Optimization and Risk Assessment of Multi-Pit Excavation Strategies in Soft Soil Conditions

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Abstract

The stability of Diaphragm Walls (DWs) in deep foundation pits is a critical concern in urban construction, where complex excavation activities can induce significant structural deformations. This study aims to evaluate the impact of different excavation sequences on the displacement behavior of DWs to improve excavation safety and structural performance. A series of numerical simulations were conducted using four distinct excavation scenarios to analyze the lateral deformation patterns of DW1, DW2 and DW3. Based on the observed results, Case 3 demonstrated the most favorable performance, with wall displacements remaining within allowable limits, indicating improved structural stability. To further assess localized structural responses, the displacement behavior of DW4, DW5, DW6 and DW7 was also analyzed under Case 3. The results showed that all walls experienced inward displacement within allowable limits. The findings highlight that displacement magnitudes are influenced by factors such as wall position, excavation-induced stress redistribution, and soil-structure interaction. DW2, serving as a shared wall between adjacent pits, exhibited higher sensitivity to excavation activities. This study underscores the importance of optimized excavation sequencing and structural interaction analysis in mitigating wall displacements and enhancing the stability of deep foundation pits in complex urban environments.

Full Text

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Keywords: Adjacent deep foundation pits, Finite element method (FEM), Excavation sequence optimization, Diaphragm wall (DW), Shared wall stability.

Introduction

With the rapid urbanization of modern cities, subway systems have become essential components of urban transportation networks. In densely populated areas, foundation works are increasingly undertaken near existing subway tunnels and adjacent structures, resulting in complex interactions between excavations. Excavating adjacent foundation pits induces significant changes in soil mechanics and structural behavior, posing potential risks such as excessive deformation, ground settlement and structural instability [1,2,3,4]. Improperly managed excavation processes can exacerbate these risks, leading to engineering failures and environmental challenges [5,6,7]. Thus, understanding the behavior of adjacent foundation pits during excavation is crucial for ensuring safety, optimizing designs and minimizing impacts on surrounding environments.

Numerous studies have explored the mechanical behavior and deformation characteristics of deep foundation pits during excavation. Xu et al. [8] observed deformation trends in a super deep foundation pit in soft soil, highlighting the pronounced deformation in narrow pit sections compared to corners. Ruan et al. [9] demonstrated the significant influence of support structure design on the impact range of adjacent pits, while Sun et al. [10] utilized finite element modeling to optimize construction processes near deep excavation sites. Chen et al. [11] analyzed field data and noted that neighboring pit excavation could reduce lateral deformation of enclosure structures, underscoring the mutual influence between pits.

In the field of numerical simulation, advanced tools such as PLAXIS 3D, FLAC 3D and Midas GTS have been employed to analyze the performance of foundation pits under various excavation conditions. Zhu et al. [12] used 3D modeling to study the internal forces and deformation characteristics of foundation pits with different rock penetration depths, while Wang et al. [13] investigated the deformation responses of conjoined double pits under different excavation sequences (sequential, simultaneous and comprehensive). Hu et al. [14] analyzed the stability of near-water foundation pits using a coupled seepage-stress model and Wei et al. [15] examined the effects of pre-existing structures on the deformation and earth pressure of pits during subway station construction. Despite these advancements, existing studies primarily focus on individual construction methods, such as bottom-up (BU) or top-down (TD), without adequately addressing the combined impact of excavation sequence and shared structural components. Furthermore, research on adjacent pits with a common diaphragm wall remains limited, despite its significance in influencing mutual deformation and load distribution. The interaction between pits sharing such a critical structural element poses unique challenges that require in-depth investigation.

This study employs PLAXIS 3D finite element software to analyze the mechanical behavior of two adjacent foundation pits sharing a common diaphragm wall. Four distinct excavation sequences are evaluated to understand their effects on critical parameters including horizontal displacement of the diaphragm wall. The findings aim to provide practical insights into optimizing excavation sequences and support design for adjacent foundation pits, ensuring construction safety and performance in dense urban environments.

2.1 Project Introduction

This study investigates the foundation pits of Line 13 Binjiang Station and Plot 23, located in the rapidly developing Nanjing Jiangbei New Area. These two adjacent pits were selected as case studies to explore the mechanical behavior, interactions and risks associated with simultaneous excavation. The shared common diaphragm wall between the two pits provides a unique opportunity to study the influence of construction sequences on the structural performance and surrounding environment, particularly in soft soil conditions.

Pit A, the foundation pit for Line 13 Binjiang Station, has a total area of approximately 9,320 m^2, with a length of 260 m and a width that ranges from 23 m to 38 m. It is a large-scale project, with the pit designed to accommodate six underground stories, which are currently under construction. The complex design of Pit A reflects its significance as a critical component of Nanjing's urban transportation infrastructure. In contrast, Pit B, corresponding to Plot 23, spans an area of approximately 9,132 m^2. It has a more compact layout, with a maximum length of 98 m and a maximum width of 100 m. Unlike Pit A, construction of Pit B has not yet commenced, providing an ideal case for evaluating and planning the optimal excavation sequence to mitigate risks and enhance construction safety.

The spatial relationship and surrounding construction environment of these two pits are shown in Figure 1 [Figure 1: see original paper], which highlights the dense urban setting and the proximity of other structures. This allows for an in-depth analysis of the interactions between the two pits, particularly with respect to their shared diaphragm wall. This research is critical for developing optimized excavation strategies that can ensure structural stability, minimize ground deformation and control construction risks in such a challenging environment.

2.2 Site Conditions

The construction site is situated within the Yangtze River floodplain, characterized by a uniform landform type with minimal variations in ground elevation. The area is geologically stable, with no adverse geological phenomena such as sand liquefaction, landslides, collapses, ground subsidence or ground fissures observed within the site. Approximately 800 meters from the site lies the Yangtze River, the largest nearby surface water body. Despite its prominence, the river has minimal direct impact on the construction activities at the station due to its distance and the local hydrogeological conditions.

Seasonal variations in groundwater levels are significant, with the highest levels occurring during the rainy season (July to August) and the lowest during the dry season (December to March of the following year). These fluctuations, primarily driven by atmospheric precipitation, range annually between 1.5 and 2.0 meters. For this research, the site stratigraphy has been simplified into six primary layers to streamline modeling and ensure better convergence during calculations, excluding the other layers. Table 1 summarized the physical and mechanical properties of these layers.

The uppermost layer (1-2) consists of plain fill soil, largely made up of anthropogenic deposits from earlier developments. Beneath this is a layer of muddy and silty clay (2-2b), which is soft and highly compressible, typical of sedimentary floodplain deposits. The third layer (2-3b) comprises interbedded muddy and silty clay with silt, reflecting alternating sediment deposition periods. Below this lies a fine sand layer (2-5d1), known for its permeability and relative stability, facilitating groundwater flow. Further below is a medium coarse sand layer (3-4d1) containing rounded gravel, providing significant load-bearing capacity. At the deepest level is a weathered mudstone and sandstone layer (K2-p3), which exhibits bedrock-like properties and offers essential support for deep excavations.

The physical and mechanical parameters of these soil strata, including water content ( ), cohesion ( ), void ratio ( ), plasticity index ( ), liquidity index ( ), vertical permeability ( ), and horizontal permeability ( ), were determined through comprehensive physical properties tests. The elastic modulus ( ) was derived from consolidation tests, while cohesion ( ) and friction angle ( ) were obtained via triaxial consolidated-drained shear tests and these parameters were available in inspection report.

3. Numerical Model and Parameters

Figure 2 [Figure 2: see original paper] presents the 3D numerical model used for the analysis, where the dimensions of the foundation pits are based on the actual geometry extracted from the project drawings. To minimize boundary effects and ensure accurate calculations, the model's dimensions are set at 600 m x 500 m x 150 m. This size is consistent with the recommendations of previous studies by Sun et al. [19] and Xu et al. [20] which suggest that the influence range of foundation pit excavation is typically within three times the excavation depth.

The retaining structure of the foundation pit is shown in Figure 3 [Figure 3: see original paper], which is designed using a diaphragm wall with a thickness of 1.2 m, and the insertion ratio of the diaphragm wall is set to 1.2. The horizontal struts in Pit A and Pit B consist of reinforced concrete beams, with cross-sectional dimensions of 0.9 m x 0.8 m. Pit A includes six levels of horizontal struts, located at depths of -1 m, -8 m, -17 m, -26 m, -34 m, and -42 m below the ground surface. In contrast, Pit B features five levels of horizontal struts, positioned at depths of -1 m, -5.30 m, -9.80 m, -13.80 m and -16.75 m below the ground surface. The groundwater level is set at -1.5 m below the ground surface.

The numerical model simulates the soil using solid elements, while the diaphragm wall is represented with plate elements and the horizontal struts are modeled with beam elements. The interaction between the wall and soil is captured through interface elements. The seven locations of DWs are represented in Figure 3 at which the displacement of DW is analyzed.

For boundary conditions, the left and right boundaries are restricted to horizontal displacement, the bottom boundary is constrained to both horizontal and vertical displacements and the top boundary is left free. The HSS (small strain hardening) model is utilized to simulate soil behavior due to its capability to realistically model the deformation and failure characteristics of both soft and hard soils, especially during deep excavation. The corresponding parameters for the HSS soil model are summarized in Table 2 .

This model has been shown to produce accurate diaphragm wall deformations and ground settlement predictions. It includes 13 parameters: cohesive force (c), internal friction angle (Φ), dilatancy angle (Ψ), secant stiffness in the standard drained triaxial test (E50 ref), tangent stiffness for primary oedometer loading (Eoed ref), triaxial unloading-reloading stiffness (Eur ref), Go is reference shear modulus at very small strains, \$ $0.7isthresholdshearstrain, powerforstress - leveldependencyofstiffness(m), Poisson'sratioforunloading-reloading(\mu), referencestressforstiffness(
(4.3to9.3)E50refareadopted.Fortheretainingwallandhorizontalstruts, whicharemadeofreinforcedconcrete,$
an elastic modulus of 3.0×10^6 MPa, and a Poisson's ratio of 0.2.

4. Methodology

To accurately simulate the excavation process, a stepwise approach is adopted mirroring the actual construction sequence. The excavation is divided into multiple phases, with each phase involving the staged removal of soil layers while simultaneously activating the corresponding structural supports. This methodology enables a detailed assessment of stress redistribution, ground settlement and diaphragm wall deformation at each excavation stage.

To effectively capture the interaction between Foundation Pit A and Foundation Pit B, four distinct construction cases are employed in the numerical simulation. The underground structures of both projects are constructed using the top-down cover excavation method. The excavation process for Pit A is divided into six phases, while Pit B follows a five-phase sequence, as outlined in Table 3 . Based on these excavation sequences, four construction cases are established for simulation, as detailed in Table 4 .

In the first case, sequential excavation is conducted, where all phases of Pit A are completed before commencing excavation of Pit B. The second case follows a partial sequential excavation with simultaneous completion, in which Pit A is first excavated to 1st layer, after which the remaining phases of Pit A and the full excavation of Pit B proceed simultaneously. The third case involves simultaneous full-depth excavation, where all excavation phases of Pit A and Pit B progress simultaneously from start to finish. The fourth case adopts a step-by-step alternating excavation, in which each excavation phase of Pit A is followed by the corresponding phase of Pit B in an alternating manner until both pits are fully excavated. These construction cases allow for a comparative analysis of different excavation strategies, enabling the evaluation of their respective impacts on soil deformation, structural performance and overall excavation stability.

4.1 Numerical Model Validation

During the construction of Foundation Pit A, the excavation of Foundation Pit B had not yet commenced. In order to assess the structural behavior of Pit A, comprehensive on-site measurements were carried out, focusing primarily on the lateral displacement of the DW. These measurements aimed to capture any potential deformations or displacements that could affect the stability of the diaphragm wall during the excavation process. Since field monitoring data for Foundation Pit B was not available for comparison, the numerical results of the study were compared against the allowable horizontal displacement limit of 28 mm, which is the prescribed maximum displacement for the diaphragm wall of Pit A.

The numerical analysis conducted during the study revealed that, in Case 1, the maximum lateral displacement at DW 1 reached 22.92 mm. This value remained well within the allowable limit. This indicates that the excavation procedure in Case 1 was effective in controlling the deformation of the diaphragm wall, ensuring that the displacement did not exceed the critical threshold. The analysis further demonstrated that, for the majority of the simulated cases, the predicted displacements were contained within the permissible range, showing only minor exceedances in specific instances. These minor exceedances, while noteworthy, did not result in significant structural concerns, highlighting the generally successful performance of the retaining system under the modeled excavation conditions.

5. Results and Discussion

The numerical analysis was conducted to evaluate the lateral displacement behavior of the DW during the staged excavation of the deep foundation pits. Four excavation cases were considered, each reflecting different construction sequences. The analysis focused on the displacement profiles of DW1, DW2, and DW3 across all four cases, while additional evaluation was performed for DW4, DW5, DW6 and DW7 in Case 3 to investigate localized effects.

The displacement profiles of DW1 under the four excavation scenarios are presented in Figure 4 [Figure 4: see original paper], demonstrating variations in lateral deformation. In Case 1, the maximum lateral displacement of DW1 reached approximately 38 mm at 0.4H, exceeding the permissible limit by 35.7%. The deformation pattern indicates stress concentration in the upper section of the diaphragm wall, suggesting the need for enhanced lateral support to mitigate excessive movement. Case 2 exhibited the highest displacement, with DW1 experiencing a peak deformation of 42 mm, surpassing the allowable threshold by 50%. The increased displacement highlights more significant soil-structure interaction effects, necessitating additional excavation control measures. In contrast, Case 3 recorded a maximum displacement of 27 mm, remaining within the permissible range. The reduced deformation suggests that the excavation and support sequence in this case effectively controlled lateral movements. Case 4 showed a maximum displacement of 37 mm, exceeding the limit by 32.1%. The displacement pattern in this case closely resembles that of Case 1, indicating similar stress redistribution mechanisms.

The displacement results for DW2 across the four cases are illustrated in Figure 5 [Figure 5: see original paper]. Unlike DW1, which also exhibited inward displacement but with positive values, DW2 experienced displacement on both sides due to its role as a shared retaining structure between two adjacent foundation pits. This makes DW2 particularly vulnerable to stress redistribution, especially in excavation sequences where neighboring pits are excavated in close succession. In Case 1, DW2 exhibited a maximum inward displacement of -30.57 mm, occurring at approximately 0.4H depth, indicating significant movement toward the excavation side of Pit A, while minor outward displacement was also observed on the side of Pit B. This significant inward shift highlights the influence of excavation-induced stress release, where soil relaxation led to pronounced movement towards the excavation side. Case 2 recorded a maximum displacement of -18.70 mm, considerably lower than Case 1. The reduced deformation suggests that the excavation sequence in this case allowed for better stress distribution, minimizing excessive movement of the diaphragm wall. In Case 3, DW2 experienced a peak inward displacement of -16.42 mm, showing further reduction in movement. The decreased deformation indicates that this excavation sequence led to improved structural stability, effectively distributing loads and mitigating excessive stress concentration. Case 4 displayed the least displacement among all cases, with a maximum inward movement of -14.71 mm. The further reduction in deformation suggests that this sequence provided the most stable excavation conditions, likely due to optimized support and load distribution mechanisms.

The displacement behavior of DW3 was analyzed under four different excavation scenarios, with the results illustrated in Figure 6 [Figure 6: see original paper]. DW3 displays more consistent displacement profiles across all cases compared to DW1 and DW2. Unlike DW1, which exhibits consistent inward displacements with positive values due to its proximity to a single excavation zone, and DW2, which demonstrates bidirectional displacement patterns owing to its shared position between two adjacent pits, DW3 displays predominantly negative displacement values. These negative values indicate a uniform inward movement toward the excavation side, suggesting a more controlled deformation mechanism. The maximum displacements recorded for DW3 are -28.46 mm, -30.62 mm, -26.67 mm, and -26.66 mm for Cases 1 through 4, respectively. These measurements are comparable in magnitude to those of DW1 and DW2 but exhibit a notably more stable trend, with minimal variation across the different cases. This consistency implies that DW3 is subject to a more balanced stress distribution, likely due to its structural configuration and optimized boundary conditions, which mitigate the influence of adjacent excavations. Furthermore, the displacement profiles of DW3 exhibit smoother gradients compared to DW2, where abrupt changes in deformation occur due to differential pressures from neighboring pits. The absence of sharp displacement fluctuations in DW3 suggests that localized stress concentrations are effectively dissipated, reducing the risk of structural instability.

In Case 3, where DW1, DW2, and DW3 exhibited minimal displacement, the behavior of DW4, DW5, DW6, and DW7 was further analyzed to assess their structural response under lower-deformation conditions (Figure 7 [Figure 7: see original paper]). All four walls demonstrated inward displacements, with maximum recorded values of 15.97 mm (DW4), -11.50 mm (DW5), 19.07 mm (DW6), and -25.55 mm (DW7). Among these, DW7 experienced the highest inward displacement, followed by DW6, DW4, and DW5, indicating varying degrees of load redistribution and support efficiency. The differences in displacement magnitudes highlight the critical role of geometric positioning relative to the excavation zone. For instance, DW7's significantly higher displacement suggests that it is subjected to greater lateral earth pressures, possibly due to its alignment along a deeper excavation section or reduced lateral support. In contrast, DW5's lower displacement may result from favorable boundary constraints or a more effective load-transfer mechanism. The observed trends underscore the importance of site-specific design considerations in deep excavation projects.

Walls with asymmetric loading conditions (e.g., DW2) require additional reinforcement to counteract differential pressures, while those with consistent displacement patterns (e.g., DW3) may benefit from optimized support layouts to further enhance stability. Future studies could explore the influence of soil-structure interaction and temporal effects (e.g., creep and stress relaxation) to refine predictive models for displacement behavior.

6. Conclusions

This study investigated the displacement behavior of DWs under different excavation scenarios using numerical analysis. The key findings and conclusions are summarized as follows:

1) The excavation sequence plays a critical role in controlling the lateral displacement of diaphragm walls. Among the analyzed cases, Case 3 demonstrated the most stable performance, with DW1, DW2, and DW3 exhibiting minimal displacements well within the allowable limits. This indicates that optimized excavation sequencing can significantly reduce deformation and enhance structural stability.

2) The displacement behavior varied considerably among different DWs, influenced by factors such as wall position, excavation depth, and adjacent structural interactions. DW2, being a shared wall between two adjacent foundation pits, exhibited displacements on both sides, making it more sensitive to excavation-induced stress redistribution. In contrast, DW3 showed more consistent and uniform displacement profiles across all cases, reflecting a relatively stable structural response under different excavation conditions.

3) The analysis of DW4, DW5, DW6, and DW7 in Case 3 revealed varying degrees of inward displacement, with maximum values of 15.97 mm, -11.50 mm, 19.07 mm and -25.55 mm, respectively. DW7 exhibited the highest inward displacement, suggesting greater susceptibility to excavation-induced stresses, while DW5 showed the least deformation. These variations highlight the influence of wall location relative to the excavation area and the distribution of lateral earth pressures.

4) The study highlights that structural interactions between adjacent walls and varying excavation sequences significantly influence wall deformation. Shared walls, such as DW2, are more affected due to the combined loading effects from adjacent pits, while isolated walls like DW3 tend to exhibit more stable displacement patterns.

5) The findings of this study emphasize the importance of considering wall-specific responses when designing excavation support systems. Optimizing excavation sequences, particularly in complex projects involving multiple adjacent pits, can effectively control wall displacements and reduce potential risks to structural integrity.

Overall, this research provides valuable insights into the displacement behavior of diaphragm walls under different excavation scenarios, highlighting the need for comprehensive planning and continuous assessment to maintain the stability and safety of deep foundation pits.

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Note: Figure translations are in progress. See original paper for figures.