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Research Article

Analysis and Field Measurement on the Internal Force Variation Laws of Steel Pipe Columns in Subway Stations

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Steel pipe columns are an important component in subway station construction and with stand stress state and internal force during the construction process. Based on the engineering background of Beijing subway, this paper introduces the geological conditions, station structure types, and internal force monitoring of steel pipe columns of 10 subway stations constructed by the PBA method. The field monitoring indicates that the greatest change in the internal force of the steel pipe column occurs during stage 1 (beam, primary support, and secondary lining buckle arch construction stage), no matter pile foundation station or strip foundation station, which accounts for about 60% to 65% of the total axial force. When the left and right spans are not synchronously arched or excavated, the steel pipe column is subjected to uneven forces and bears a large bending moment is produced. When the depth of overburden is between 7 m and 15 m, the internal force of the steel pipe changes positively correlated with the overburden depth. During the construction process, the internal force of the steel pipe varies widely in the silty sand stratum. Also, the steel pipe columns in stations affected by groundwater bears about twice of the axial force compared with other stations are not affected by groundwater. In addition, the construction period is also a factor that affects changes in internal forces. This research is conducive to update the database of the world subway projects and can serve as a practical reference for similar geological condition.

1. Introduction

In recent years, with the increase of urban traffic pressure in China, rail transit has utilized urban underground space at an unprecedented rate, and the construction methods of subway stations are open excavation and concealed excavation, while the latter is divided into the new Austrian tunneling method, the shallow mining method, and the construction method that combine concealed excavation and cover excavation [1]. Shallow underground excavation is a construction method commonly used in the construction of urban subway stations, which can effectively reduce surface disturbance and settlement [2] and show the great adaptability in urban subway construction [3]. In 1986, the shallow mining method was first applied to the construction of the Fuxingmen Turnback Line of the Beijing Metro Fuba Line [4]. In 1990, Xidan Station of the Beijing Subway was the first subway station in China to use the shallow burying and undercutting method for construction [5, 6]. Currently, this method is divided into the side hole method, middle hole method, and hole pile (column) method (also called PBA method, i.e., pile-beam-arch method) based on the construction sequence [7]. The PBA method is a new flexible and versatile construction method based on traditional shallow mining method combined with the characteristics of the cover excavation method, which consists of a side pile, a middle column, and the combination of a longitudinal beam and top arch to form the initial force system. This method has been successfully applied in many metro stations in Beijing [8], Guangzhou, Shijiazhuang, and so on.

Some scholars have performed related work for the construction of subway stations. For example, Luo and Jiang [9] conducted a comprehensive analysis of the construction of the station constructed by the tunnel-pillar method according to the stratigraphic conditions in Beijing. The sedimentation in descending order is silt fine sand and medium coarse sand layer, silt, silty clay layer, and cobble to pebble layer. Liu et al. [10] used FLAC3D software to analyze the mechanical properties of a large-diameter shield tunnel in the process of building a subway station and its impact on surface settlement and concluded that pilot tunnel construction is the key to controlling the final surface settlement. Zheng [11] analyzed the ground settlement during the construction of a multispan subway station through the combination of numerical simulation and field measurement and concluded that ground reinforcement should be carried out before the excavation of the secondary lining buckle arch and small pilot tunnel arch. The arc-shaped excavation of the pilot pit should be selected, and the core soil should be reserved to minimize the surface settlement. Wang et al. [12, 13] analyzed the date from the three-dimensional finite element calculation model and field monitoring and found that the total settlement, deformation, and differential settlement of the pipeline-soil of the rigid joint pipeline are closely related to the relative position of the pipeline and the tunnel. Li et al. [14, 15] used software to establish a three-dimensional numerical model, analyzed the surface settlement caused by the excavation of the subway station, and found that the excavation of the pilot tunnel during the construction process was the main cause of surface settlement and can effectively control the surface settlement. Liu et al. [16] used ANSYS to simulate the entire construction phase of the PBA subway station, and the results show that when the soil under the station is excavated, the ground settlement can be effectively reduced under the protection of the secondary lining structure.

During the construction of the subway station, the main vertical bearing structure is the concrete-filled steel pipe column whose stress state is relatively small as well as the overburden of the exposed and cut-and-cut stations. The underground excavation PBA station inherits the characteristics of both cover excavation and conventional underground excavation stations. Due to the relatively thick soil and the construction sequence is complicated in such stations, the effect of other procedures on the force of the steel pipe column needs to be further studied. In subway projects that have been built and are under construction all over the country, small pilot tunnels have experienced large deformations after the completion of the construction. Whether the subsequent process will affect the stress of steel pipe column and then affect the safety of the entire station structure needs to be deeply studied. At present, most of the studies on the subway construction process focus on the surface settlement [17], but few studies involve the influence of the subway station construction sequence on the force of the steel pipe column. One of the most effective ways to reveal the changes in the internal force of the steel pipe column is to monitor it in real time and dynamically adjust the overall construction process [18–25]. This article introduces the engineering background of 10 Beijing subway stations constructed by the PBA method. Based on monitoring results, the internal force results of the pile foundation method and strip foundation method of the two types of subway stations are classified, and many influencing factors such as the impact of different structure types, the depth of the upper layer of the station, the stratum structure, the groundwater conditions, and the construction period on the steel pipe columns are systematically explained. The results provide a technical basis for similar station construction.

2. Introduction to the PBA Construction Method and Project Monitoring Plan

2.1. Introduction to PBA Method. The PBA method, i.e., the pile-beam-arch method, is a supporting frame system composed of side piles, steel pipe columns, top (bottom) longitudinal beams, and top arches, which jointly bear the load during construction. Based on shallow buried excavation method, combined with the characteristics of cover excavation method. The method requires to excavate smaller pilot holes to reduce the height and span of one-time excavation and then reuse mechanical and artificial construction of side piles, middle columns, and arches to form a permanent vertical support system to withstand vertical soil loads. Therefore, under the overall support system composed of sidewall support structure and vault support, the soil under the arch roofs is excavated in full section. Its core idea is to divide the excavated large section into several small sections and excavate under the support of each small section for security and thus finally form a large section.

2.2. Subway Stations Constructed by PBA. According to the different types of bearing structures at the bottom of subway stations, the PBA approach can be divided into the pile foundation PBA approach (Figure 1(a)) and strip foundation PBA approach (Figure 1(b)), as shown Figure 1.

The specific construction process (shown in Table 1) mainly includes the following steps:

(a) Excavation of upper (lower) pilot tunnel and shotcrete to form a temporary support structure

(b) Excavation by hand, construction of piles and columns (the strip foundation station needs to cast the bottom longitudinal beam in the lower guide hole first)

(c) Casting crown beam and longitudinal beam

(d) Excavation the upper soil between the pillars and the initial arch construction

(e) Construction of the secondary lining structure after the initial support reaches the design strength

(f) Construction of the middle plate and side wall after soil excavation of the station hall layer

(g) Construction of the bottom plate and side wall after soil excavation of station platform layer

In terms of the double-layer three-span station, whether the pile foundation method or the strip foundation method is employed, the stress stage of the steel pipe column during the construction process is divided into the following three stages: the stage of beam, primary support, and second lining buckle arch construction (Table 1 (c–e)); the stage of station hall layer soil excavation and mid-slab construction

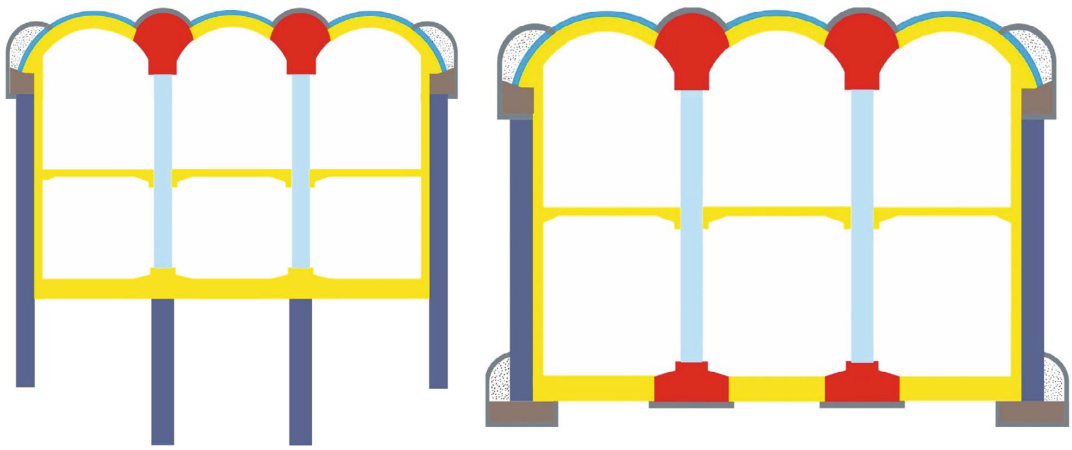


Figure 1: Standard cross section of the underground excavation station obtained by PBA approach: (a) pile foundation station and (b) strip foundation station.

(Table 1 (f)); and the stage of platform layer soil excavation and floor construction (Table 1 (g)).

2.3. Monitoring Scheme. To monitor the stress of the steel pipe column during the construction process in real time, a group of vibrating string strain gauges include 4 gauges. It set up approximately 0.5 m under the bottom of the longitudinal beam at the top of the steel pipe column, approximately 0.5 m under the bottom of the middle longitudinal beam, and approximately 0.5 m above the top of the bottom longitudinal beam and at the middle position of the steel pipe column on each floor of the station. Each group is evenly arranged at 90° intervals on the steel pipe columns along the longitudinal and transverse directions of the station. Each steel pipe column is arranged with 5 monitoring sections. The measuring point arrangement of the double-deck and three-span stations is shown in Figure 2.

To prevent the sensor and cable from being damaged during the construction process, protective shell and hose are installed on the surface. During installation, the sensor wire is tied in a knot, and a certain amount of redundancy is maintained. The opening of the protective shell is prepared, and the sensor wire is gently pulled to ensure that the wire knot is stuck inside the reserved hole during the pulling process, as shown in Figure 3.

The conditions of the 10 subway stations constructed using the PBA method are shown in Table 2. Among the PBA stations under construction as shown in Figure 4, most are double-deck-triple-arch stations (Figure 4(2) and (3) and Figure 5(2) ~ (5)), some are flat-topped double-deck-triple-arch stations (Figure 4(1)), and a small number of them are three-deck-triple-arch stations (Figure 4(4) and (5)). The average width is approximately 24.1 m, and the average height is approximately 17.62 m. The thickness of the overlying soil on the station is between 7.0 m and 15.0 m. Most of station is located in silty sand and gravel cobble stratum, and some are located in the silty clay layer. The structural forms, geological conditions, and installation of the measuring points of each station are shown in Figures 4 and 5.

3. Stress Characteristics of the Steel Pipe String during Construction

Through calculation and analysis of the on-site monitoring data, the stress conditions of the steel pipe column during the construction by the pile foundation method and the strip foundation method are systematically introduced, respectively.

3.1. Internal Force Calculation Method. The temperature and frequency monitored on site are converted into strain values through formula conversion, and the corresponding axial force and bending moment are obtained through calculation. The basic analysis and calculation ideas are summarized as follows.

When the internal force of the concrete-filled steel pipe column is calculated, the combined modulus method is used to calculate the axial compression stiffness of the concrete-filled steel pipe member, and the section stiffness is calculated according to the following formulas:

$$EA = E_s A_s + E_c A_c, \tag{1}$$

$$EI = E_s I_s + E_c I_c, \tag{2}$$

where EA denotes the equivalent axial compression stiffness of the concrete-filled steel pipe column, EI denotes the equivalent bending stiffness of the concrete-filled steel pipe column, E_s denotes the elastic modulus of the steel pipe column, E_c denotes the elastic modulus of the concrete, I_s denotes the section intersection moment of the steel pipe column, and I_c denotes the section intersection moment of the concrete.

The average strain of the four sensors in the monitoring section of the steel pipe column is shown in Figure 6. In order to record the data more accurately, we stipulated that the north direction of the sensor is no. 1, and the numbers are 2, 3, and 4 in the clockwise direction. The numbers in the figure represent the four positions on the steel pipe

Table 1: Construction sequence of the PBA method.

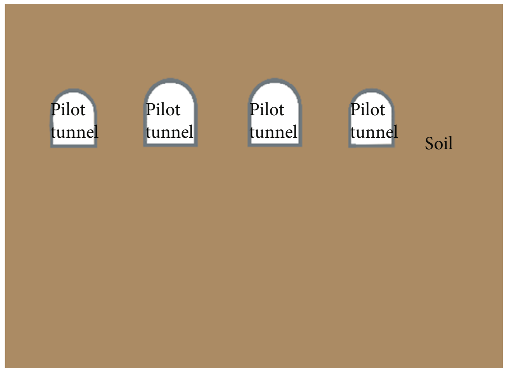
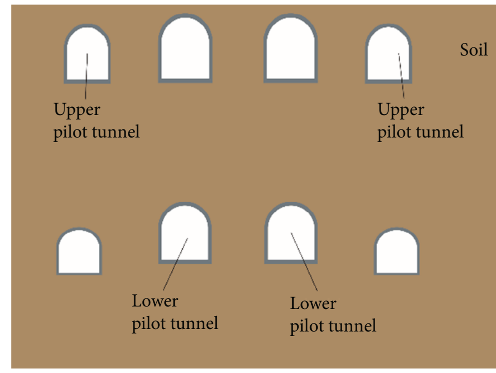
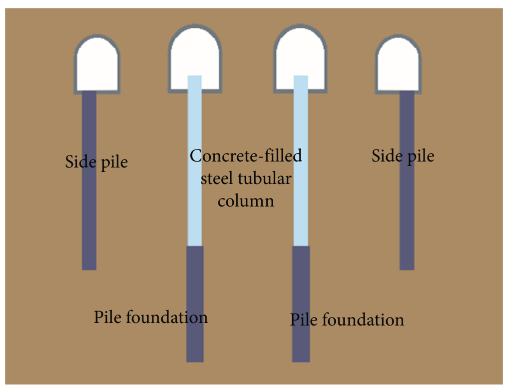
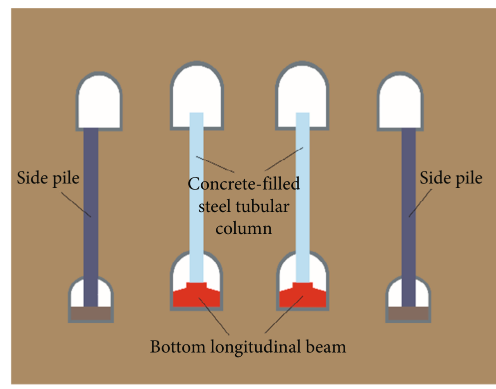
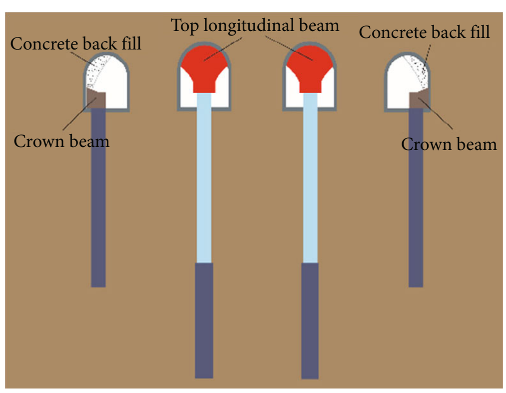
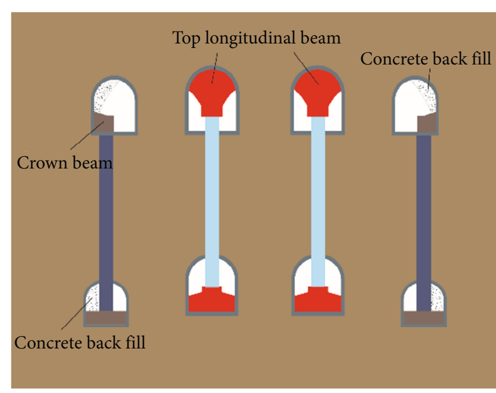
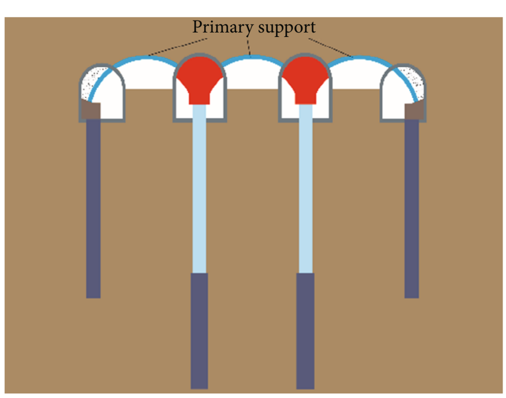
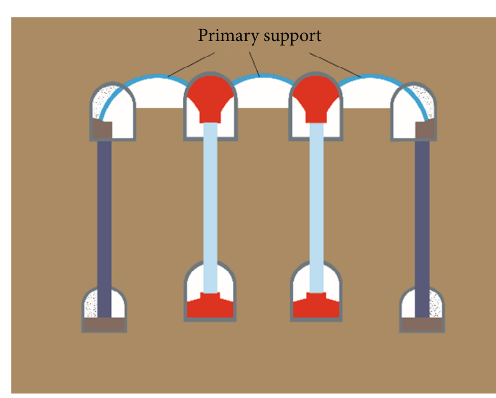
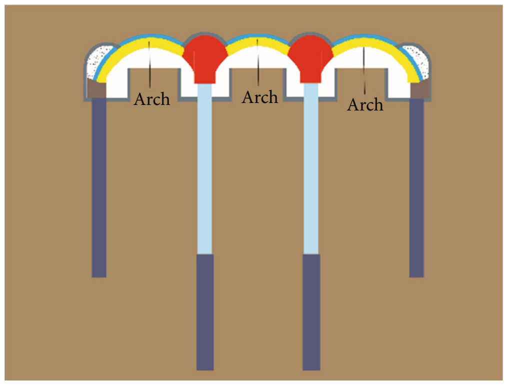
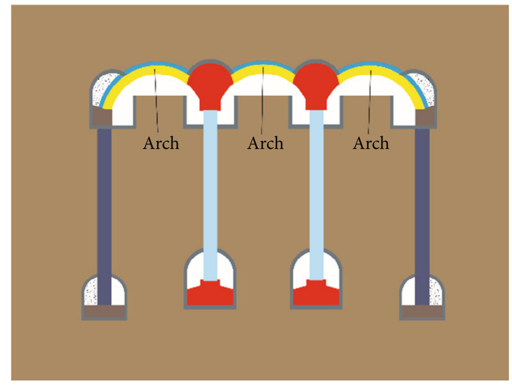
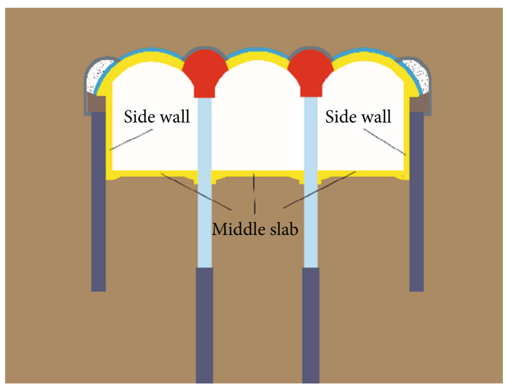
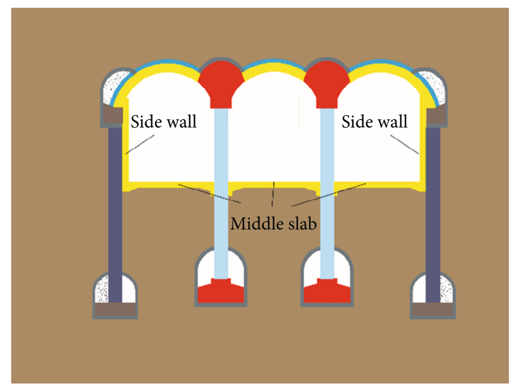
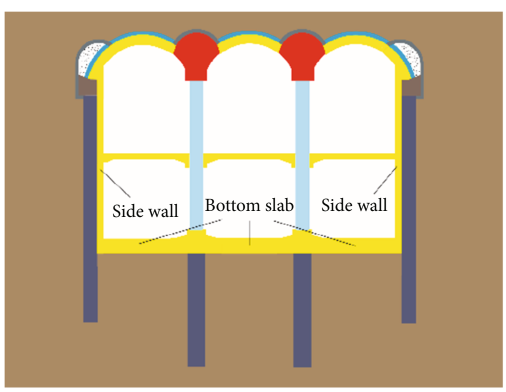
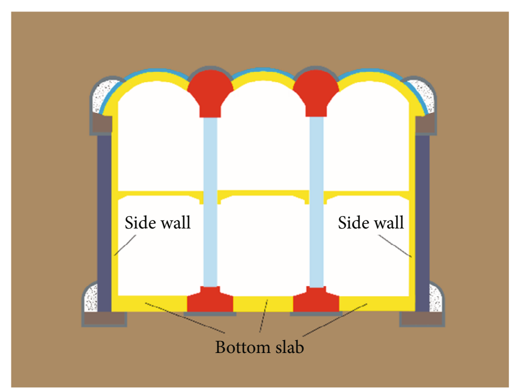
Construction stage	Pile foundation station	Strip foundation station
(a)		
(b)		
(c)		
(d)		

Table 1: Continued.

Construction stage	Pile foundation station	Strip foundation station
(e)		
(f)		
(g)		

column, namely, north, east, south, and west. The axial force based on the stiffness is calculated as follows:

$$\bar{\varepsilon} = \frac{\varepsilon_1 + \varepsilon_2 + \varepsilon_3 + \varepsilon_4}{4}, \tag{3}$$

$$F = EA\bar{\varepsilon}, \tag{4}$$

where ε_1, ε_2, ε_3, and ε_4 denote the strain monitoring values of the concrete-filled steel pipe column in different positions; $\bar{\varepsilon}$ denotes the average axial strain.

When the bending moment of a single steel pipe column is calculated, the four sensors of the monitoring section (shown in Figure 7) are divided into two groups of sensors perpendicular to each other, and the average strains in the two vertical directions and the bending moment can be calculated in Eqs. (5) and (6) as below. The requirements for the signs of the bending moment are as follows: the bending moment of 01 under tension and 03 under compression is positive. The bending moments of 02 under tension and 04 under compression are positive (the specific positions of 01, 02, 03, and 04 are shown in Figure 2(d)), and the bending moments are all negative under other conditions.

$$\begin{cases} \bar{\varepsilon}_{13} = \dfrac{\varepsilon_1 - \varepsilon_3}{2}, \\ \bar{\varepsilon}_{24} = \dfrac{\varepsilon_2 - \varepsilon_4}{2}, \end{cases} \tag{5}$$

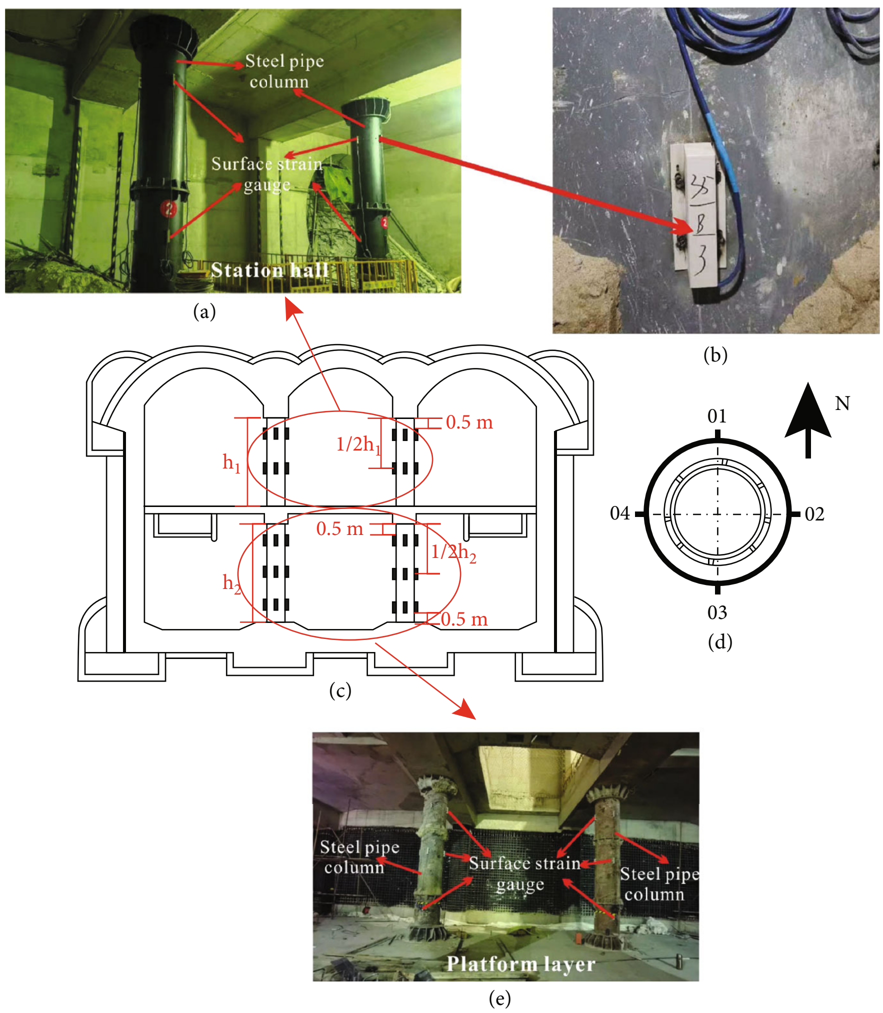


Figure 2: Schematic diagram of the installation of the measuring points: (a) surface strain gauge installation in station hall, (b) surface strain gauge, (c) position and layout of measuring points in whole cross section, (d) layout of the four surfaces strain gauge, and (e) surface strain gauge installation in platform layer.

$$\begin{cases} M_{13} = \dfrac{2EI\varepsilon_{13}}{D}, \\ M_{24} = \dfrac{2EI\varepsilon_{24}}{D}, \end{cases} \quad (6)$$

where ε_{13} denotes the average strain difference in $01 - >03$ directions; ε_{24} denotes the average strain difference in $02 - >04$ directions; D denotes the outer diameter of the concrete-filled steel pipe column (mm).

3.2. Pile Foundation Stations. For the five stations constructed by the hole pile method, the average axial forces during the three construction stages are shown in Figure 8. Among them, the construction of station P3 has not yet been completed. When the measuring points of stations P4 and P5 are installed, the beam, initial support, second lining buckle arch, soil excavation of the station hall layer, and construction of the middle slab were completed. The changes in the internal force of the steel pipe column were not captured. Among the three construction phases, the increase in the axial force mainly occurs in the first and second phases. The average increase in the axial force increment in the phase of beam, initial support, and second lining buckle arch is mainly concentrated in the range of 8000 to 9000 kN. The average axial force increment during the excavation and midslab construction of the station hall layer is mainly in the range of 1500 to 3000 kN. The average axial force increment during the excavation and floor construction of the platform layer is mainly in the range of 1000 to 3000 kN. The proportion of axial force increment in each construction stage is shown in Figure 9. The change in the internal force of the steel pipe column mainly occurs in the first construction stage, which accounts for approximately 65% of the total. The axial force increment of the steel pipe column in each construction stage is shown in Table 3.

3.3. Strip Foundation Station. For the four stations constructed by the strip foundation, the axial forces during the three construction stages are shown in Figure 10. Among them, the construction of stations S3 and S4 has not yet been completed, and the beams, initial support, and second lining buckle arch have been completed when the measuring points

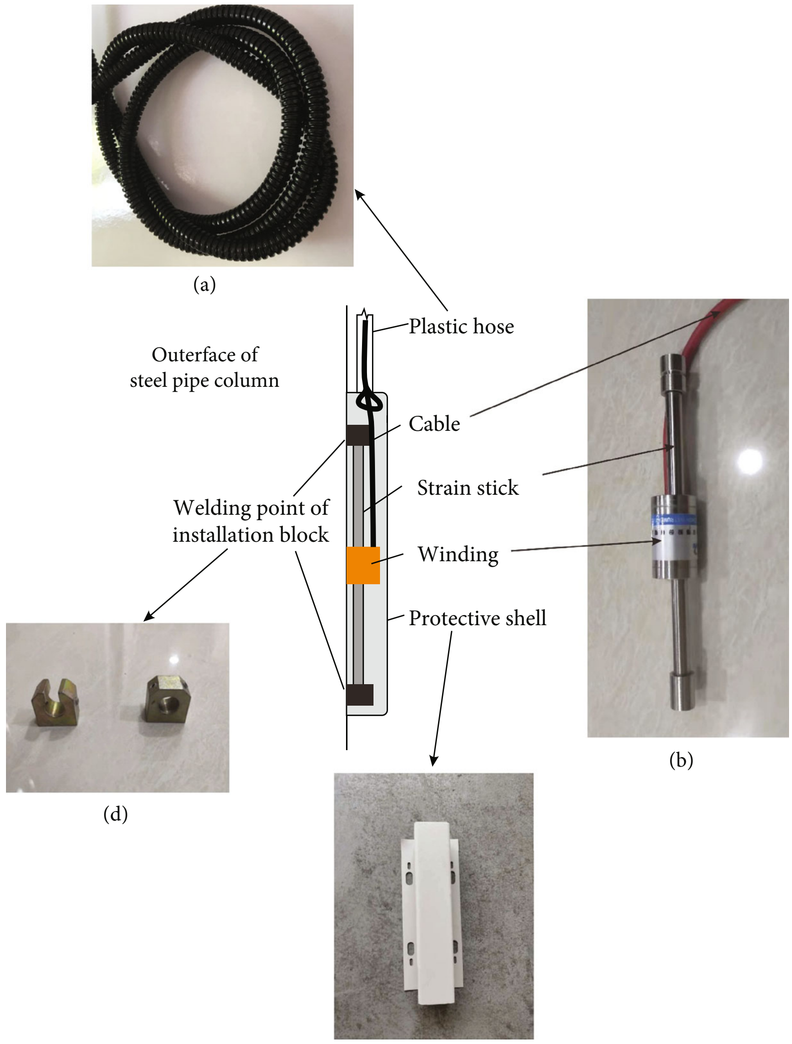


Figure 3: Strain gauge installation schematic diagram: (a) plastic hose, (b) surface strain gauge, (c) protective shell, and (d) installation block.

of station S2 installed. When the measuring points of station S5 were installed, the beam, primary support, second lining buckle arch, soil excavation of platform layer, and medium plate application had been completed. Therefore, the complete internal force change of the steel pipe column cannot be monitored. In the three construction phases, the increase in the axial force is mainly in the first and third phases. The average increase in the axial force increment in the beam, initial support, and second lining buckle arch phase is mainly concentrated in the range of 9000 to 10000 kN. The average axial force increment during the excavation and midslab construction of the station hall layer is mainly in the range of 1000 to 3000 kN. The average increase in the axial force in the soil excavation and floor construction of the platform layer is mainly in the range of 2500 to 5000 kN. The proportion of axial force increment of each construction stage is shown in Figure 11. The change in the internal force of the steel pipe column mainly occurs during the first construction stage. The axial force increment of the steel pipe column is approximately 60% of the total, and the axial force increment of the steel pipe column in each construction stage is shown in Table 4.

3.4. Comparison of the Pile Foundation and Strip Foundation Stations. The average value of the axial force of the steel pipe column during each construction stage of the pile foundation and strip foundation station is shown in Figure 12. When the strip foundation station is constructed in the first stage, the average value of the axial force increment of the steel pipe column (9299 kN) is much larger than that of the second (2540 kN) and third stages (3879 kN). Compared with the pile foundation station, when the strip foundation station is constructed at the platform level, the small pilot hole in the lower layer needs to be broken, which causes the change in the internal force of the steel pipe column. Therefore, the average value of the axial force increment of the steel pipe column of the pile foundation station in the third stage (2324 kN) is much smaller than that of the third stage (3879 kN) of the strip foundation station. The average value of the axial force increment in the third construction

Table 2: Information of the subway stations.

Station ID	Station	Metro line	Construction method	Overburden depth (m)	Main soil type	Station size (m)
P1	Youanmen Station	19	Pile foundation station	7.20	Silty sand and gravel cobble	22.6*17.29
P2	Jinrongjie Station	19	Pile foundation station	11.90	Silty sand and gravel cobble	23.5*16.87
P3	Beitaipingzhuang Station	12	Pile foundation station	13.70	Silty sand, silty clay, and gravel cobble	23.5*16.67
P4	Beitaipingzhuang Station	19	Pile foundation station	14.64	Silty, silty sand, silty clay, and gravel cobble	23.5*23.97
P5	Niujie Station	19	Pile foundation station	9.60	Silty, silty sand, gravel cobble	23.3*23.49
S1	Xiangheyuan Station	17	Strip foundation station	7.85	Silty clay and silty sand	21.4*19.27
S2	Shilihe Station	17	Strip foundation station	12.20	Silty clay and silty sand,	25.5*15.6
S3	Dongdaqiao Station	17	Strip foundation station	15.18	Silty clay, silty sand, and gravel cobble	24.5*19.57
S4	Guangqumen Station	17	Strip foundation station	10.80	Silty clay and silty sand	26.20*16.42
S5	Mudanyuan Station	19	Strip foundation station	12.00	Silty, silty clay, silty sand, and gravel cobble	24.5*16.8

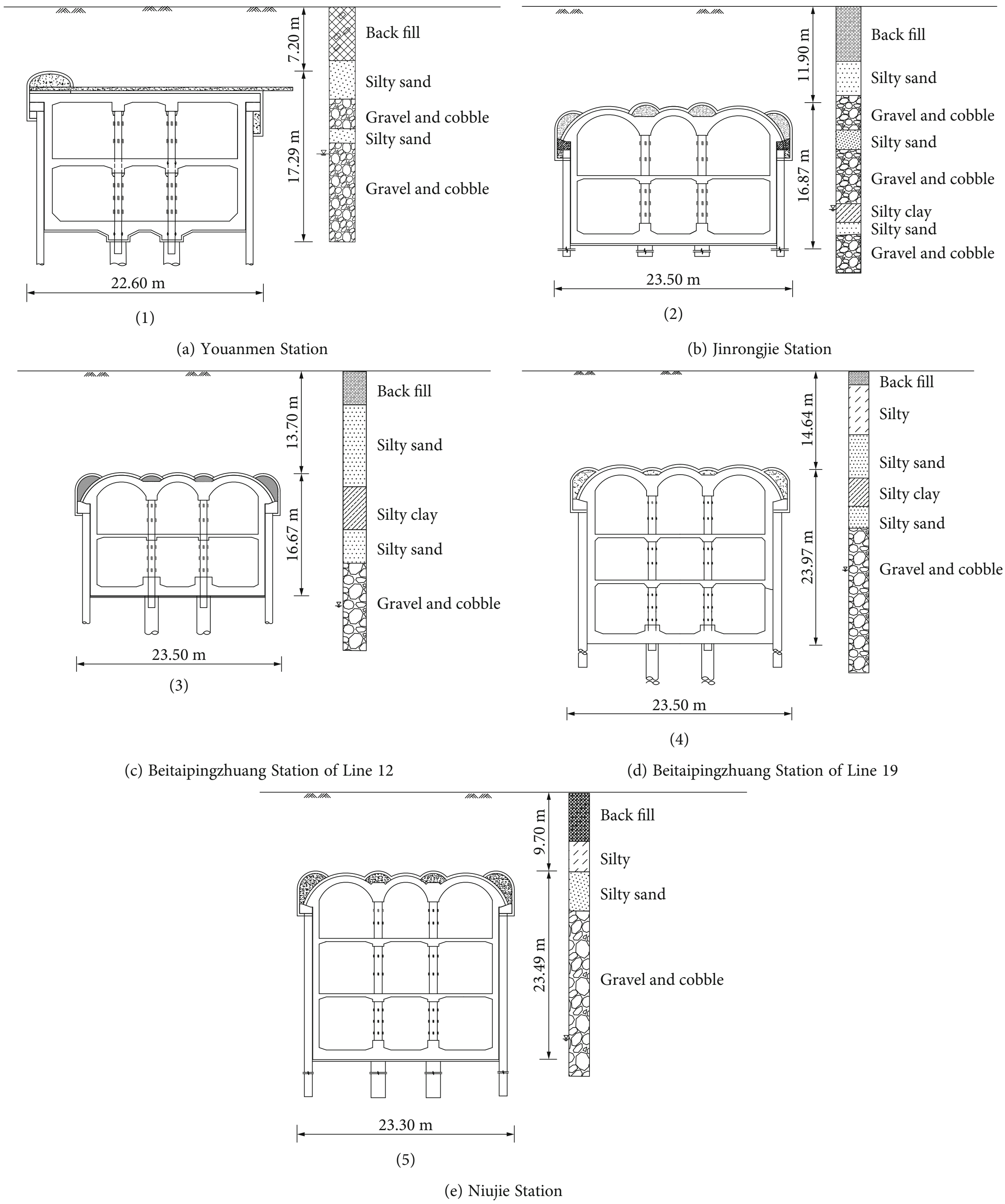


Figure 4: Cross sections of the pile foundation stations of the Beijing Subway.

stage of the strip foundation station is approximately 1.7 times that of the pile foundation station. The average total axial force of the strip foundation station is 15718 kN, which is approximately 1.2 times that of the pile foundation station (13210 kN). During the construction process, the force of the steel pipe column of the strip foundation station is more complicated than that of the pile foundation station.

The main stage of the change in the internal force of the steel pipe column caused by the PBA method occurs in the first stage, which accounts for more than 60% of the average

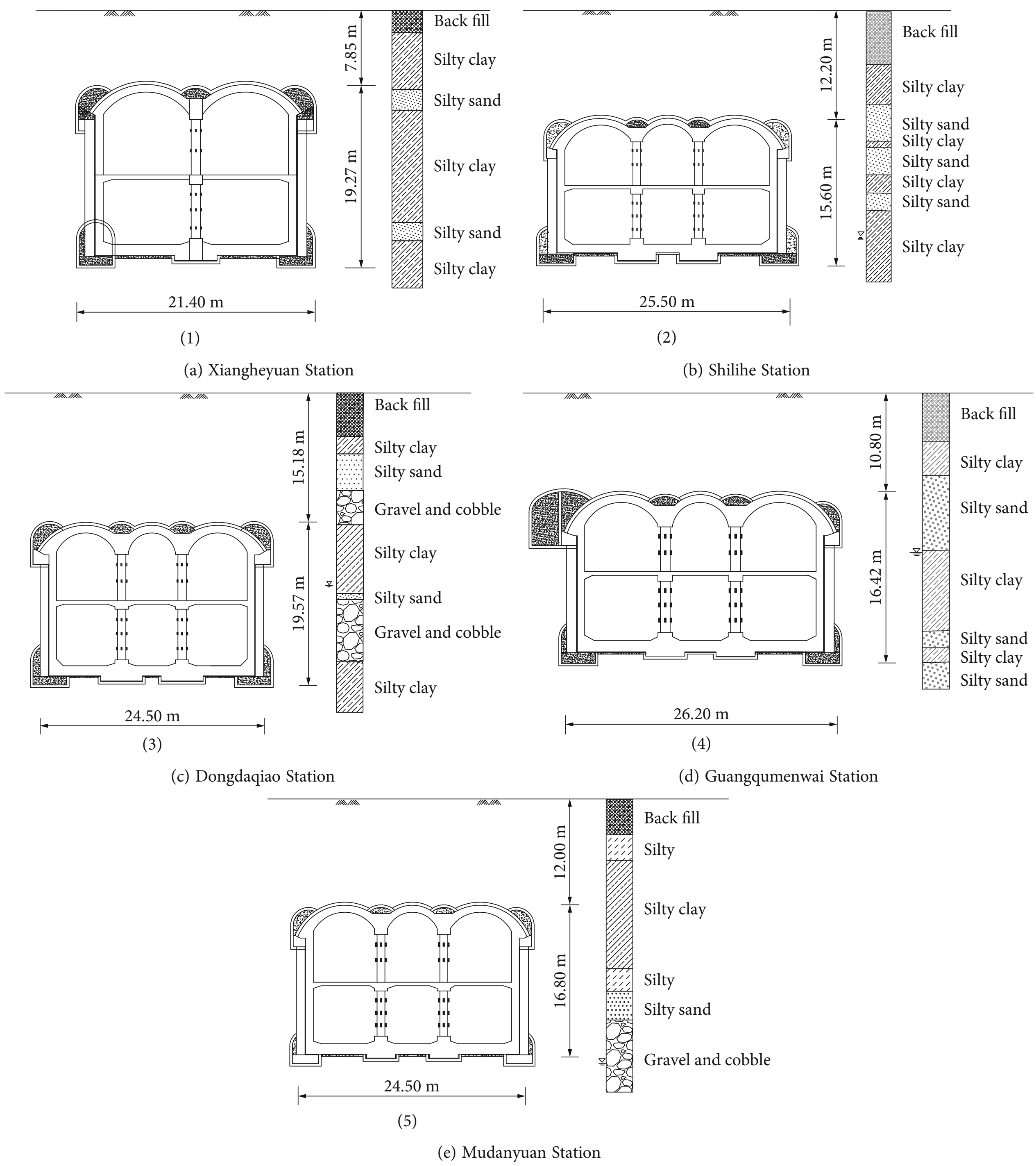


Figure 5: Cross sections of the strip foundation stations of the Beijing Subway.

total axial force is shown in Figure 13. After the second lining buckle arch is completed, the station forms a relatively complete pile-beam-arch system. Theoretically, under the support of the secondary lining structure, the internal force of the steel pipe column will not change significantly. However, in the actual monitoring process, it is found that the internal force of the steel pipe column also undergoes major changes during the earth excavation stage. Before excavating, the soil is both external load and bearing structure, which can bear part of the load. With the soil excavation in the station, the original ground stress balance is broken, and the stress is redistributed, thereby causing the change of external force exerted on the steel pipe column.

3.5. Forces of Steel Pipe Columns in Different Construction Stages. After the second lining buckle arch is completed, the station has formed a relatively complete pile-beam arch system. Theoretically, under the support of the second lining

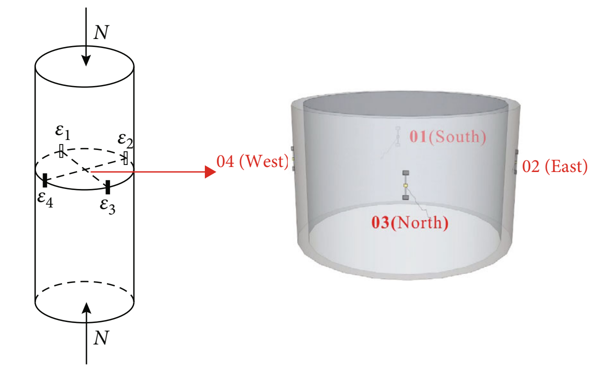


Figure 6: Schematic diagram of the axial force calculation.

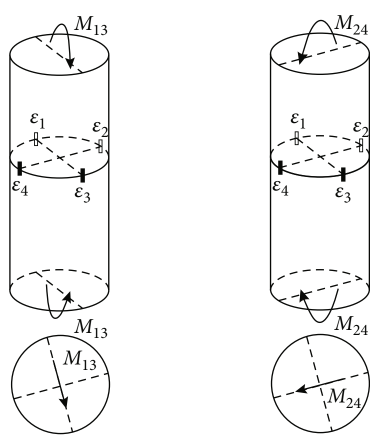


Figure 7: Schematic diagram of the bending moment.

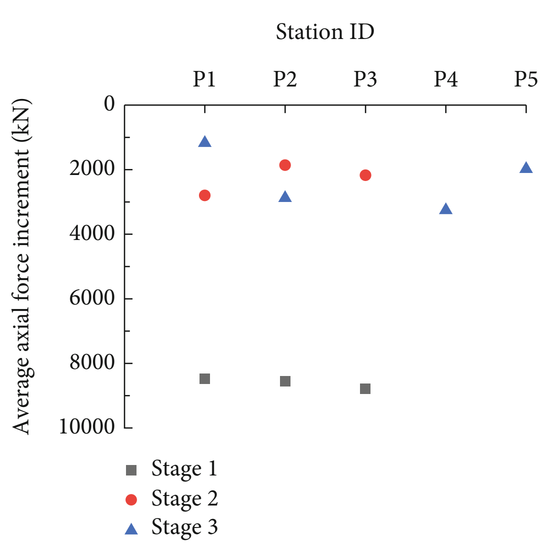


Figure 8: Axial force increment of steel pipe columns in three construction stages of the pile foundation station.

structure, the internal force of the steel pipe column will not change significantly. After a large amount of monitoring data is analyzed, the axial force of the steel pipe column changes significantly during the soil excavation stage. By analyzing the internal forces of the two steel pipe columns

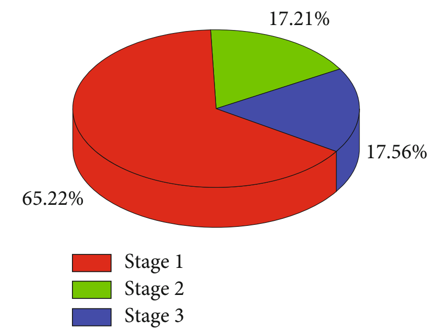


Figure 9: Axial force increment proportion in different construction stages of the pile foundation station.

at the same monitoring section of the Jinrongjie Station during the construction process, the axial force and bending moment of the two steel pipe columns are significantly different. This is because when the side span buckles, the left and right spans of the arch are not buckled at the same time, thereby resulting in unbalanced forces on the two steel pipe columns of the same section. The structural load-bearing system changes, as shown in Figure 14.

It can be seen from Figure 15 that during the entire construction process, the axial force and bending moment of the steel pipe column showed an increasing trend. In the first construction stage, with the initial support of the pilot tunnel broken, the steel pipe column became a vertical load. The top arch completed by the construction transfers the upper load to the steel tube column. At this stage, the axial force has increased by 8554 kN on average. With the excavation of the soil, the soil around the steel pipe columns and side piles is missing. The soil that originally shared part of the load is suddenly missing, which redistributes the soil stress around the station and causes the change of internal force of the steel pipe columns. After the floor construction is completed, the station has formed a complete supporting frame system of piles, beams, and arches, and the axial force of the steel pipe columns no longer changes significantly, as shown in Figure 15(a).

Since the secondary lining buckle arch is a segmental buckle arch, the secondary lining buckle arch of the middle is carried out first (Figure 13(1)), so that the force of the steel pipe column is unbalanced and the eccentric force is generated. In construction stage 1, the average bending moment in the 1,3 directions and 2,4 directions is 176 kN·m and 285 kN·m, respectively. At the same time in the soil excavation stage, failed to do a symmetrical excavation of soil, making the left and right spans asymmetrical, resulting in eccentric force, and causing a large bending moment. After the construction of the bottom plate is completed, the steel pipe column is restrained to a certain constraint and caused the eccentric force gradually reduced, making the bending moment gradually decrease and tend to be stable. In the whole construction stage, the maximum bending moment in the 1,3 directions and 2,4 directions is 222 kN·m (Figure 15(b)) and 335 kN·m (Figure 15(c)), respectively.

The analysis of field monitoring data indicates that the two side spans should buckle synchronously during the

Table 3: Axial forces increment of steel pipe columns in different construction stages of the pile foundation stations (unit: kN).

Station ID	Station	Axial force increment of the steel pipe columns				
		Stage 1	Stage 2	Stage 3	Total	Remark
P1	Youanmen Station	8482	2797	1177	12456	——
P2	Jinrongjie Station	8554	1862	2881	13297	——
P3	Beitaipingzhuang Station of line 12	8792	2173	—	10465	Stage 3 has not yet begun
P4	Beitaipingzhuang Station of line 19	—	—	3257	6414	Construction in stages 1 and 2 has been completed when the measuring points installed
P5	Niujie Station	—	—	1982	1982	Construction in stages 1 and 2 has been completed when the measuring points installed

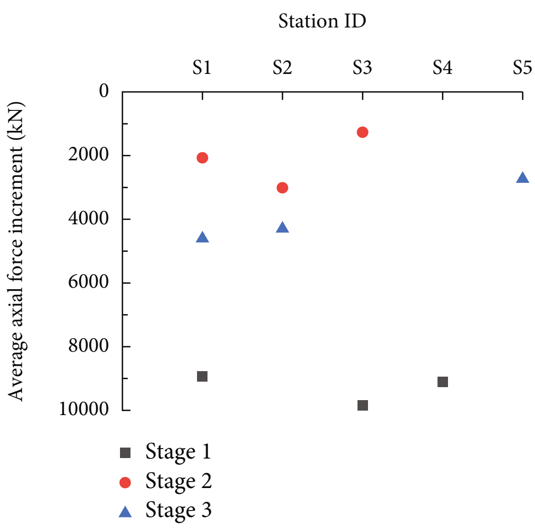


Figure 10: Axial force increment in three construction stages of strip foundation stations.

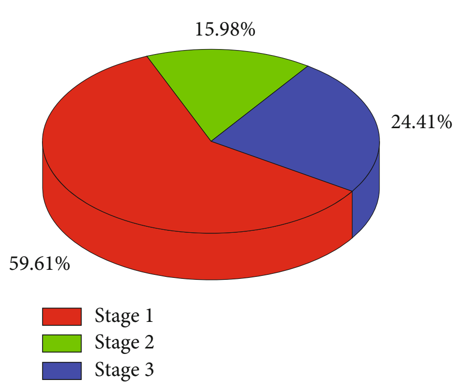


Figure 11: Axial forces increment proportion in different construction stages of the strip foundation stations.

second lining buckle arch. In the soil excavation stage, simultaneous excavation of the side spans is attempted to reduce the occurrence of large excavation steps at one time. The construction of the middle slab and the bottom slab can be performed timely, which can effectively improve the stability of the station structure.

4. Effects of Different Factors on the Variation in the Axial Force of the Steel Pipe Columns

During the construction of a subway station, many influencing factors such as the depth of the upper layer of the station, soil conditions, groundwater, and the construction period all have a certain impact on the internal force of the steel pipe column during the construction process.

4.1. Overburden Depth. The axial force of each construction stage is shown in Figure 16. The monitoring results indicate that the axial force of the steel pipe column increases with the increase of the cover depth during the second lining buckle arch stage. When the overburdened depth is between 7 and 15 m, regardless of the excavation of the station hall layer or platform layer, as the covering depth increases, the axial force of the steel pipe column tends to increase during the construction process. The soil content of the upper layer of the station increases with the overburdened depth, and the load imposed on the top of the station also increases, thereby causing the internal force of the steel pipe column to increase. When the overburden soil on the upper layer of the station reaches a certain depth or the second lining buckle arch is completed, and when the soil at the top of the station reaches a certain strength and rigidity, stable closed-loop load bearing is formed from arches, beams, and columns. The lower structure of the station during construction will not be greatly impacted by the change in the cover depth.

4.2. Soil Condition. Theoretically, during the construction of the subway station, the internal force of the steel pipe column will not change significantly after the second lining buckle arch is completed. However, in the actual monitoring process, the internal force of the steel pipe column undergoes obvious changes during the soil excavation stage. Also, the soil of the Beijing subway is generally not homogeneous but distributed in layers. The typical soil of the cross section of the station is mainly silty sand, silty clay, or gravel and cobbles. Under different soil conditions, the boxplots of the axial force increment generated by the steel pipe column in the soil excavation stage are shown in Figure 17. The five horizontal lines represent the maximum, upper quartile, median, lower quartile, and minimum axial forces in the soil

Table 4: Axial forces increment in different construction stages of the strip foundation stations (unit: kN).

Station ID	Station	Axial force increment of the steel pipe columns Stage 1	Stage 2	Stage 3	Total	Remark
S1	Xiangheyuan Station	8943	2069	4606	15618	
S2	Shilihe Station	—	3010	4298	7308	Stage 1 construction has been completed when the measuring points installed
S3	Dongdaqiao Station	9843	1268	—	11108	Proceeds to stage 2 but did not implement the midplate
S4	Guangqumen Station	9110	—	—	9110	Stages 2 and 3 have not yet been reached
S5	Mudanyuan Station	—	—	2736	2736	Construction in stages 1 and 2 has been completed when the measuring points installed

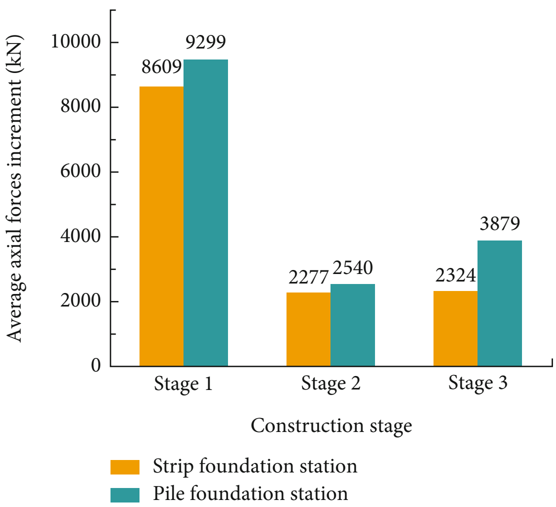


Figure 12: Comparison of the average axial forces increment of steel pipe columns of two types of subway stations in different construction stages.

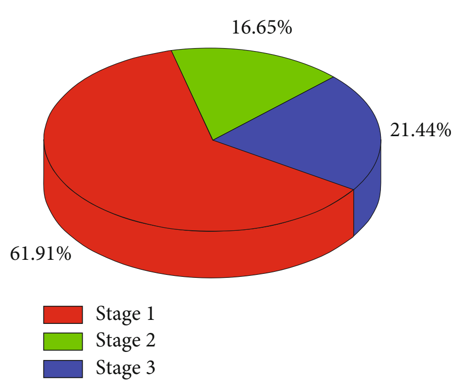


Figure 13: Proportion of axial force increment in each construction stage.

excavation stage. In the soil excavation stage, the average axial force increment of the steel pipe column in the silty sand was 1926 kN, which was the largest change in the axial force of the three soil layers. In the silty clay layer, the average axial force of the steel pipe column was 1803 kN, which was approximately 1.25 times that of the gravel and cobble. In addition, the distribution range of the axial force in the silty clay is relatively large, indicating that the variance in the axial force in the silty clay formation is also the largest among the three soil layers.

During the excavation stage, the axial force of the steel pipe column in the silty sand is relatively large because the silt fine sand has low cohesion and poor physical properties. The silty sand appears to be loose during the construction process and has poor stability. During excavation, the silty sand easily collapses due to the influence of external forces. The original wrapped state around the steel pipe column is suddenly destroyed. Part of the load originally shared by the soil will gradually be borne by the steel pipe column as the soil is excavated. The distribution range of the axial force in the silty clay is relatively large due to the reduction of the cohesive force and internal friction angle of the soil with abundant groundwater, as well as the shear strength. When disturbed, prone to cracks, and collapse, although the change in the axial force is relatively small in the gravel and cobble layer, such layer is relatively unstable and tends to collapse during the excavation process [26].

4.3. Groundwater Impact. The bottom plate of Beitaipingzhuang Station of Line 19 is located in gravel and cobble with abundant groundwater. During the construction period, dewatering construction was carried out. However, after bottom plate construction is completed, the station reduces the use of pumping equipment, which makes the internal force of the steel pipe column larger. The change in the curve of the average axial force of the station during the construction period is shown in Figure 18. From the start of monitoring to the completion of the main structure, the total axial force of the steel pipe column was 3257 kN. However, after the construction of the bottom plate was completed, the internal force of the steel pipe column increased significantly to 6414 kN. As the water level increased, the internal force of the steel pipe column gradually decreased.

The floor of the station is located in pebble cobbled stratum, with remarkable water permeability. Changes in the groundwater level can cause the increase in the pone water and decrease in the effective stress and cohesion, which may reduce the soil stability and increase the risks in the construction process. The pressure difference caused by the water head difference between the upstream and downstream of the subway line will cause the pressure around the station and the unstable structure of the overall station.

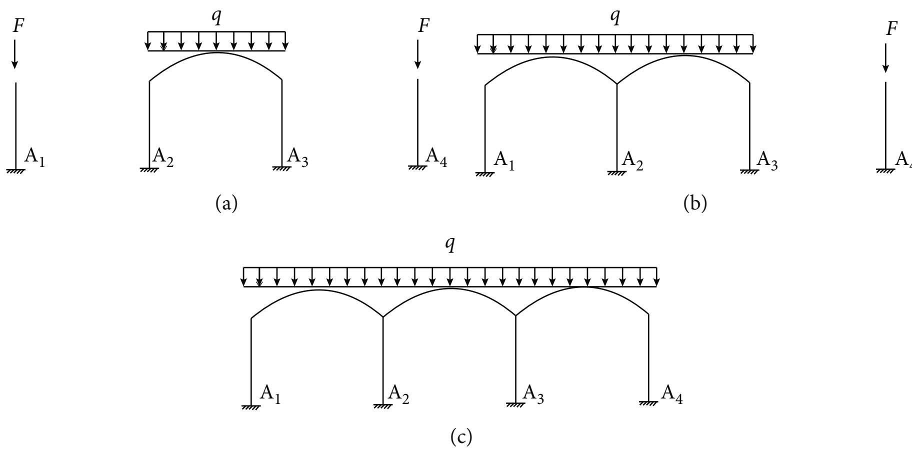


FIGURE 14: Changes in the force of the structural load-bearing system. (a) Middle arch of the secondary lining buckle. (b) Left arch of the secondary lining buckle. (c) Right arch of the secondary lining buckle.

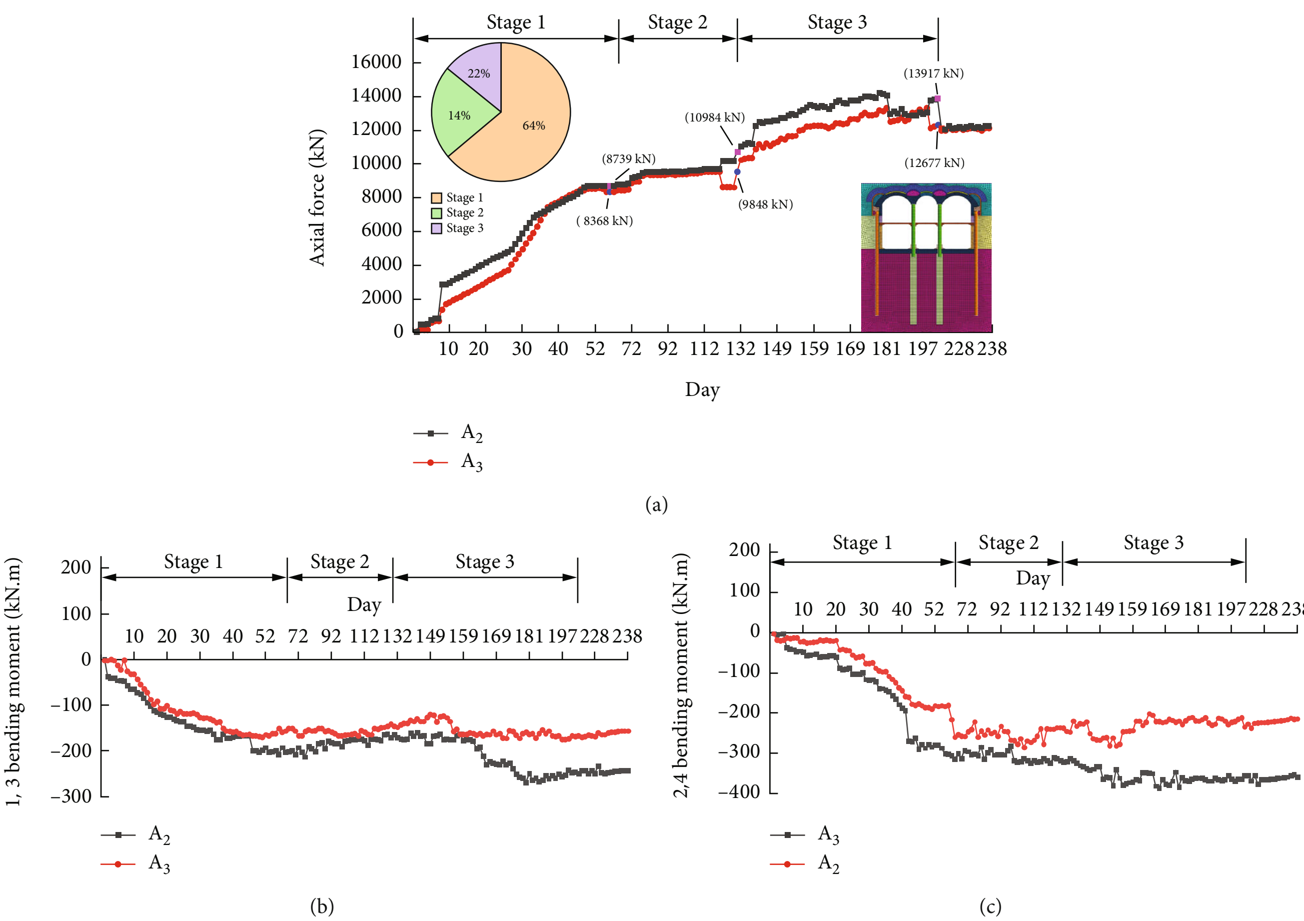


FIGURE 15: Internal change of the steel pipe column in the construction process of the Jinrongjie Station. (a) Axial force change during the construction. (b) Bending moment change in 1,3 directions during the construction. (c) Bending moment change in 2,4 directions during the construction.

Also, the rise in groundwater level induces the increase of the internal force of the bottom plate and the external force in the steel pipe column, while the upper part of the station is more stable and can be regarded as a fixed end. The bottom of the steel pipe column experiences an upward thrust, which causes the steel pipe column compressed so that the internal force increases. Therefore, precipitation construction is usually adopted during the construction period.

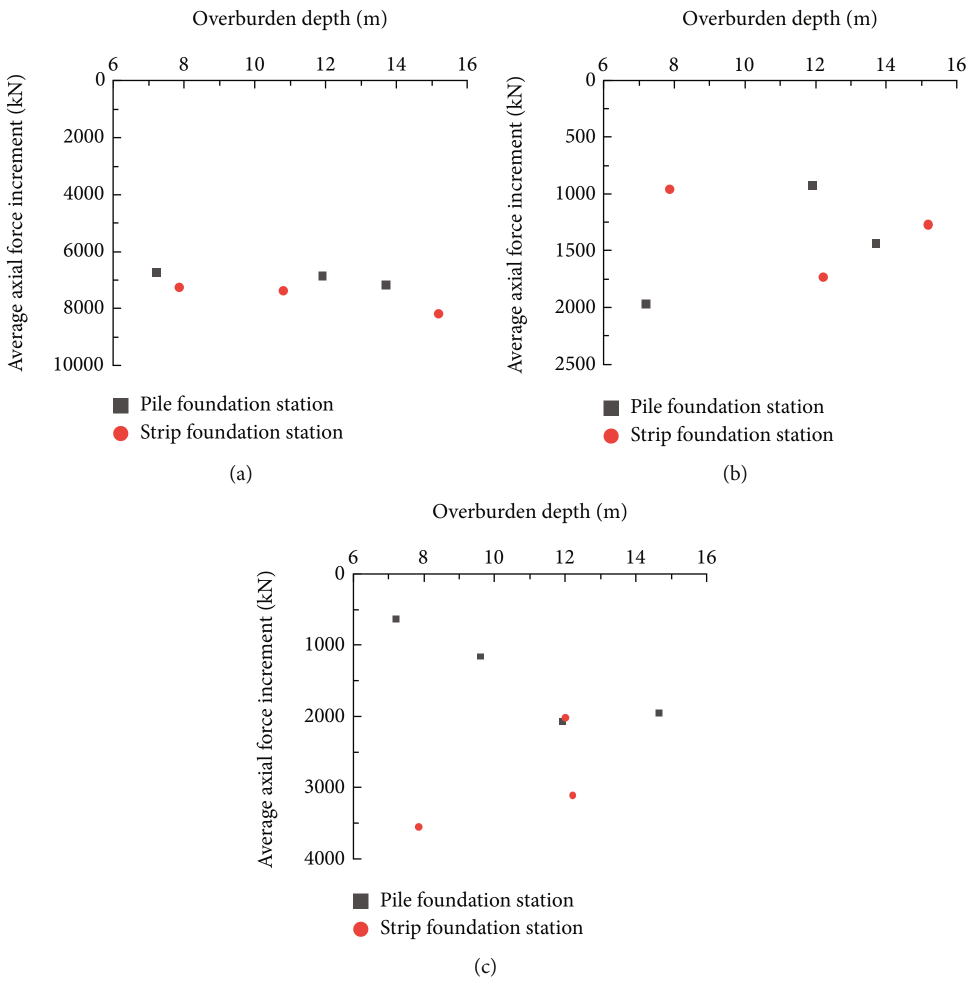


FIGURE 16: Statistics of the axial force of the steel pipe column in each construction stage: (a) buckle arch stage of the second lining buckle, (b) soil excavation of the station hall, and (c) soil excavation stage of the platform layer.

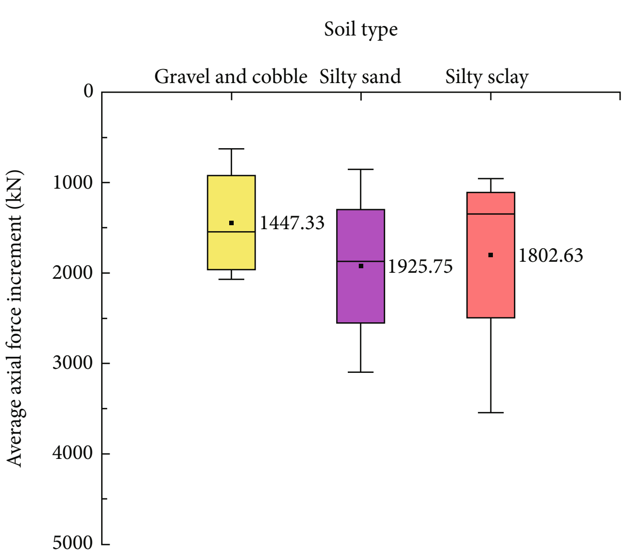


FIGURE 17: Axial force increment boxplots of the steel pipe column in the soil excavation stage.

4.4. Construction Period. Taking the measured data of two types of subway stations as examples, the influence of the construction period on the internal force of the steel pipe column is studied. The pile foundation stations are selected from the Jinrongjie Station and Youanmenwai Station (Figure 4(1) and (2)), and the strip foundation stations are selected from Shilihe Station and Mudanyuan Station (Figure 5(2) and (5)). The station structure is the same, with a similar stratum structure, but in the same construction stage and different construction periods, the internal force of the steel pipe column is quite different. The change in the axial force with time during the construction of the two types of stations is shown in Figures 19 and 20.

The excavation stage of the soil caused the release and redistribution of the ground stress and finally the change in the internal force of the steel pipe column. The length of the excavation time has a great impact on the force of the steel pipe column. The Jinrongjie Station and the Youanmenwai Station on the pile foundation require 218 days and 187 days separately from the second lining buckle arch of the side span to the completion of the bottom plate construction. Specially, the construction periods of stage 2/3 for the two stations are 60/70 and 88/57 days,

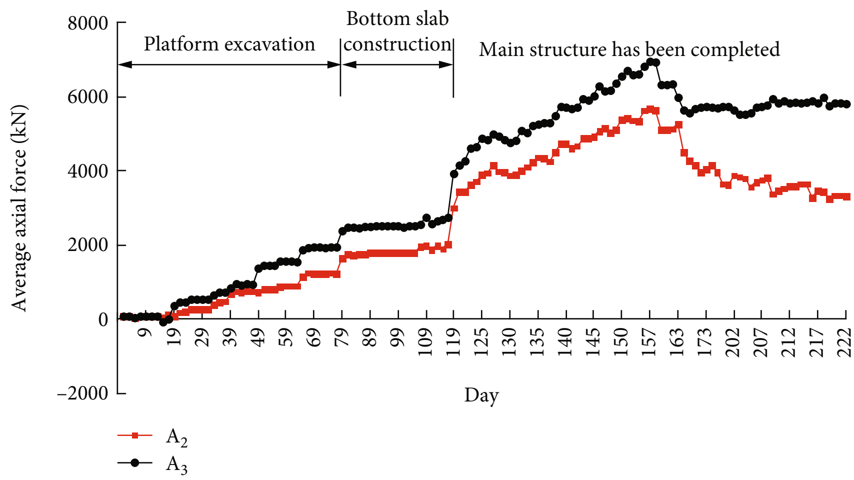


FIGURE 18: Time axis force curve at Beitaipingzhuang Station of Line 19.

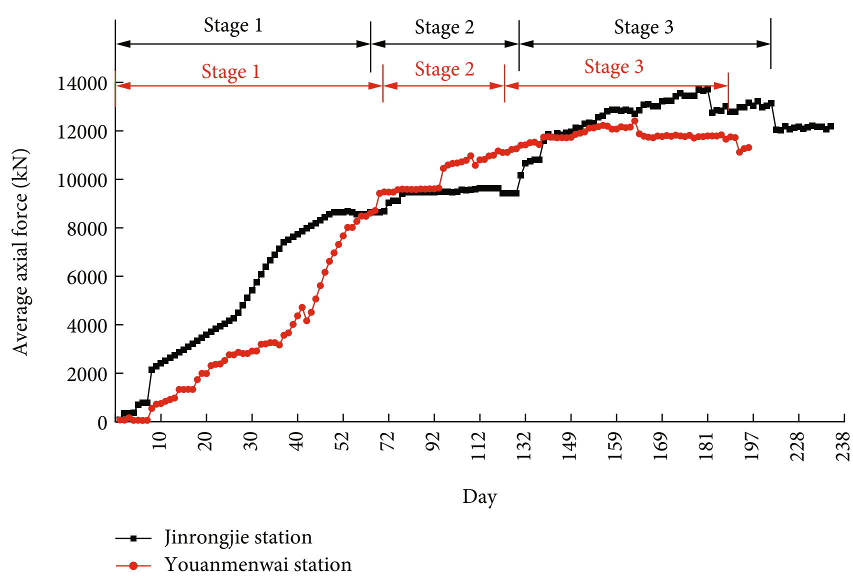


FIGURE 19: Time versus force curve of the pile foundation station.

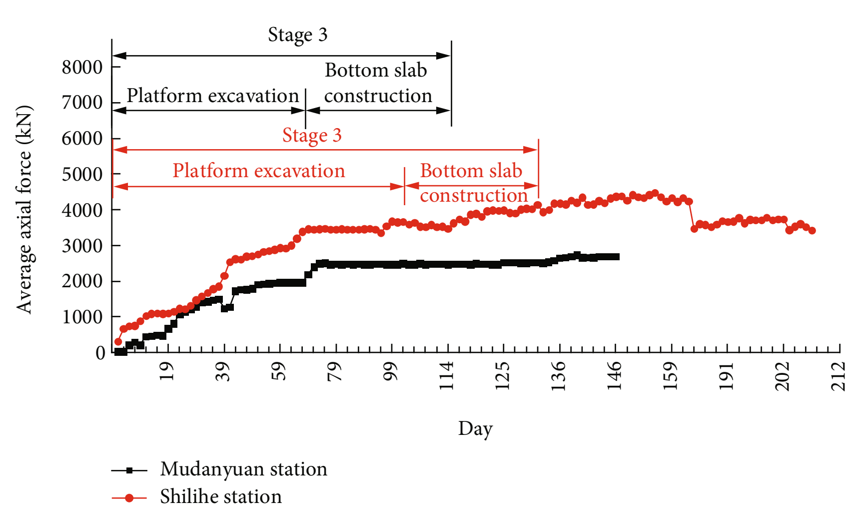


FIGURE 20: Time versus force curve of the strip foundation station.

respectively. Also, the axial forces increase by 1862/2797 and 2881/1177 kN separately similarly as above.

During the earthwork excavation phase of Mudanyuan Station and Shilihe Station at the strip foundation station, the construction periods were 67 days and 103 days, respectively, and the axial force increased by 2736 kN and 4298 kN, respectively. Before excavating, the soil is both external load and bearing structure, which can bear part of the load. With the excavation of the soil in the station, an empty surface is formed inside, and the construction time of the floor is prolonged, thereby causing the station unable to form a closed and bearing mode in time. The stress state is changed, and the stress of the arch is transferred to the steel pipe column and the retaining pile, thus inducing the rapid increase in the internal force of the steel pipe column. Therefore, timely construction of the bottom plate can improve the construction quality, which is beneficial to reducing the stress on the steel pipe column and improving the overall stability of the station.

5. Conclusion

Based on the on-site monitoring data of the pile, beam, and arch subway station during the construction process, this paper analyzes the internal force of the steel pipe column in different construction stages, and the following conclusions are drawn:

(1) During the construction of the subway station, the internal force of the steel pipe column is mainly pressure, which increases gradually especially in the secondary lining arch and the soil excavation. In the stage of the beam, initial support, and second lining buckle arch, the average axial force increment is about 8000 to 10000 kN, accounting for approximately 60% of the total value. The construction stage 1 (the stage of the beam, primary support, and second lining buckle arch construction) is the main cause of internal force change

(2) The biggest feature of the PBA method is the synergy between the pile (column) and the top arch. Before the construction of the buckle arch, the primary support plays the main role of support. When the second lining buckle arch is completed, the load conversion is converted. The load previously assumed by the initial support is transferred to the steel pipe column through the top arch, resulting in the gradual internal force of the steel pipe pile. However, when the side span buckled the arch, the left and right spans failed to buckle the arch at the same time. Also, the soil was not symmetrically excavated, which made the left and right spans asymmetrical and caused the steel pipe column to be eccentric. In the future station construction, synchronous arching and excavation are required to reduce the eccentricity of the steel pipe column

(3) Whether earth excavation occurs at the station hall layer or platform layer, the average axial force increment on the steel pipe column tends to rise with the increasing of covering depth (between 7 and 15 m). The increase in the overburdened soil content of the station will cause the rise of the load imposed on the top of the station also as well as the internal force of the steel pipe column to increase. When the overburden soil on the upper layer of the station reaches a certain depth and the second lining buckle arch is completed, the soil on the top of the station reaches a certain strength and rigidity, and a stable closed loop load bearing form of arches, beams, and columns is formed. The lower structure of the station will no longer have a major impact with the change in the depth of the cover

(4) In the earth excavation stage of the silty clay formation, the average axial force of the steel pipe column is smaller than that of the silty fine sand formation, which is approximately 1.25 times that of the pebble formation. The axial force increment of the steel pipe column in the silty sand formation is the most obvious, both of which are larger than those of the other two formations. Therefore, the station in the silty sand formation should not excavate a large span at one time during the earth excavation stage to prevent collapse occurs during the digging process

(5) During the construction of the subway station, the presence of groundwater may influence the stability of the station structure. At a certain stage after the completion of the construction, the axial force of the steel pipe column in the station affected by the groundwater is approximately twice that of other normal stations. Precipitation construction should be performed in time and many monitoring points are required if the stations are surrounded by abundant groundwater

(6) Under the same conditions, the construction period is also an important factor that affects the force of the steel pipe column. The extension of the construction period virtually continued the formation of the free surface, which makes the station unable to form a closed loop bearing mode in time and caused the deformation of the supporting structure. Thus, the bottom plate should be implemented in time in the future station construction process to make the station form a stable form of force as soon as possible

Although this article has made some meaningful research, there are still some shortcomings. For example, due to the limited types of data currently monitored, only the internal force changes of the middle column can be monitored, and the stress changes of other structures during the construction process cannot be understood. In the future research, and other monitoring projects can be considered. For example, for the monitoring of the stress and deformation of the vault and side piles, numerical simulation can also be added to more comprehensively understand the stress of the bearing structure in each construction stage.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

No potential conflicts of interest were reported by the authors.

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