displacement changes of the retaining structure at the same measuring point are not much different, and the change trend is basically the same, which indicates that the composite support of shaped steel has strong stability without the constraint of high-strength bolts. In the case of unrestrained eccentric compression, there is also a strong stability. When unconstrained eccentric pressurization, the maximum displacement is also generated under the maximum load condition, and the difference between the maximum displacement of the retaining structure and the maximum displacement generated by the previous two compressions is no more than 2 mm, which further proves that the composite support of shaped steel has strong adaptive stability and can better control the displacement of the retaining structure.

Three times of cyclic pressure were applied to the support of the same section steel composite, normal axial pressure - pressure relief - unconstrained the axial pressure - pressure relief - unconstrained the eccentric pressure - pressure relief at one monitoring point of the retaining structure is shown in Fig. 7. Normal axial compression to the maximum load of 13820.5 kN, and the unrestrained shaft is pressurized to the maximum load of 10767 kN, unrestrained eccentric compression to the maximum load of 10767 kN, and the maximum compression load is about 8 times of the designed total prestress of 1800 kN. However, most of the deformation of the retaining structure is elastic deformation, only the first normal axial compression and unloading process produces a large hysteresis line, and the residual deformation is about 3 mm. The second time to unrestrained axial compression and unloading process produces a small hysteresis line, and the residual deformation was increased by about 1 mm; the third unconstrained eccentric pressurization unloading process has no hysteresis line and no new residual deformation is produced. It is proved from the side that the stability and reliability of the steel composite support performance, and the prestress applied to the steel composite support can effectively and reliably control the pit displacement of the retaining structure.

Under normal conditions, when the axis is pressurized to 13820.5 kN. The displacement of the retaining structure at a-measuring point in the southeast is less than the displacement of the d-measuring point retaining structure. The displacement of the retaining structure at e-measurement point in the north is slightly smaller than the displacement of the retaining structure at the f-measurement point. The maximum displacement of the retaining structure is 14.51 mm. Unconstrained step-by-step pressurization to 10767 kN, and the displacement of the retaining structure at the measuring point changes rapidly with the increase of the applied pressure. The same as the first test, the displacement of the enclosure structure at the measuring point inside the support is smaller than that at the measuring point outside, and the maximum displacement of the enclosure structure is 12.47 mm. The unconstrained eccentric compression is added to 10767 kN step by step. The displacement of the retaining structure at the f and d measuring points outside the profile steel is significantly larger than that of the inner a and e measuring points, and the maximum displacement is 10.54 mm. The test proves that there is obvious side-angle effect on the displacement of the supporting structure on both sides of the support. The displacement of the inner and outer retaining structure is affected by the force state of the triangular force transmitting member, while the difference in displacement between the retaining structure at the southeast end and the retaining structure at the northwest end is affected by the distribution of the soil layer in the passive zone outside the base pit at both ends.

3.2 Steel support deformation
Through three times of compression test, the deformation of the steel support is calculated and it is against the theoretical deformation, as shown in Fig. 8, the theoretical calculation formula is shown in equation (1), in the figure, the horizontal axis represents the load applied by the jack, while the vertical axis represents the compression amount of the section steel; The straight line represents the theoretical deformation amount, the origin represents the deformation of the axial compression steel, the upper
triangle represents the deformation of the axial compression steel under the unconstrained condition, and the lower triangle represents the deformation of the unconstrained eccentric compression steel.

The formula for calculating the compressive deformation of steel supports is:

\[ \Delta L = \frac{F \cdot L}{A \cdot E} \]  

In the formula: \( \Delta L \) - the amount of compression deformation of the steel support under pressure, unit mm;
F - The load applied by the jack, unit kN;
L - The original length of the steel support, unit mm.
A - Steel support cross-sectional area, single cross-sectional area \( A_0 = 0.02195 \text{m}^2 \);
E - Elastic modulus of steel, \( E = 206 \text{ GPa} \).

It can be seen from Fig. 8, with the increase of load, the compression amount of the steel composite support also increases substantially linearly. However, the comparison of different pressure conditions shows that the deformation of the normal axial compression steel is smaller than the deformation of the unconstrained axial compression and the unconstrained eccentric compression steel, because the latter two pressure relief steel supports and beams The high-strength bolts are connected, and the beam and the steel support can limit the axial deformation of the steel support through the high-strength bolt connection; the actual deformation is generally greater than the theoretical deformation. The main reasons for the analysis are as follows:

First, in the early stage of loading, the measured displacement increases rapidly, and the slope is significantly larger than the theoretical value, mainly due to the gap between the steel bars.

Second, in the later stage of loading, both the theoretical value and the measured value increase linearly, but the increase slope of the theoretical value is slightly smaller than the measured value, mainly due to the fact that on the field profile steel, in order to facilitate the assembly and hinge, there are many openings, and the cross section of the profile steel is smaller than the theoretically calculated cross section.
4. Conclusion
In this paper, a foundation pit with a prestressed steel composite support in Hangzhou is taken as the background, and a large span gusset is used to carry out the pressure test using the hydraulic jack, and three tests are carried out in sequence: the axial pressure test under normal conditions, the axial pressure test under unrestrained conditions, and the eccentric pressure test under unrestrained conditions. To explore the deformation performance of the steel composite support under pressure and its influence on the displacement of the retaining structure, and draws the following conclusions:

(1) The displacement of the retaining structure changes linearly with the compressive load, but the displacement of the outer side of the angle brace is greater than that of the inner side, and there is a significant side-angle effect. The maximum displacement of each measuring point under three different compression conditions differs little, which proves that the steel composite support has strong adaptive stability.

(2) Most of the displacements of the retaining structure under three different compression conditions are elastic deformation, which proves that the composite support of the steel has good stability and reliability.

(3) The maximum load of the compression test far exceeds the total prestress value of the support design, and the compression deformation of the steel support presents as elastic deformation. Under the three test conditions, the compression deformation of the profiled steel supports is close to each other, which proves that the steel composite support can withstand large loads and has a large security redundancy value.

(4) The measured compression deformation of the steel support is greater than the theoretical compression deformation, mainly due to the joint gap and the reduction of cross section with more holes in the beam.

References
[1] Qiu Bao-xing. From Green Building to Low Carbon Eco-City [J]. Urban Development Studies, 2009, 16 (07): 1 - 11. (In Chinese).
[2] ZHANG Kuang-cheng, LI Ji-min. Accident analysis for ‘08.11.15’ foundation pit collapse of Xianghu Station of Hangzhou metro [J]. Chinese Journal of Geotechnical Engineering, 2010, 32 (S1), 338 - 342. (In Chinese).
[3] Xiao Xiao-chun, Yuan Jin-rong, Zhu Yan-fei. Causation Analysis of the Collapse on Singapore MRT Circle Line Lot C824 (Part I) - Project Background and Process of Collapse [J]. Modern Tunnelling Technology, 2009, 46 (05): 66 - 72. (In Chinese).
[4] Xiao Xiao-chun, Yuan Jin-rong, Zhu Yan-fei. Causation Analysis of the Collapse on Singapore MRT Circle Line Lot C824 (Part II) - Critical Design Errors in Temporary Retaining System [J]. Modern Tunnelling Technology, 2009, 46 (06): 28 - 34. (In Chinese).
[5] Xiao Xiao-chun, Yuan Jin-rong, Zhu Yan-fei. Causation Analysis of Singapore MRT Circle Line C824 Nicoll Highway Collapse (Part III) - Technically Breaching Back Analysis and Insufficient Instrumentation [J]. Modern Tunnelling Technology, 2010, 47 (01): 22 - 28. (In Chinese).
[6] LI Ying, CHEN Dong, LIU Xing-wang, et al. Application of prestressed assemble steel support system in retaining structures for foundation pits in soft soils. Chinese Journal of Geotechnical Engineering, 2014, 36 (S1): 51 - 55. (In Chinese).
[7] Liu Fa-qian. Stability Design of Assembled SteelInner Suppor [J]. Urban Roads Bridges & Flood Control, 2016 (05): 81 - 83+10 - 11.
[8] LIU Xing-wang, TONG Gen-shu, LI Ying, et al. Stability Analysis of Assembly Steel Struts In Deep Excavation [J]. Engineering Mechanics, 2018, 35 (4): 200 - 218. (In Chinese).