Monitoring and Analysis of Subway Shaft Construction Displacement

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Abstract. According to the construction site monitoring of a subway tunnel shaft in Beijing, the deformation laws of surface settlement, horizontal displacement and vertical displacement of retaining structure during shaft construction were analyzed. The results show that: firstly, the ground settlement around the shaft can be divided into two stages, the rapid settlement stage before the floor construction and the stable settlement stage after the floor construction. The settlement rate and value of the middle point of the long side of the shaft is faster and bigger than the corner point and the middle point of the short side. The settlement value first increases and then decreases with the increase of the distance to the pit side. The maximum settlement is located at (0.61 ~ 1) times the excavation depth behind the diaphragm wall. Secondly, the horizontal deformation of the long side of diaphragm wall is obviously different from the short side. The horizontal deformation of the long side is larger than the short side, and the position of the maximum horizontal deformation is deeper than the short side. The horizontal deformation curve of the middle point of the long side has obvious inflection point, and the middle point of the short side presents reciprocating type. The variation range of horizontal displacement of diaphragm wall top is between 10 mm, and the maximum horizontal displacement is 0.037% of shaft depth. Finally, the vertical displacement of the top of the diaphragm wall settles rapidly before the excavation of the bottom plate, and the settlement value decreases gradually after the excavation, and the increase rate of the diaphragm wall settlement is the largest when it is excavated to the bottom of the shaft. This deformation law can provide reference for the optimization of support design of similar projects.

1. Introduction
As a main component of subway construction, a shaft is the main channel for underground excavation or shield construction of subways [1], and it is the originating and receiving structure of the shield machine especially for shield construction. Shafts at the intersection of lines have a large excavation area and depth. The retaining structure and adjacent buildings will undergo great deformation under the effect of unloading after soil excavation. Research on the law of and cause analysis of the deformation of subway shaft retaining structure can provide a basis for the deformation control of works of the same type and ensure the safety of the structure and adjacent buildings.

Many scholars have carried out research on the deformation law of the retaining structure and achieved corresponding results. Hsieh et al. [2] gave two prediction methods for the settlement of the
surrounding environment caused by the excavation of foundation pits – triangle and groove, and proposed the main influence area and the secondary influence area. Dai [3] analyzed the surface settlement data of more than 10 stations on Beijing Metro Line 6 and found that the surface settlement in Beijing was not directly or inversely proportional to the buried depth of stations and that the distance between the point of inflection of the settlement trough and the center line of the tunnel was 10 ~14 m. Li et al. [4] studied the temporal and spatial distribution law of surface settlement, pile displacement, axial force of support and pit bottom uplifts caused by deep foundation pit construction in Beijing. Li et al. [5] conducted an in-depth study on the lateral deformation of underground diaphragm walls in subway station construction and found a great influence of time effect on the deformation and the law of lateral deformation in different construction periods and meanwhile found that the deformation occurred fastest in the period from the completion of pit bottom excavation to floor pouring. Fan et al. [6] conducted a numerical analysis considering the characteristics of the contact surface between the diaphragm wall and the soil and found that the calculation method considering the characteristics of the contact surface was more consistent with the measured results.

Research on the deformation of the retaining structure of foundation pits has made rich achievements. However, there are few studies on shaft deformation, especially the deformation of shafts receiving multiple shield machines. This paper studied the deformation of a shaft receiving 4 shield machines at the same time, which was very deep. Moreover, many working procedures were crossed in the construction process, causing inconsistency between its deformation law and the conventional law. Therefore, studying the deformation law of deep and large shafts with crossed construction of multiple working procedures and items is of great significance to ensure their construction safety.

2. Project overview

2.1. Foundation pit overview

The No. 2 shaft of a tunnel was mainly used as a shield receiving shaft, the retaining structure of which was an underground diaphragm wall. The shaft structure had a length of 41.6 m, a width of 14 m, a thickness of end and side walls of the main structure of 0.8 m~2.0 m and a design depth of 41.046 m. The underground diaphragm wall had a grooving depth of 68 m and was at safety level I.

2.2. Geological conditions

The proposed site is located in Chaoyang District, Beijing, in the east of the Xishan sediments in the Yanshan fold and thrust belt of the North China Platform. Types of the foundation soil within the depth of the site survey are mainly the Quaternary Holocene alluvial-diluvial strata and the Quaternary Upper Pleistocene alluvial-diluvial strata. The soil in the area is dominated by artificial fill, clay, silty clay, silt and fine sand. The bottom of the shaft is composed of clay, medium sand and silty clay of different thicknesses. Geological conditions of the shaft site are shown in Table 1.

| Soil layer No. | Soil layer name | Thickness of soil layer (m) | Natural gravity γ (KN/m³) | Cohesion (KPa) | Internal friction angle ϕ° | Compactness | Basic bearing capacity (KPa) |
|---------------|-----------------|----------------------------|---------------------------|----------------|-----------------------------|-------------|-----------------------------|
| ① | Miscellaneuous fill | 3.6 | - | - | - | - | - |
| ② | Silt | 4.5 | 19.6 | 15 | 22 | Moderately compact | 140 |
| ③ | Silty clay | 8.2 | 17.7 | 25 | 18 | Plastic | 110 |
| ④ | Silt | 1.2 | 19.8 | 15 | 22 | Moderately compact | 160 |
| ⑤ | Silty clay | 5 | 20.3 | 20 | 24 | Compact | 180 |
| ⑥ | Silt | 2 | 18.5 | 35 | 21 | Plastic | 180 |
### 2.3. Design scheme of retaining structure

The shaft had a large excavation depth, rich groundwater and complex soil easy to form quicksand. There were high requirements for the protection of underground pipelines and the surrounding environment. The stability of the foundation pit was ensured with underground diaphragm walls, four reinforced concrete supports and three steel pipe supports. Both reinforced concrete supports and steel pipe supports were diagonal and inclined struts with clear force transmission.

### 3. Deformation monitoring of underground diaphragm wall

Emphasis was placed on the detection of deformation of the underground diaphragm wall and changes in its axial force of support in the construction process in order to grasp the deformation of the shaft structure itself and the surrounding stratum, ensure the normal use of buildings and underground pipelines within the construction affected area and avoid excessive deformation, instability or collapse. Main monitoring items of the No. 2 shaft included the surrounding surface settlement (DB), horizontal displacement of the underground diaphragm wall (ZQT), internal force of support (ZQL), horizontal displacement of the top of the wall (ZQS), vertical displacement of the top of the wall (ZQC), and groundwater level change (ZSW), etc. The layout of monitoring points is shown in Fig. 1. This paper mainly analyzed the spatial and temporal distribution of monitoring data of surface settlement, horizontal displacement of the wall and vertical displacement of the top of the wall. To deeply study the deformation law of the No. 2 shaft in different periods in the construction process, it was divided into 12 working conditions, as shown in Table 2.

### Table 1: Soil properties

| Soil Type   | Plasticity | Liquid限 | Plastic limit | Water limit | Compaction | Density |
|-------------|------------|----------|---------------|-------------|------------|---------|
| Medium sand | 4.7        | 20.2     | 0             | 38          | Compact    | 450     |
| Clay        | 4.2        | 17.2     | 42            | 15          | Plastic    | 160     |
| Fine sand   | 5.8        | 18.6     | 0             | 32          | Compact    | 300     |
| Silty clay  | 9.2        | 19.5     | 45            | 22          | Compact    | 200     |
| Medium sand | 26.7       | 20.3     | 0             | 38          | Compact    | 450     |
| Silty clay  | 14.4       | 19.6     | 45            | 22          | Compact    | 200     |

![Fig. 1: Layout plan of monitoring points of shaft retaining structure](image)
Table 2 Construction conditions division

| Conditions | Construction content |
|------------|----------------------|
| I          | Shaft excavation to the third floor underground and construction of the lower ring frame beam on the same floor |
| II         | Excavation of the fourth floor underground and construction of the ring frame beam on the same floor |
| III        | Excavation and construction of upper ring frame beam on the track layer |
| IV         | Excavation and construction of lower ring frame beam on the track layer |
| V          | Floor excavation |
| VI         | Floor construction |
| VII        | Construction of side wall between the floor and the lower ring frame beam on the track layer |
| VIII       | Construction of side wall between upper and lower ring frame beams on the track layer |
| IX         | Side wall between the upper ring frame beam on the track layer and the ring frame beam on the fourth floor underground, and beam and slab on the fourth floor |
| X          | Sandwich side wall on the third floor underground |
| XI         | Sandwich side wall on the third floor underground and beam and slab of axes B–C on the second floor underground |
| XII        | Side wall on the second floor underground and beam and slab of axes B–C on the roof |

3.1. Analysis of surface settlement around the shaft

Experts and scholars have done a lot of research on the distribution law of surface settlement outside foundation pits and achieved some results. Clough et al. [7] studied the law of surface settlement outside pits in sandy soil and clay areas and found that the spatial distribution was triangular. Hsieh proposed two prediction methods - triangle and groove - for the law of surface settlement outside pits [2]. Li et al. studied the spatial distribution law of surface settlement from the corner of the pit to its middle and found that the settlement was divided into three areas - rapid growth area, transition area and flat area [4]. Wu studied the spatial distribution law of surface settlement and found that the settlement increased rapidly in the final soil excavation and floor construction stage, reached the maximum and then tended to be stable gradually [8].

In this paper, four groups of typical settlement sections - long side midpoints (DB02-02, DB02-05, DB02-08), long side corner points (DB02-01, DB02-06, DB02-07), short side midpoints (DB01-02, DB01-05, DB01-08) and short side corner points (DB03-01, DB03-06, DB03-07) of the No. 2 shaft were analyzed to study the temporal and spatial distribution law of surface settlement under different working conditions.

3.1.1. Temporal distribution law of surface settlement outside the pit

Fig. 2 shows the temporal distribution curves of surface settlement at the four groups of monitoring points on the north and east sides of the shaft at a distance of 25 m from the edge of the pit. According to the figure, (1) the surface settlement continued to increase rapidly as the excavation depth increased before floor construction (condition VI), and the largest settlement occurred at the midpoint of the long side. (2) After floor construction, the overall settlement decreased and tended to be stable as the excavation depth increased, with a fluctuation range of about 5 mm. (3) The midpoint of the long side had the largest and fastest settlement during the construction of the shaft. The settlement at the corner point and the midpoint of the short side was small and relatively slow, indicating that the middle of the long side is the key position for settlement control. (4) The maximum settlement $\delta_{V_m}$ of No. 2 shaft
was 11 mm and \( \frac{\delta_{vm}}{H_e} = 0.027\% \) (\( H_e \) is the excavation depth), which is inconsistent with the research result of Tan [9] et al. that \( \frac{\delta_{vm}}{H_e} \) ranges from 0.03% to 0.2%. There are two main reasons: first, the shaft had a smaller excavation area and larger depth than the foundation pit and was therefore less affected by the space effect; second, the soil around the shaft had a higher strength and thereby smaller settlement. (5) The surface settlement around the shaft after completion was within 8 mm, which is small and is related to the grouting reinforcement behind the wall at the site.

3.1.2. Spatial distribution law of surface settlement outside the pit

Fig. 3 shows the surface settlement distribution curves under 12 conditions at the four monitoring points at the midpoint of the long side on the north of the No. 2 shaft at 0 m, 25 m, 75 m and 100 m from the edge of the pit. According to the figure, (1) the surface settlement first increased and then decreased as the distance from the pit increased, which basically conforms to the groove law. There was an obvious main influence area and secondary influence area [2]. (2) The maximum settlement occurred at 0.61\( H_e \) behind the wall. The main control area of surrounding surface settlement was at (0.61~1) \( H_e \) behind the wall based on the research results of Hsieh [2]. (3) The shaft had a small excavation depth and a ring frame beam was constructed under condition I. There was a slight uplift of the surface due to the support of the frame beam. The uplift value decreased with the increase of the distance from the edge of the pit and tended to be zero gradually. (4) The surface settlement reached the maximum under condition V and gradually decreased and tended to be stable after condition VI. This shows that floor excavation is a critical period for settlement control, and floor construction can well control the amount of settlement.
3.2. Analysis of horizontal displacement of underground diaphragm wall

Many experts and scholars have done a lot of research on the change law of horizontal displacement of underground diaphragm walls. Li conducted an in-depth study on the lateral deformation of underground diaphragm walls at subway stations and found different lateral deformation laws of such walls at different positions, mainly including in-situ reciprocating type, reverse bending type, inner convex type, cantilever type and multi-stage type [5]. Li studied temporal and spatial change laws of the lateral deformation of subway station piles [4]. Most studies focus on the deformation law of foundation pits of subways and buildings currently. Few focus on vertical shafts. Sun et al. found that the displacement of underground diaphragm walls presented a cantilever-type distribution when the foundation pit was shallow in the mixed support section and a parabolic distribution as the excavation depth of the pit increased [10]. Li et al. found that the spatial distribution of lateral displacement of the foundation pit was mainly affected by factors such as the excavation sequence, the nature of the soil layer and exposed corners of the pit in the case of shallow soil excavation (within a depth of 2 m) and that the side displacement manifested an obvious spatial effect [11]. This paper selected the midpoint of the long side ZQT4 and the midpoint of the short side ZQT6 of the shaft retaining structure - underground diaphragm wall to study its horizontal displacement and deformation laws. The lateral deformation curves at the midpoint of the long side of the wall are shown in Fig. 4(a), and those at the midpoint of the short side are shown in Fig. (b).

![Figure a](image_url)

![Figure b](image_url)

Fig.4 Transverse deformation curves of the midpoint of the diaphragm wall

According to Fig. 4 (a), the deformation curves at the midpoint of the long side have the following laws: (1) The deformation curves can be divided into two stages, namely the stage from condition I to condition III in which the diaphragm wall had in-situ reciprocating type deformations and the lateral deformation ranged from -7 to 7 mm, and the stage from condition IV to condition XII in which the lateral deformation of the wall was in the shape of "belly bulging" and the maximum deformation reached about 17 mm which occurred under condition VI. (2) The deformation curves under all working conditions had a point of inflection near the depth of 5 m of the wall mainly because the depth was in the middle of the first support and the second support, with weak support. (3) The maximum lateral deformation of the wall occurred near the shaft depth of 35 m in the stage from conditions IV to XII, indicating that the shaft depth of 35 m is the key position to control the lateral deformation of the wall, where the observation frequency should be increased. (4) The maximum lateral deformation of the wall \( \delta m = 17 \text{ mm} \); the excavation depth of the foundation pits \( H_e = 41.046 \text{ m} \), \( \delta m / H_e = 0.041\% \). According to statistical data, the maximum lateral deformation of the foundation pit ranged from 0.1\% to 1\% [12]. It can be seen that the lateral deformation of the shaft is much smaller than that of the foundation pit. There are two main reasons. First, the foundation pit has a large excavation area, which is greatly affected by the space effect, while the shaft has a small excavation area, high supporting strength and small lateral deformation. Second, the amount of lateral deformation is closely related to soil properties of the site. The soil within the shaft has good properties, mainly including clay and silt and containing no soft soil, so the lateral deformation is small.
According to Fig. 4 (b), the deformation curves at the midpoint of the short side have the following laws: (1) The horizontal displacement ranged from -5 to 2.5 mm as the construction progressed at the depth of 5 m due to the shallow depth and the significant combined effect of construction disturbance, earth pressure behind the wall and supports. (2) The lateral displacement reached the maximum at the depth of 25 m. The maximum lateral displacement occurred in the stage from conditions III to VI. Therefore, it should be monitored intensively in the construction process. (3) Constrained by the soil at the bottom of the pit, the underground diaphragm wall had very small lateral deformation at the depth of 35 m to 45 m.

The following can be obtained through comparison of figures (a) and (b). (1) The lateral deformation of the long side of the shaft was generally greater than that at the midpoint of the short side. The maximum deformation occurred at a larger depth. Therefore, they shall be treated differently in terms of the key control of lateral deformation. (2) The deformation curve at the midpoint of the long side had an obvious point of inflection, and that at the midpoint of the short side presented a reciprocating type. (3) The horizontal displacement of the top of the underground diaphragm wall ranged within 10 mm from -15 to -5 mm. The maximum horizontal displacement was 0.037% of the shaft depth, which is large and should be controlled intensively.

3.3. Analysis of vertical displacement of the top of underground diaphragm wall

Scholars have done research on the change law and mechanism of the vertical displacement of the top of underground diaphragm walls. The large-area unloading due to soil excavation of the foundation pit causes soil rebound in the pit and vertical movement of the retaining structure, which will affect the vertical displacement of the connected underground structures and pipelines, threatening the safety of the structure and other structures. There are many factors that affect the uplift and settlement of the retaining structure and columns, such as the excavation depth and area of the foundation pit, the support form, the insertion ratio, soil conditions at the pit bottom and the length of column piles [13-15]. Xiao et al. studied the influence mechanism of foundation pit excavation on the vertical deformation of the retaining wall and found that the wall had a downward displacement (δ) after excavation and the displacement increment became higher as the excavation progressed in the pure clay model and that the wall had an upward displacement and the displacement increment became smaller as the excavation progressed in the sandy soil model and the combined soil model [16].

According to Fig. 5 which shows vertical deformation curves of the top of the wall, (1) the wall at all monitoring points settled rapidly before completion of floor excavation and the settlement value gradually decreased after excavation. The fastest settlement occurred in the stage from conditions IV to V and the fastest uplift occurred in the stage from conditions V to VI. The main reason is that the wall was a reinforced concrete structure with its own gravity greater than the weight of the undisturbed soil, and the friction between the wall and the soil it reached the minimum in the stage from conditions IV to V. The shaft was constructed under dry conditions after pumping. The reduction of the groundwater level caused the settlement of soil at the bottom of the pit. The wall settled rapidly in the excavation stage under the combined effect. However, the floor produced a binding effect on the wall after construction, so the settlement value of the structure gradually decreased. (2) In the initial stage of shaft excavation, an uplift occurred at monitoring points 1 to 6 and 8 and subsidence occurred at point 7. After the completion of shaft construction, there were still uplifts at points 1 to 5, ranging from 2mm to 5mm; the settlement at points 6~8 decreased rapidly and the final settlement value was between 1mm and 5mm. The main reason for the above is the great difference in soil properties at the bottom of the pit according to research results of Xiao et al. combined with soil properties at the bottom of the shaft. The deformation at middle points 1 and 2 was dominated by uplifts due to the minimum clay stratum thickness and maximum medium sand thickness in the middle of the bottom of the shaft. Both uplifts and subsidence occurred at points 3, 4, 5 and 8 as the construction progressed due to the gradual increase of clay thickness and decrease of fine and medium sand thickness on both sides. The deformation at points 6 and 7 was dominated by settlement. (3) The deformation of the wall at points 1 and 2 was dominated by uplifts in the whole shaft construction process. The deformation at points 3, 4, 5 and 8
included both uplifts and subsidence as the construction progressed. The deformation at points 6 and 7 was mainly settlement. The maximum settlement at point 7 reached 13 mm.

4. Conclusion
(1) The surface settlement around the shaft can be divided into two stages - the rapid settlement stage before floor construction and the stable settlement stage after floor construction. This indicates that the period of floor excavation is a critical period for settlement control and the timely floor construction is conducive to controlling the settlement. The surface settlement of the shaft at the midpoint of the long side was faster and greater than that at its corners and the midpoint of the short side, and first increased and then decreased with the increase of the distance from the pit, which conforms to the groove law. The maximum settlement occurred at (0.61~1) H_e behind the wall. Therefore, the part at the midpoint of the long side (0.61~1) H_e away from the pit is the key control position.

(2) The maximum lateral deformation of the underground diaphragm walls on the long side reached 17 mm, which occurred at the shaft depth of 35 m and under condition VI. That on the short side reached 10 mm, which occurred at the shaft depth of 25 m and under condition IV. The lateral deformation of the shaft at the midpoint of the long side was generally greater than that at the midpoint of the short side, and the position where the maximum deformation occurred was deeper. Therefore, they shall be treated differently in terms of the key control of lateral deformation. The deformation curve at the midpoint of the long side had an obvious point of inflection, and that at the midpoint of the short side presented a reciprocating type. The horizontal displacement of the top of the underground diaphragm wall ranged within 10 mm from -15 to -5 mm. The maximum horizontal displacement was 0.037% of the shaft depth, which is large and should be controlled intensively.

(3) In terms of vertical displacement, the top of the wall settled rapidly before the completion of floor excavation and the settlement gradually decreased after excavation. Moreover, the settlement increase rate was the highest when the excavation reached the bottom of the shaft. There were both uplifts and subsidence in the whole construction process.

Acknowledgments
National Natural Science Foundation of China (41672308, 51878554, 51378182); General Special Scientific Research Project of Shaanxi Provincial Department of Education( 20JK0748 ) Key projects of basic research program of natural science in Shaanxi Province(2018JZ5012 )

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