Analysis of influence of subway station deep foundation pit excavation on adjacent bridge piles

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Abstract. Based on the engineering background of the deep foundation pit construction of Shenyang metro Line 10, the numerical simulation software Midas GTS NX, and the three-dimensional integral calculation model considering the interaction of foundation pit supporting structure, surrounding soil and viaduct is established, and the numerical simulation value and the measured data are compared and analyzed, the applicability of the model is verified, the influence of foundation pit excavation on the deformation of pile foundation is studied, and the optimization scheme is given. The construction plan of Simulation + forecast is established to guide the practical construction of the project. The results show that when the depth of the pile foundation is 1.5 times the depth of the foundation pit, and the horizontal displacement of the pile foundation is within 1/2 of the control value, this is the optimal depth of the pile foundation. This is the minimum standard safe distance when the pier is 1/2 from the depth of the foundation pit.

1. Introduction
Excavation of deep foundation pit will disturb the surrounding soil, cause horizontal displacement of the enclosure structure, vertical settlement of soil in the range of 1 times excavation depth around the foundation pit.

The deep foundation pit project is a very complicated problem of geotechnical engineering which involving soil properties, supporting structures, groundwater, etc.

When the deep foundation pit is under construction, it will affect the stability of the adjacent viaducts and cause safety hazards.

Now the site monitoring of deep foundation pit construction is used as the background. Considering the mutual coupling relationship between the deformation of the support structure of the foundation pit and the vertical deformation of the bridge, a three-dimensional model was built using MIDAS GTS NX. The model includes foundation pits, supporting structures and viaducts, simulate the entire excavation process of foundation pit, analyze the simulation results, understand the impact of deep foundation pit excavation on the viaduct, and then feed back to the site construction to solve the actual engineering problems and guide similar engineering construction [1].
2. Engineering background
Shenyang Metro North Daying Street Station is the transfer station for Metro Line 10 and Line 4. The main body of the station adopts the construction method of open pit excavation. Bored piles + steel supports are used as supporting structures, the method of precipitation is precipitation outside the pit. The excavation depth of the main structure of the foundation pit is 20.5 m. The length of the retaining pile is 26.6 m. The viaduct is located 9.0 m to the east of Line 10 of Beidaying Street Station.

The pile foundation of the viaduct is a bored pile with a buried depth of 28 m. To ensure that vehicles on the viaduct can pass through during the construction of the subway, monitor the horizontal displacement of the pile body of enclosure pile in the deep underground layer and understand the horizontal deformation of the enclosure pile.

Compare the numerical simulation results with the actual monitoring results to verify the rationality of the mode.

![The North Street station layout.](image)

3. Numerical Simulation

3.1. Constitutive model
Using Mohr-Coulomb criterion for numerical simulation in foundation pit construction stage [2].

Mohr-Coulomb criterion:
According to the Mohr criterion, the damage is generally expressed by the following equation:

$$|\tau| = f(\sigma)$$  \hspace{1cm} (1)

The simplest Moir’s damage envelope is a straight line, and the straight line envelope equation is as follows:

$$|\tau| = c + \sigma \tan \phi$$  \hspace{1cm} (2)

The meaning of each item in the above formula is as follows:

- $\phi$ - effective internal friction angle,
- $\sigma$ - effective normal stress on the failure surface,
- $\tau$ - shear stress on the failure surface (kPa),
- $c$ - effective cohesion (kPa).
In 1900, Mohr according to the stress circle of the ultimate stress state when the strength is destroyed, an envelope curve tangent to the stress circle is obtained. The expression of the curve equation is:

\[
\frac{\sigma_1 - \sigma_3}{2} - \frac{\sigma_1 + \sigma_3}{2} \sin \varphi - c \cos \varphi = 0
\]  

(3)

Moore-Coulomb is expressed by principal stress \( (\sigma_1 \geq \sigma_2 \geq \sigma_3) \), and the equation of the failure surface is as follows:

\[
\sigma_1 \left(1 - \frac{\sin \varphi}{2c \cos \varphi}\right) - \sigma_3 \left(1 + \frac{\sin \varphi}{2c \cos \varphi}\right) = 1
\]  

(4)

From (4), we can know that the ultimate shear stress \( \tau \) in any plane is only related to the normal stress \( \sigma \) in the same plane.

According to this calculation model, the following assumptions are made [3]:

- steel supports and other components of the same material are isotropic materials;
- in the analysis of the construction phase, the influence of the water level is not considered;
- underground continuous wall is a linear elastic model, and there is no relative slippage between the wall and the soil;
- the ground surface around the foundation pit is set as a uniform load and the load value is 50 kPa;
- in the analysis process, the influence of the excavation time and space on the calculation results is not considered [4].

### 3.2. The establishment of a numerical model

The actual soil structure for excavation of foundation pits is shown in table 1:

| Serial number | Geological stratification | \( \gamma \) (\( kN/m^3 \)) | C (kPa) | \( \Phi \) (\(^\circ \)) | E (MPa) |
|---------------|--------------------------|------------------------|--------|-----------------|--------|
| 1             | Miscellaneous fill       | 18.4                   | 33.8   | 11.4            | 3.5    |
| 2             | Silver sand              | 17.4                   | 0      | 23.5            | 11.0   |
| 3             | Round                    | 21.0                   | 0      | 35.0            | 26.2   |
| 4             | Round gravel             | 21.8                   | 0      | 36.4            | 32.2   |
| 5             | Gravel sand              | 20.8                   | 0      | 36.0            | 29.0   |

Due to the excavation of the foundation pit in layers. Before each layer of soil is excavated, the water will drop below the soil layer. The simulation did not consider water.

Drilled cast-in-place piles are the main components of the enclosure structure. Mainly bear the lateral pressure of soil and lateral pressure of steel support. This value simulation, in order to facilitate the establishment of the enclosure structure model and improve the accuracy of the calculation, an underground continuous wall with equal stiffness are replaced by cast-in-place piles in the simulation.

In this simulation, in this simulation, the wall unit simulation using the plate unit simulation is more in line with the actual situation of the foundation pit excavation.
In the GTS simulation, the underground continuous wall is adopted rectangular plate element to simulate the enclosure structure. Assume that the bored pile diameter is $D$, pile spacing is $t$.

Then a single pile should be equivalent to wall-type underground continuous wall with a length of $D + t$.

If the equivalent thickness of the ground wall after the equivalent is $h$, from the principle of equal stiffness can be obtained as follows:

$$\frac{1}{12} (D + t) h^2 = \frac{1}{64} \pi D^4$$

$$(5)$$

$$h = 0.589 D^{1.5} \sqrt{\frac{1}{1 + \frac{t}{D}}}$$

$$(6)$$

In the excavation of the foundation pit, after consulting the drawings, the diameter of the enclosure pile $D = 1.0$ m and the pile spacing $t = 0.4$ m. After calculation, $h = 0.50$ m can be obtained.

Therefore, the equivalent underground continuous wall with thickness $h = 0.50$ m is used in the simulation of the enclosure pile. underground continuous wall adopts linear elastic model.

The concrete strength grade is C30, the elastic modulus of concrete is $E = 30$ GPa, Poisson's ratio is 0.2. The main steps for building a model using Midas GTS software are as follows:

1. Drawing a 2D plan using Autodesk CAD - first define the size and location of the foundation and pier and the soil and structure within the affected area according to the project overview, then draw the flat shape in Autodesk CAD and save the file as “.dxf” format. Midas GTS “Extend” command - after importing the plane figure into the GTS software, Extend the "line" into a solid through the "Extend" command, it consists of three parts: the foundation pit, the pier and the surrounding soil within the affected area.

2. Midas GTS "Extension" command: after the flat graphics are imported into the GTS software, the "line" is expanded into entities by the "expand" command, including the foundation pit, the pier and the surrounding soil within the influence range.

3. Boolean Operation - Embedded Command: the overlapped part of the entity generated by the extended command, by embedding commands, the foundation pit and the bridge pile body are embedded in the soil within the scope of influence. So that no overlapping parts appear.

4. The division of the grid: use 3D automatic meshing, use the Hybrid Grid Builder to mesh all the entities step by step, while defining the grid group properties separately. At the same time define the grid group attributes. Divide grids from inside to outside and from small to large. The quality of the mesh has a great influence on the results of the finite element analysis. The calculation accuracy has a direct relationship with the mesh quality. The finer the mesh, the higher the accuracy of the calculation. In this simulation of the number of values. The soil is a flexible material and the enclosure structure is a rigid material. Therefore, the grid in the excavation area of the pit is properly encrypted, and the farther away from the pit is, the sparser it is. Check the mesh topology after meshing to determine if the meshes are coupled [5].

5. "Extended grid" command: the “Extended Grid” command - expands the foundation pit, the pier and the surrounding soil to the negative direction of the z-axis, respectively. According to the excavation sequence of the foundation pit, the information on the expansion of the foundation pit, the pier and the surrounding soil is consistent, so that the foundation pit analysis can be performed accurately. After the expansion grid is complete click on "Check command" to check the mesh topology. The free faces are all orange, indicating that the expanded grid is correct and will prepare for the subsequent definition of the construction phase.
(6) After "Extract" command: after the mesh is completed, use the extraction command to divide the underground continuous wall and bridge pile grid, and define the grid group attributes. At the same time, 1D grids such as steel supports and ring beams are divided, and steel supports and ring beams are extracted from the nodes to 1D.

(7) The foundation model is established, define the construction phase to simulate the process of foundation pit excavation. In the construction phase, the excavation, lining and support structure installation and erection of the soil are mainly accomplished through the “activation” and “passivation” of the grid group elements, boundary conditions, and static loads. Define the construction phase as shown in table 2 below.

Table 2. Numerical simulation of construction condition tables.

| Construction state | Simulation content                                      |
|--------------------|--------------------------------------------------------|
| Project Status 1   | Initial Stress Analysis                                 |
| Project Status 2   | Building diaphragm wall                                |
| Project Status 3   | Excavate the first layer of soil to -2.50 m            |
| Project Status 4   | Set up the first steel support at -2.00 m, excavate the second layer of soil to -8.90 m |
| Project Status 5   | Set up a second steel support at -8.40 m and excavate the third floor to -12.40 m |
| Project Status 6   | Set up the third steel support at -11.90 m, excavate the fourth floor to -16.70 meters |
| Project Status 7   | The fourth steel support is erected at -16.2 meters and the fifth layer of soil is excavated to 20.50 meters |

Figure 2 is a three-dimensional numerical model of the foundation pit and bridge. Figure 3 is a schematic diagram of enclosure pile, steel support and bridge pile foundations. The model is cuboid soil which overall size of 110.0 m by 106.0 m by 42.0 m. The soil is divided into 5 layers according to geological conditions.

The simulated foundation pit is in the central position of the overall model. The green part of the model is the surface monitoring point. The standard section of the foundation pit is 21.3 m wide, and the viaduct is 9.0 m outside the foundation pit.

The bridge piers and bridge piles are automatically coupled with the soil, and the boundary conditions of the foundation are set, and then the displacement of the pile foundation is cleared.

The “self-weight” and “auto-constraint” functions in the software were used to simulate the model's deadweight and boundary conditions.

Then calculate and analyze the model. Study the influence of excavation of deep excavation on the bridge pile foundation. In order to make the excavation simulation process almost reasonable. The role of groundwater and soil consolidation and creep are ignored in calculations [6].
3.3. Simulate the horizontal displacement of the enclosure structure

Deep excavation will certainly disturb the surrounding soil during excavation. Enclosure structure will produce horizontal deformation, figure 4 is a horizontal displacement deformation cloud chart of the retaining pile.
The enclosure structure near one side of the bridge is inclined to the inside of the foundation pit, and horizontal deformation occurs from the top to the middle and lower parts [7].

Figure 4. Enclosure wall horizontal displacement nephogram Y direction.

Figure 4 shows that the horizontal displacement of the wall of the enclosure wall near the side of the bridge is greatly deformed at the middle and upper part of 10.0 m.

The surrounding soil will inevitably loosen. At the same time, the bridge pile produces horizontal deformation towards the inside of the foundation pit.

Figure 5 shows the measured values of field monitoring. The maximum is 9.52 mm.

Figure 6 shows the numerical simulation.

The combination diagram shows that the deformation of the enclosure pile is toward the inside of the foundation pit during the initial process of the entire foundation pit. And the amount of deformation is related to the excavation depth of the foundation pit.

The excavation of the foundation pit is completed, and the enclosure piles are bow-shaped deformation [8]. The maximum displacement of the enclosure pile is at the upper middle position of the enclosure pile.

The numerical simulation results are similar to the on-site monitoring data trends, prove the rationality of the three-dimensional model.

Therefore, the numerical simulation can effectively predict the deformation of the enclosed structure and the bridge pile foundation during the construction of the deep foundation pit, and guide the construction on site.
Figure 5. Site monitoring of CX-9 enclosure pile.

Figure 6. Numerical simulation of CX-9 enclosure pile.
3.4. Analysis of horizontal displacement of bridge piles
When the soil deforms, the bridge pile will also be affected. The safety of the bridge pile directly affects the safety of the viaduct.

Figure 7 shows the horizontal deformation displacement diagram of the pile foundation. The overall deformation of the pile foundation is also "bow-shaped" with the maximum displacement in the middle of the pile foundation. The maximum displacement value is 6.42 mm and the pile foundation controlling value is 10 mm. Under the conditions of the foundation pit construction, the deformation of the pile foundation is in a stable state. Through the horizontal deformation diagram of retaining piles and bridge piles, it can be seen that the changes show similar trends.

![Figure 7. Horizontal deformation of pile body of bridge pile.](image)

4. Influence of deep foundation pit construction on pile body

4.1. At the same time of excavation of deep foundation pits, the influence of different depths of buried soil of pile foundation on horizontal displacement of pile foundation is analyzed
The depth of grave of the bridge pile foundation has a certain influence on the deformation of the pile foundation.

Analyze the relationship between the depth of pile foundation and the depth of foundation pit, and then analyze their influence on the horizontal deformation of pile foundation, and the optimum depth of the pile foundation is obtained.

Combining the actual engineering to establish a corresponding three-dimensional numerical model, maintain the excavation conditions of foundation pits, the depth of the buried enclosure pile, the structural parameters of the soil and the parameters of the enclosure structure remain unchanged. Divide the depth of pile foundation into six categories: 21.0 m, 24.0 m, 27.0 m, 30.0 m, 33.0 m, and 36.0 m. Through the numerical simulation calculation, the deformation curve of the pile foundation is obtained, and then analyze the influence of pile foundation depth on horizontal deformation of pile foundation.
Figure 8. The horizontal displacement curve of pile foundation of different depth of pile foundation.

As shown in figure 8, during the actual excavation of the foundation pit project, the different depths of the pile foundations have some influence on the horizontal displacement of the pile foundation. When the depth of the pile foundation is 21.0 m, the maximum displacement of the pile foundation is 10.2 mm. When the depth of pile foundation is more than 30.0 m, the maximum horizontal displacement of the pile does not decrease significantly with the depth of pile foundation. The change of the horizontal displacement of pile foundation is reduced, and the variables are all within 1mm. It shows that when the soil depth of the pile foundation of the bridge is 30.0 m, it is approximately 1.5 times the depth of the foundation pit, and the horizontal displacement of the pile foundation is within 1/2 of the controlling value.

The controlling value is 10 mm, which is the optimum depth of the pile foundation. Under this engineering background and project profile, when the soil depth of the pile foundation is 2 times the depth of the foundation pit, the influence of excavation of the deep foundation pit on the horizontal deformation of the pile foundation is negligible.

4.2. Analysis of the influence of different distances to the foundation pit adjacent to the pile foundation

Set up a three-dimensional construction numerical model for deep foundation pits and bridges, study the effect of different distances from the bridge pier on the horizontal displacement of adjacent piles, and maintain the parameters of the soil and the parameters of the enclosure.

The distance from the bridge pier to the edge of the foundation pit is 5.0 m, 8.0 m, 10.0 m, 13.0 m, 16.0 m and 20.0 m respectively. The excavation depth is constant and the construction conditions are not changed. Analyze the effect of different distances on the horizontal deformation of the pile foundation and obtain the safety distance.
As can be seen in figure 9, as the distance from the pile foundation to the edge of the foundation pit increases, the overall horizontal displacement of the pile foundation gradually decreases. When the bridge pier is 5.0 m away from the edge of the foundation pit, the maximum horizontal displacement of the pile foundation is 12.24 mm.

When the pier is 22.0 m away from the edge of the foundation pit, the maximum horizontal displacement of the pile is 3.87 mm. When the distance is more than 22.0 m, it is almost considered that this distance has no effect on the bridge pile foundation. When the distance is 8m, the settlement of pile foundation has reached the control value.

Therefore, when the distance between the pier and the edge of the foundation pit is less than 8 m, corresponding protection measures must be taken. This shows that when the distance from the bridge to the foundation pit is less than 1/2 of the depth of the foundation pit, it is necessary to strengthen construction monitoring or adopt some protective measures.

4.3. Construction optimization and protection measures

Based on the above research contents, the design scheme is optimized based on the original design scheme. Based on the premise of ensuring the safety of adjacent foundation pits, the distance between foundation pits and bridge piers and the soil depth of pile foundations were optimized. See table 3 for a list of optimization parameters for the construction of foundation pits.

Modify the previous model and re-simulate the calculation.

Table 3. Parameters optimization of shield construction.

| Optimization project                              | original plan | optimization |
|---------------------------------------------------|---------------|--------------|
| The distance between pile foundation and foundation pit | 9.0 m         | 14.0 m       |
| Pile foundation depth                             | 28.0 m        | 34.0 m       |
Figure 10. Comparison of horizontal displacement curves of the original plan and the optimization plan.

The numerical simulation method was used to analyze the optimized design scheme. As can be seen from figure 10, the overall horizontal displacement of the optimization scheme becomes smaller, the curve is flatter than the original scheme, and the fluctuation range is small. The maximum value of the horizontal displacement of the optimized pile foundation is 4.90 mm, which is less than 1/2 control value and can be considered to achieve the optimization effect. In the subsequent actual projects, the on-site design plan is compared with the optimized plan. Then through numerical analysis for calculation and analysis, to predict the possible hazards of construction, effective control the safety of construction workers and the construction progress.

The commonly used method of soil reinforcement in the project [9] is to protect the pile foundation. Soil reinforcement has two methods.

The first type is to reinforce the surrounding soil of the foundation pit, increase the strength of the surrounding soil, and thus reduce the deformation of the soil to achieve the role of protecting the pile foundation.

The second type is the foundation of the reinforcement pile foundation to improve the foundation bearing strength of the pile foundation. Inhibit the deformation of the pile foundation and protect the safety of the viaduct. Soil reinforcement methods include pre-grouting method, freezing method, and high-pressure spin-spray mixing method [10]. This project adopts the pre-grouting method and uses cement paste to reinforce the surrounding soil of the foundation pit, to increase the strength of the surrounding soil. Reduce the disturbance of the surrounding soil to achieve a stable pile foundation.

5. Conclusion
This paper takes the deep foundation pit project of the station of No. 10 line of Beidaying Street Station in Shenyang as the research background, combined with on-site monitoring. Using the finite element
analysis software MIDAS GTS NX to establish three-dimensional models of deep foundation pits, supporting structures and viaducts, the influence of deep foundation pit excavation on the bridge pile foundation under different conditions was studied and the conclusions are as follows:

- when the depth of the piled foundation of the bridge is 30.0 m, it is about 1.5 times the depth of the foundation pit; the horizontal displacement of the pile foundation is within 1/2 of the control value, which is the optimum depth of the pile foundation;
- when the distance between the pier and the pit is 1/2 times the depth of the pit, it is the minimum safety distance; less than this distance, we must strengthen construction monitoring or take some protective measures;
- the data monitored at the site often lags behind actual changes; therefore, based on the actual project, this paper uses numerical simulation method to simulate the deep excavation and establish a “simulation-prediction” information construction program.

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