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*Research Article*

# Investigation effect of metro entrance and exit construction on pedestrian overpass safety using numerical modelling and simulation

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**Abstract**

Due to the complex working conditions of deep burial, proximity, and multiple interferences unique to subway engineering, the construction process inevitably causes additional deformation or even local damage to adjacent existing structures. In order to systematically study the settlement of pedestrian overpass foundation and deformation mechanism of upper structure caused by the construction of a certain subway entrance and exit, this paper takes the structural load characteristics and construction sequence of the subway entrance and exit as the starting point, integrates regional traffic organization and on-site construction constraints, and constructs a three-dimensional dynamic construction numerical model. The displacement response of pedestrian overpass foundation during the entire excavation and support loading process was accurately simulated using nonlinear coupling algorithm. The final results show that the established support system and construction parameter control provided best values in terms of horizontal and vertical displacements. The maximum horizontal displacement of the pedestrian overpass pile foundation induced by subway entrance and exit construction is 0.3 mm. The maximum vertical displacement of the main span pile foundation is 1.9 mm. Both values are considered lower than the standard limits, including the allowable total settlement value of the pile foundation of 127 mm and the horizontal displacement limit of the pile foundation of 31mm. The above results quantitatively verify the "controllability" of the impact of subway entrance and exit construction on the structural safety of pedestrian overpasses, which can provide theoretical basis and technical paradigm for risk assessment and dynamic control similar to adjacent construction.



## 1. Introduction

During With the acceleration of urbanization, rail transit has become an important part of the urban traffic system, and more metros and tunnels are being developed and utilized [1]. Tunnel construction, especially in hilly areas, is mainly related to complex geology and uncertainty [2]. As the integration of urban underground transportation networks and underground spaces becomes increasingly close, the interference of adjacent building activities has a greater impact on existing infrastructure [3]. For example, urban bridges and subways often exhibit a closely coupled symbiotic relationship in spatial layout [4]. The internal forces of bridge structures are extremely sensitive to environmental disturbances, and even small changes in boundary conditions can cause a redistribution of the transmission path [5].

Urban metro construction, due to its long construction period and mostly in the bustling areas of the city, is mainly shallow buried and excavated [6]. According to the particularity of metro projects, shallow buried tunnels will affect the surface rock and soil, which may lead to ground

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collapse and road damage, and these factors will damage the structure of surrounding structures, making the impact of metro construction on the safety of adjacent buildings increasingly prominent [7]. He Y et al. [8] investigated the effect of subway foundation pit excavation and train-induced vibrations on adjacent architectural heritage through a case study of the City Square Station in Shaoxing. Li Q et al. [9] Explored the safety evaluation method for adjacent buildings during shield tunnel construction. Among them, the ground movement induced by metro construction and its impact on nearby buildings and the huge losses caused have made the accurate prediction of surface settlement and the provision of control standards a focus of research in the field of underground space engineering [10].

Zhou Limei [11] used numerical analysis and on-site detection to conduct safety impact analysis on the main risk points during the construction process of the station. Zhang JT et al. [12] analyzed the surface settlement caused by shallow tunnel excavation, as well as the deformation and internal forces of pile foundations. They found that the maximum horizontal displacement of the pile foundation (3.63 mm) exceeded the deformation control index (3 mm) and had a significant impact on the internal forces of adjacent pile foundations. Liu Z et al. [13] established the relationship between shield parameters and strata in finite element calculations, analyzing the impact of different shield parameters and support conditions on the force and deformation of existing viaduct group piles on both sides of the tunnel. Li L et al. [14] designed orthogonal experiments to analyze the sensitivity of parameters affecting buildings above the metro shield construction. Ju X [15] conducted research on the deformation impact of tunnel shield construction on surface structures and derived surface deformation formulas, obtaining a reasonable range of support parameters. Some scholars used numerical analysis software to conduct numerical analysis on the impact of urban metro construction on surface settlement [16]. Luo Q et al. [17] conducted a three-dimensional fine numerical simulation study on artificial freezing during the construction of subway pedestrian crossings. Yi LB et al. [18] used Midas/GTS software for finite element analysis to study the characteristics of displacement changes of the bridge deck, piers, abutments, and bridge piles during the construction process of the Beijing Extra Large Bridge of the Beijing Shanghai High speed Railway under the large section underground excavation section. Hu B et al. [19] used ABAQUS software to simulate the impact of soil disturbance caused by deep excavation on the displacement of underground pipelines. Zhou Y et al. [20] used finite element software ADINA for numerical simulation of excavation of foundation pits, analyzing the effects of horizontal and vertical displacement of foundation pits, as well as pre stress and angle of anchor rods on the displacement of support structures. The previous studies have significantly advanced the research on surface structure safety assessment during subway construction. However, there are still shortcomings in previous research on safety assessments of surface structures during subway construction. The assessments are data utilization, refined risk, multi-factor coupling, and surrounding buildings impact. Therefore, further and depth research is required in the structural safety field of the subway.

The safety of surface structures of metro construction excavation has always been a focus of many scholars and experts. This paper investigates the safety impact of a certain metro entrance and exit construction on a pedestrian overpass. It combines the structural characteristics of the pedestrian overpass and the spatial relationship with the metro entrance and exit. Furthermore, the current research aims to focus on the construction methods and characteristics of the metro entrance and exit using numerical modeling (three-dimensional finite element model) and simulation (Midas Gen 2022 structural analysis software). This study analyzes the adverse effects of metro entrance and exit construction on the pedestrian overpass. It focuses on the deformation of the pedestrian overpass step section and the main span foundation structure, and then it analyzes the structural safety of the pedestrian overpass.

## 2. Research Methodology

### 2.1 Project Overview

The construction site of a certain subway entrance and exit is located directly below a pedestrian overpass. The main span of the overpass is approximately 40.5 m. The subway entrance and exit consist of a dark excavation section and a straight section, which are mainly composed of standard sections and civil air defense sections. Among them, the standard section is 8.0 m, and the civil air defense section is 9.0 m. The subway entrance and exit are positioned relative to the overpass pile foundation as shown in Fig. 1. The bottom of the pile foundation is 0.86 meters away from the net distance of the straight section of the subway entrance and exit. The escalator section is constructed to pass under the stair section of the pedestrian overpass, and the bottom of the main span pile foundation of the overpass partially overlaps with the local position of the foundation of the escalator section. The escalator section will directly cut off the overlapping pile foundation during excavation. Fig. 2 shows the longitudinal cross-sectional view of the subway entrance and exit and the overpass pile foundation.

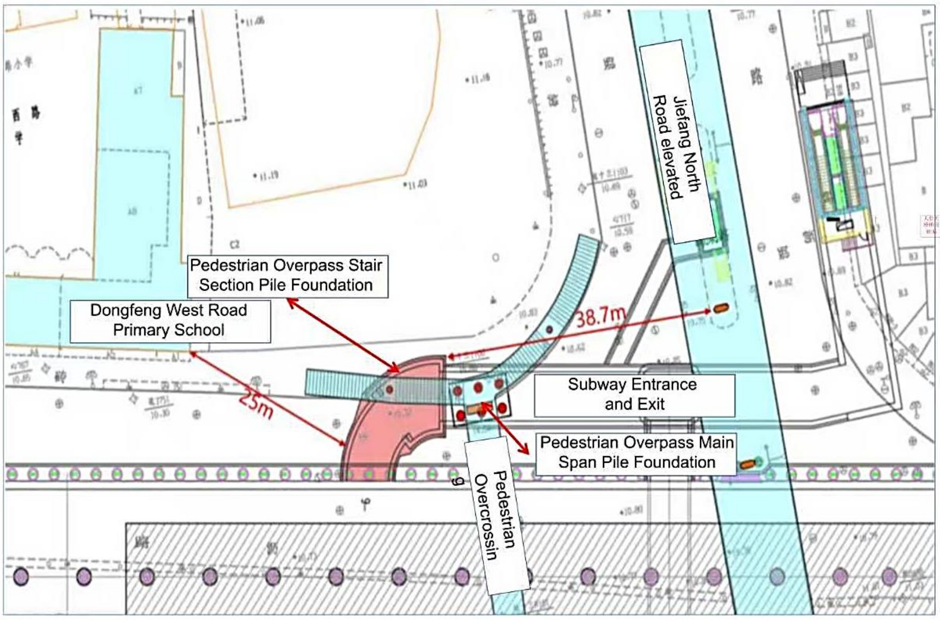



Fig. 1. Relative position of pile foundation of subway entrances and pedestrian bridge

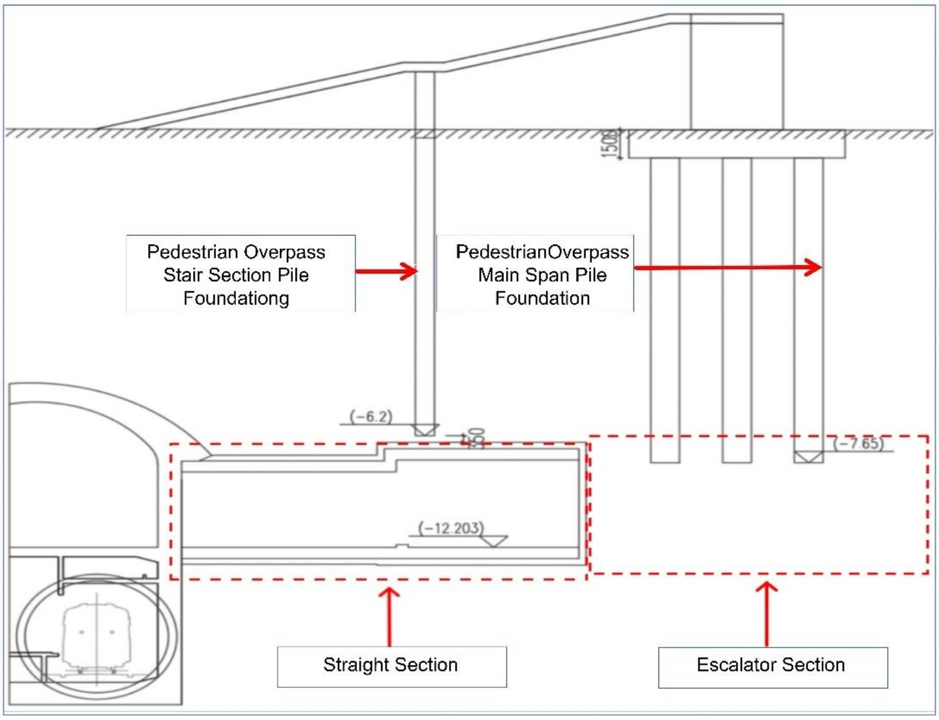



Fig. 2. Longitudinal section of pile foundation of subway entrance and exit and pedestrian bridge

## 2.2. 3D Modeling and Simulation

According to the three-dimensional relationship of pedestrian bridge and subway entrance and the construction characteristics, the 3D finite element calculation model is established. As shown in Fig. 3 is the 3D dimensional finite element integral model, and Fig. 4 shows the construction condition of subway entrance and exit. A three-dimensional finite element model was established using Midas Gen 2022 software, and solid elements were used for soil and bridge structures. The soil parameters of the model are detailed in Table 1, and the load parameters of the model are detailed in Table 2. The three-dimensional finite element model of this study is established based on nonlinear coupling algorithm, considering the soil structure interaction and the nonlinear contact between bridge pier foundation support structure. The computational model adopts the Mohr Coulomb criterion, which is based on the definition of ideal elastic-plastic behavior. For general nonlinear analysis of rocks and soils, this behavior is assumed. The results are completely reliable and therefore widely used to simulate most rock and soil types.

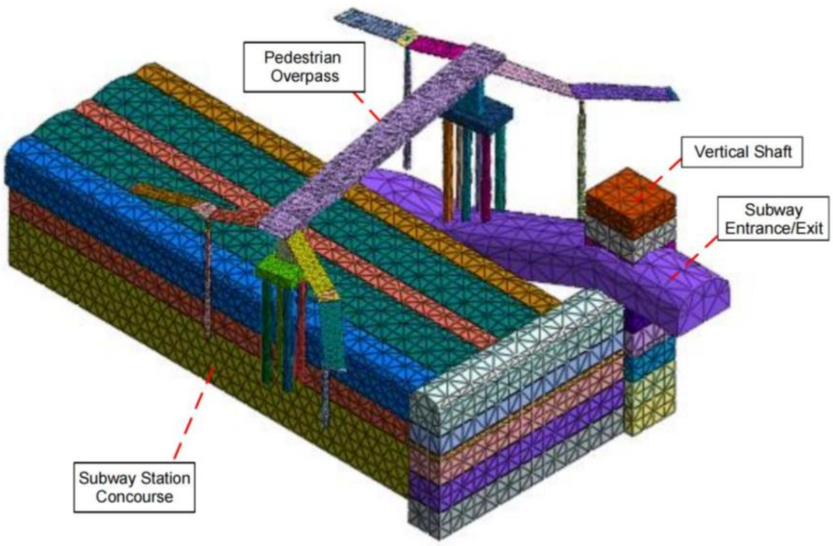



Fig. 3. 3D Finite element overall model

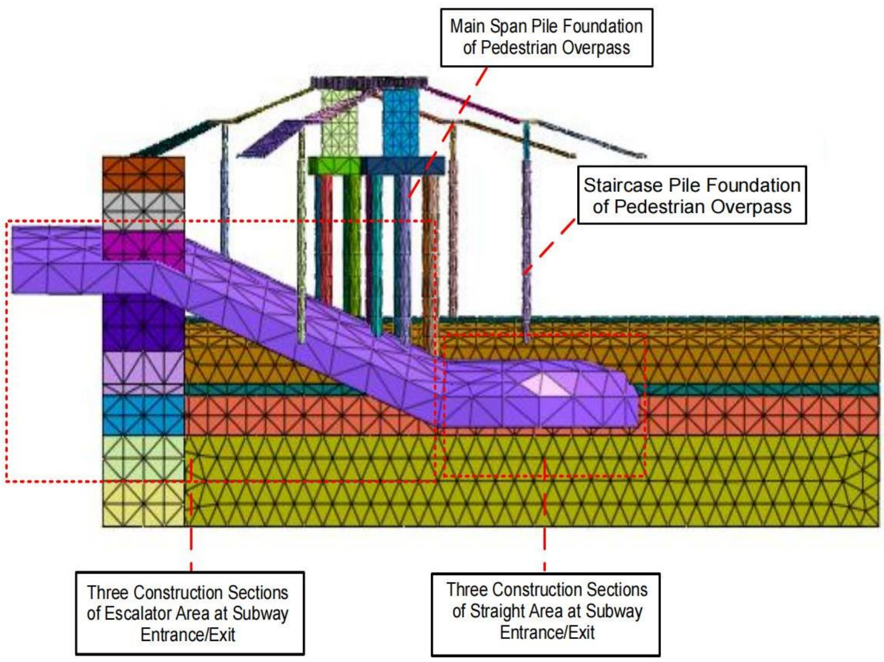



Fig. 4. Construction condition of the subway entrance and exit

Table 1. Soil parameters of the 3D finite element model

| Soil layer name | Natural density ($g/cm^3$) | Side friction resistance (kPa) | Soil foundation coefficient (MPa/m) | Coefficient of earth pressure at rest |
|---|---|---|---|---|
| Plain fill | 1.91 | 12 | 8 | 0.50 |
| Silty fine sand | 1.93 | 15 | 12 | 0.38 |
| Plastic powdery clay | 1.53 | 25 | 20 | 0.45 |
| Silt | 1.53 | 8 | 5 | 0.75 |
| Mucky soil | 1.77 | 8 | 7 | 0.75 |

Table 2. Load parameters of 3D finite element model

| Load name | Load parameters |
|---|---|
| self-weight | The self-weight of reinforced concrete is calculated at 25 $kN/m^3$ |
| Cover soil load | The soil cover weight is $\gamma$=20 $kN/m^3$, and under anti floating conditions, it is taken as $\gamma$=18 $kN/m^3$ |
| Lateral soil and water load | Cohesive soil is calculated based on water and soil, while sandy soil is calculated based on water and soil |
| Water level | The water level on the outer side of the foundation pit is taken from the surface, and the inner side is 0.5 m below the bottom of the pit |
| Construction load | 5 kPa |

According to the relative position relationship between the straight section and the escalator section and the pedestrian overpass pile foundation, the excavation section of the straight section is divided into three construction processes, and the escalator section is also divided into three construction processes. The 3D dynamic construction simulation conditions of the influence of the subway entrance and exit construction on the pedestrian bridge foundation structure are shown in Table 3. The research flowchart of this article is shown in Fig. 5

Table 3. Construction conditions

| Construction state | Main construction content |
|---|---|
| Working condition 1 | Initial ground stress field analysis of the site |
| Working condition 2 | Construction of the subway station hall was completed |
| Working condition 3 | Initial construction of the straight section of the subway entrance and excavation 1 |
| Working condition 4 | Construction of the straight section 1 lining structure |
| Working condition 5 | Initial construction of the straight section of the subway entrance and excavation 2 |
| Working condition 6 | Construction of the straight section 2 lining structure |
| Working condition 7 | Initial construction of the straight section of the subway entrance and excavation 3 |
| Working condition 8 | Construction of the straight section 3 lining structure |
| Working condition 9 | Initial construction of escalator section of subway entrance and excavation 1 |
| Working condition 10 | Construction of the lining structure of the escalator section 1 |
| Working condition 11 | Initial branch construction and excavation of escalator section of subway entrance and exit 2 |
| Working condition 12 | Construction of the lining structure of the escalator section 2 |
| Working condition 13 | Initial construction of escalator section of subway entrance and excavation 3 |
| Working condition 14 | Construction of the lining structure of escalator section 3 |

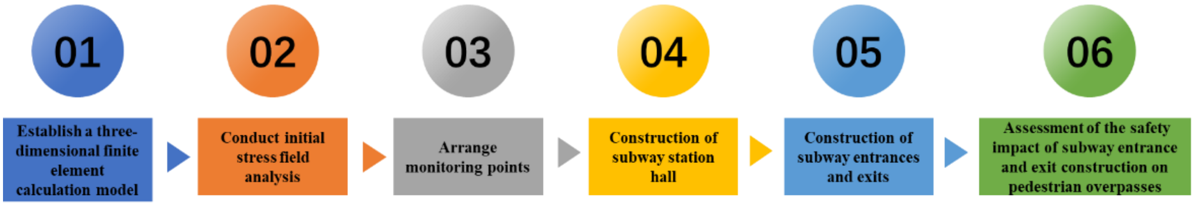



Fig. 5. Research flowchart

## 3. Results and Discussion

The influence of subway entrance and exit construction on the pedestrian bridge foundation has been investigated in X, Y, and Z directions using displacement results of 3D simulation analysis as shown in (Figs. 6-11). The staircase section and main span pile foundation displacements of pedestrian bridge under key working conditions during construction of subway entrance and exit are presented in Tables 4 and 5. From the data in Table. 4, it can be seen that the maximum X displacement of the staircase section pile foundation of pedestrian bridge is 0.2 mm, the maximum Y displacement is 0.4 mm, the maximum vertical displacement is 1.3 mm, and the maximum total displacement is 1.3 mm. From the data in Table. 5, it can be seen that the maximum X displacement of the main span pile foundation of pedestrian bridge is 0.3 mm, the maximum Y displacement is 0.4 mm, the maximum vertical displacement is 1.9 mm, and the maximum total displacement is 1.9 mm. According to the results in the Tables 4 and 5, during the construction of the proposed project, the maximum settlement of the main span pile foundation on the north and south sides of the adjacent foundations of the pedestrian bridge is 1.9 mm and 1.6 mm respectively, and the maximum settlement difference is 0.3 mm. The maximum settlement difference between the staircase section and the main span pile foundation is 0.6 mm.

Based on the three-dimensional simulation analysis of displacement results and on-site construction environment, this article analyzes the mechanism of settlement of pedestrian overpass foundations caused by subway entrance and exit construction as follows: (1) During excavation of foundation pits or subway entrance and exit construction, the original soil is removed, causing changes in the stress state of the surrounding soil, resulting in unloading rebound and lateral soil pressure reduction, which in turn causes settlement or uplift of the soil below the foundation of adjacent pedestrian overpasses; (2) If the foundation of a pedestrian overpass is located on a soil layer, soft soil layer, or mixed soil layer, and the subway construction disturbs these soil layers, it will cause a decrease in the local bearing capacity of the foundation and result in uneven settlement; (3) If precipitation or groundwater disturbance occurs during the construction process, it will cause a decrease in pore water pressure, leading to an increase in effective stress in the soil and further exacerbating settlement.

According to the industry standard of the People's Republic of China (Specifications for Maintenance of Highway Bridges and Culverts, JTG 5120-2021), the allowable total settlement value for simply supported bridge pile foundations is 127 mm, and the horizontal displacement limit for pile foundations is 31 mm. In view of the displacement of controllable, is far less than the allowable value of foundation deformation, so the subway entrance construction does not endanger the safety of the pedestrian bridge pile foundation. Therefore, it is considered that the construction of subway entrances and exits has little impact on the safety of the pedestrian bridge pile foundation. Therefore, it is suggested to pay close attention to the monitoring data of the bridge foundation in the construction process and carry out information construction.

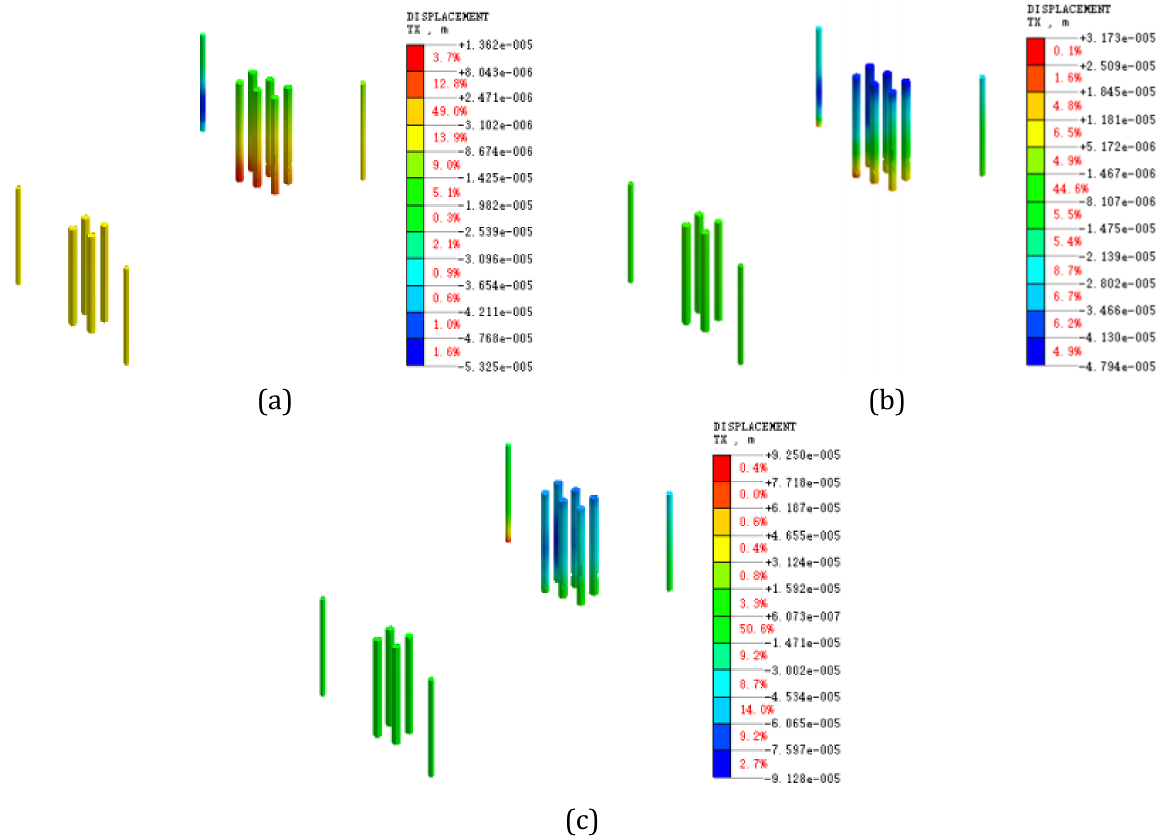



Fig. 6. X-direction displacements of pedestrian bridge pile infrastructure in (m) using initial support construction and excavation of subway entrance and exit straight sections (a) case 1 (b) case 2 (c) case 3

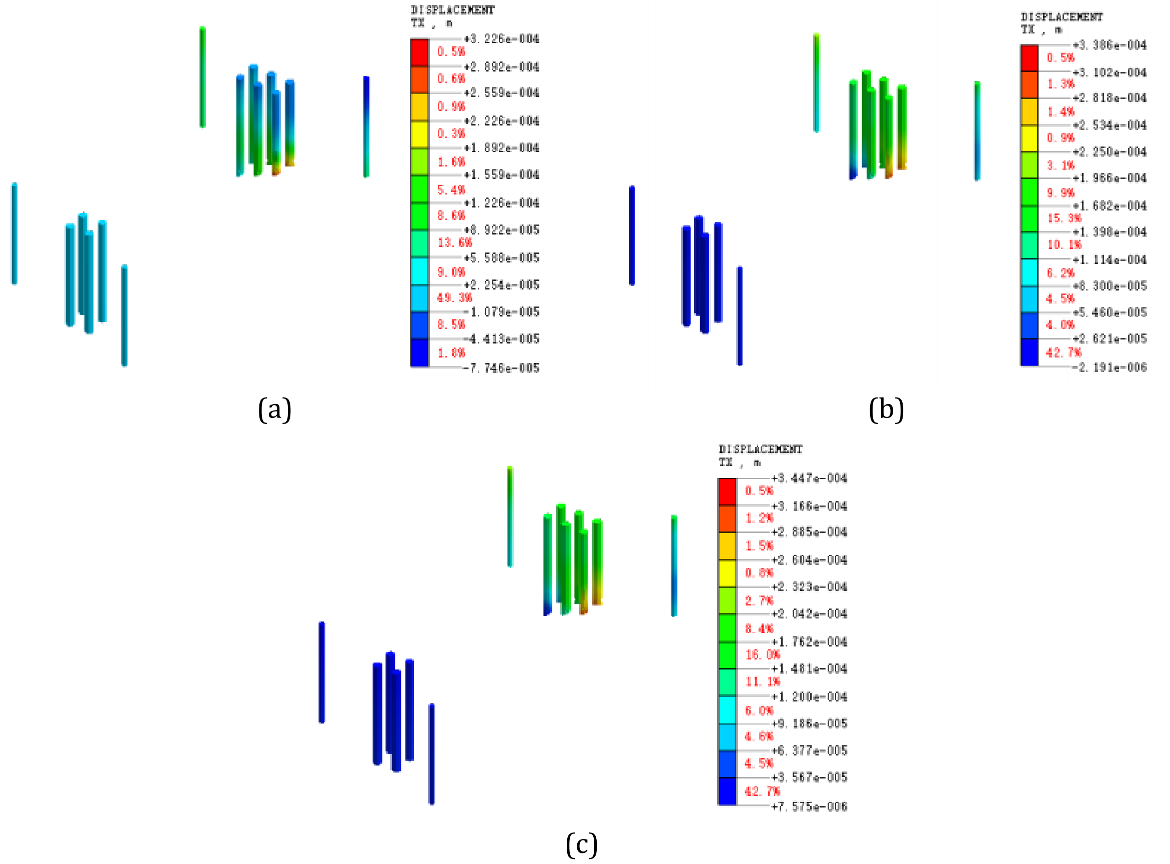



Fig. 7. X-direction displacements of pedestrian bridge pile infrastructure in (m) using initial support construction and excavation of escalator sections at subway entrance and exit (a) case 1 (b) case 2 (c) case 3

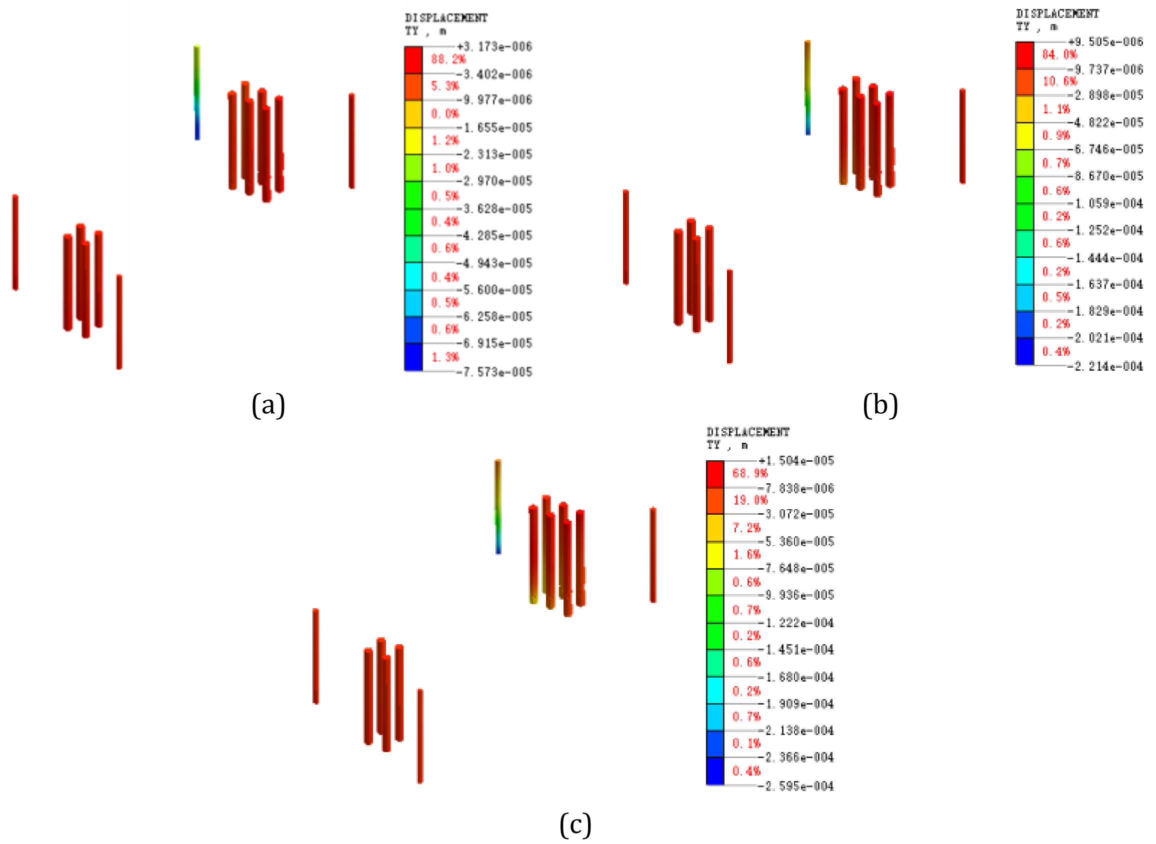



Fig. 8. Y-direction displacements of pedestrian bridge pile infrastructure in (m) using initial support construction and excavation of subway entrance and exit straight sections (a) case 1 (b) case 2 (c) case 3

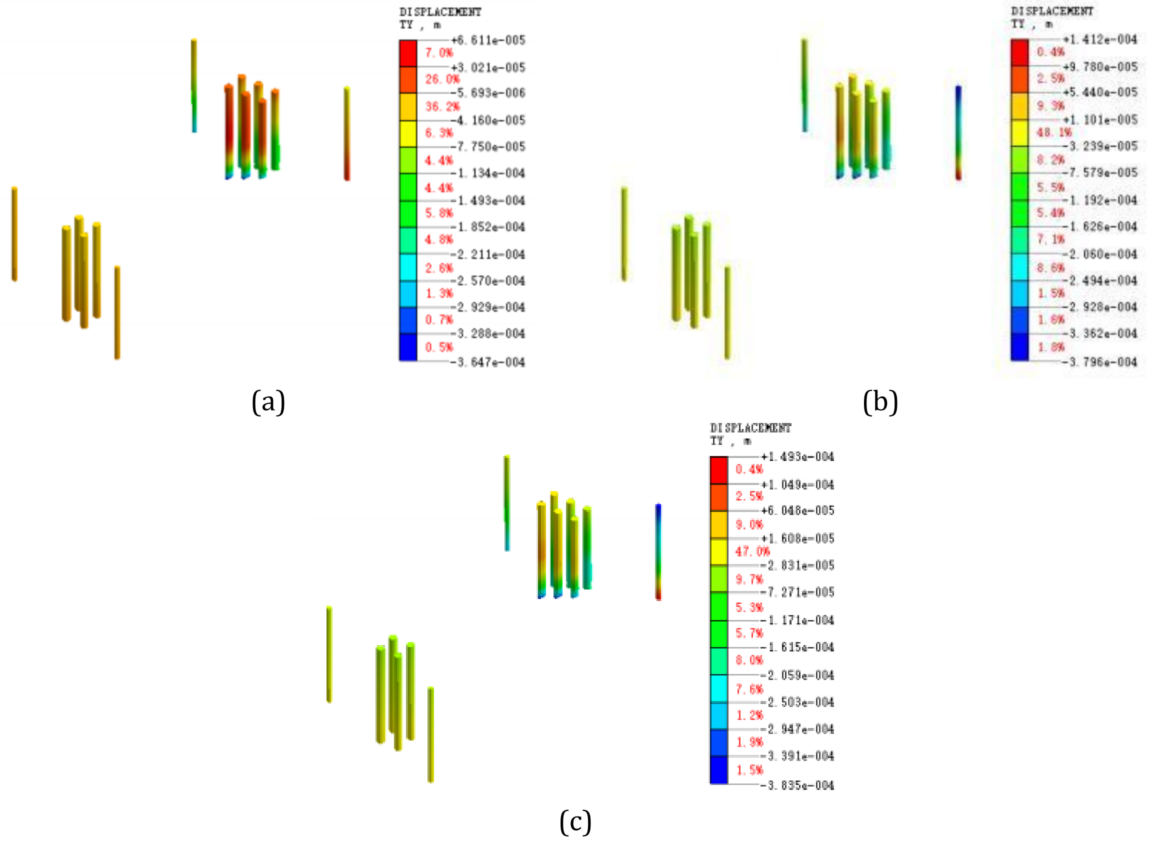



Fig. 9. Y-direction displacements of pedestrian bridge pile infrastructure in (m) using initial support construction and excavation of escalator sections at subway entrance and exit (a) case 1 (b) case 2 (c) case 3

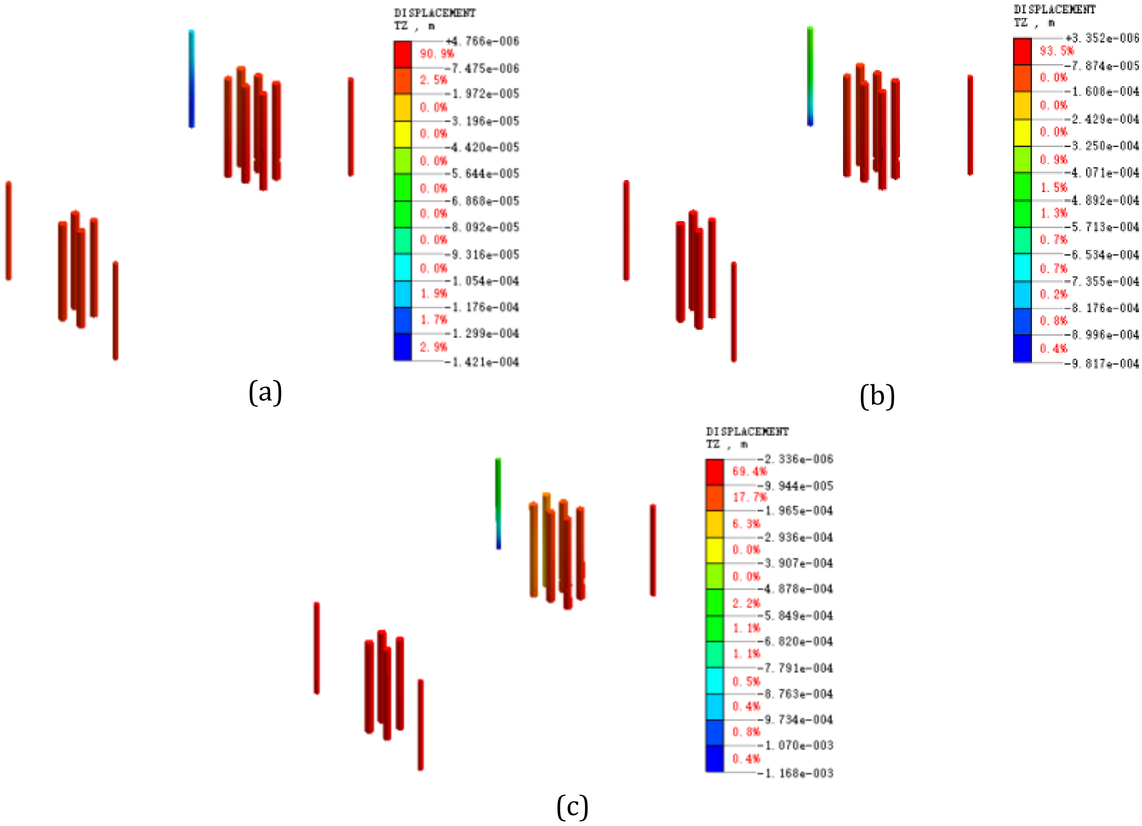



Fig. 10. Z-direction displacements of pedestrian bridge pile infrastructure in (m) using initial support construction and excavation of subway entrance and exit straight sections (a) case 1 (b) case 2 (c) case 3

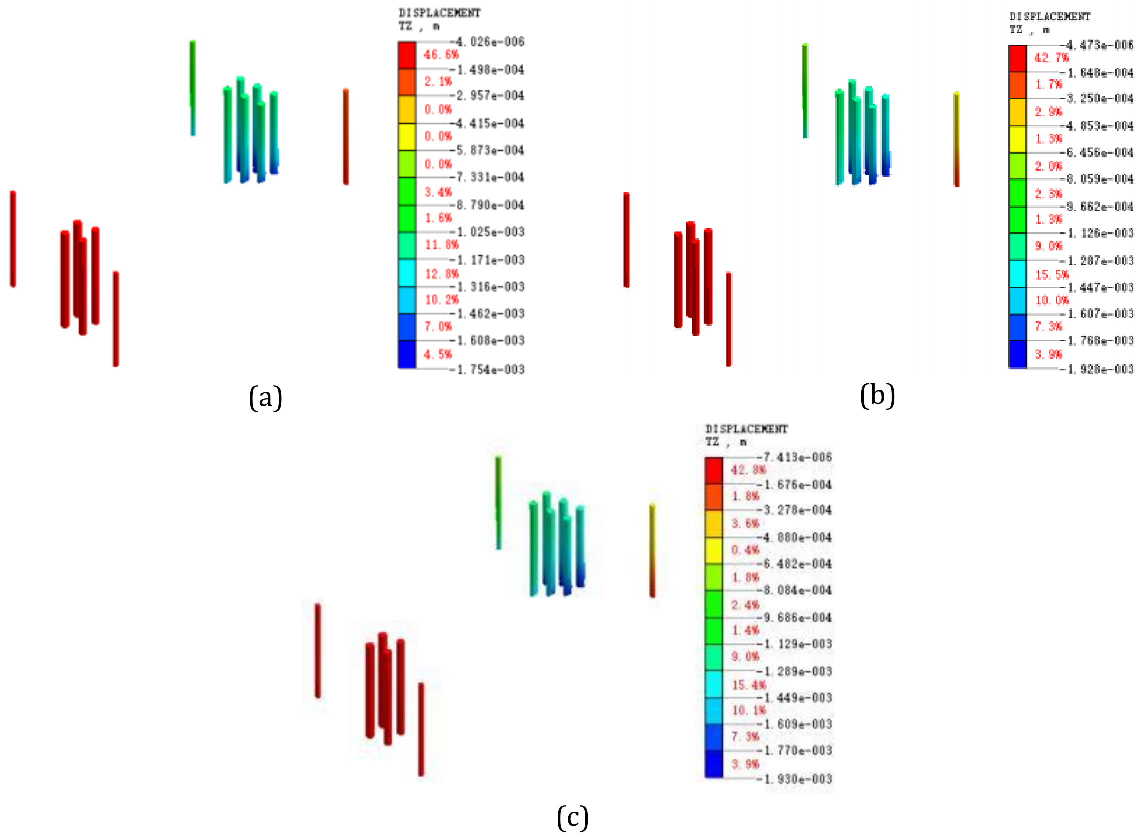



Fig. 11. Z-direction displacements of pedestrian bridge pile infrastructure in (m) using initial support construction and excavation of escalator sections at subway entrance and exit (a) case 1 (b) case 2 (c) case 3

Table 4. Staircase section pile foundation displacements of pedestrian bridge in (mm) during construction of subway entrance and exit

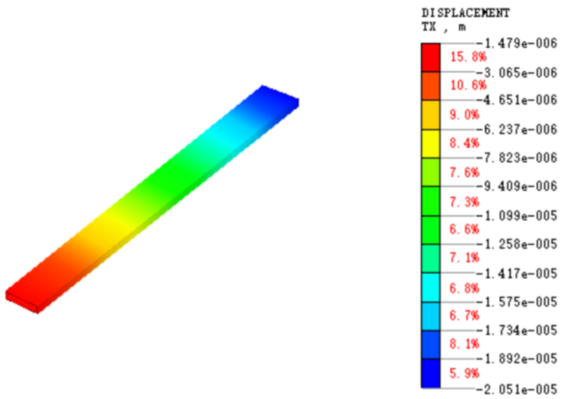
| Calculation condition | Maximum displacements in mm | | | |
|---|---|---|---|---|
| | X displacement | Y displacement | vertical displacement | Total displacement |
| Construction of the subway station hall was completed | 0.0 | 0.0 | 0.0 | 0.0 |
| Initial construction of the straight section of the subway entrance and excavation 1 | 0.1 | 0.1 | 0.1 | 0.1 |
| Construction of the straight section 1 lining structure | 0.1 | 0.1 | 0.1 | 0.1 |
| Initial construction of the straight section of the subway entrance and excavation 2 | 0.1 | 0.2 | 0.9 | 0.9 |
| Construction of the straight section 2 lining structure | 0.1 | 0.2 | 0.9 | 0.9 |
| Initial construction of the straight section of the subway entrance and excavation 3 | 0.1 | 0.3 | 1.2 | 1.2 |
| Construction of the straight section 3 lining structure | 0.1 | 0.3 | 1.2 | 1.2 |
| Initial construction of escalator section of subway entrance and excavation 1 | 0.1 | 0.3 | 1.3 | 1.3 |
| Construction of the lining structure of the escalator section 1 | 0.1 | 0.3 | 1.3 | 1.3 |
| Initial construction of escalator section of subway entrance and excavation 2 | 0.2 | 0.4 | 1.3 | 1.3 |
| Construction of the lining structure of the escalator section 2 | 0.2 | 0.4 | 1.3 | 1.3 |
| Initial construction of escalator section of subway entrance and excavation 3 | 0.2 | 0.4 | 1.3 | 1.3 |
| Construction of the lining structure of the escalator section 3 | 0.2 | 0.4 | 1.3 | 1.3 |

The influence of subway entrance and exit construction on the pedestrian bridge superstructure has been investigated in X, Y, and Z directions using displacement results of 3D simulation analysis as shown in (Figs. 12-17). The footbridge superstructure displacements under key working conditions during construction of proposed project are presented in Table. 6. The maximum X displacement of the upper part of the pedestrian bridge is 0.3 mm, the maximum Y displacement is 0.1 mm, the maximum vertical displacement is 1.3 mm, and the maximum total displacement is 1.3 mm.

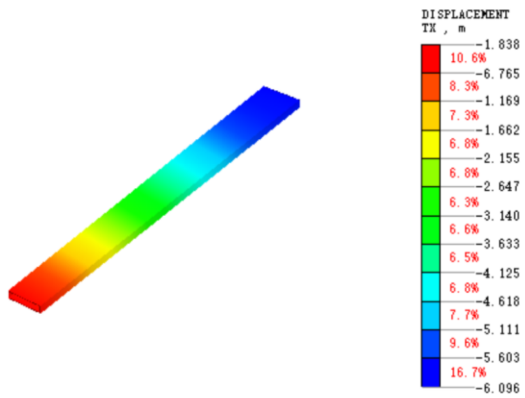
Based on the three-dimensional simulation analysis of displacement results and on-site construction environment, this article analyzes the deformation mechanism of the upper structure of pedestrian overpasses caused by the construction of subway entrances and exits as follows: (1) The structure of pedestrian overpasses is sensitive to the difference in foundation settlement. If the settlement of the foundations on both sides is uneven, the upper structure of the pedestrian bridge will experience distortion, tilting, beam cracking, or node misalignment; (2) The construction of subway entrances and exits may be accompanied by pile loads, construction machinery loads, or temporary structural loads, which are transmitted through the soil to the foundation of the overpass, causing additional settlement and redistribution of structural internal forces; (3) Dynamic loads such as pile driving, blasting, and mechanical vibration during the construction process may cause instantaneous deformation or fatigue damage to the upper structure, especially steel structure overpasses that are more sensitive to vibration. During the construction of the subway entrance and exit structure, the reinforcement measures of the pile foundation and the main span and the bridge structure, the pile foundation and superstructure of the bridge are less affected by the construction. In view of the small displacement and force of the main span steel box girder structure on the upper part of the pedestrian bridge induced by the subway entrance and exit construction, it is believed that the construction of the subway entrance and exit has little impact on the safety of the steel box girder structure on the upper part of the pedestrian bridge. It is suggested to pay close attention to the monitoring data of the bridge structure during the construction process and carry out information construction.

Table 5. Main span pile foundation displacements of pedestrian bridge in (mm) during subway entrance and exit construction

| Calculation condition | Maximum displacements in mm | | | |
|---|---|---|---|---|
| | X displacement | Y displacement | vertical displacement | total displacement |
| Construction of the subway station hall was completed | 0.0 | 0.0 | 0.0 | 0.0 |
| Initial construction of the straight section of the subway entrance and excavation 1 | 0.1 | 0.1 | 0.1 | 0.1 |
| Construction of the straight section 1 lining structure | 0.1 | 0.1 | 0.1 | 0.1 |
| Initial construction of the straight section of the subway entrance and excavation 2 | 0.1 | 0.1 | 0.1 | 0.1 |
| Construction of the straight section 2 lining structure | 0.1 | 0.1 | 0.1 | 0.1 |
| Initial construction of the straight section of the subway entrance and excavation 3 | 0.1 | 0.1 | 0.3 | 0.3 |
| Construction of the straight section 3 lining structure | 0.1 | 0.1 | 0.3 | 0.3 |
| Initial construction of escalator section of subway entrance and excavation 1 | 0.3 | 0.4 | 1.7 | 1.7 |
| Construction of the lining structure of the escalator section 1 | 0.3 | 0.4 | 1.8 | 1.8 |
| Initial construction of escalator section of subway entrance and excavation 2 | 0.3 | 0.4 | 1.9 | 1.9 |
| Construction of the lining structure of the escalator section 2 | 0.3 | 0.4 | 1.9 | 1.9 |
| Initial construction of escalator section of subway entrance and excavation 3 | 0.3 | 0.4 | 1.9 | 1.9 |
| Construction of the lining structure of escalator section 3 | 0.3 | 0.4 | 1.9 | 1.9 |

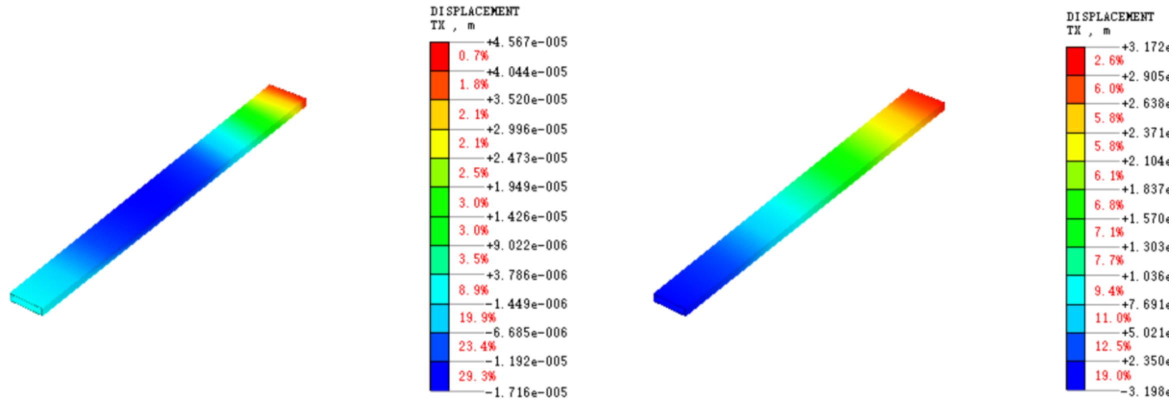



(a)



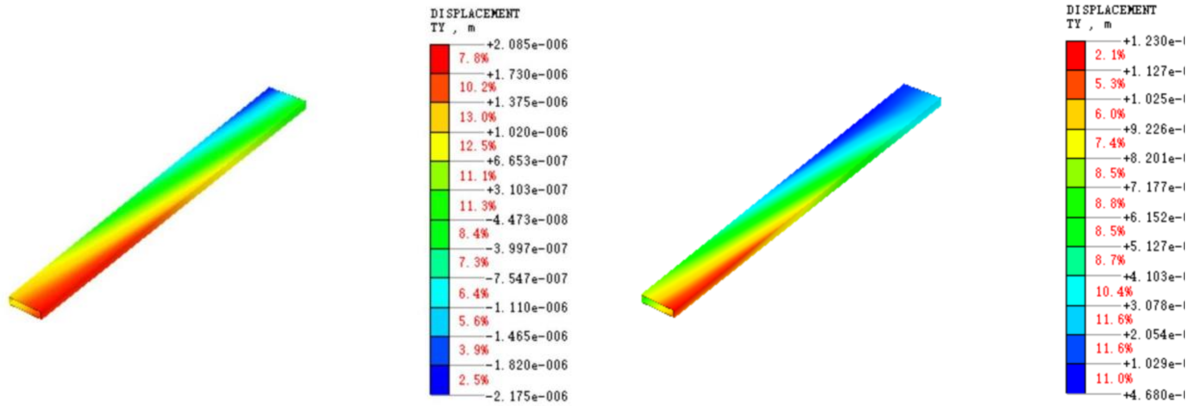

(b)

Fig. 12. X-direction displacements of main span box beam structure of pedestrian overpass pile in (m) using initial support construction and excavation of subway entrance and exit straight sections (a) case 1 (b) case 2



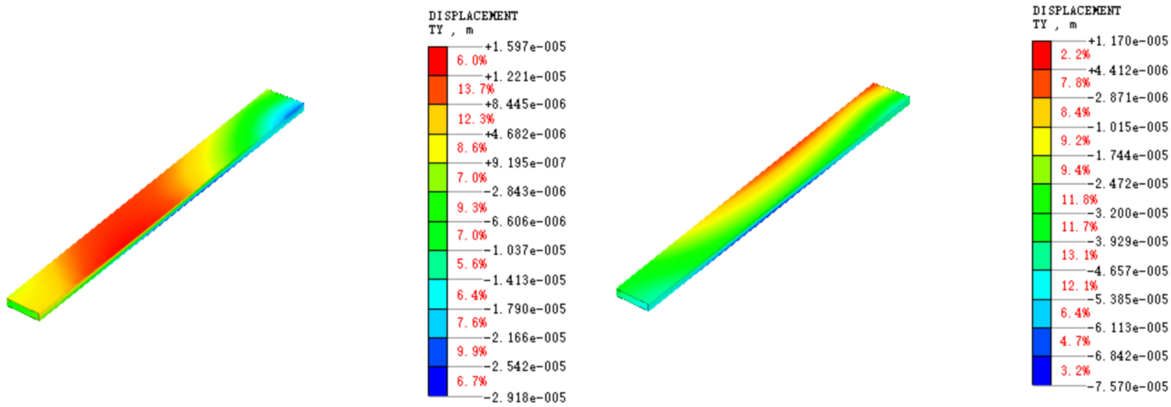

(a) (b)

Fig. 13. X-direction displacements of main span box beam structure of pedestrian overpass pile in (m) using initial support construction and excavation of escalator sections at subway entrance and exit (a) case 1 (b) case 2



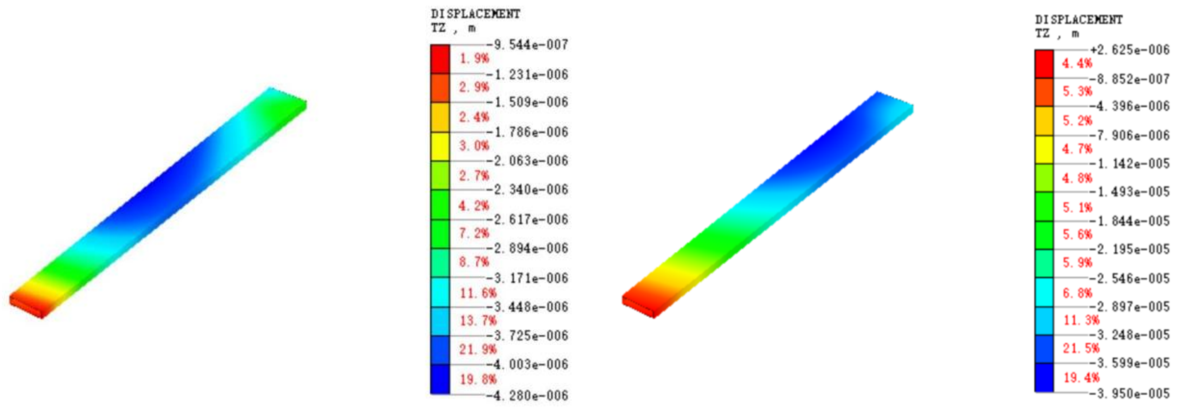

(a) (b)

Fig. 14. Y-direction displacements of main span box beam structure of pedestrian overpass pile in (m) using initial support construction and excavation of subway entrance and exit straight sections (a) case 1 (b) case 2



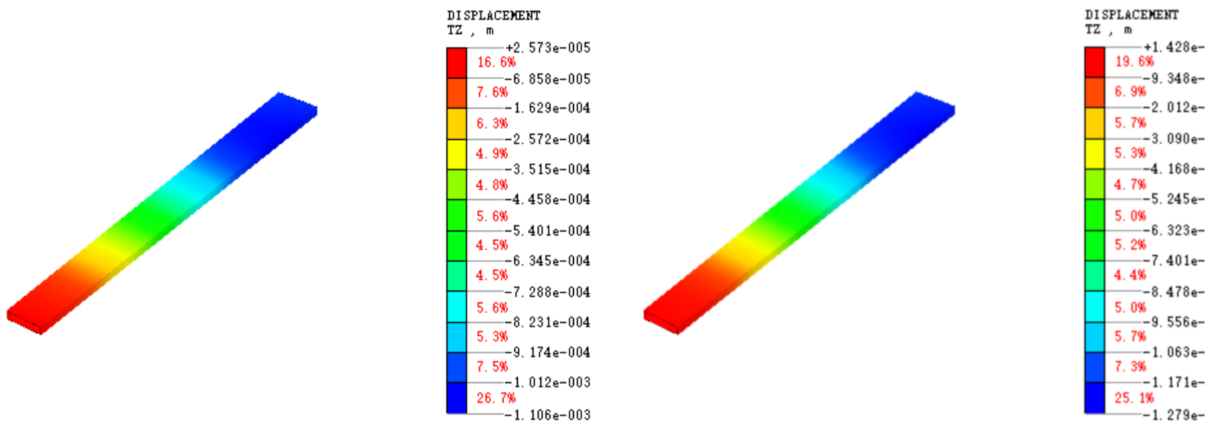

(a) (b)

Fig. 15. Y-direction displacements of main span box beam structure of pedestrian overpass pile in (m) using initial support construction and excavation of escalator sections at subway entrance and exit (a) case 1 (b) case 2




(a) (b)

Fig. 16. Z-direction displacements of main span box beam structure of pedestrian overpass pile in (m) using initial support construction and excavation of subway entrance and exit straight sections (a) case 1 (b) case 2




(a) (b)

Fig. 17. Z-direction displacements of main span box beam structure of the pedestrian overpass pile in (m) using initial support construction and excavation of escalator section at subway entrance and exit (a) case 1 (b) case 2

Table 6. Footbridge superstructure displacements in (mm) during construction of proposed project

| Calculation condition | Maximum displacements in mm | | | |
|---|---|---|---|---|
| | X displacement | Y displacement | vertical displacement | Total displacement |
| Analysis of the initial ground stress field at the site | 0.0 | 0.0 | 2.5 | 0.0 |
| Initial construction of the straight section of the subway entrance and excavation 1 | 0.1 | 0.1 | 0.1 | 0.1 |
| Initial construction of the straight section of the subway entrance and excavation 2 | 0.1 | 0.1 | 0.1 | 0.1 |
| Initial construction of the straight section of the subway entrance and excavation 3 | 0.1 | 0.1 | 0.1 | 0.1 |
| Initial support construction and excavation of escalator section at subway entrance and exit 1 | 0.1 | 0.1 | 1.1 | 1.1 |
| Initial support construction and excavation of escalator section at subway entrance and exit 2 | 0.3 | 0.1 | 1.3 | 1.3 |

## 4. Conclusion

This article is based on the design characteristics of subway entrance and exit structures, and the structural characteristics of pedestrian overpasses. A three-dimensional dynamic construction numerical model is constructed using a nonlinear coupling algorithm to study the safety impact of subway entrance and exit construction on pedestrian overpasses. Based on the final results of this research, the following conclusions can be drawn:

- The unloading and disturbance of surrounding rock soil units caused by the construction of subway entrances and exits are the fundamental sources that induce additional responses from adjacent pedestrian overpasses.
- Disturbance stress is transmitted step by step through the "pile foundation–pier–upper structure", resulting in secondary internal force redistribution and cumulative deformation in key components of the bridge.
- When the deformation amplitude exceeds the threshold, it may endanger the safety of the bridge structure.
- The established support system and construction parameter control provided the best values for horizontal and vertical displacements.
- The maximum horizontal displacement of the pedestrian overpass pile foundation caused by the construction of subway entrances and exits is 0.3 mm.
- The maximum vertical displacement of the main span pile foundation is 1.9 mm.
- Both values of displacement are considered minimum than the allowable total settlement value of the pile foundation of 127 mm, and the horizontal displacement limit of the pile foundation of 31 mm.
- Strengthen the automation monitoring of key deformation parameters and set warning thresholds.
- Once the monitoring data approaches the threshold, emergency control measures should be immediately activated to ensure the functionality and safety of the surrounding structures during subway construction.

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