Analysis of the Necessity for Steel Changing Brace Erection During the Foundation Pit Excavation in Metro Station End Shaft

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Abstract. Under the engineering background of end shaft construction in an underground two-story metro station, the change and development laws of supporting axial force, enclosure structural deformation and internal force during the end shaft excavation process were analyzed through the field measurement, and the measured values were statistically compared with the design values. The results indicate that it is very necessary to erect steel changing brace in the design, which exerts an unobvious effect on mitigating the enclosure structural deformation of the foundation pit in practical engineering, but apparently affects the axial force of adjacent steel braces in the steel changing brace. The results can be verified through the long-term monitoring at different points during the subsequent metro construction, and other steel changing brace forms convenient for the construction should be considered to substitute the conventional steel changing brace.

1. Introduction
The urbanization has been accelerated throughout China in recent years, and the metro construction is also flourishing in various regions, where the open cut method is mostly used[1]. During the foundation pit excavation process in station, the stratal movement and deformation will be triggered by excavation disturbance, stratum loss, consolidation settlement, etc., so the current metro design is being transformed from the traditional strength control design into displacement control design[2]. Widely applied to the foundation pit design of metro station, the steel brace system bears the lateral water and soil pressure of foundation pit jointly with the enclosure structure[3]-[5]. The station end shaft is usually arranged using oblique steel braces to resist against the external forces in two directions[6]-[7]. Under the engineering background of a typical underground two-story metro station in Tianjin, the depth of foundation pit in the end shaft is mostly 19-20 m in consideration of shield launching and arrival construction. Therefore, five braces are arranged at the end shaft from top to bottom, and one steel changing brace is erected between the 4th and 5th braces. In view of tight construction schedule at the end shaft construction site, controversies remain whether the steel changing brace should be erected at the construction site. Based on the field measured data, the change and development laws of supporting axial force, enclosure structural deformation and internal force in the end shaft excavation process were statistically compared with the design values, and the necessity of arranging steel changing brace was analyzed.
2. Engineering Background

A metro station in Tianjin was taken as the study object. This station was an underground two-story station, the depth of foundation pit at the end shaft was 19.12 m, the underground diaphragm wall 800 mm in thickness was used as the enclosure structure, five braces and one steel changing brace were successively arranged from the top to bottom in the foundation pit. The first brace was reinforced concrete (C30) brace with the sectional dimension of 1.0 m × 1.0 m, other four braces and one changing brace were all circular steel tube (Q235) braces, where the diameter and wall thickness in their sectional dimensions were φ 800 mm and 16 mm, respectively, and the steel changing brace was placed between the 4th and 5th braces. A temporary upright column was arranged at the steel brace, beneath the column was the φ 1000 mm cast-in-situ bored pile foundation, the pile length was 18 m, and the temporary upright column was inserted into the foundation pile by a depth of 3 m. The brace arrangement plan of foundation pit at the station end shaft is seen in Figure 1-Figure 4.

Figure 1. Layout Plan of Concrete Braces in the Foundation Pit at Station End Shaft.

Figure 2. Layout Plan of Steel Braces in the Foundation Pit at Station End Shaft.

Figure 3. Layout Plan of Steel Changing Brace in the Foundation Pit at Station End Shaft.
3. Engineering Geology and Hydrogeological Situation
From top to bottom, the strata in the foundation pit at the station end shaft are 1-1 miscellaneous fill, 4-1 silty clay, 6-1 silty clay, 6-3 silt, 6-4 silty clay, 7-1 silty clay, 8-1 silty clay, 8-21 silt, 8-22 silty sand, 9-1 silty clay, 10-1 silty clay, 11-1 silty clay, etc. The main parameters of the above soil layers used in the enclosure structural design of the foundation pit are listed in Table 1, where the direct shear-consolidation-fast shear index is used for the sandy soil, and direct shear-fast shear index for the clayey soil.

| Name of soil layer       | Unit weight (kN/m³) | Cohesion (kPa) | Internal friction angle (°) |
|--------------------------|---------------------|----------------|-----------------------------|
| 1-1 miscellaneous fill   | 19.0                | 5.0            | 10.0                        |
| 4-1 silty clay           | 19.8                | 12.1           | 10.1                        |
| 6-1 silty clay           | 19.4                | 11.0           | 13.0                        |
| 6-3 silt                 | 19.8                | 14.0           | 27.0                        |
| 6-4 silty clay           | 19.2                | 13.2           | 16.5                        |
| 7-1 silty clay           | 19.9                | 13.2           | 12.7                        |
| 8-1 silty clay           | 20.2                | 18.0           | 18.0                        |
| 8-21 silt                | 20.6                | 16.0           | 30.0                        |
| 8-22 silty sand          | 20.2                | 14.4           | 32.2                        |
| 9-1 silty clay           | 19.7                | 22.0           | 14.4                        |
| 10-1 silty clay          | 20.1                | 17.0           | 15.0                        |
| 11-1 silty clay          | 20.0                | 24.0           | 13.0                        |

The static buried depth of groundwater at the station is 1.2-1.9 m, and the annual variation amplitude is generally 0.50-1.00 m. The primary confined aquifer mainly occurs at the 8-21 silt layer and 8-22 silty sand layer in the secondary continental riverbed-floodplain alluvial deposit, with the good water permeability. The 9-1 silty clay and 10-1 silty clay with poor water permeability beneath the confined aquifer serve as the lower confining bed of the confined aquifer. The buried depth of confined water head is about 4.6 m beneath the current ground surface. The station enclosure structure already cuts off the primary confined aquifer.:
4. Enclosure Structural Design
The importance is attached to the following mechanical numerical values in the foundation pit excavation and backfill process: horizontal displacement of underground diaphragm wall, axial force of steel brace and internal force of underground diaphragm wall. Both safety class and deformation control class of the foundation pit supporting structure are Class II, the importance coefficient is taken as 1.1, the ground surface settlement as ≤ 0.1% H, the horizontal displacement of underground diaphragm wall as ≤ 0.14%H and ≤ 30 mm (H is the excavation depth of foundation pit). The “m” calculation is adopted, and m is the proportionality coefficient regarding the growth of horizontal subgrade reaction coefficient of soil layer with the depth of foundation pit.

The concrete calculation results considering or not considering the erection of steel changing brace in the design are compared as seen in Table 2.

Table 2: Comparison Table of Design Calculation Results

| Calculated working condition | Construction condition | Horizontal displacement of underground diaphragm wall (mm) | Bending moment of underground diaphragm wall (kN*m) | Axial force of the lowermost brace (kN/m) |
|------------------------------|------------------------|----------------------------------------------------------|------------------------------------------------|------------------------------------------|
| Erection of steel changing brace | Excavation till the pit bottom | 17.7 | 1,075.3 | 1,018.8 |
| | Demolition of the 5th brace after the construction of base plate | 18.1 | 934.5 | 928.4 |
| | Demolition of the fourth brace after the erection of steel changing brace | 18.8 | 834.0 | 656.3 |
| No erection of steel changing brace | Excavation till the pit bottom | 17.7 | 1,075.3 | 1,018.8 |
| | Demolition of the fourth and fifth braces after the construction of base plate | 23.2 | 1,253.1 | 976.4 |

As seen in Table 2, if no steel changing brace is erected in the design calculation, when the fourth and fifth braces are directly demolished after the structural base plate is constructed, the deformation value of underground diaphragm wall will be increased by 5.5 mm, and the bending moment by 177.2 kN*m. The underground diaphragm wall can still meet the stress-carrying and deformation requirements, but the limiting value is approached, and the reinforcement ratio of underground diaphragm wall should be increased, thus resulting in the waste of engineering quantities. The change in the supporting axial force is mainly manifested at the third brace, when no steel changing brace is erected, its axial force will be increased by 320.1 kN/m, which brings about hidden dangers to the internal and external stability of the plane. Therefore, the erection of steel changing brace between the fourth and fifth braces is still preferred in the design in consideration of the construction cost and safety.

5. Statistics of Field Monitoring Data
Monitoring points of supporting axial force and underground diaphragm wall deformation are arranged at the station end shaft, and the concrete monitoring values are seen in Table 3. In consideration that the practical engineering construction should follow the design drawings, the monitoring results are the results under the construction of steel changing brace.
Table 3: Comparison Table of Design Calculation Results

| Calculated working condition | Construction condition                          | Horizontal displacement of underground diaphragm wall (mm) | Axial force of the lowermost brace (kN/m) |
|-----------------------------|-------------------------------------------------|----------------------------------------------------------|------------------------------------------|
| Erection of steel changing brace | Excavation till the pit bottom                  | 13.1                                                     | 818.2                                    |
|                              | Demolition of the fifth brace after the construction of base plate | 13.6                                                     | 626.7                                    |
|                              | Demolition of the fourth brace after the erection of steel changing brace | 17.3                                                     | 418.9                                    |

Through the data comparison of Table 2 and Table 3, it can be known that when the steel changing brace is erected in practical engineering, the deformation of underground diaphragm wall will be increased by 4.2 mm, which is greater than the design value under the erection of steel changing brace and approximate to the design value without the erection of steel changing brace. Therefore, the erection of steel changing brace does not exert any significant effect on the horizontal deformation of enclosure wall in the actual construction. It can be clearly observed from Figure 5 that the horizontal displacement of underground diaphragm wall is obviously increased when no steel changing brace is erected or when the brace at the base plate is demolished in the actual construction.

Figure 5. Comparison Chart of Horizontal Displacement of Underground Diaphragm Wall.

By comparing the supporting axial force, except the circumstance where the actual monitoring value is much smaller than the design value, the erection of steel changing brace can exert a stabilizing effect on the third brace, and the decrement in the axial force value of the third brace is equivalent to the design value. It can be known that the effect of steel changing brace is manifested by the change in the axial force of the third brace, namely, it shares the force borne by the third brace. The comparison charts of the monitoring values of the third and fourth braces with the design values are seen in Figure 6 and Figure 7, respectively.
6. Conclusion
During the construction process of station end shaft, whether a steel changing brace should be set on the construction site has been controversial for a long time due to the restricted site space and tight construction schedule, and the construction organization is mostly based on its construction experience. According to the previous analysis, the following conclusions are drawn: (1) From the design angle, the erection of steel changing brace can reduce the internal force of underground diaphragm wall, save the reinforcing steel bars and relieve the horizontal deformation of underground diaphragm wall, and ensure the internal and external stability of steel changing brace. Therefore, it is necessary to arrange the steel changing brace; (2) From the field monitoring results, the steel changing brace erected ensures the stability of steel brace, but it has no obvious influences on the internal force and deformation of underground diaphragm wall. From another angle, that the internal force of underground diaphragm wall is not obviously increased after the erection of steel changing brace does not occur; (3) By combining the comparative analysis results of design values and field monitoring values, it can be known that it is still recommended to erect a steel changing brace at the station end shaft. In consideration of field construction space and construction period, the section steel brace, which is more convenient for splicing and hoisting, can be used to replace the conventional circular steel tube changing brace, and the feasibility of this method can be verified through the long-term monitoring in other projects, thus providing a reference for the relevant projects.

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