Hindawi
Geofluids
Volume 2023, Article ID 5022418, 17 pages
https://doi.org/10.1155/2023/5022418

Research Article

The Influence of Pile-Beam-Arch Construction on the Stratum and Station Support Structure

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Received 14 August 2022; Revised 29 September 2022; Accepted 28 November 2022; Published 30 January 2023

Academic Editor: Dongjiang Pan

The PBA construction method is suitable for urban subway construction in situations with dense traffic and many surrounding buildings and can effectively reduce surface disturbance and control surface subsidence. Based on field-measured data, this study creates numerical finite element models of 3D stratum-structure, studies the influence of each process conversion on the subsidence of the ground surface and the force of the station supporting structure during the construction of the PBA station, and clarifies the optimal construction parameters. The research results show that the consistency between the field monitoring data and the simulation data is more than 80%, which verifies the correctness of the model. It is concluded that the formation of the pile-beam-arch is the main part of the supporting structure and that digging the pilot tunnel and the formation of the beam arch are the control factors of surface settlement. Based on this, the best sequence of pilot tunnel excavation and arch buckle of the two-story two-span station is obtained, and the optimal pilot tunnel excavation scheme of first the middle and then the side, first the upper and then the lower, and the best arch buckle scheme of the synchronous arch buckle on both sides is determined. The results of the research can serve as a guideline when selection the construction parameters for similar PBA stations.

1. Introduction

Underground transportation has become the daily means of travel for people. Due to its shallow burial depth and large span, subway stations often produce unavoidable disturbance to the ground during construction processes, causing deformation and displacement of the surrounding strata. Station structures under vertical loading also experience different degrees of deformation due to construction.

Many scholars have studied construction methods to enhance the stability of stations. The most commonly used method in urban subway construction is shallow underground excavation (SUE). It can effectively control surface subsidence [1–3], which is more suitable for urban subway construction [4]. In 1990, the Xidan station was the first subway station in China to use the shallow burying and undercutting method for construction [5, 6]. Therefore, many cities already use this method to build subways [7–9].

The main idea of the PBA method is to construct the vertical bearing structure by constructing a pile beam, then constructing the lateral bearing system by the top buckle arch, and finally carrying out the main operation of the station under the overall bearing system. Up to now, most of the research on this construction method has been aimed at surface subsidence. S.B. Chang et al. [10] studied the stress and displacement generated during the construction of Korean subway stations through onsite monitoring. During digging the side guide tunnel, the vault and sidewalls had a settlement of 3–4 mm. The top of the excavation stage produces a large number of measurement peaks, and the lower part of excavation has little effect on the increase in settlement and stress. Fang et al. [11] conducted an advanced study of the surface deformation characteristics caused by shallow burial and underground excavation methods for 9 subway stations under the same geological conditions using different construction sequences. The result proves that the PBA method is superior to other methods in controlling land subsidence. Luo and Wang [12], according to the geological conditions of the study area, found that the surface subsidence caused by construction is the largest in the

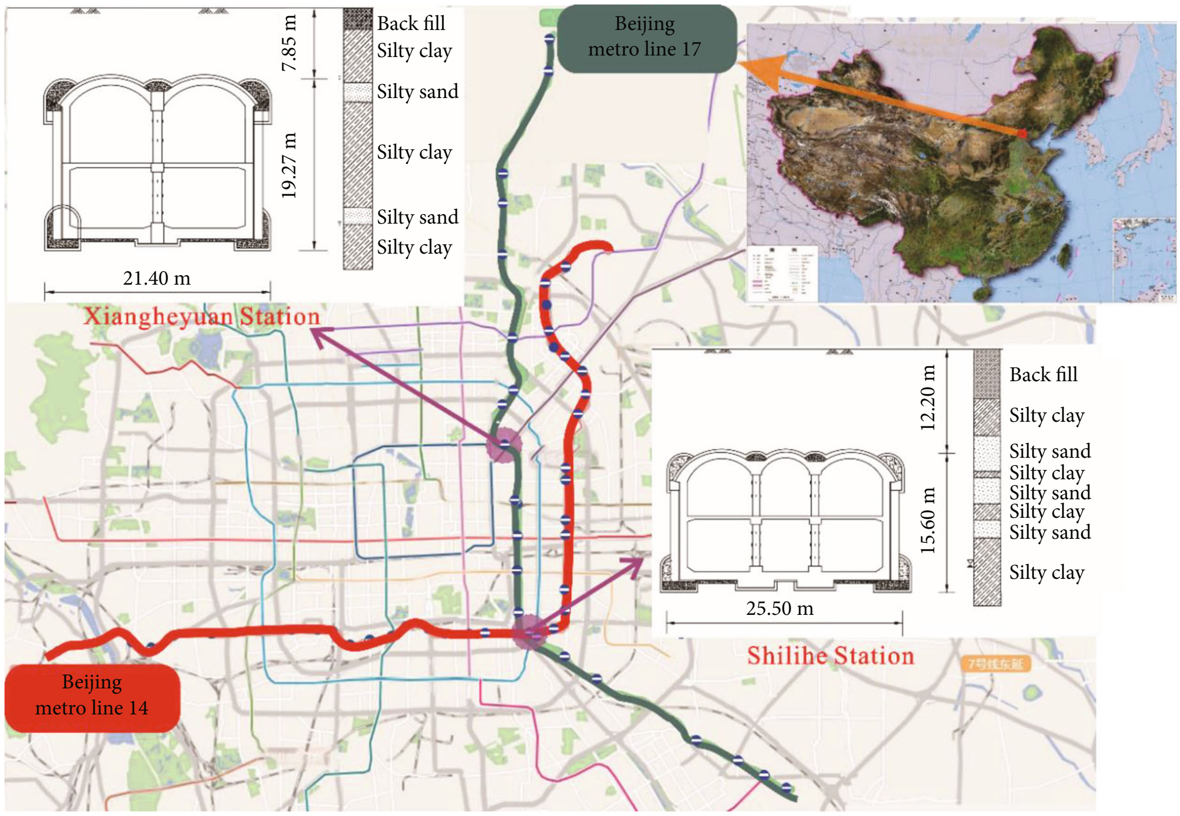


FIGURE 1: Location and geological structure section of Xiangheyuan station and Shilihe station.

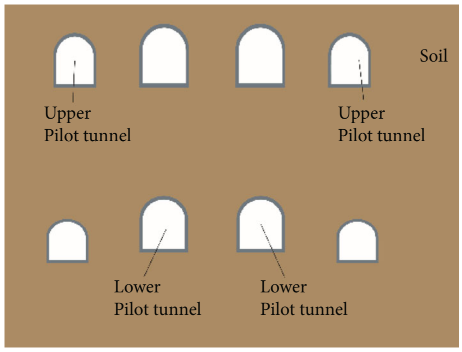
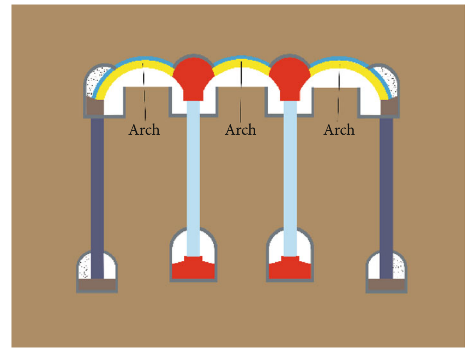
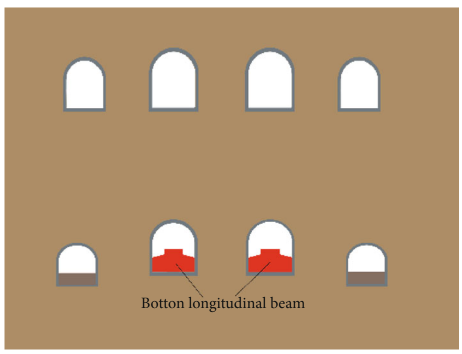
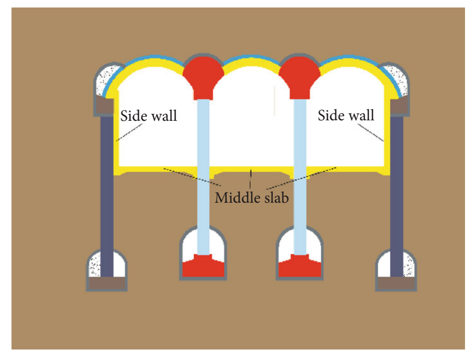
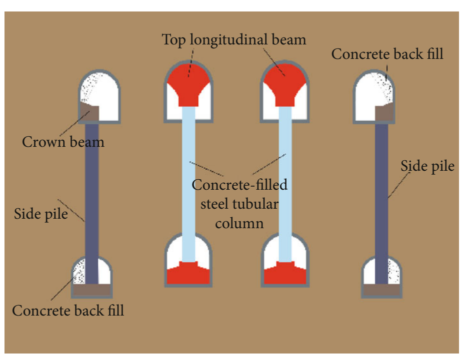
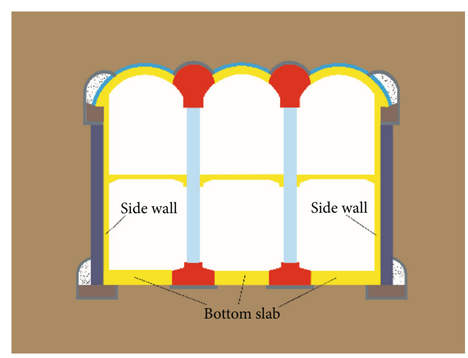
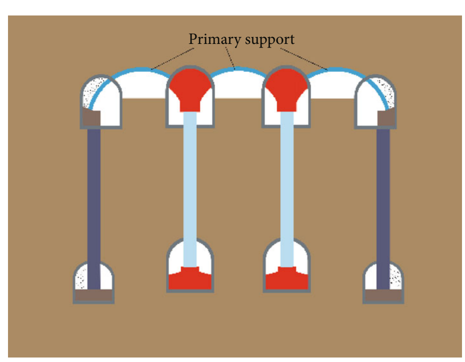
silty-fine sand stratum and the smallest caused by the round gravel and pebble stratum under anhydrous conditions. Gou et al. and Cui and Tian [13, 14] used the field data of the surface settlement of Shanghai Metro Line 1 and analyzed the settlement situation of the operating tunnel and the surrounding of the subway station. Differential settlement is related to tunnel length. Proper grouting during construction and increasing the strength and number of bolts can effectively enhance the strength of the tunnel and reduce the generation of differential settlement. Wang et al. and Yang and Wang [15, 16], through onsite monitoring data and simulation results, analyzed the characteristics of the ground settlement trough of subway stations.

In the process of excavation, vertical bearing structures are primarily composed of concrete-filled steel tube columns (STCs) [17, 18]. At present, most studies on the subway construction mainly focuses on settlement, eccentric compression columns, and impact on surrounding buildings, while there is almost no impact on the internal structure of the station. [19–24]. In addition, the platform width of some stations is wider, and the difference between the side span and the middle span of stations is greater. During the process of supporting a large arch in the PBA construction method, the side arch and the middle arch cannot be constructed synchronously, resulting in an unbalanced horizontal force on the center column. As a result, the ability to withstand loads of the central column is decrease. For example, the positioning deviation in central column construction and the deviation of the verticality of the installation will generate additional internal force on the STC, which will adversely affect the bearing capacity of it. The STC is a permanent stress member. When something goes wrong, tweaks or fixes are costly. The STC of a subway station is the main vertical force-bearing member. Based on the above reasons, it is of great significance to study the force of central columns during the digging and construction of the structure. This article analyzes the field-measured data of concealed excavation stations built by the cavern-column method at Xiangheyuan station and Shilihe station of Beijing Metro Line 17 and further conducts numerical simulations to derive the force changes of the stratum and station support structure in the process of building stations by the PBA method.

2. Study Area Description

2.1. Xiangheyuan Station. Xiangheyuan is the middle station of Line 17, which was constructed by the combination of open and underground excavation. Its plane position is shown in Figure 1. The station is geographically sensitive and surrounded by many buildings, and the station crosses the human defense channel and rainwater and sewage pipes, which constitutes a large environmental risk. The main station body is set along the east and west axes. There is a length of 19.27 m and a width of 21.4 m in the standard section, with an 8.5 m burial depth. Within the station area, the phreatic level is 0.6 m on the top of the station, and the

Table 1: Construction steps.

Construction stage	Schematic	Construction stage	Schematic
(1)		(5)	
(2)		(6)	
(3)		(7)	
(4)			

confined water level is about 0.8 m below the bottom of the station.

2.2. Shilihe Station. Shilihe station is a transfer station for Lines 10 and 14 and is constructed using the hole-pillar method, as shown in Figure 1. There are many buildings above the station, which requires higher construction precision and settlement control of buildings. The main station body is set along the east and west directions. The station structure is relatively wide. There is a length of 15.6 m and a width of 25.5 m in the standard section, with a 12.2 m burial depth. Within the station area, the phreatic level is

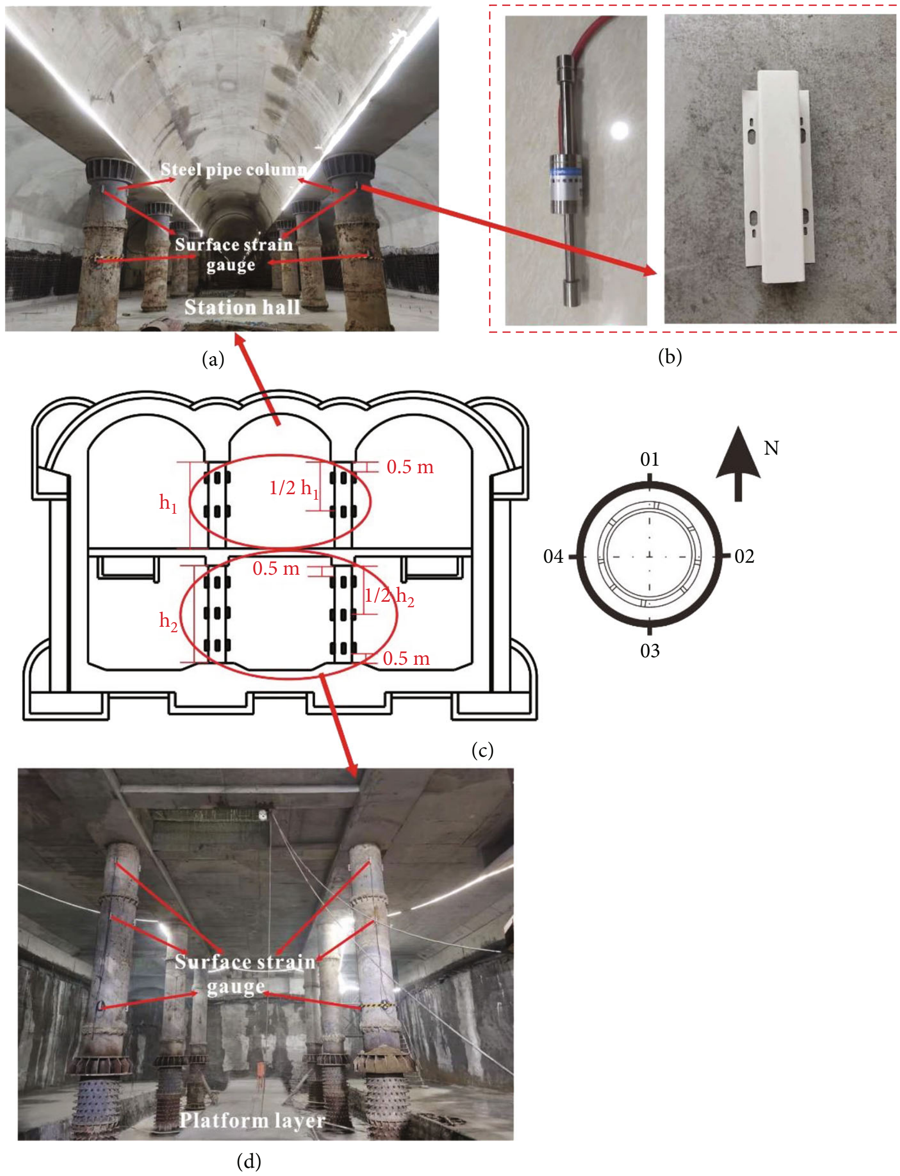


FIGURE 2: Sketch of onsite installation: (a) installation in the station hall; (b) sensor and protective shell; (c) sensor layout diagram; and (d) installation in the platform layer.

located in the middle of the pilot tunnel, with a water level elevation of 20.39 m; the confined water level is located approximately 2 ~ 6 m above the station.

3. Construction Technology and Internal Force Monitoring of the Middle Column by the PBA Method

3.1. PBA Method Introduce [25]. Construction process mainly involves 7 steps, as shown in Table 1.

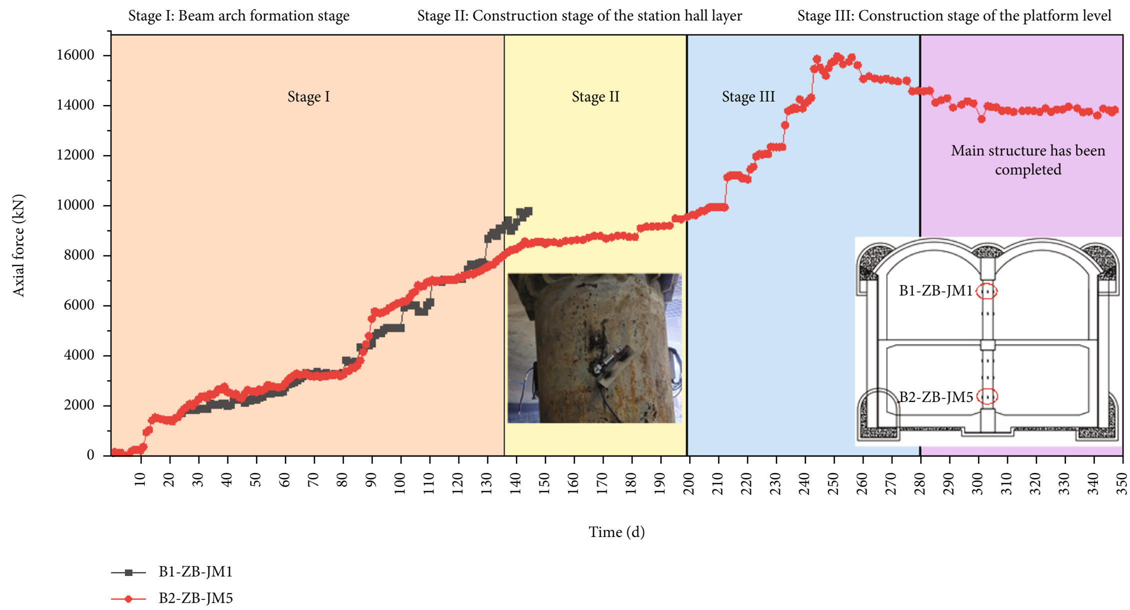
Step 1. After deep hole grouting reinforces the stratum, the upper and lower small pilot holes are excavated.

Step 2. The strip foundation and bottom longitudinal beam in the lower pilot tunnels are constructed after the pilot tunnels are stabilized.

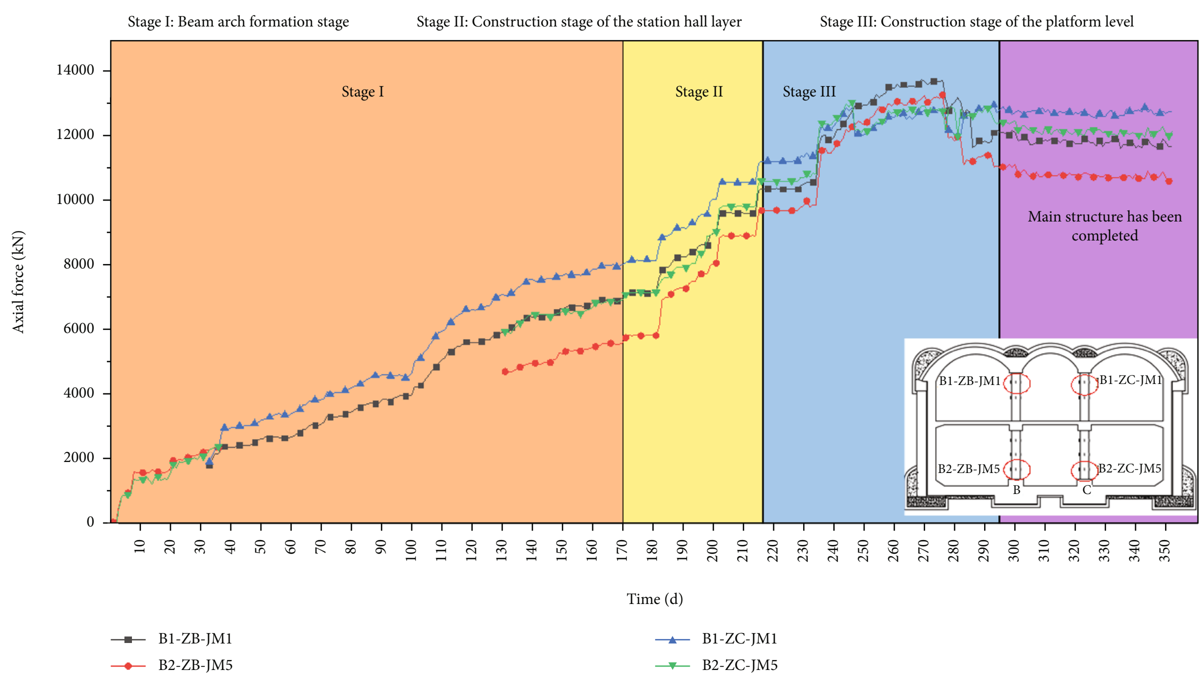
Step 3. Holes are dug in the upper and lower pilot, and then, the side piles, middle columns, top longitudinal beams, and crown beams are constructed and installed. Support structures for beams and columns are formed at this point.

Step 4. Excavation of the station's upper soil is performed, and the arches' initial lining is installed.

Step 5. After excavating a certain distance of the arches for the primary linings, several steps are taken to excavate the soil under the arch. Then, the primary support of the small



(a)



(b)

Figure 3: Axial force change in the central column during construction: (a) XHY station and (b) SLH station.

pilot tunnel (PT) is removed in sections, and the secondary lining structure of the vault is simultaneously constructed.

Step 6. Under the protection of the vault structure, the full-section step method is used to excavate the earthwork of the station hall layer, and when the specified depth is reached, the middle plate and sidewalls are built.

Step 7. Excavation of the platform layer is carried out, and the bottom plate and sidewall are applied when the specified depth is reached.

The PBA method is suitable for urban soft soil conditions. PT with a smaller size is excavated to reduce the one-time excavation. A key component of this method is to decompose the large excavated section into a series of subsections and beneath each small section to form a large section.

3.2. Measuring Point Installation. We set up a set of monitoring points (4 string strain gauges) on the lower surface of the top longitudinal beam (TLB), the lower surface of the middle longitudinal beam (MLB), the upper surface of the bottom longitudinal beam (BLB) about 0.5 m, and between the every layer of the station, respectively. In addition, the strain gauges should be arranged at 90 degrees on the middle column and evenly spaced [25]. Both stations have the same requirement, as shown in Figure 2.

3.3. Mechanical Characteristics of the Middle Column during Construction. The monitoring data of two station structures (double-layer double-span and double-layer three-span) were selected for analysis. Because the process during the construction with the method is complicated and the center column is only subjected to stress after the TLB starts to be constructed, the stress of the center column is divided into three. The monitoring results of the two stations are shown in Figure 3. Among them, the measuring in the topmost and bottommost sensors can obtain the force of the whole excavation process. During earthwork excavation, due to improper operation by onsite construction personnel, the sensor on the steel pipe column was damaged, so the data after the B1-ZB-JM1 stage II in Figure 3(a) are missing.

3.3.1. Beam-Arch Formation Stage. With the formation of piles, columns, crown beams, and top and bottom longitudinal beams, the load on the upper part of the station is mainly borne by the arch and the initial support of the PT. When the arch buckles, the load on the upper part of the station is gradually transferred from the TLB to the middle column. When the top arch with two linings buckles, the middle column is mainly constructed to bear the vertical load, and it mainly bears the vertical load transmitted from the top arch structure. Therefore, the force increases continuously, and the force accounts for 51% of the total during the stage. Since buckling on the left and right is not carried out during the same period, the forces of the two middle columns on the same horizontal plane are different.

3.3.2. Construction Stage of the Station Hall Layer. Following the completion of the secondary lining buckle arch. According to past experience, it is believed that the axial force of the middle column will not change greatly under the upper vault [25]. However, discovered through field data analysis the middle column axial force changed significantly during the digging soil stage. Because the previous stress balance of the study site was broken after the digging the lower soil, the stress is redistributed and cause the internal force of column to change. During this stage, the force accounts for approximately 9% to 19% of the total.

3.3.3. Construction Stage of the Platform Level. During earth excavation at this stage, the lower PT need to be removed at the same time. With the extension of the digging time of the lower soil layer in the station, so that the station cannot form a complete bearing system in time, which changes the force. The force accounts for approximately 30% to 38% of the total axial force.

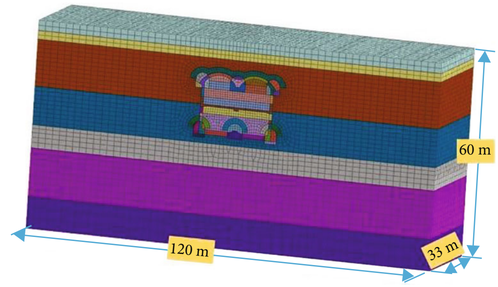


Figure 4: 3D numerical model.

4. Numerical Simulation of Construction with the PBA Method

4.1. Calculation Model and Parameters. To understand the force change law of the stratum and other supporting structures of the station during the building process, according to the above construction sequence, the model for the three-dimensional calculation of the "structural layer" is established in Figure 4. To reduce an effect induced by boundaries, considering the influence of the spacing effect and previous simulation experience, the length of the entire model along the longitudinal direction is station's five longitudinal spans, and the width in the lateral direction is 120 m, which is five times the station span.

The soil is modeled with solid elements and a modified M-C constitutive model and assumes that the formation is homogeneous. The station structure adopts a linear elastic constitutive model without considering its plastic deformation. The load consists of three parts: the soil mass, the weight of the structure itself, and the additional overload. The parameters of model are shown in Table 2.

Grouting reinforcement is completed in one-time construction before soil excavation during the simulation process. The initial support of the pilot hole is composed of a steel grid and shotcrete covering it, which is simplified as a plate element in the model. The concrete and steel grid are equivalent to concrete, and the stiffness conversion formula is as follows:

$$E = E_0 + \frac{S_g + E_0}{S_c}, \quad (1)$$

where E denotes the young's modulus of the converted concrete (MPa); E_0 denotes the young's modulus of the sprayed concrete (MPa); S_g denotes cross-sectional area of grid steel frame (m^2); and S_c denotes concrete cross-sectional area (m^2).

4.2. Construction Process Simulation. Construction of the station is carried out using the six-pilot hole-pillar method. The process of model building will be simulated according to the practical construction sequence of 3.1. In the simulation process, grouting reinforcement of the stratum was completed in one step before construction, the small PT was excavated with a full section, and the footage was 2 m per cycle. The construction is in the order

Table 2: Parameters of the soil and station structure.

Material	Young's modulus (MPa)	Cohesion (kPa)	Poisson's ratio	Volume weight (kN/m^3)	Friction angle (°)	Depth (m)
Strata 1	35	8	0.32	19	10	0 ~ 3.8
Strata 2	40	15	0.3	20	30	3.8 ~ 6.8
Strata 3	100	26	0.25	21	25	6.8 ~ 9
Strata 4	35	26	0.3	20	30	9 ~ 16.8
Strata 5	150	0	0.22	23	40	16.8 ~ 30.4
Strata 6	55	31	0.28	20	25	30.4 ~ 36.4
Strata 7	160	0	0.20	25	42	36.4 ~ 60.0
Pile foundation	$3E + 04$	—	0.2	23.7	—	—
Initial support	$2.8E + 04$	—	0.2	23.7	—	—
Other station structures	$3.25E + 04$	—	0.27	25	—	—

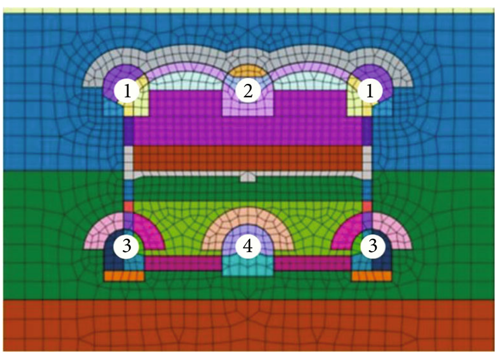


Figure 5: Sequence of pilot hole excavation.

(1)→(2)→(3)→(4), as shown in Figure 5. Through the horizontal passage, first, the upper side pilot tunnels are excavated synchronously and symmetrically (1), and then, the upper middle PT is excavated (2). After digging the upper PT, the lower side PT is excavated synchronously and symmetrically (3), and finally, the lower middle PT is excavated (4. Initial support follows the excavation of the PT. When the PT is excavated at each layer, the PT at the lag on both sides of the middle PT is excavated at 9 m. The excavation principle is as follows: first up and then down and the first side and then middle. After the excavation of the PT is completed, the strip foundations and BLB are constructed in the lower PT. In the next step, side piles, steel pipe columns, crown beams, and TLB are constructed in the upper PT, and the PT gap is backfilled. The soil layer below the arched is excavated step by stept, and the initial support is carried out. After a certain distance, the primary support of the small pilot hole is dismantled in stages, and the side arch lining structure is installed simultaneously. The earthwork of the hall layer and the platform layer should be excavated by the full-section step method, respectively, and the middle slab, the bottom slab, and the sidewalls should be constructed in time.

5. Numerical Analysis Results

Because the various boundary conditions are added to the model, there will be boundary effects around the model. Therefore, the calculation model will be different from the actual situation, resulting in calculation errors. To obtain more accurate data, the numerical model selects the longitudinal five-span length of the station for calculation and analyzes the calculation results of the structure and the ground settlement (the relative position in Figure 6).

5.1. Force of the Middle Column. As the main structure bears vertical loads, the central column is also subjected to complicated forces during the construction process. In the construction process, the axial force changes of the central column are shown in Figure 7. To facilitate the analysis, the data of each stage are completely processed.

By comparing the simulated axial force time curve with the monitoring data, the stress state of the central column shows a gradually increasing trend, which also verifies the correctness of the research results. However, due to the limitations of the simulation and the site, it is impossible to fully quantitatively analyze the force situation, which is mainly caused by the soil quality, construction process, etc. under the site conditions. In the numerical simulation, most of them choose one excavation, so the stress of the center column is in a relatively smooth line shape; however, in actual operation, there is no way to remove a piece of soil at once. During the excavation process, it is likely that a small piece of soil is excavated, resulting in stress concentration on the center column, which is relatively common in construction, resulting in a relatively obvious inflection point in the measured results. During the TLB completion, the axial force reaches 1415 kN, accounting for approximately 7% of the total. With the digging of the arch soil, the top load of the station is mainly transmitted to the STC through the initial support of the top arch and the TLB. The axial force of the middle column reaches 8121 kN, accounting for approximately 42% of the total. Before the second lining of the dome is installed, the primary support mainly plays a supporting role. After the second lining of the dome is installed, the existing structure realizes load conversion. Therefore, when the construction of the second lining of the dome installed, the primary support of the small pilot hole is already removed, and it is mainly supported by the vertical structure. The force reaches 14015 kN and accounting for 73% of the total. The growth rate of the axial force is obviously relieved

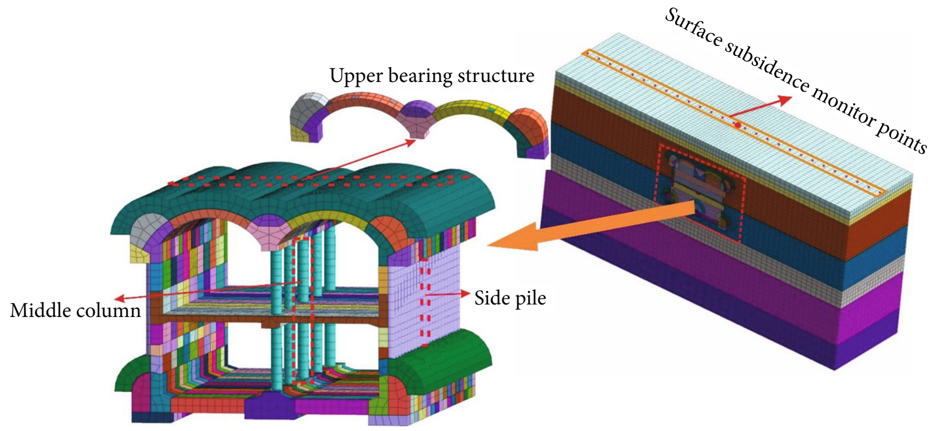


Figure 6: Numerical model.

and finally stabilized. The figure shows that in the various stages of construction, the maximum of the central column appears near the bottom.

During TLB construction, arch soil excavation and secondary lining buckled arch construction, the top-down flexural torque of the middle column is extremely small, and the fluctuation is small. After the lining buckled arch is completed, the flexural torque reaches 35.45 kN•m at the top. During the process, the maximum flexural torque appeared at the lower part of the station because when the soil at the lower part of the station was excavated, the support provided by the soil around the center column was removed and the soil was excavated during excavation. In the construction process, the maximum flexural torque occurs at the completion stage of station hall construction. This is because the support provided by the soil around the middle column is removed when the soil at the bottom of the station is excavated, and in the earthwork excavation stage, the soil is not excavated symmetrically, which makes the spans of the left and right two spans asymmetric so that the eccentric force of the STC is generated, resulting in a large flexural torque. After the lower structure is completed, the STC is subjected to a certain extent. After station construction is completed, the maximum flexural torque reaches 186 kN m, an increase of 81%. The maximum flexural torque also showed a downward trend and was located in the lower of the middle column.

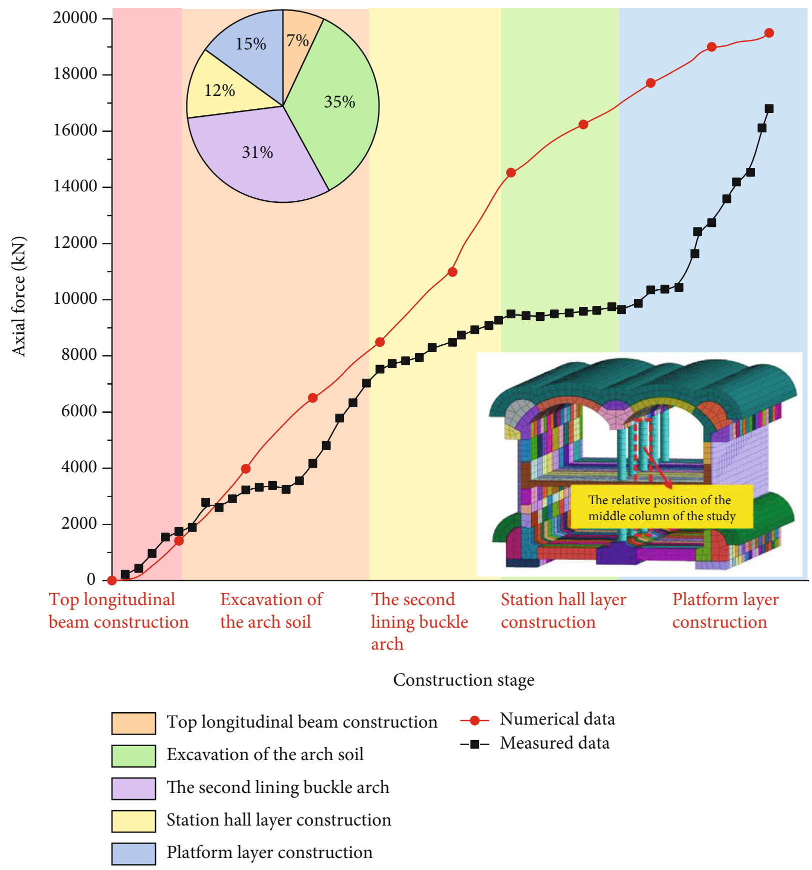
In the most unfavorable state, the maximum axial design value of the CFST column is 34500 kN. The monitoring data and numerical simulation data on site are far smaller than the design value of the maximum axial of the CFST column. Model results can guide the construction of the same station structure under the same geological conditions.

5.2. Force on the Upper Bearing Structure. During the construction process, the arch, longitudinal beam, and crown beam together form the upper bearing structure, which makes the frame bearing system perfect, and it withstands the digging release stress during the process of construction. Therefore, the stress analysis of the upper bearing structural system must be carried out.

According to Figure 8, during the construction stage of the supporting arch, tensile stress primarily concentrated at the joint between the TLB and middle column, which is 5.1 MPa; the maximum compressive stress occurs at the connection between the TLB and the middle column, which is -12.9 MPa. The main reason for this is that it is there is a connection between the TLB and the STC, and there is an inevitable phenomenon of stress concentration; however, the stress concentration area is small, which is approximately 1.0 MPa. With the soil digging at the lower part, the tensile stress in the upper part of the station is redistributed, which increases the tensile stress at the TLB and the center column junction, and the maximum is 5.86 MPa. After the construction completed, the tensile stress decreases. This is because the upper bearing system has not been completed during the supporting arch stage, so the center column still needs to bear a large load, resulting in a large stress at the joint between the middle column and the TLB. After the construction completed, the stress system is formed, so the stress at the connection between the TLB and the center column is also reduced.

5.3. Stress of the Side Pile. In the structural bearing system, the side piles must not only bear the inclination pressure provided by the supporting arch and the initial support of the pilot hole but also bear the horizontal earth pressure exerted by the extruded pile body of the soil. A typical top to bottom distribution of internal forces in side piles during construction is shown in Figure 9. For convenience, the axial force value has been taken as an absolute value.

The axial force and flexural torque increase considerably with the arch soil digging and the buckle arch. The maximum axial force and flexural torque appear near the top of the column. This is because the original closed load-bearing structural system was damaged, the soil on the upper side of the pilot hole lost its support, and the side piles began to bear the pressure of the upper soil, making the axial force of the side piles increase significantly in these two stages. In addition, the internal force of the side piles also increase as the soil is excavated in the lower part. This is because the lateral resistance of the pile provided by the soil inside the side pile disappears. After the completion of the



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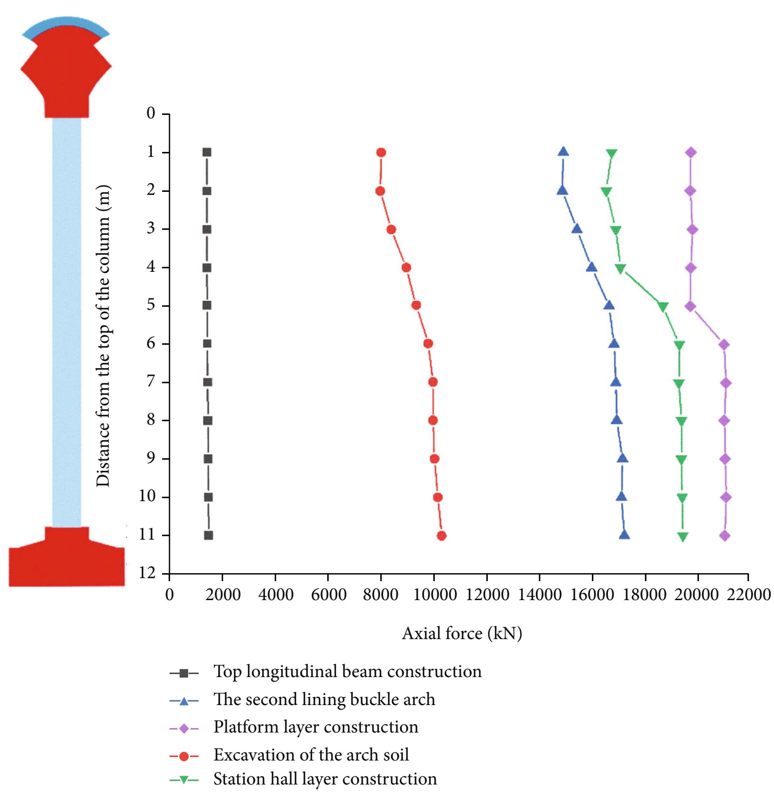
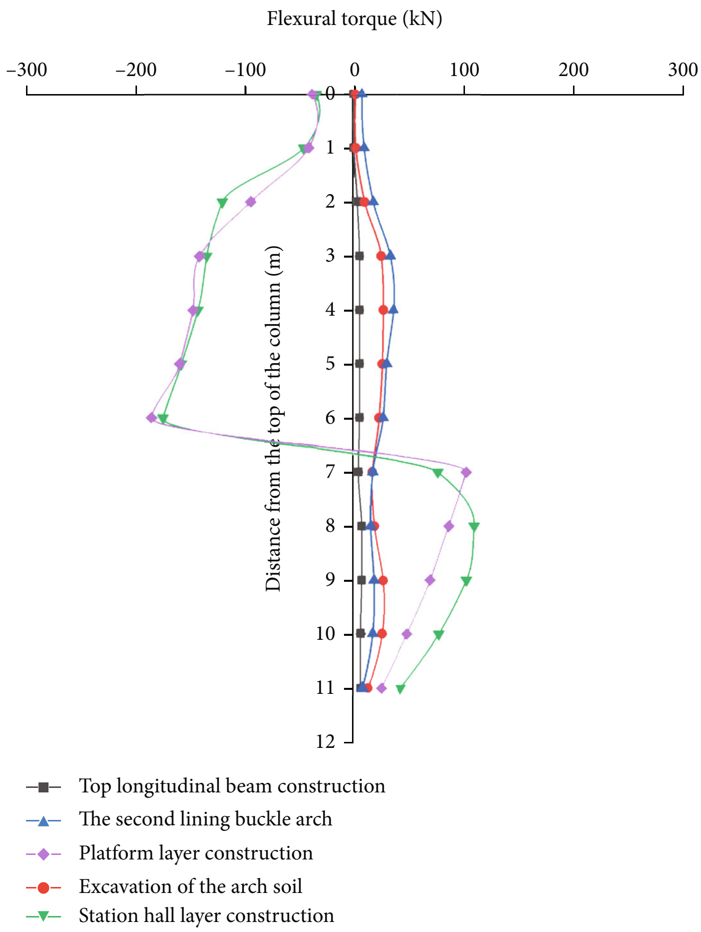


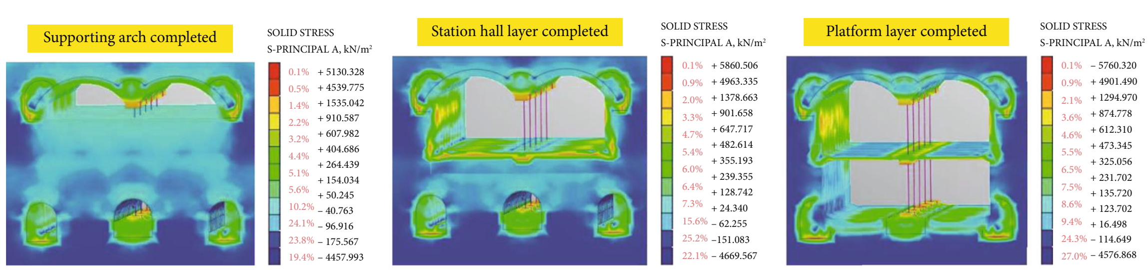
(b)

Figure 7: Continued.



(c)

Figure 7: Internal force changes. (a) Variation of the axial force of the middle column. (b) Distribution of the axial force of the central column from top to bottom in each stages. (c) Distribution of the flexural torque force from top to bottom in different construction stages.



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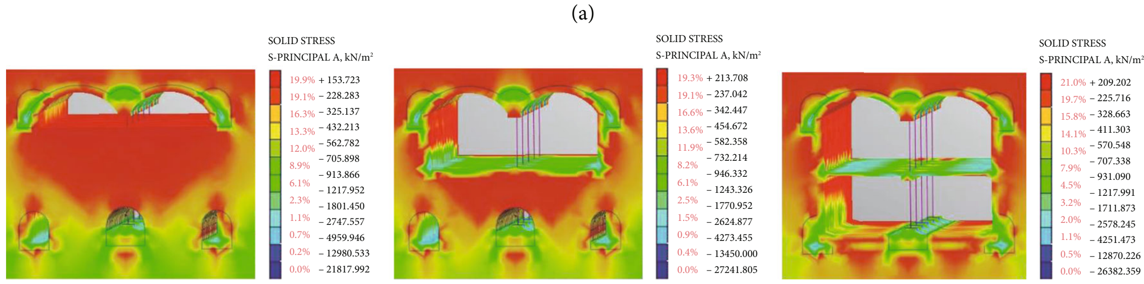


(b)

Figure 8: Stress contour of the upper bearing structure: (a) first main stress and (b) third main stress.

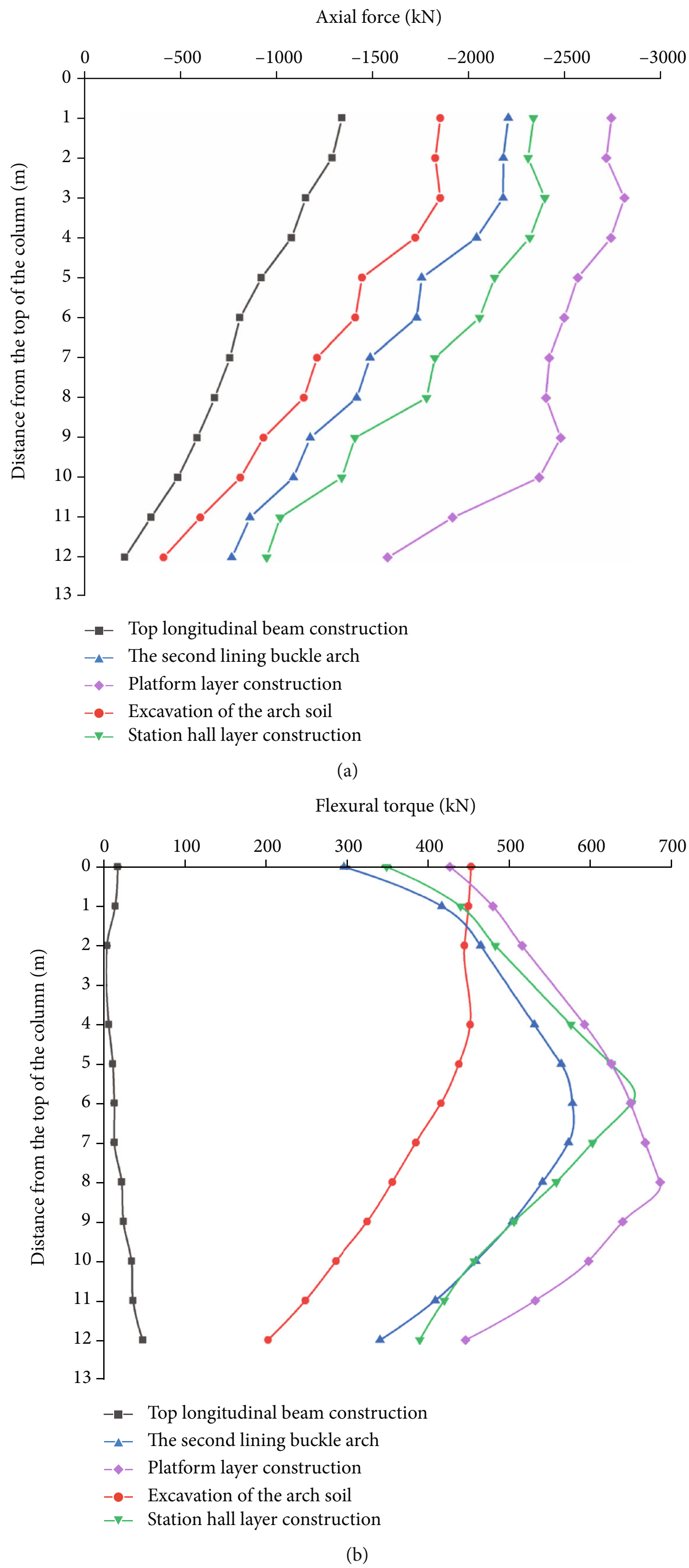


Figure 9: Distribution of the internal force of side piles from top to bottom in different construction stages. (a) Distribution of the axial force. (b) Distribution of flexural torque.

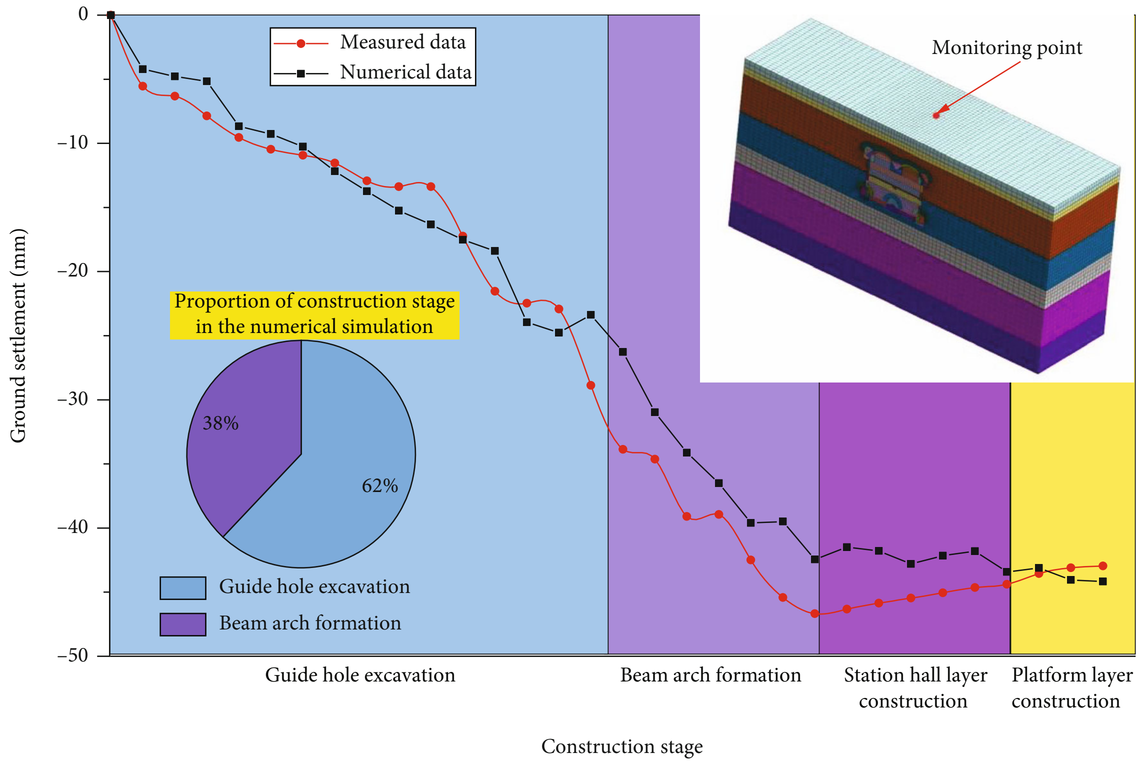


Figure 10: Ground surface settlement process.

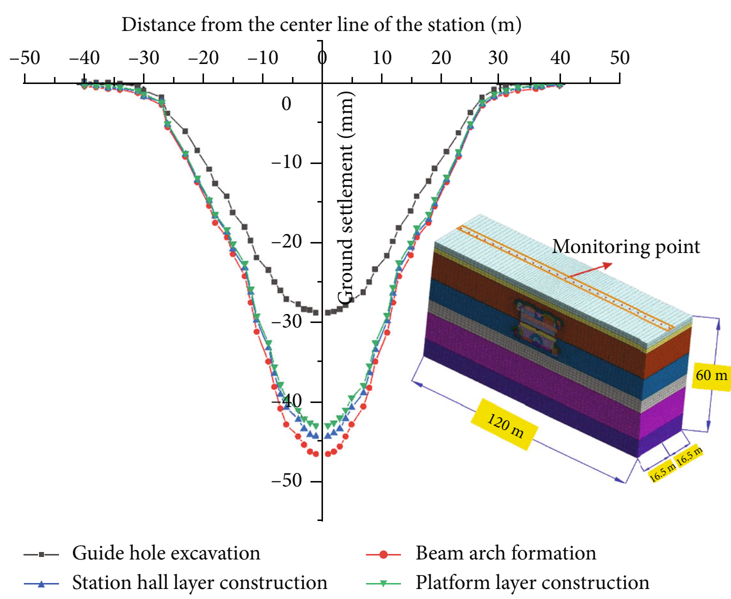


Figure 11: Ground surface settlement trough.

main structure of the station, the increasing trend of the flexural torque is curbed, and it decreases by a certain amount. This is because the middle and bottom plates replace the lateral support of the excavated soil layer on the side pile, which has a significant inhibitory effect.

5.4. Ground Settlement. The settlement proportions of different construction stages are different, and the settlement proportions from large to small are as follows: guide hole excavation > beam-arch formation > station hall layer construction > platform layer construction.

Taking the surface center point as the monitoring point, Figure 10 shows the change process of surface subsidence. There are four stages of ground settlement based on the construction stage: during the excavation stage, the guide hole reached 28.87 mm, and in the beam-arch formation stage, it reached 46.67 mm; compared with that in the guide hole excavation stage, it increased by 17.8 mm.

In the beam-arch-forming stage, the resulting surface subsidence is less than the excavation of the PT. This is because the beam-arch column supports system forms, which has a certain supporting effect on the upper stratum of the station. Therefore, the surface subsidence was somewhat reduced. With the completion of the station, the final ground settlement was 42.96 mm, which was reduced by 3.71 mm, and the ground settlement rebounded obviously. After the vault on the upper part of the station is formed, it will not only bear soil pressure from the outside but will also restrain soil inside the structure, creating a structure-soil system. With the reduction of the internal soil will reduce the dead weight will decrease, causing the station to float to a certain extent and causing the surface to bulge.

The numerical analysis results and monitoring data are in good agreement in terms of the deformation law, subsidence rate, and proportion. The final ground settlement in actual monitoring is 46.67 mm, while that in numerical simulation is 44.18 mm. The difference between the simulated and measured final settlement values is approximately 5%, which shows the rationality of the simulation. However, due to the limitations of numerical simulation and the field, it is impossible to fully quantitatively analyze the force situation. In the numerical simulation, most of them choose one excavation. However, there are a series of uncertain factors in actual operation, and these factors cannot be simulated by software.

The displacement data of a series of grid nodes in the middle of the surface are selected to form the settlement tank shown in Figure 11. As a result of the construction of the tunnel-pillar method, the surface subsidence is roughly distributed along the station's centerline, and the maximum surface subsidence is approximately 46.67 mm, which is above the center of the station. It is estimated that approximately 62% of the final settlement is caused by ground settlement caused by digging and supporting the pilot tunnel during construction. When the secondary lining is constructed, the accumulated ground settlement reaches its maximum, and approximately 38% of the final settlement comes from surface settlement. In the subsequent stages of soil digging, the surface settlement rebounded, resulting in a decrease in the cumulative surface settlement. Surface subsidence can be controlled by installing a pilot tunnel and forming a beam arch during the closed construction stage.

Perhaps the piles, beams, arches, and columns formed a space frame system for the main force in the early stage. The construction environment was safe, and the surface displacement caused was small. Excavation and unloading of the lower part of the earthwork led to the uplift of the bottom plate, but the detailed mechanism needs to be studied further.

6. Factors Controlling the Surface Subsidence and the Force of the Central Column

Through the above analysis, the digging of the PT is the key factor causing the surface subsidence, and the force of the central column is mainly affected by the buckle arch. The following is a comparative analysis of the sequence of the excavation of the PT and the buckle arch, and the optimal construction scheme is obtained.

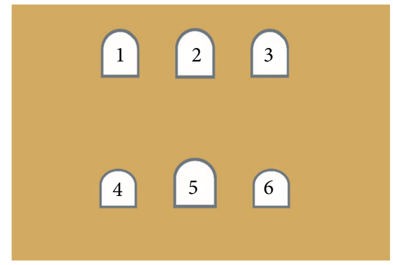


Figure 12: Pilot tunnel number.

Table 3: Ground subsidence of different pilot tunnel excavation schemes.

Number	Scheme	Maximum ground settlement (mm)
1	1&3 ⟶ 2 ⟶ 4&6 ⟶ 5	46.67
2	4&6 ⟶ 5 ⟶ 1&3 ⟶ 2	47.06
3	5 ⟶ 4&6 ⟶ 2 ⟶ 1&3	46.73

6.1. Influence of the Excavation Sequence of the PT.

The influence of the excavation of each PT is superimposed on the disturbance of the stratum, resulting in a group cave effect, which affects the surface subsidence. To reduce this effect, the optimal pilot tunnel construction plan is determined. The following three construction schemes are compared and analyzed, the guide hole label is shown in Figure 12:

(1) 1&3 ⟶ 2 ⟶ 4&6 ⟶ 5 (the existing scheme of the station)

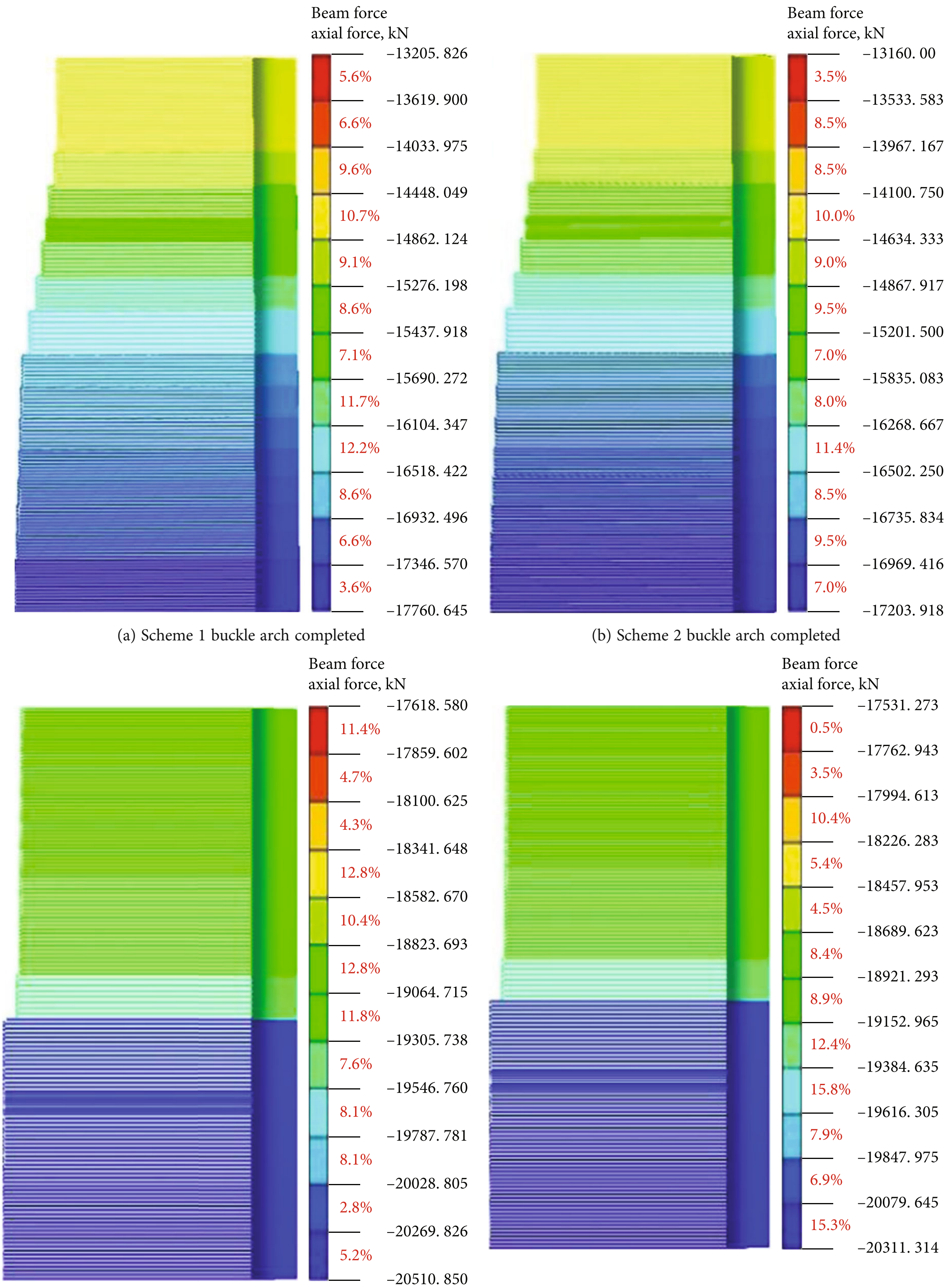
(2) 4&6 ⟶ 5 ⟶ 1&3 ⟶ 2

(3) 5 ⟶ 4&6 ⟶ 2 ⟶ 1&3

The above three schemes are simulated, respectively. During the simulation process, only the construction sequence of the PT changed, and the subsequent construction was carried out according to the actual construction scheme. The statistics of surface settlement caused by the excavation of PT in different sequences are shown in Table 3.

By comparing the maximum value of the surface subsidence under the excavation sequence of each pilot tunnel, it is found that scheme 1 (46.67 mm) < scheme 3 (46.73 mm) < scheme 2 (47.06 mm). This shows that in the vertical direction, the construction scheme "upper PT first, followed by the lower PT" and in the horizontal direction, the construction scheme "middle PT first, followed by the side PT" has little effect on surface settlement. Therefore, it can be inferred that the best excavation plan is "upper first, followed by lower, first middle and then side."

Designing scheme 4 to verify the correctness of the model, the construction sequence of the PT in scheme 4 is 2 ⟶ 1&3 ⟶ 5 ⟶ 4&6. The final surface settlement



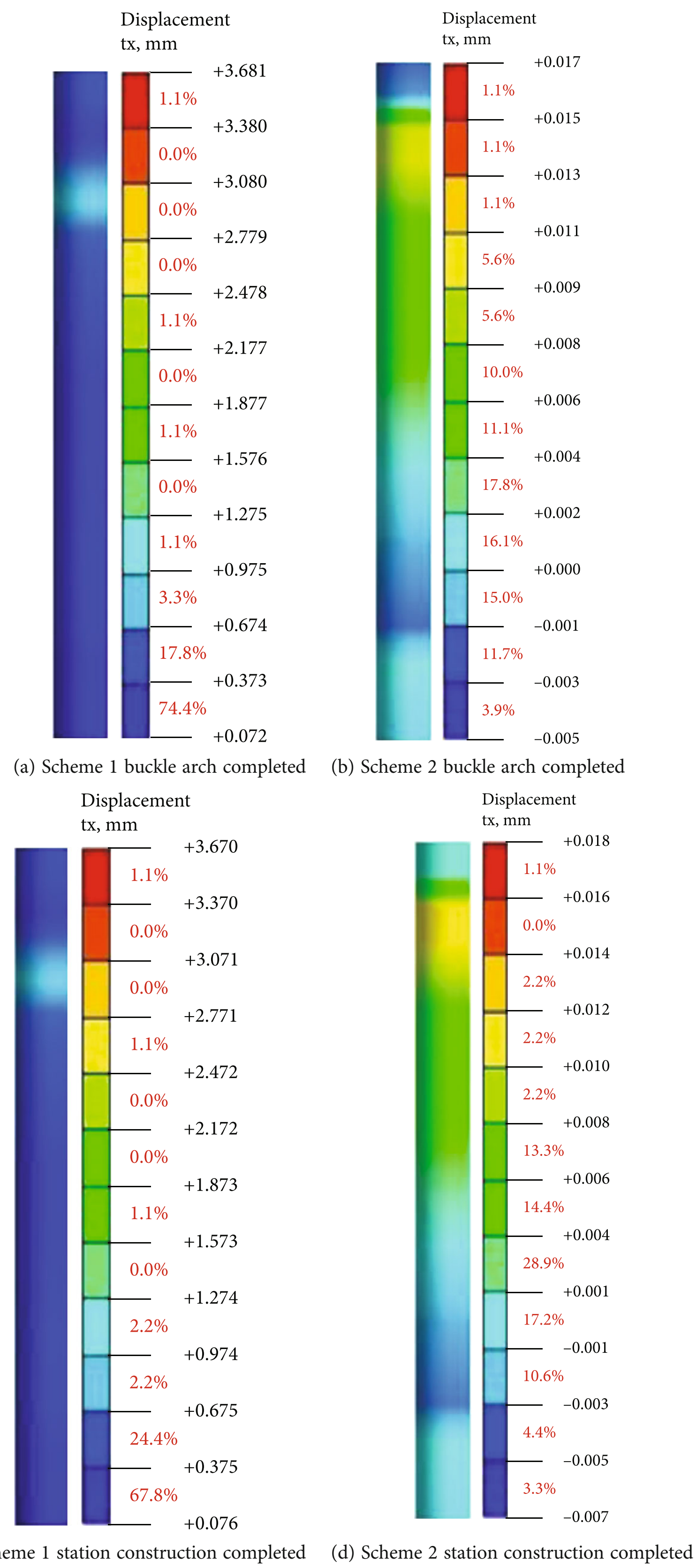
(a) Scheme 1 buckle arch completed

(b) Scheme 2 buckle arch completed

(c) Scheme 1 station construction completed

(d) Scheme 2 station construction completed

Figure 13: Contrast cloud diagram of the axial force of the central column in schemes 1 and 2.



(a) Scheme 1 buckle arch completed (b) Scheme 2 buckle arch completed

(c) Scheme 1 station construction completed (d) Scheme 2 station construction completed

FIGURE 14: Contrast cloud diagram of the lateral displacement of the middle column in schemes 1 and 2.

Table 4: The force and displacement of the central column with different arching sequences.

Number		1	2
Scheme		The left arch is constructed first, and the two arches are staggered by 8 m.	Construction of the left and right side arches is carried out at the same time
Axial force (kN)	Buckle arch is completed	17761	17204
	Station construction completed	20510	20311
Lateral displacement (mm)	Buckle arch is completed	1.036	0.011
	Station construction completed	0.997	0.012

caused by this scheme is 45.32 mm, and the minimum is caused by the no.4, which is consistent with the conclusions of the first three schemes and verifies the correctness of the conclusions. In view of such geological and construction conditions, the best pilot tunnel excavation scheme for a strip foundation station is "upper first, followed by lower, first middle, and then side."

6.2. Effect of the Buckle Arch Sequence. Through analysis, the completion of the buckle arch reaches approximately 73% of the total axial force value. Buckle arch construction is the most important process in the PBA method construction process. At this stage, the central column is subjected to the largest force and deformation. To obtain the best buckle arch sequence, the following two buckle arch schemes are compared and analyzed:

(1) The left arch is constructed first, and the two arches are staggered by 8 m
(2) Construction of the both side arches is carried out at the same time (the existing scheme of the station).

The above two schemes are simulated, and other construction conditions during the simulation process are examined according to actual construction. The contour diagrams of the axial force and lateral displacement of the central column caused by different arching sequences are shown in Figures 13 and 14.

The specific comparison is shown in Table 4.

By comparing the two buckling arch sequences, the axial force changes of the center column have similar trends, and near the bottom of the center column; after the second liner buckling arch is applied, scheme 1 (20510 kN) > scheme 2 (20311 kN), and the axial force value of scheme 1 is 1% larger than that of scheme 2. The absolute lateral displacement value of scheme 1 after station construction is completed is 0.997 mm > scheme 2 (0.012 mm), which shows that the synchronous buckled arch on both sides can reduce the deviation of the center column and improve the safety of the station structure.

7. Conclusion

In this study, the influence of PBA construction process conversion on the stress and surface settlement of the station support structure was studied through onsite measured data and numerical simulation. The key factors affecting the structural stress and surface settlement were clarified, and the optimal pilot tunnel excavation and buckled arch construction sequence plan were obtained. The main research conclusions are as follows:

(1) The PBA construction process can be divided into 7 stages: (1) digging of the PT, (2) construction of the BLB, (3) formation of the beam-column support system, (4) excavation of the station's upper soil and initial support construction, (5) arch formation, (6) station hall layer construction, and (7) platform layer construction. In the field measurement and numerical simulation, the stress state of the center column shows a gradually increasing trend, which also verifies the correctness of the research results

(2) Through numerical simulation, the construction of the pile-beam-arch has a great influence on the supporting structure of the station. During this period, the maximum axial force increment of the central column is 14015 kN, accounting for approximately 73% of the total; the maximum tensile stress of the vault is 5.1 MPa, accounting for approximately 89% of the total; and the maximum axial force increment of the side pile is 2300 kN, accounting for approximately 80% of the total. This shows that pile-beam-arch formation is the main construction stage of the support structure force

(3) Digging the PT and formation of the beam and arch led to a gradual increase in the surface subsidence. The two account for 62% and 38% of the surface subsidence, and the maximum surface subsidence is 46.67 mm. Formation of the pile-beam-arch makes the station form a stable load-bearing structure, and the settlement is basically unchanged after that, indicating that digging the PT and formation of the beam and arch are the factors controlling surface settlement

(4) When the digging sequence of the PT is $2 \longrightarrow 1\&3 \longrightarrow 5 \longrightarrow 4\&6$, the surface subsidence is the smallest; the surface subsidence is the largest when the order $4\&6 \longrightarrow 5 \longrightarrow 1\&3 \longrightarrow 2$ is followed. The optimal plan for digging the PT is obtained, which is the upper first followed by the lower, first middle, and then side, which can provide a reference for the PBA station with two floors and six PT

(5) The displacement and internal force of the central column caused by the synchronous buckled arch on both sides are the smallest. To improve the structural stability of the station, the construction scheme of the synchronous buckled arch on both sides is the best, which can provide a reference for the two-span PBA station

Data Availability

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

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

The research described in this paper was financially supported by the National Natural Science Foundation of China (Grant No. U1261212).

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