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Research Article

Interactions of Foundation Pit on the Underlying Adjacent Existing Underground Structures

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The influence of foundation pit excavation on deformation and stability of the supporting structure of underlying adjacent existing tunnel is a comprehensive geotechnical engineering problem, including unloading effect of foundation pit excavation and the coupling effect of deformation of the tunnel surrounding rock and supporting structure. Using numerical calculation methods, this paper changes the different excavation depths and widths of foundation pit and discusses the evolution law about force and deformation of tunnel supporting structure, and the changing relationship of the axial force of tunnel anchor with the distance between foundation pit and tunnel is obtained and compares the influence of different excavation way of foundation pit on the axial force of anchor rod near the existing tunnel. It is found that with the increase of distance between foundation pit and tunnel, the axial force of anchor rod at the top of tunnel under the foundation pit entirely symbolizes a trend of increases first and then decreases, the axial force of the leftmost anchor rod changes from pressure to tension, then decreases gradually. When the foundation pit depth increases, the axial force of the anchor rod at the top of the tunnel increases, the axial force of the leftmost anchor rod decreases, and the width of foundation pit absolutely has little effect on the axial force of the leftmost and the top tunnel.

1. Introduction

In the process of accelerating city modernization, the aboveground space has not gradually been adequate for the needs of the people. Therefore, it is an urgent need to develop underground space that includes underground station tunnels, underground complexes, underground garages, etc. [1, 2]. Sequentially, quantities of foundation pit engineering are build up. Many engineering are located in the densely populated areas of city and adjacent to the existing underground spaces, such as underground tunnel. The excavation of foundation pits leads to the change of soil constraints (mainly lateral constraints) [3, 4]. With the increase of excavation volume, the original lateral support of rock and soil disappears, so there are more possibilities for instability and damage of the foundation [5, 6]. What is more, the lateral displacement also continues to increase [7, 8]. At the same time, it leads to the uneven settling of nearby ground surface and the movement of stratum, which affects the stress changes of rock and soil of surrounding tunnel and deformation and seriously even causes the tunnel supporting structure undergoes cracking failure (Figure 1).

As a result, more and more scholars began to keep focus on these influence [9, 10]. Due to the expansion of the tunnel crack, it will lead to the instability of the rock mass [11, 12]. Kouretzis et al. [13] found that the displacement of

Figure 1: Cracking of tunnel lining.

the pit side walls, the deformation of the pit envelope, and the settling of the pit backfill soil would lead to the horizontal displacement of underground pipeline. Through experience formula, the horizontal displacement adjacent existing underground pipeline based on excavation of the pit was computed and analyzed, and the computation results were improved according to the actual measurement parameters. Under the condition of pit excavation, the calculation formulas of deformation and surface settlement of adjacent buildings in foundation pit excavation were derived, and the corresponding prevention measures were put forward by Laefer et al. [14]. According to the actual engineering example of adjacent buildings cracking caused by foundation pit excavation, Blackburn and Finno [15] studied the influence of rigid support pits and flexible support pits on the safety of adjacent buildings, what is more, the cracking reasons why pits excavation lead to the adjacent building structure and the measures to avoid cracking were explored. Nowadays, many research achievements qualitatively analyzes the mutual influence of underground engineering depending on actual engineering experience, field data, and the combination of half experience and half theoretical formula [16, 17]. With the development of numerical computing technology, masses of scholars studied have programmed their own programs through geotechnical numerical simulation software to study the geotechnical problem [18–20]. Finno et al. [21] established 3D model of foundation pit by using the finite element crisp and analyze the size effect and excavation effect of 3D computational model of foundation pit. In the past research, the stabilization of the tunnel rock and soil after pit excavation was mostly considered, and there was not much in-depth study of the influence of tunnel supporting structure [22, 23]. Therefore, in this paper, under the condition of different work, numerical calculation is chosen to study the influence of pit excavation on adjacent existing tunnels, especially tunnel supporting structure. And the mutual influence rule between pit and tunnel was discussed to get the variation relationship of axial force of tunnel anchor rod with the distance between pit and tunnel, and the influence of different pits excavation ways on adjacent existing axial force of tunnel anchor rod was compared.

2. Establishment of Numerical Calculation Model

Such as an excavation of foundation pit, the original landform element is river alluvial terraces, and according to the site survey report, it can get soil calculation parameters in Table 1.

In the site, there is a 6-meter tunnel in diameter passing through the whole site along the length direction. At present, spray anchor support is widely used in tunnel support [24–26], the change of the axial force of the anchor rod can reflect the stability of the tunnel. In order to accurately analyze the influence of pit excavation on adjacent existing tunnels, it is necessary to have a statistical analysis about the change of the axial force of the anchor rod [27, 28]. This paper used FLAC3D to establish the numerical computational model as Figure 2. FLAC3D can better simulate the interaction between rock mass and structure, as well as the large deformation mechanical properties of rock mass [29, 30]. Mohr-Coulomb criterion is used to judge the failure of geotechnical materials [31, 32]. The left and right sides of model both have a restraint for vertical boundary conditions, and the bottom side restrains the displacements of 3 direction. Located directly below the foundation pit, the support form of the tunnel is spray anchor support, in which the anchor is full grout anchor rod. Concrete is blasted after arranging the anchor rod, and the computation parameters of tunnel anchor rod, mortar, and blasted concrete are shown in Tables 2 and 3. The cable element is used. There are 7 nodes and 6 construction elements that are numbered 1 ~ 6 due to the bolt length is 6 m. Component 1 is closest to the edge of the tunnel, and component 6 is farthest from the edge of the tunnel [7], as shown in Figure 3.

3. Computation Result and Analysis

3.1. Influence of the Relative Distance between Foundation Pit and Tunnel on the Axial Force of the Tunnel Anchor Rod. First, taking a 20-meter-width and 12-meter-depth pit model for an example, the axial force of the top anchor and the leftmost anchor is considered as the research objects, and the axial forces of the top anchor and the leftmost anchor located 6 m, 10 m, 16 m, 22 m, and 28 m below the foundation pit are computed, and the variation rule of axial force of tunnel anchor rod with the distance between foundation pit and tunnel is obtained. This paper stipulated that the pressure is minus, and the tension is plus. It is shown that the variation condition of the axial force of the anchor rod at the top of the tunnel at different distances from the 20-meter-width and 12-meter-depth pit as Figures 4 and 5.

From Figure 4, it can be seen that, in general, the anchor rod at the top of the tunnel is subjected to tension, and axial force of each section decreases with the outward direction of the tunnel radius. With the increase of the distance between tunnel center and the bottom of the foundation pit, anchor rod at the top of tunnel tend to increase first and then decrease. Figure 5 further shows the variation law of each element of anchor rod with the distance between tunnel center and the bottom of foundation pit. It can be seen that axial

Table 1: Calculation parameters of site soil mass.

Cohesion (kPa)	Friction angle (°)	Unit weight (kN/ m^3)	Deformation modulus (MPa)	Poisson's ratio	Bulk modulus (MPa)	Shear modulus (MPa)
30	25	18	14.0	0.3	11.67	5.385

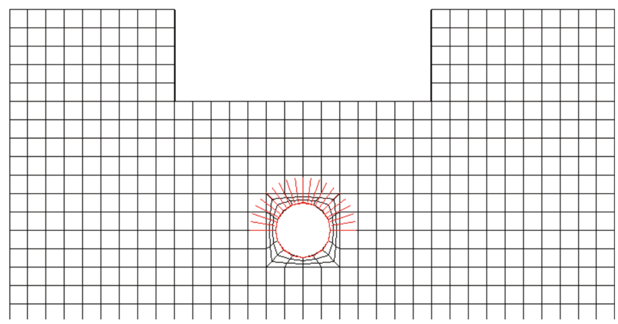

Figure 2: Numerical calculation model.

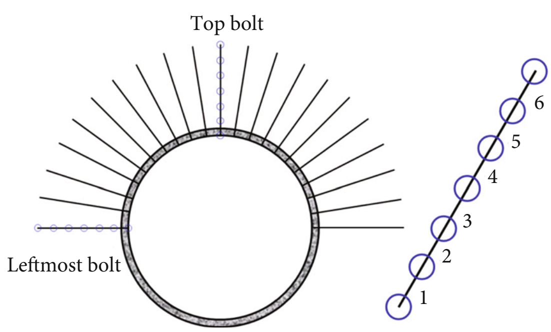

Figure 3: Tunnel bolt monitoring position and bolt monitoring point numbering.

force of each section of anchor rod increases first and then decreases with the increase of the distance between tunnel center and the bottom of the foundation pit. The smaller the number is, the greater the axial force of each section of anchor rod closer to the tunnel is, and the greater the fluctuation degree with the distance is. On the contrary, the smaller the number is, the smaller axial force of each section of anchor rod farther from the tunnel is, and the smaller of the fluctuation degree with the distance is. There are slight changes for axial force of anchor rod section with the largest number with the increase of the displacement, and the displacement which correspond to the maximum value of each axial force curve of anchor rod change also increases with the increase of the number of the anchor rod section.

Figures 6 and 7 show the change condition of axial force of the leftmost side anchor rod in tunnel directly below the foundation pit at different distance from the 20-meter-width and 12-meter-depth pit. Figure 6 shows that the first section of the leftmost anchor rod of tunnel 6 m below the foundation pit appears tension, then with the increase of number of each anchor section, tension decreases to 0 and turns into pressure. The pressure reaches the maximum value increasing to the forth section, then decreases, and finally tends to be a state of press all along. While the leftmost anchor of tunnel at other distances below the foundation pit also shows tension in the first section, and then with the increase of number of each anchor section, the tension is also reduced, and then a small pressure is shown in the middle section, and finally tend to a state of nonforce. The greater the bottom distance of tunnel and foundation pit is, the smaller the number of the element corresponding to the maximum pressure of the leftmost anchor is. Figure 7 further shows the force of anchor sections with the same number on the leftmost anchor that tends to increase first and then decrease with the increase of the distance between the foundation pit and the underlying tunnel, and the extreme value of each anchor element is shown in the pit 10 m below the tunnel. The tension is shown in each section with the number of anchor 1, and the anchor section with the number of anchor 2 starts to be compressed. With the increase of the distance, the pressure is reduced to zero and then turns into tension in the opposite direction. The tension is reduced to zero after it increases to the maximum value, and then, it is compressed in the opposite direction. The rest of the anchor sections are all under pressure, with the increase of distance between pit and tunnel, the pressure tendency is decreasing first and then increasing slightly for the anchor section numbered 3, 4, and 5, and the anchor section numbered 6 always keeps decreasing which the change is the most gentle.

3.2. Influence of the Depth and Width of Pit on Axial Force of Anchor Rod of Existing Tunnel under the Foundation Pit. To study the influence of the depth and width of pit on axial force of anchor rod of existing tunnel under the foundation pit, in this paper, the foundation pits with the widths of 20 m and depths of 6 m, 8 m, 10 m, 12 m, and 14 m are selected, and the axial force of the top and leftmost anchor in the tunnel with a distance of 6 m from the bottom of pit is recorded, respectively, and then this paper selects the pit with the depths of 10 m and widths of 12 m, 16 m, 20 m, 24 m, and 28 m, records the axial force of the top and leftmost side anchor in the tunnel with a distance of 6 m from the bottom of pit, and then compares and analyzes them.

Figures 8 and 9 describe the variation of anchor axial force of the top tunnel directly below the foundation pit with the widths of 20 m and different depths. It can be seen from Figure 8 that under the condition with the same width of the foundation pit, the deeper the depth is, the greater the stress of anchor rod is, and all of them are tension. At the same depth, the larger the number of each anchor section is, it means that the farther from the tunnel is, and the smaller the tension is. The tension of the endmost section of anchor rod far away from the tunnel is almost equal, that is, it does not affected by the width of the foundation pit. Figure 9 shows that the depth has the largest influence on the tension

Table 2: Calculation parameters of bolt.

Bolt diameter	Sectional area	Mortar diameter	Mortar perimeter	Bolt tensile strength	Bolt prestress
22 mm	3.50 cm^2	100 mm	0.314 m	250 kN	60 kN
Bolt length	Mortar cohesion	Mortar friction	Mortar stiffness	Bolt number	Adjacent bolts angle
3 m	20 kPa	25°	22.33 MN/m^2	21	9°

Table 3: Calculation parameters of shotcrete.

Type	Weight	Deformation modulus	Poisson ratio	Thickness
C20	25 kN/m^3	25.3 GPa	0.266	0.3 m

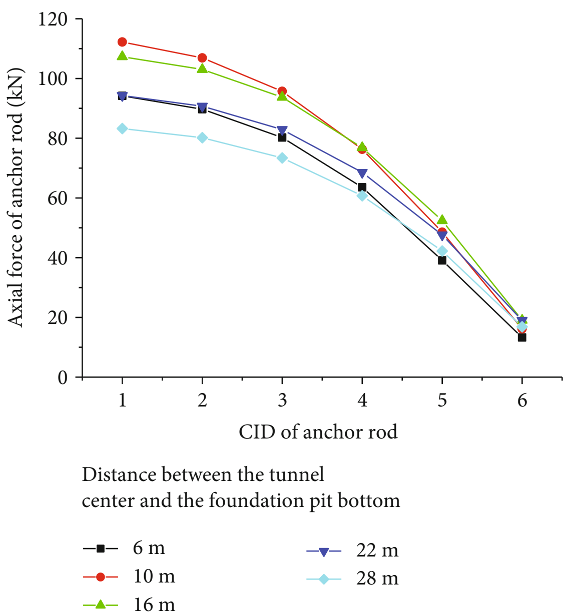

Figure 4: Axial force of anchor rod at different distances from the top of tunnel under foundation pit.

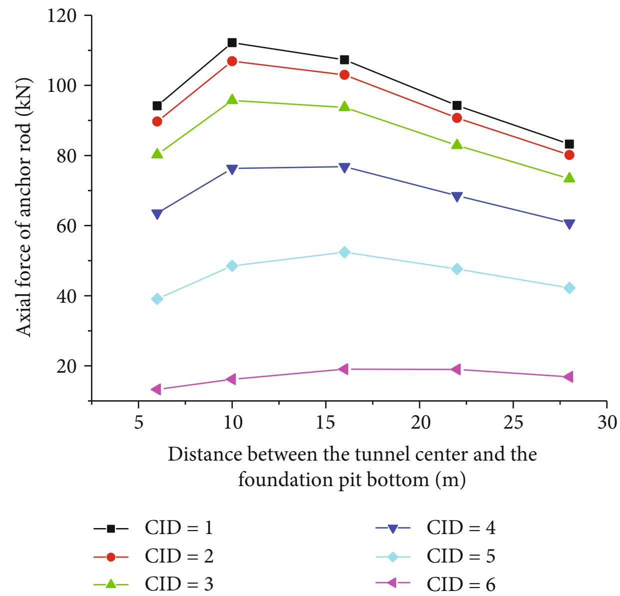

Figure 5: Axial forces of each section of tunnel roof bolt lying at different distances under foundation pit.

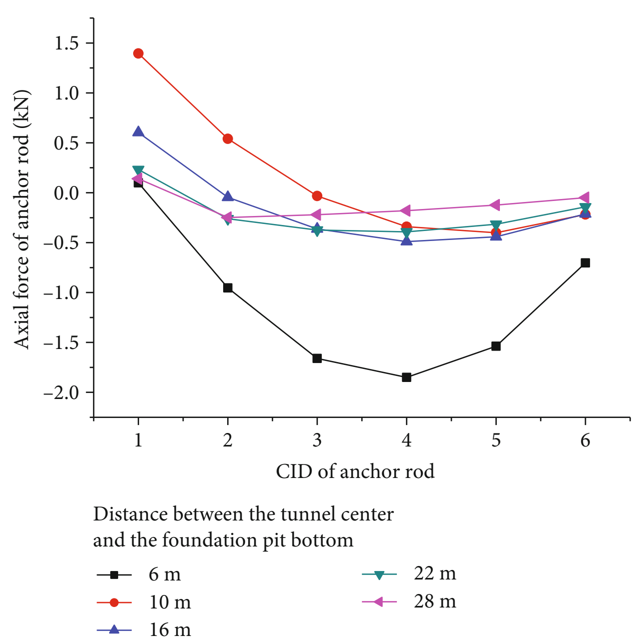

Figure 6: Axial force of the leftmost anchor bolt at different distances under the foundation pit.

of anchor sections with small numbers. With the increase of the numbers, the curve of the numbers of each anchor section with depth is gradually slow, the tension curve of the anchor sections numbered 6 is horizontal, and it is further shown that tension is not be affected by the width of the foundation pit.

Figures 10 and 11 show the variation of axial force of anchor rod of at the top of tunnel under a depth of 10 m foundation pit with the width of the foundation pit. It can be seen from Figure 10 that under the condition of the same depth of pit, the wider the foundation pit is, the greater the axial force of tunnel anchor rod is, all of which are tension, and the overall force of the anchor rod changes less with the width. When the width is same, the larger the number of anchor section is, the smaller axial force of this section is. Figure 11 shows the change of axial force of different section of anchor rod with the width of pit. As can be seen, the

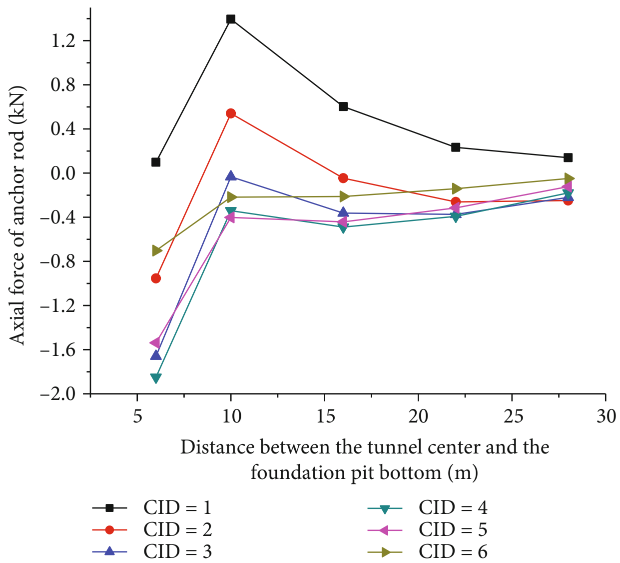

Figure 7: Axial forces of each member of the leftmost anchor bolt at different distances under the foundation pit.

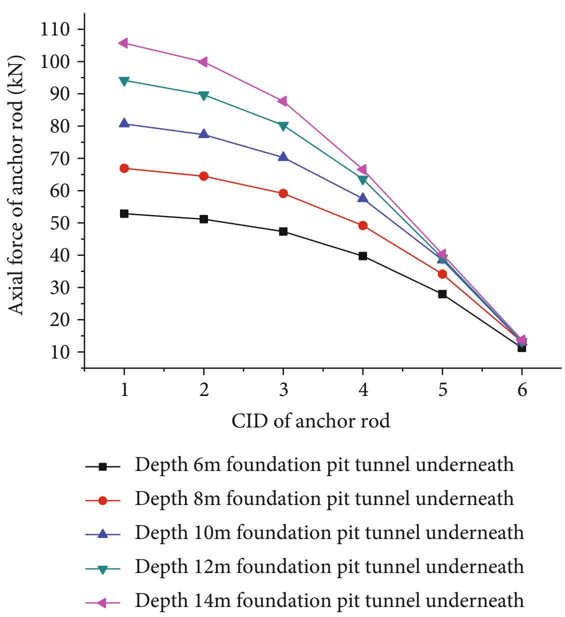

Figure 8: Axial force of anchor rod at the top of tunnel 6 m beneath a 20 m wide pit with different depths.

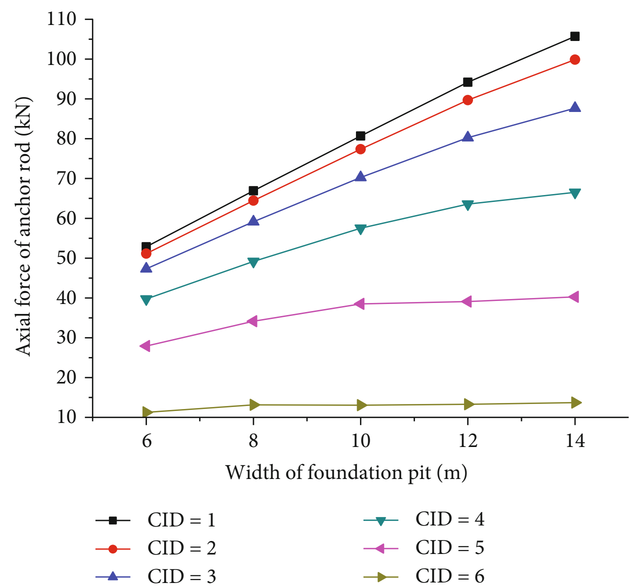

Figure 9: Variation curve of axial force of each member of anchor bolt at the top of tunnel with foundation pit depth under 20 m wide foundation pit.

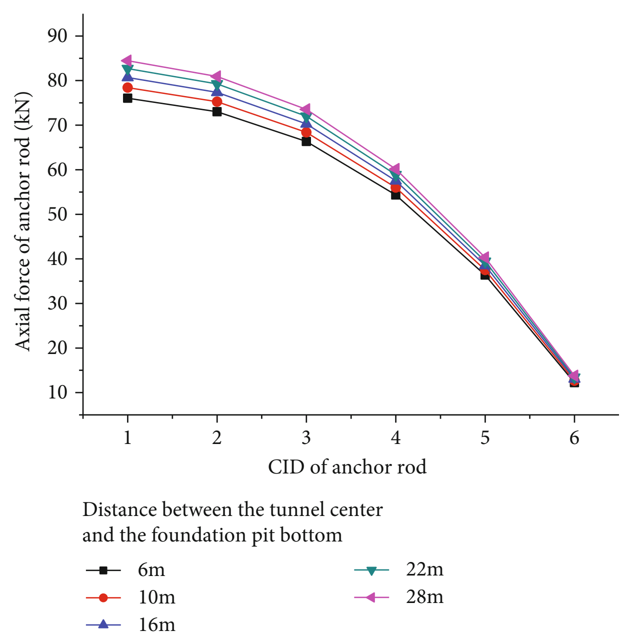

Figure 10: Axial force of tunnel anchor bolt under 10 m deep foundation pit with different widths.

axial force of the lesser numbered anchor section increases slightly as the width of pit increases, while the axial force of the bigger numbered anchor section absolutely is horizontal, that is, it is not be affected by width. Generally, there is little influence of width of the pit on axial force of the anchor on the top of the underlying tunnel, far less than the depth of the foundation pit.

Figures 12 and 13 show the variation of axial force of the leftmost anchor rod of the underlying tunnel under a width of 20 m and different depths foundation pit. It can be seen from Figure 12 that when the pits have the same width, the overall axial force of the leftmost anchor rod of the lower tunnel appears a change process in which tension decreases first and then the reverse pressure increases with the increase of the depth of the pit. Under the small depth of pit as 6 m, 8 m, and 10 m, the axial force of each section of the tunnel leftmost anchor rod appears tension, and with the increase of number, it decreases and tends to 0. Under the large depths of pits as 12 m and 14 m, the axial force of each anchor section shows pressure, and a change process is shown, in which it increases first and then decreases and tends to 0 with the increase of number. From Figure 13, it

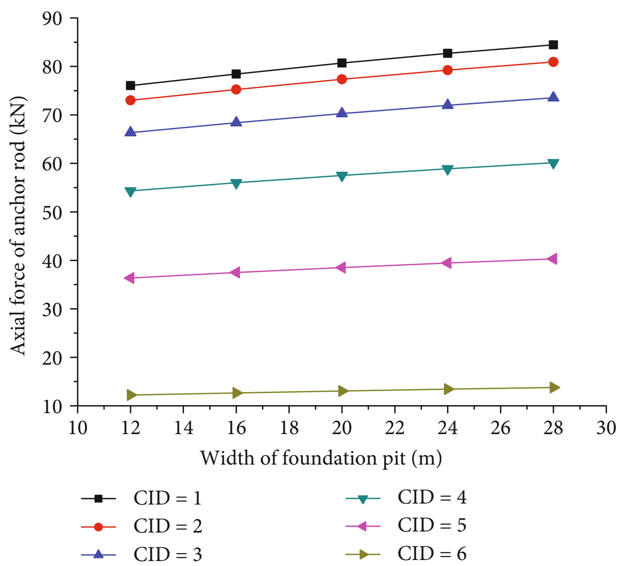

Figure 11: Variation curve of axial force of each component of anchor bolt at the top of tunnel under 10 m deep foundation pit with the width of foundation pit.

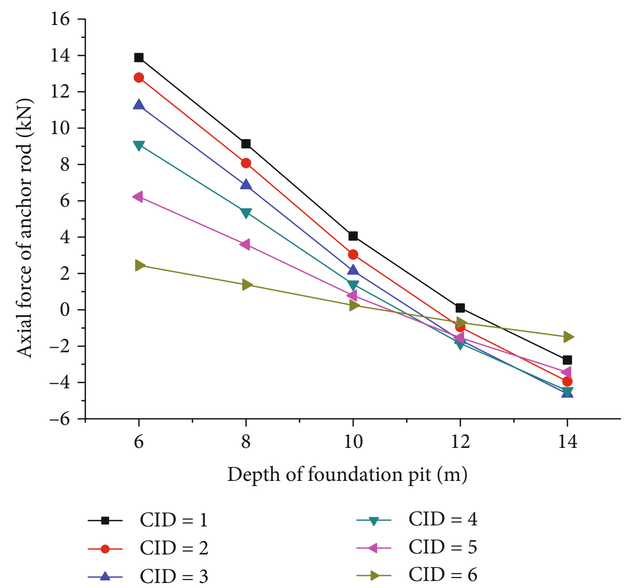

Figure 13: Variation curve of axial force of each member of the leftmost anchor bolt in a 20 m wide tunnel with foundation pit depth.

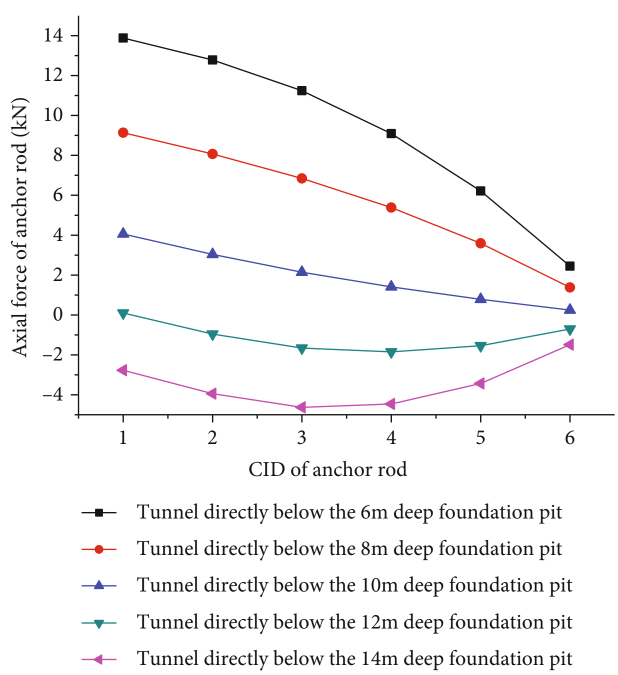

Figure 12: Axial force of the leftmost anchor rod in the foundation pit with 20 m width and different depths.

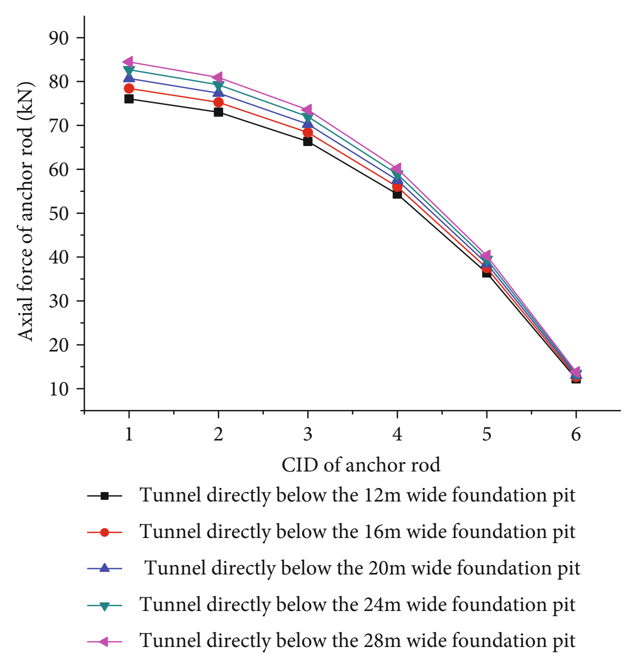

Figure 14: Axial force of the leftmost anchor bolt of a buried tunnel under a 10 m deep pit of different widths.

can be seen that the tension of each number anchor decreases to 0, and then, reverse pressure increases as the depth of the foundation pit. The smaller the number of each anchor section is, the greater the change range of the axial force as the depth of pit, the change extent of anchor rod in the sixth section is the smallest, and absolute value of axial force is also smallest, changing around 0.

Figures 14 and 15 show the variation of axial force of the anchor rod at the top of the underlying tunnel of in a depth of 10 m and different width foundation pit. From Figure 14, when excavating the pit with the same depth, axial force of the leftmost anchor rod of the underlying tunnel is very similar, and the change of axial force of each section of anchor rod with the number is extremely similar, all of which decrease with the increase of the number and tend to the same value. Figure 15 shows that axial force of less numbered section increase slightly with the increase of the width, and as for larger numbered section, the curve of axial force

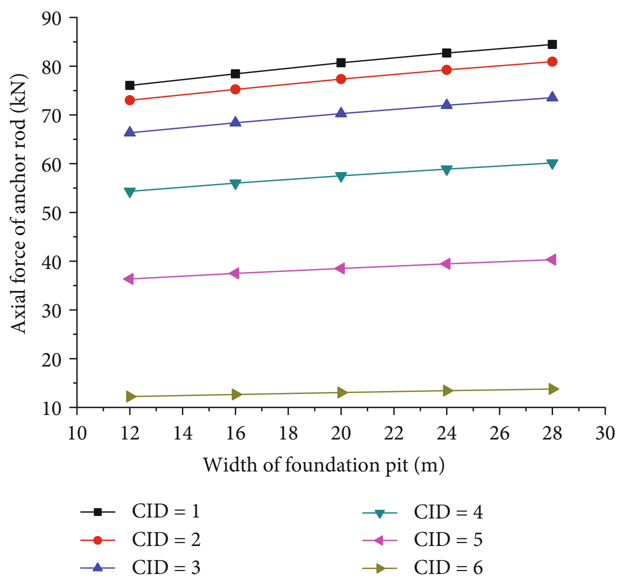

FIGURE 15: Variation curve of axial force of each member of the leftmost anchor bolt in a deep 10 m foundation pit with the width of foundation pit.

of each section of the anchor rod and the width of pit almost maintain a horizontal state. When the distance between tunnel and foundation pit is constant, the width of foundation pit excavation has a greater influence on tunnel deformation than the depth of foundation pit excavation. As a whole, the width of pit almost have no influence on axial force of the leftmost anchor rod of the underlying tunnel.

4. Conclusions

(1) The anchor rod at the top of the tunnel is subjected to tension, and axial force of each section decreases with the outward direction of the tunnel radius. With the increase of the distance between tunnel center and the bottom of the foundation pit, anchor rod at the top of tunnel tends to increase first and then decrease

(2) The closer to the tunnel is, the greater the axial force of each section of anchor rod is. Under the condition with the same width of the foundation pit, the deeper the depth is, the greater the stress of anchor rod is, and all of them are tension. At the same depth, the farther away from the tunnel, the smaller the tensile force, and the tension of the endmost section of anchor rod far away from the tunnel are almost equal, that is, it does not get affected by the width of the foundation pit

(3) There is little influence of width of the pit on axial force of the anchor on the top of the underlying tunnel, far less than the depth of the foundation pit. When the pits have the same width, the overall axial force of the leftmost anchor rod of the lower tunnel appears a change process in which tension decreases first, and then, the reverse pressure increases with the increase of the depth of the pit

Data Availability

Some or all data, models, or code that support the findings of this study are available from the corresponding author upon reasonable request.

Conflicts of Interest

On behalf of all authors, the corresponding author states that there is no conflict of interest.

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