Preliminary numerical analysis of the influence of pit-in-pit excavation on the stability of the foundation pit supported by diaphragm wall

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Abstract. Pit-in-pit is common in foundation pit-engineering practice. Pit-in-pit excavation disturbs the stress field in the passive zone of the foundation pit, which induces the loss of soil resistance in the passive zone and adversely affects the safety of the foundation pit. Based on a real foundation pit supported by diaphragm wall in Hohhot, this study used the finite difference software FLAC3D to establish a finite difference model of the foundation pit. At different construction steps and excavation parameters, the horizontal displacements of the diaphragm wall, the vertical displacement of the soil around the foundation pit, and the plastic zone of the model were analyzed. It was found that the excavation of the inner pit intuitively impacted the deformation of the diaphragm wall, and the asymmetry of the position of the inner pit led to the whole pit’s deformation in a certain direction. Furthermore, we reported that the increase in excavation parameters \( h \) and \( l \) increased the subsidence of the soil closer to the inner pit. Moreover, excavation parameters, including \( L \), \( h \), and \( l \), are proportional to the volume of the plastic area. This study provides reference value for designing foundation pits containing pit-in-pit.

Keywords: diaphragm wall, numerical analysis, FLAC3D, pit-in-pit excavation.

1. Introduction
By accelerating urban infrastructure construction, deep foundation pits have become continuously common in engineering construction. The pit-in-pit is often used in certain specific structures such as elevator shafts, water collection wells, different depth foundations of the main building and podium, and other underground projects that require a long-term interface. Therefore, pit-in-pit is inevitably used in constructing the project [1]. Many designers underestimate the impact of pit-in-pit when designing foundation pits, leading to many accidents because of design defects [2].

Currently, Mingliang et al. [1] studied the passive earth pressure of pit-in-pit and reported that the existence of the inner pit will reduce the passive earth pressure of the outer pit; Weiming [3] reported that pit-in-pit considerably impacted the overall stability of the basement pit supporting structure; Lianxiang et al. [4] used finite element software to examine the influence of pit-in-pit and summarized the horizontal displacements of deep soil behind the pile. Feng et al. [5, 6], Zheng et al. [7], Huo et al. [8], Xie et al. [9], and many other scholars studied the influence of pit excavations on cantilever structures and obtained the influence of digging depth and different inner and outer pit spacing on the deformation of the retaining structure. Yang et al. [10] obtained the structural deformation and internal
force that agree with the actual engineering observation using the elastic fulcrum method. Yi et al. [11] proposed a pit prediction method of surface settlement of pit-in-pit. Currently, most studies on pit-in-pit center on the deformation and settlement of the retaining structure; however, few studies have been conducted on destructing soil.

FLAC3D is extensively used in foundation pit engineering [12–14] and it is an effective tool in examining foundation pit engineering. Presumably, no studies have been conducted on the failure of the soil of the pit-in-pit. In this study, we used the finite difference software FLAC3D to study the impact of the excavation of pit-in-pit. Importantly, we studied the influence of the excavation parameters of the inner pit. By analyzing the deformation of the structure, the settlement of the surrounding soil, and the failure of the soil, the effect of the inner pit excavation on the deformation of the foundation pit was studied.

2. Engineering background
The proposed project is located at Linger New District, Hohhot. The project is an underground foundation pit of the urban expressway. The shape of the foundation pit is rectangular. The average depth of the foundation pit is 10–18 m. Both diaphragm wall and the inner support are the primary support method of the foundation pit. The depth of the foundation pit in the study area is 9.5 m, the depth of the diaphragm wall is 24 m, and the width of the foundation pit is ~40 (39.4) m. The two inner supports are placed at a depth of 0 m and a depth of 4.2 m. Figs. 1 and 2 show the schematic of the proposed site and the cross-sectional view of the foundation pit.

3. Numerical simulation model of FLAC3D
To easily model and calculate, the engineering problem was simplified. First, we ignored the slope at the bottom of the foundation pit and considered the foundation pit to be horizontal. Second, we considered that the area along the outward half of the width of the foundation pit (20 meters) is unaffected by excavating the foundation pit. Third, horizontal displacement of the bottom of the model was ignored.

In this study, the model used the Mohr–Coulomb model [15]. The Mohr–Coulomb model is an ideal elastoplastic model; it includes Young’s modulus, cohesion, internal friction angle, Poisson’s ratio, and other important parameters that are obtained from geotechnical experiments. The calculation speed is fast and the deformation of the soil is accurately simulated. The size of this model is 80 m × 1 m × 24 m. (Fig. 3). The left and right boundaries and the bottom of the model were fixed in the x-direction, and the whole model is fixed in the y-direction.
The excavation and support sequence of the model is as follows:

The first step is to excavate the foundation pit to 4.2 m and set the first steel support at 0 m; the second step is to excavate the foundation pit to the bottom of the 9.5 m and set the second steel support at 4.2 m; and the third step is to excavate the inner pit of the foundation pit and support the inner pit. The excavated model is shown in Fig. 4. The model used liner elements to simulate the diaphragm wall and beam element to simulate inner support. Moreover, the model used cable and liner elements to simulate the cable and shotcrete of the inner pit.

To examine the effect of different excavation parameters, we changed three excavation parameters, including the distance between the left wall of the inner pit and the left wall of the outer pit (L), the width of the inner pit (I), and the depth of the inner pit (H).

As per the results of the geological investigation report, the parameters and physical distribution of rock and soil are shown in Table 1.

### Table 1. Stratum parameter

| Name of stratum | Depth (m) | density | Cohesion (kPa) | Internal friction angle (°) | Elastic modulus (Pa) | Poisson’s ratio |
|-----------------|-----------|---------|----------------|-----------------------------|---------------------|----------------|
| Backfill        | 0 to −4.2 | 1780    | 5              | 10                          | 1.00 × 10^7         | 0.3            |
| Gravel sand 1   | −4.2 to −8.8 | 1600 | 0              | 34                          | 2.30×10^6          | 0.27           |
| Gravel sand 2   | −8.8 to −18.5 | 1840 | 0              | 32                          | 5.50×10^6          | 0.27           |
| Silty sand 1    | −18.5 to −23.6 | 1740 | 0              | 28                          | 2.50×10^6          | 0.3            |
| Clay silt       | −23.6 to −26.0 | 1920 | 24.6           | 21.5                        | 8.96×10^6          | 0.38           |
| Silty sand 2    | −26.0 to −30.0 | 1950 | 0              | 28                          | 1.50×10^7          | 0.3            |

Tables 2 and 3 show the parameter of the diaphragm wall and the inner support.

### Table 2. The parameter of diaphragm wall

| name             | Material   | Cross-section width (mm) | Elastic modulus E/GPa |
|------------------|------------|--------------------------|-----------------------|
| Diaphragm wall   | C30 concrete | 800                      | 30                    |

### Table 3. The parameter of inner support

| Name  | material | Cross-section size | Elastic modulus E/GPa | Poisson’s ratio |
|-------|----------|--------------------|-----------------------|-----------------|
|       |          |                    |                       | μ               |
The first and second steel support

|        | A609 steel | R = 609, t = 16 | 206         | 0.3         |
|--------|------------|-----------------|-------------|-------------|

4. Calculation and discussion

To study the deformation of the foundation pit’s side wall after excavation, we selected the nodes on the diaphragm wall and studied its horizontal displacement. We then selected the nodes within 20 m on both sides of the foundation pit to study its vertical displacement. Moreover, we analyzed the soil’s failure situation by the plastic zone.

4.1 Horizontal displacement of the diaphragm wall

Fig. 5–8 show the deformation of the diaphragm wall with different construction steps and excavation parameters. Fig. 5 shows that the two sides of the diaphragm wall was displaced 5–10 mm to the right side after excavating the inner pit. When the foundation pit is excavated to 4.2 and 9.5 m, because of the symmetry of the model, the displacement of the diaphragm wall on the right is the same as the left one but the direction is opposite. After excavating the inner pit, the left-hand ground wall was displaced 2–10 mm to right. The asymmetrical position of the inner pit caused the entire foundation pit right shift; thus, the inner pit considerably affected the horizontal deformation of the whole pit.

![Figure 5](image1.png)

**Figure 5.** The displacement of diaphragm wall. (a) The left side of the foundation pit. (b) The right side of the foundation pit.

Fig. 6 shows that the distance between the left walls of the inner pit and the outer pit affects the displacement of diagram wall somewhat. When \( L > 0 \) m, the left wall of the inner pit is supported by shotcrete and cable; thus, these displacements of diagram wall are different from the displacement when \( L = 0 \) m.

![Figure 6](image2.png)

**Figure 6.** The displacement of the diaphragm wall with different \( L \). (a) The left side of the foundation pit and (b) the right side of the foundation pit.
Fig. 7 shows that the deepening of the inner pit increases the displacement of the diagram wall closer to the inner pit; however, deepening of the inner pit alleviates the displacement of the diagram wall far from the inner pit.

![Figure 7](image)

**Figure 7.** The displacement of the diaphragm wall with different h. (a) The left side of and (b) the right side of the foundation pits.

Fig. 8 shows that the deepening of the width of the inner pit increases the displacement of the wall closer to the inner pit. Moreover, deepening of the width of the inner pit hardly affects the displacement of the wall far from the inner pit. Furthermore, the displacement of the left wall increases along the depth of the inner pit.

![Figure 8](image)

**Figure 8.** The displacement of the diaphragm wall with different l. (a) The left side and (b) the right side of the foundation pit.

### 4.2 Surface subsidence around the foundation pit

Figs. 9–12 show the vertical displacement of the soil with different construction steps and excavation parameters. Here, we report that a bulge of the soil appears on the side close to the foundation pit; as the distance from the edge of the pit increases, the bulge of the soil decreases and eventually stabilizes. We speculated that the displacement at the bottom of the diaphragm wall is much larger than the top displacement, which caused the upper soil to be squeezed and expanded. Moreover, we reported that excavating the inner pit has little effect on the vertical displacement of the soil around the outer pit. Furthermore, excavation parameters, including L, h, and l, affects little on the subsidence of soil far from the inner pit. Excavation parameter L affects little on the subsidence around foundation pit. The increase in excavation parameters h and l increased the subsidence of the soil closer to the inner pit.
Figure 9. Vertical displacement of the soil. (a) The left side and (b) the right side of the foundation pits.

Figure 10. Vertical displacement of the soil with different L. (a) the left side and (b) the right side of the foundation pit.

Figure 11. Vertical displacement of the soil with different h. (a) the left side and (b) the right side of the foundation pits.
Figure 12. Vertical displacement of the soil with different l. (a) the left side and (b) the right side of the foundation pits.

4.3 Plastic zone comparison

Fig. 13 shows that no plastic zone appeared before the inner pit was excavated, indicating that the soil was undamaged. After excavating the inner pit, a plastic zone appears on the right side of the inner pit, indicating that tensile failure occurs. The reason for this phenomenon is considered that the inner pit is completely in the gravel sand layer and the cohesive force is low; thus, tensile failure is easy to occur.

Figure 13. The plastic zone

Fig. 14 shows that the closer the distance between the inner pit and the outer pit is, the more area arrives into plastic. Moreover, the plastic area appears around the inner pit and the top of the diagram wall.

Figure 14. The plastic zone with different excavation parameters L

Fig. 15 shows that the deeper the inner pit is, the more area arrives into plastic. Moreover, the plastic area mostly appears on the left side of the diagram wall.
5. Conclusion

Based on a foundation pit in Hohhot, this study built a model using FLAC3D. Moreover, this study analyzed the displacement of the diaphragm wall and the vertical displacement of the soil around the foundation pit at different construction stages and of different excavation parameters. Furthermore, this study analyzed the failure state of the soil after excavation. The following conclusions had been reached:

1. Excavating a pit-in-pit increases the horizontal displacement of the side wall of the foundation pit. Importantly, the asymmetry of the position of the pit-in-pit causes each side of the diaphragm wall to move left simultaneously.

2. Our study reveals that excavation parameter L slightly affects the subsidence of foundation pit. Excavation parameters including h and l slightly affect the subsidence of the soil far from the inner pit. The increase in excavation parameters h and l increased the subsidence of the soil closer to the inner pit.

3. Excavating the inner pit induces the failure of the soil around the inner pit. Excavation parameters, including L, h, and l, are proportional to the volume of the plastic area.

Acknowledgments

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