Mechanical properties of active nodes and their influences on overall bearing capacity of steel bracing system in excavation engineering

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ABSTRACT

In the braced excavation engineering, steel tube bracing consists of steel tubes and active node. Most of the studies on the active node remain qualitative and there is no reliable quantitative calculation or experimental data. In order to quantitatively study the mechanical characteristics of active node and the effect of the active node on the support system, the indoor test of the active nodes and the theoretical calculation of the steel supports were carried out, and comparative analysis showed that: The yield load and stiffness of three active nodes are highly discrete. The active node determines the overall bearing capacity of the support system.

Keywords: excavation engineering; steel bracing; active node; bearing capacity; mechanical properties

1 INTRODUCTION

In the braced excavation engineering, an active device is required between the steel support and the cap beam or the enclosed purlin, and at present, the steel wedge type active node is mostly used at this place. The active node can adjust the length of the steel support, which is beneficial to support erection, disassembly and it can apply pre-axial force. The active node is one of the important joints of the whole steel support system. However, due to the irregularity of its own structure, the active node is likely to cause stress concentration. At present, domestic and foreign scholars have conducted some research on the mechanical properties of steel tube support and active node. The research on steel tube support is relatively early and comprehensive, and the stress-strain relationship of steel support can be accurately fitted through existing research results. In terms of the active node, the research is relatively limited, and basically stays in the study of the use criteria, lack of reliable quantitative calculations and experimental studies. In addition, many experts and scholars have analyzed the previous foundation pit accidents and thought that the weak nodes in the support system are likely to cause continuous collapse of the foundation pit. To a certain extent, nodes are more important than the components they connect to, because node failures cause all components connected to them to fail, then the various functions of the components are lost. The steel tube support and the active node are "connected" together, whether the "equal strength, equal stiffness" requirement can be achieved, and where is the weak point of the steel support system, and so on, has not attracted everyone's attention. In this paper, the influence of the active node on the bearing capacity of the whole steel tube support system is revealed by comparing and analyzing the mechanical properties such as the bearing capacity and stiffness of the active node and the steel tube support,and find the control node that the carrying capacity of the support system

2 STEEL LOAD-DISPLACEMENT CURVE FITTING

In China, when the pit of the subway station is constructed, the length of the single-span steel support is generally not less than 19m. The length of the currently known maximum single span steel support is 25m. Then take the 19m, 20m and 25m foundation pit as an example for calculation. The sum of the active node and the length of the steel support is approximately equal to the span of the foundation pit, wherein the length of the active node is taken as 1m, then select φ609mm, t=16mm, lengths of 18m, 20m, 24m steel tube supports to calculate their yield load, ultimate bearing capacity and stiffness for comparison with the active node.

2.1 Calculation of bearing capacity of steel support

2.1.1 Calculation of ultimate bearing capacity

When calculating the ultimate bearing capacity of the rod, the Euler Formula can only be applied if the flexibility λ of the strut is greater or equal to the limit value λ_p of the flexibility. The expression written as the length of the pressure bar is:

$$l \geq \sqrt{\frac{\pi^2 EI}{\sigma_p A}} \tag{1}$$

The steel used for this calculation is Q235, Young modulus E=2.06×105N/mm^2, proportional limit σ_p=215MPa, A stand for cross-sectional area, I stand for inertial moment. Then:

$$l \geq \sqrt{\frac{\pi^2 EI}{\sigma_p A}} = \sqrt{\frac{\pi^2 E(D^2+d^2)}{16\sigma_p}} = \sqrt{\frac{\pi^2 \times 2.06\times10^5 (609^2+577^2)}{16\times 215\times 10^6}} = 20.6\text{m}$$

It can be found that in the ideal state, the Euler

Formula is established only when the length of the steel tube support is greater than 20.6m.Therefore, the ultimate bearing capacity of the 24m steel tube support is:

$$P_{cr.24}=\frac{\pi^2 EI}{(\mu l)^2}=\frac{3.14^2\times 2.1\times 10^5\times 1.31\times 10^9}{24000^2}=4709kN$$

Among them μ represents Length factor is taken as 1.0.When l<20.6m, only the bearing capacity controlled by the strength limit is considered. Therefore, the double effect of strength control and bending stability is considered in calculating the ultimate bearing capacity of 18m and 20m steel supports.

$$\begin{cases}\sigma_1=N_{cr}/A\\ \sigma_2=\beta_{mx}\times M_x/(\gamma_x\times W_{1x}(1-0.8\times N_{cr}/N_{EX}))\\ \sigma_1+\sigma_2=\sigma_b\end{cases} \tag{2}$$

Among them:

N_{cr} ----The ultimate bearing capacity of the rod;

β_{mx} ----The equivalent bending moment coefficient, taken as 1.0;

M_x ----The maximum bending moment across the middle;

W_{1x} ----Section resistance moment;

γ_x ----Plastic development coefficient, taking 1.15;

N_{EX} ----Euler critical force, $N_{EX}=\pi^2EA/(\lambda^2)$.

Among them, the selected steel is Q235, ultimate strength σ_b=372MPa, ultimate flexibility λp=100.

By taking parameters of Q235 steel into the formula (2), the ultimate bearing capacity of the 18m steel tube support can be found as:

$$N_{cr.18}=8209\text{kN}$$

In the same way, the ultimate bearing capacity of the 20m steel tube support can be obtained.

$$N_{cr.20}=6925\text{kN}$$

2.1.2 Steel support yield load calculation

The failure mode of the 24m steel support is unstable failure, that is, it has been destroyed and cannot be carried before without reaching the yield, so this section does not calculate the 24m steel tube support yield load.

The yield load of the 18m and 20m steel tube supports is calculated by the yield stress formula, as follows.

$$\sigma_y=a-b\lambda \tag{3}$$

$$F_y=A\sigma_y \tag{4}$$

The values of a and b are respectively 304MPa and 1.12MPa , a, b and λ bring into the formula(4) σ_y can be obtained:

$$\sigma_{y.18}=a-b\lambda_{18}=304-1.12\times 86=207.7\text{MPa}$$

$$\sigma_{y.20}=a-b\lambda_{20}=304-1.12\times 95=197.6\text{MPa}$$

The yield loads of 18m and 20m steel tube support are:

$$F_{y.18}=A\sigma_{y.18}=0.029811\times 207.7\times 10^3=6191\text{kN}$$

$$F_{y.20}=A\sigma_{y.20}=0.029811\times 197.6\times 10^3=5891\text{kN}$$

2.2 Steel support stiffness calculation

The formula for calculating the stiffness of the rod is:

$$k=\frac{EA}{l} \tag{5}$$

Bring l_{18}=18000mm, l_{20}=20000mm, and l_{24}=24000mm into formula (5) respectively:

$$k_{18}=\frac{EA}{l_{18}}=\frac{2.06\times 10^5\times 29811.3}{18000}\times 10^{-3}=341.2\text{kN/mm}$$

$$k_{20}=\frac{EA}{l_{20}}=\frac{2.06\times 10^5\times 29811.3}{20000}\times 10^{-3}=307.0\text{kN/mm}$$

$$k_{24}=\frac{EA}{l_{24}}=\frac{2.06\times 10^5\times 29811.3}{24000}\times 10^{-3}=255.9\text{kN/mm}$$

2.3 Steel support Δ_u calculation

Δ_u refers to the deformation value corresponding to the ultimate load in the P-Δ curve of the material, which can be obtained by multiplying the value of ε_u by the length of the rod, ε_u from the σ-ε relationship curve of the material. For the σ-ε relationship of metal materials, the Ramberg-Osgoog (1943) model with Hill correction can be used. The model formula is:

$$\varepsilon=\frac{\sigma}{E_0}+\sigma_{yp}\left(\frac{\sigma}{\sigma_y}\right)^n \tag{6}$$

Van der Merwe fitted σ_y and n of Q235 steel through several experiments, taking σ_{yp}=0.002 and n=9.2524. E_0 represent deformation modulus is 206000N/mm^2.

Thus, the ultimate strain ε_u of the 18m and 20m steel supports can be calculated by the formula (6). σ_u in the formula (6) can be obtained from $\sigma_u=\frac{F_u}{A}$.

$$\varepsilon_{u.18}=\frac{\sigma_{u.18}}{E_0}+\sigma_{yp}\left(\frac{\sigma_{u.18}}{\sigma_y}\right)^n=0.0093$$

$$\varepsilon_{u.20}=\frac{\sigma_{u.20}}{E_0}+\sigma_{yp}\left(\frac{\sigma_{u.20}}{\sigma_y}\right)^n=0.0032$$

Therefore,

$$\Delta_{u.18}=\varepsilon_{u.18}\times l_{18}=0.0093\times 18000=167.4\text{mm}$$

$$\Delta_{u.20}=\varepsilon_{u.20}\times l_{20}=0.0032\times 20000=64\text{mm}$$

Summarize the calculation results in Table 1.

Table 1. Calculation results

Length	Yield load /kN	Ultimate bearing capacity /kN	Stiffness /kN/mm	Δ_u/mm
18m	6191	8209	341.2	167.4
20m	5891	6925	307.0	64.0
24m	-	4709	255.9	-

2.4 Load-displacement curve fitting result

The load-displacement curve of the rod in the necking stage is descending, that is, the rod no longer has the bearing capacity in this stage, so the deformation of the steel tube support in the necking stage is not discussed. And the curve of the strain hardening stage is simplified and simplified into a horizontal straight line whose value is always F_u.

According to the calculation of the yield load, ultimate bearing capacity and stiffness of the steel tube support and the simplification of the stress-strain curve, the load-displacement curves of the 18m, 20m and 24m steel tube supports are obtained, as shown in Fig. 1.

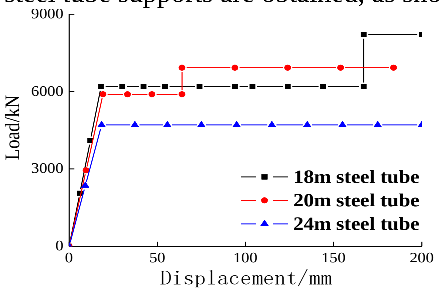

Fig. 1. The load-displacement curves of three lengths of steel support

3 STEEL WEDGE TYPE ACTIVE NODE INDOOR LOADING TEST

3.1 Structural composition

The single-box active node is generally made of steel tube combined with two channel steels, as shown in Figure 2.

The double-box active node is generally made by a 20mm thick Q235 steel plate, as shown in Figure 3.

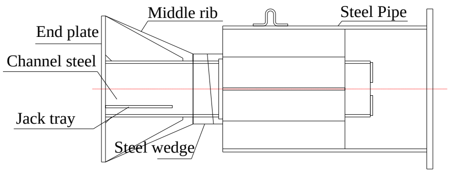

Fig. 2. Single-box active node

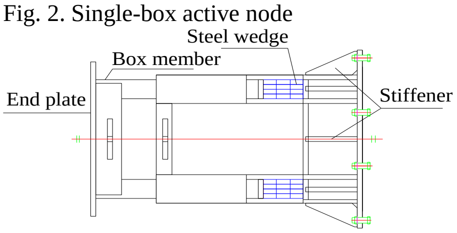

Fig. 3. Double -box active node

3.2 Group number of the test piece

Three active nodes were taken at the Beijing subway construction site as test pieces and transported to the laboratory for indoor loading tests. Named DXD, DXC and SX respectively. The test piece DXD and the test piece DXC are two kinds of single-box active nodes commonly used in foundation pit engineering; the test piece SX is a double-box type active node. The specific parameters of each test piece are shown in Table 2.

Table 2 Specimen parameter

Test No	Material	Height/ m	Weight/ t	Adjustment /mm
DXD	Q235	1.2	0.95	100
DXC	Q235	1.5	0.89	100
SX	Q235	1.0	0.54	100

3.2 Test plan

The test piece was loaded using the 4000t hydraulic pressure testing machine of Beijing University of Technology Laboratory, and the axial pressure was applied. Displacement acquisition using Percentimeter Acquisition System, the system is a fully intelligent data acquisition system for traveling. The data output is a synchronous serial transmission mode. A total of 2 displacement gauges are installed for each test piece.

3.3 Test result : load-displacement curve

The load-displacement curves of the test pieces of each group were no obvious yield step. Therefore, the stress at the residual strain of 0.2% was taken as the conditional yield point. The origin to the yield point is the elastic stage. The load corresponding to the yield point is defined as the yield load, denoted as F_y. The stiffness is the slope of the line connecting the origin and the conditional yield point, denoted as k_a The deformation rate is a ratio of the absolute deformation of the test piece to the length of the test piece.

Figure 4 shows the *P–Δ* curves of the test pieces DXD, DXC and test piece SX. The mechanical parameters of the three test pieces are highly discrete, which is not conducive to the quality control of the use process, and the stiffness is reduced quickly, which is not conducive to the maintenance of steel bracing prestress. However, all three specimens have good ductility and no brittle failure

The mechanical parameters of each test piece are summarized, as shown in Table 3.

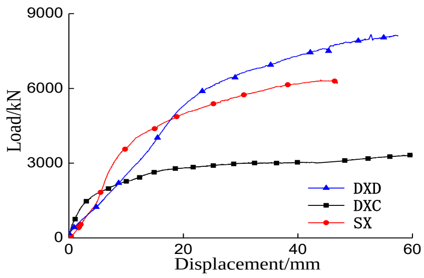

Fig. 4. Load-displacement curve of three specimens

Table 3 The test result summary of active nodes specimens

Test No	Yield load F_y/ kN	Deformation rate/ %	Average stiffness k_a/ kN/mm
DXD	4790	5.1	266.7
DXC	1780	4.3	428.6
SX	2750	4.6	400

4 COMPARATIVE ANALYSIS OF ACTIVE NODE AND STEEL SUPPORT

By comparing and analyzing the load-displacement curves of the steel tube support and the active node, it can be determined whether the entire support system has weak node and which part of the support system is determined.

Figure 5 is a comparison of the *P–Δ* curve of the test piece DXD with three different lengths of steel tube support. The mechanical properties of the test piece DXD are close to that of the 24m steel tube, but that lower than the 18m and 20m steel supports. The yield load and stiffness of the specimen DXD are about 77% of the yield load and stiffness of the 18m steel tube, which is about 80% of the yield load and stiffness of the 20m steel tube support. In terms of ultimate bearing capacity, the test piece DXD is close to the 18m steel tube support, which is about 8029kN.

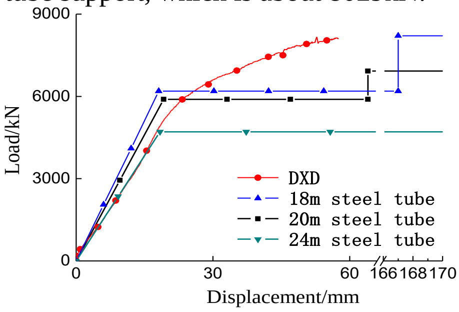

Fig. 5. Comparison of load-displacement curves between DXD specimen and steel tube support

Figure 6 is a comparison of the *P–Δ* curve of the test piece DXC with three different lengths of steel tube support. The test piece DXC has a large rigidity but a low load carrying capacity. The stiffness of the test piece DXC is 428.6kN/mm which is 1.3 times the steel support stiffness of the 18m steel tube, but its yield load is only 1780kN, which is 28% of the yield load of the 18m steel tube support and 30% of the 20m steel tube support's yield load. In terms of ultimate bearing capacity, the ultimate bearing capacity of the test piece DXC is 3280kN, which is much lower than the ultimate load of any length steel tube support, which is only equivalent to 69% of the ultimate load of the 24m steel tube. The lower bearing capacity of the test piece DXC is due to the poor integrity of the ribs, which are welded by two steel plates.

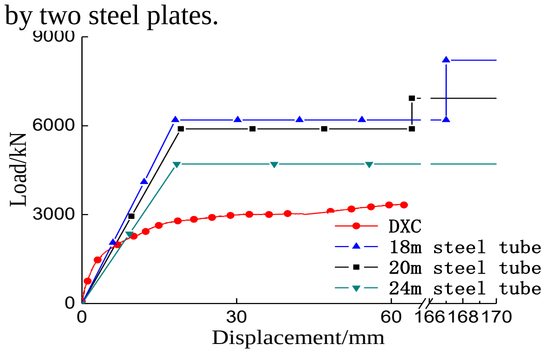

Fig. 6. Comparison of load-displacement curves between DXC specimen and steel tube support

Figure 7 is a comparison of the *P–Δ* curve of the test piece SX with three different lengths of steel tube support. The stiffness of the test piece SX in the elastic section is close to that of the 20m steel tube support. The specimen has a slight increase in stiffness between 2100kN and 4000kN. This is because the steel wedges on both sides of the double-box active node are difficult to place in an absolute level. At 2100 kN, the steel wedges on both sides are pressed to the same level, so the rigidity is slightly increased. At 3500kN, the sidewall of the active node is unstable and the stiffness drops rapidly. In terms of yield load, the yield load of the specimen SX is 2750kN, which is much lower than the yield load of 18m and 20m steel tube support, which is only 44% of the 18m steel tube support, which is equivalent to 46% of the 20m steel tube support. In terms of ultimate bearing capacity, the ultimate bearing capacity of the test piece SX is 6210kN, which is between the ultimate bearing capacity of the 20m steel tube of 6925kN and the 24m steel tube of 4709kN.

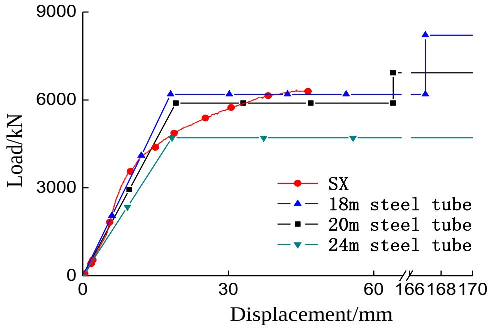

Fig. 7. Comparison of load-displacement curves between SX specimen and steel tube support

5 CONCLUSION

(1) The three active node yield loads and stiffnesses are highly discrete. The yield load of the test piece DXD is up to 4790kN. The specimen DXC has a minimum yield load of 1780 kN, which is only about 37% of the yield load of the test piece DXD. However, the rigidity of the test piece DXC is about 428kN/mm, the rigidity of the test piece DXD is only 266.7kN/mm, and the rigidity of the test piece DXD is about 62% of the rigidity of the test piece DXC.

(2)For the foundation pit with single span steel support within 24m, the steel wedge type active node determines the overall bearing capacity of the support system. Simply improving the bearing capacity of the steel tube is ineffective.

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