Deformation of an existing metro station attachment structure under the influence of adjacent construction of a covered excavation pit

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Abstract. The existing metro station buildings closest to the cover excavation pit will inevitably be more damaged as a result of pit construction. A three-dimensional finite element model was created using ANSYS software based on a deep foundation pit adjacent to an existing metro station in Beijing to simulate the cover excavation pit construction process and discuss the impact of the pit construction process on the deformation of the attachment structures of the existing station. The distance between the existing structure and the new pit, as well as the shape of the existing structure and the connection between the attachment structure and the main station, all play a role in how much the existing station attachment structure is impacted by the tendency to sink during pit construction.

Keywords: Pit construction; Metro station; Attachment structure; Numerical simulation; Deformation law

1 Introduction

The number of crossings between lines likewise rises annually as the urban rail network's population density does [1]. Year after year, more and more “Complementary Projects” are carried out to enhance the infrastructure services in the area after the opening of the metro stations [2]. These “Complementary Projects” invariably have an impact on the operational safety of the existing metro stations during construction, particularly on the attachment structure of the adjacent stations [3].

Some research has been done on new foundation pits close to existing metro stations by academics in China and abroad.

Xin et al. [4] used a deep foundation pit project connected to a metro station in Tianjin as their background to investigate the impacts of excavation of the foundation pit on both sides on the deformation of the existing station and tunnel. Three distinct excavation sequence construction techniques are coupled with a finite element method that considered the soil’ s minor strain hardening characteristics. Song et al.[5]conducted a

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dynamic study on two construction schemes, namely the open excavation and smooth construction method and the cover excavation and reverse construction method, for the foundation pit. The foundation pit project of Qianhaiwan Station of Shenzhen Line 11 is used as a backdrop, and created a three-dimensional numerical model using finite element software, considering the interaction of the soil, enclosure structure, and supporting system. Wu et al. [6] combined the Greenland Centre deep foundation pit project at the Bund Bridge Station of Ningbo Rail Transit Line 2, which is adjacent to the one that is being built, and conducted a comparative analysis of the effect of displacement control of the nearby metro station under four measures, including increasing the stiffness of the enclosure wall, adding soil reinforcement to the pit, increasing the number of support courses, and increasing the depth of the deep foundation pit. Wang [7] combined the working conditions and geological parameters of a foundation pit project in Shanghai to establish a numerical calculation model to analyze the impact of zonal excavation of large foundation pits in soft soil areas on the deformation of the base slab of adjacent metro stations and to optimize the excavation method of foundation pits. To compare and analyze the deformation law of the adjacent metro station caused by deep foundation excavation under various construction sequences, Xiang [8] combined an example of a metro station project in the Changsha area, based on numerical methods, and to investigate the deformation characteristics of the enclosure structure and the main structure of the station at different excavation depths in the open cut and cover excavation reverse section of the station As a backdrop, Wu [9] used the construction of a complex foundation pit at the Tianhe City Shopping Center in Tianjin. He used 3D numerical analysis to calculate the settlement values of the nearby Tianjin Metro Line 3 Heping Road Station caused by two excavation options for the foundation pit and evaluated the effects of the two schemes on the safety of the metro structure. Li [10] evaluated the effects of an oversized deep foundation excavation on the structure of a nearby existing metro station by comparing data such as settlement and horizontal displacement of the station structure in each working condition, along with a comparative analysis of site monitoring.

This paper analyzed the deformation law of the attachment structure of an existing station under the influence of pit construction using numerical simulation based on a deep foundation pit next to an existing metro station in a “Complementary Projects” in Beijing, serving as a theoretical foundation and point of reference for related projects.

2 Engineering situation

Following the completion of the planning and operation of the Beijing Metro Line A and Metro Line B, a “Complementary project” was designed and constructed in Beijing to enhance the area’s overall industrial structure and infrastructure, as shown in Figure 1.

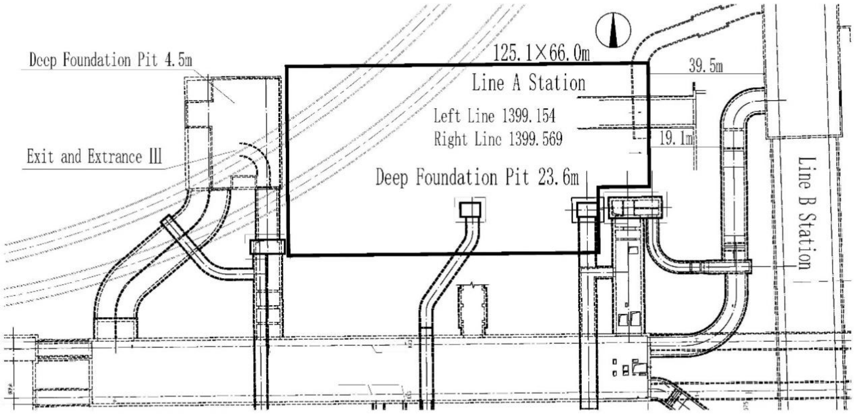


Fig. 1. Map of the project surroundings

The size of the new foundation pit is very enormous, with a depth of 23.6 meters, a length of 125.1 meters, and a width of 66 meters. The top slab's overburden is 1.6 meters high and the bottom slab is buried about 24.62 meters. The cover excavation reverse method is used to build the project's box frame construction, which has a longitudinal and transverse beam system. The central column uses a steel pipe concrete column, and the pile foundation is set under the column. The infill pile and the structure lining wall form a composite wall structure, and the waterproof layer is set between them. The retaining piles are also used as vertical load-bearing pile foundations, primarily to bear the vertical force of the structure during the construction stage of the cover excavation inverse method, as shown in Figure 2.

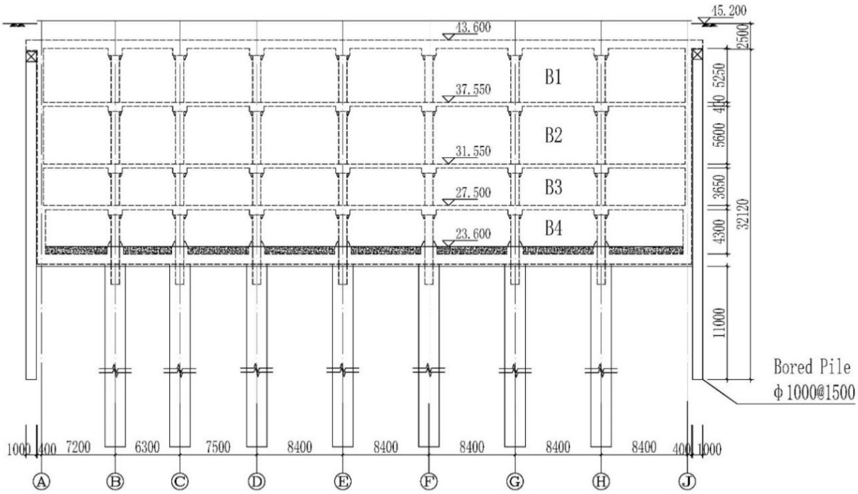


Fig. 2. Section of new foundation pit

At 19.1 meters on the east side, 2.6 meters away on the west, 4 meters away on the southeast, and 19.1 meters away on the west from Station Dust 2#, the new foundation pit is the closest to the Metro Line A Transfer Channel 2# (Metro Line A Station and Metro Line B Station Transfer Channel).

Entrance #3 open excavation structure is a three-story underground box frame structure made of longitudinal and transverse beams. It is 38.8 meters long and 33.1 meters wide, with a top slab overburden thickness of about 6.22 meters and a bottom slab depth of about 25.82 meters. The structure was built using the open excavation method, and the foundation pit was built using grouting piles and an internal support structure. The side wall is 0.7 meters thick, and the passage's interior width is 8 meters.

Duct #1 is an underground, one-story, two-layered arch structure that was built using the mining method. Its overburden thickness is 14.25 meters at its top and is around 25.25 meters deep at its bottom. The building is 14.8 m wide and 9 m high, with a single 6 m span, and thicknesses of 0.9 m at the bottom, 0.8 m at the side walls, and 0.5 m at the central partition.

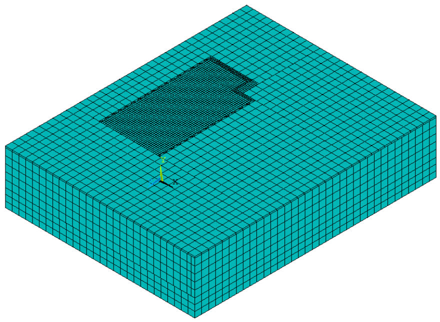
Duct #2 is built using the inverted shaft wall method; it has a rectangular shape, an outside profile of excavation measuring 7.5 by 18.5 meters, and an excavation depth of approximately 33.2 meters. The mining method was used to build Duct #2, a single-span, two-story straight wall arch construction with an outside profile of 11.1 meters wide and 16.12 meters high, a top cover of about 15.2 meters, and a bottom slab sunk at a depth of about 31.3 meters.

With an excavation width of 7.8 meters and a height of 6.17 meters at its connection to the evacuation tunnel, the Transfer Channel #2 structure has a subgrade burial depth of roughly 24.97 meters and an overburden of about 18.8 meters. It is a single-span, one-story straight-walled arch structure.

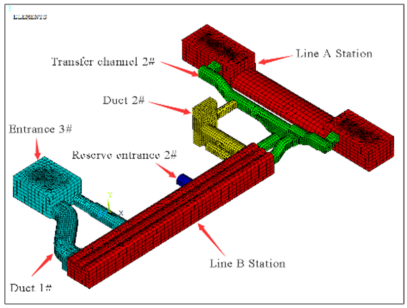
The geotechnical strata at the pit construction are, from top to bottom: ①$_1$ house residue, ③$_1$ silty clay, ④fine sand, ④$_1$ medium-coarse sand, ⑤pebbles, ⑥ silty clay, ⑥$_1$ clay, ⑦pebbles.

3 Modeling

If the soil adheres to the elastic-plastic material ontological model and that the Drucker-Prager yield criterion is satisfied, a three-dimensional solid finite element numerical model is established using ANSYS, including the metro station and attachment structures is established considering the effects of practical engineering. The model is 280 meters long from east to west, 220 meters long from north to south, and 60 meters deep. The inter-station connection (including the station transfer channel and ducts and other linkage structures) will be simulated using Shell63 shell units, while the soil and major structure of the existing station will be simulated using Solid45 solid units, as shown in Figure 3.



(a) Overall model



(b) New foundation pits and existing structures

Fig. 3. Three-dimensional finite element models

3.1 Model assumptions

(1) The soil is a homogenous, isotropic, perfect elastic-plastic body, with simplified layers and surfaces that are uniformly stacked in the horizontal direction;

(2) The geotechnical body reaches an equilibrium state under self-weight before the foundation pit is dug because the initial ground stress in the model calculation only takes the soil body's self-weight stress into account; the structural stress of the geotechnical body is not considered;

(3) Based on the soil parameters listed in the engineering ground investigation report, choose the model's necessary soil parameters.

3.2 Model parameters

A weighted average of the comparable soil parameters was calculated based on the stratigraphic characteristics of the geological survey report. The model soil parameters are shown in Table 1.

Table 1. Table of physical and mechanical properties of soil layers

Soil layer number	Name of the Geotechnical	Cohesion (kPa)	Angle of internal friction (°)	Poisson's ratio	Elastic modulus (MPa)
①$_1$	House residue	—	8	—	133.27
③$_1$	Silty clay	36	12	0.31	217.78
④	Fine sand	6	30	0.26	336.82
④$_1$	Medium coarse sand	—	35	0.25	380.8
⑤	Pebbles	—	45	0.23	859.91
⑥	Silty clay	42	18	0.29	349.45
⑥$_1$	Clay	38.3	16.3	0.35	350
⑦	Pebbles	—	45	0.21	1045.93

The structure parameters are provided in Table 2, while both new and existing structures are considered as linear elastic materials according to the calculation assumptions.

Table 2. Table of structure parameters

Serial number	Name of structure	Concrete strength	Density (kg/m^3)	Poisson's ratio	Elastic modulus (MPa)
1	Station outline structure	C40	2380	0.24	3.25×10^4
2	Station center floor slab and longitudinal beam	C40	2380	0.24	3.25×10^4
3	Structural columns in the station	C55	2430	0.23	3.55×10^4
4	Entrance #3 main structure	C35	2360	0.24	3.15×10^4
5	Entrance #3 and exit structure column	C55	2430	0.23	3.55×10^4
6	New pit retaining piles	C50	2420	0.23	3.45×10^4
7	Structural columns in new foundation pits	C55	2430	0.23	3.55×10^4
8	New foundation floor slab and longitudinal beam	C35	2360	0.24	3.15×10^4
9	New foundation pit inner side wall	C40	2380	0.24	3.25×10^4

The construction sequence of the pit cover excavation was simulated using the "Life and Death Unit" of ANSYS based on the created 3D solid model, as shown in Figure 4. The simulation process included 20 stages, including the construction of the retaining pile, the construction of the pile foundation, the excavation of the soil layer, and the construction of the structure.

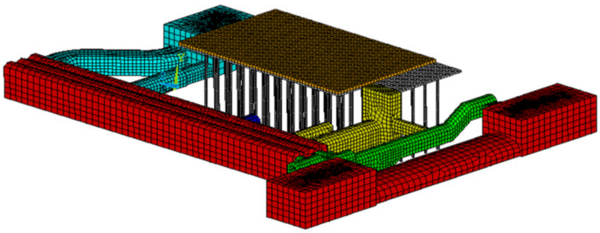


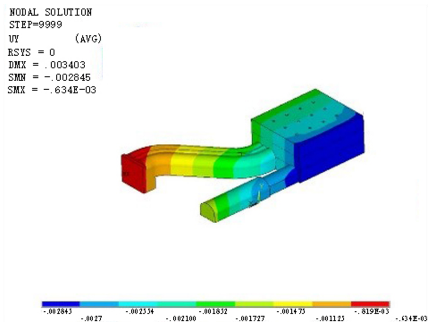
Fig. 4. Schematic representation of typical construction stages

4 Analysis of simulation results

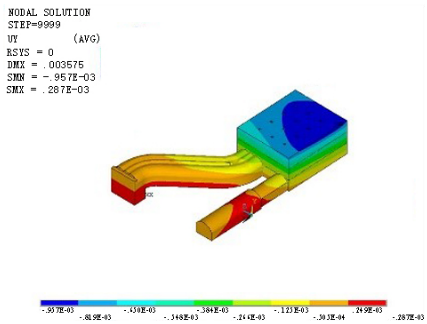
The final deformation findings for the attachment structures in each construction phase of the metro station were computed numerically using ANSYS finite element software utilizing a static analysis solver.

4.1 Overall structure of Entrance 3# and Duct 1#

The overall structural appendage of metro Entrance #3 and Duct #1 experiences some extra deformation as a result of the building of the new foundation pit cover excavation in reverse. The final horizontal deformation of the structure is 0.957 mm, moving towards the excavation side of the pit, with the deformation area close to the northwest side wall of the pit. The final vertical deformation of the structure is 2.845 mm, which is a sinking deformation, and the deformation starts as a slight uplift and gradually increases in the sinking direction, as shown in Figure 5.



(a) Nephogram of maximum vertical



(b) Nephogram of maximum horizontal deformation

Fig. 5. Deformation cloud of the attachment structure

The development of the pit will have a big impact on Entrance #3 and Duct #1 since they are the closest structures to the pit and are situated on its western side, 3.8 meters from its western sidewall, and 2.8 meters from its outer side retaining piles.

To examine the degree of deformation in each construction phase and its deformation trend over time, a total of three structural critical control points—CK1, CK2, and CK3—were chosen from the trend of the cloud diagram, as shown in Figure 6.

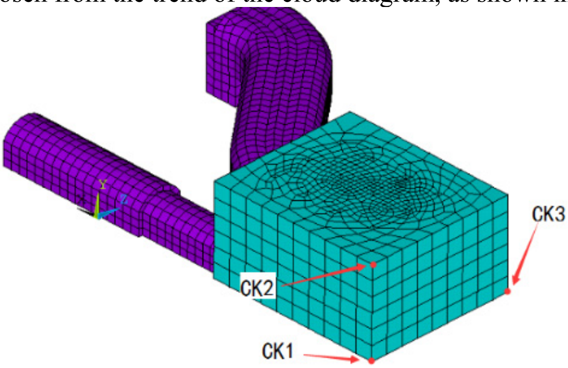
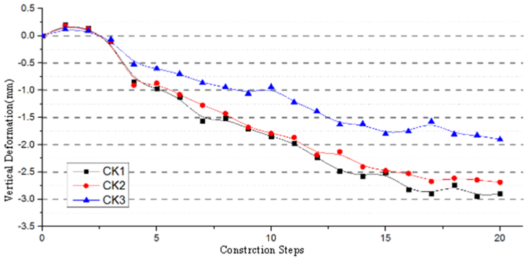
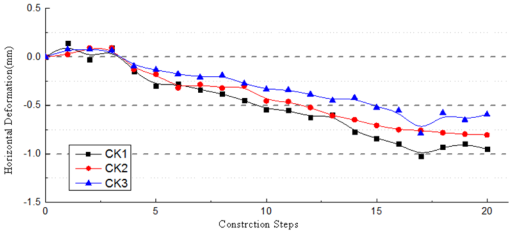


Fig. 6. Location of selected structural key points

Figure 7 displays the time course curves for the vertical and horizontal deformation of the three sites. The overall deformation curve demonstrates that the structure's main body is sinking, and the values for horizontal deformation and sinking deformation at the base of the structure (CK1) are marginally higher than those at the top (CK2) and distal end (CK3) of the structure, with the difference tending to grow gradually. With a difference between the upper and lower ends of the structure between 0.2 and 0.35 mm, the higher end of the structure has slightly less subsidence deformation.



(a) Vertical deformation

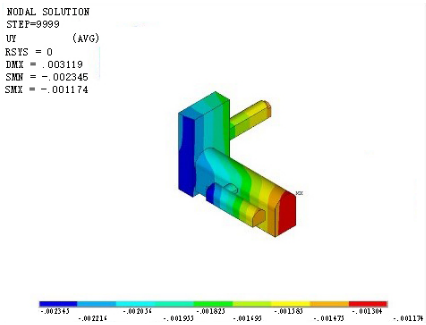


(b) Horizontal deformation

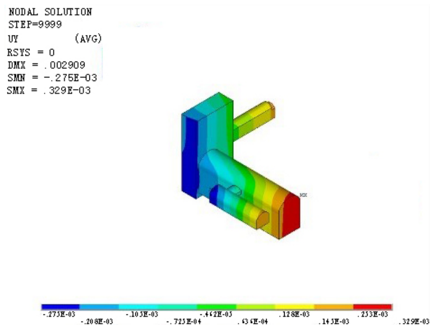
Fig. 7. Vertical and horizontal deformation curves at key points

4.2 Duct structure 2#

Figure 8 illustrates the additional deformation that the new pit cover excavation against the work caused to the existing Duct #2 structure. Maximum horizontal deformation is 0.329 mm, which is biased towards the excavated side of the pit, and the deformation is close to the southeast sidewall on the pit side. Maximum vertical deformation is 2.346 mm, a subsidence deformation, which occurred close to the southeast position of the pit.



(a) Nephogram of maximum vertical deformation



(b) Nephogram of maximum horizontal deformation

Fig. 8. Deformation cloud of the attachment structure

Duct #2 structure, which is influenced by pit excavation and is an important structure to watch, is situated at the southeast corner of the pit, between 3.1 and 4.5 meters from the site of the pit enclosing piles. Four observation stations (as illustrated in Figure 9) were chosen by the constructed model to monitor the structure's deformation trend and degree.

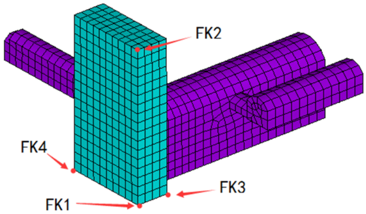
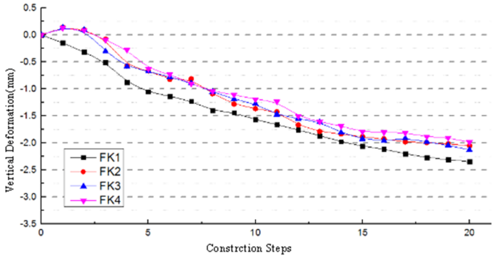
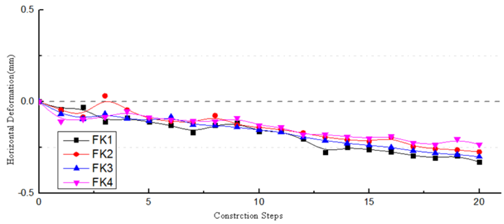


Fig. 9. Location of selected structural key points

The numerical results for the north and west sides of the duct structure next to the pit were extracted to determine the vertical and horizontal deformations of FK1 to FK4 at each construction stage, and their time-course curves were shown as shown in Figure 10. The size of the structure's sinking value and rate of sinking were somewhat bigger than the remaining three critical sites. The deformation of the structure from the lower proximal position of the pit (FK1) has been greater, with a final sinking deformation value of 2.342 mm. Duct #2 structure is a tiny attachment structure that is attached to the transfer channel and the main body of the metro station directly. As a result of the considerable limits placed on the structures, there is little fluctuation in the deformation's horizontal location.



(a) Vertical deformation

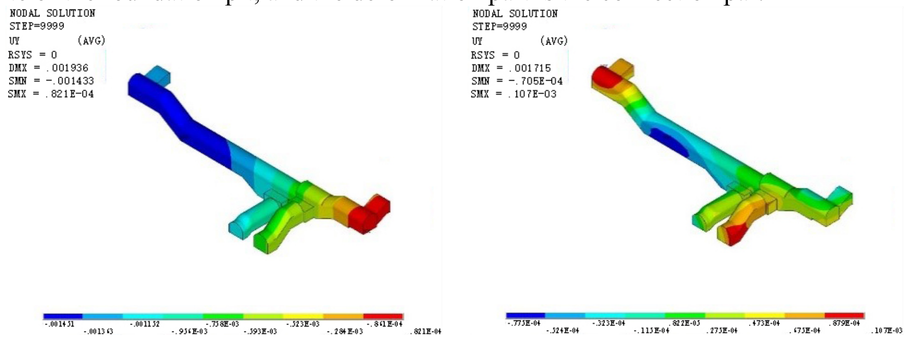


(b) Horizontal deformation

Fig. 10. Vertical and horizontal deformation curves at key points

4.3 Transfer channel #2 structure

The existing Transfer Channel #2 structure has experienced some additional deformation as a result of the construction of the new foundation pit cover excavation, as shown in Figure 11. The maximum vertical deformation is 1.431mm, which is subsidence deformation and occurs close to the location of the foundation pit due east; the maximum horizontal deformation is 0.705 mm, which moves away from the excavation site of the foundation pit, and the deformation part is the connection par.



(a) Nephogram of maximum vertical deformation (b) Nephogram of maximum horizontal deformation

Fig. 11. Nephogram of the attachment structure deformation

The northernmost portion of the tunnel is the closest to the foundation pit position, which is 25.1 m away. Transfer Channel #2 that connects the metro line A station and the metro line B station. Its geometry is complicated and the tunnel sections differ from one another in many places. As depicted in Figure 12, three points—TK1 closest to the location of the foundation pit excavation, TK2 lower endpoint of the north side where the main structure of the metro line B station meets, and TK3 lower endpoint of the north side where the main structure of the metro line A station meets—were all chosen. The closest point to the excavation site is designated as TK1, the lower endpoint at the northern side where the main structure of the metro line B station meets at TK2, and the major structure of the line A station at the northern side at TK3.

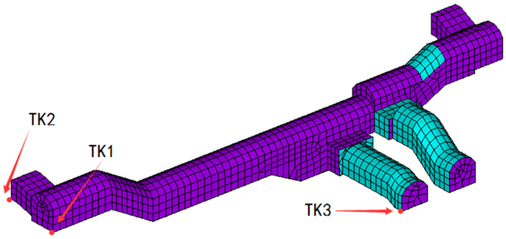
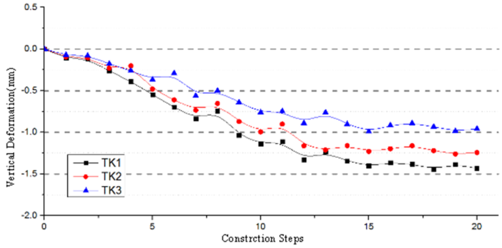


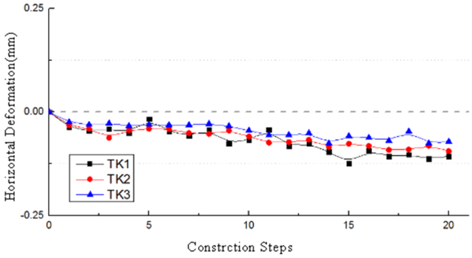
Fig. 12. Location of selected structural key points

According to the requirements, the values of variation of the three points at each step of construction were extracted, and corresponding time curves were created, as shown in Figure 13. The closest location of Transfer Channel #2 structure to the foundation pit (TK1) experienced a final vertical settlement of 1.426 mm and a final horizontal deformation of 0.107 mm, both of which were in the direction of the excavation of the foundation pit and to a lesser extent at the connection to the main station structure. The final vertical deformation at TK2 and TK3 experienced final vertical deformation of

1.236 mm and 0.943 mm, respectively, while their respective horizontal deformations were both less than 0.1 mm. Because Transfer Channel #2 is a tube wall structure without any internal vertical support structures like columns, its overall stiffness is lower than that of the main body of the station, which is supported by a column structure.



(a) Vertical deformation



(b) Horizontal deformation

Fig. 13. Vertical and horizontal deformation curves at key points

5 Conclusion

The degree of the pit construction's impact on the existing metro attachment structure was examined through the development of an ANSYS 3D finite element model. The existing station attachment structure displayed a sinking trend while the new pit was being built, and the deformation of the overall structure of the closest Entrance #3 and Duct #1 was 2.845 mm, followed by the deformation of Duct #2 structure at 2.346 mm, and the structure of Transfer Channel #2 was 1.431 mm because of its design. Due to the inherent nature of the Transfer Channel #2 structure, its deformation is 1.431 mm.

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