Study on the Influence of Wall Spacing on Double Diaphragm Wall Supporting Structure for Ship Lock Expansion

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Abstract. Given China’s economic growth, current river ship locks in the Beijiang channel are reaching saturation. Ship lock expansion at key navigation terminals is imminent. This paper took Qingyuan’s new second-line ship lock in Guangdong, China as the engineering case, were a double diaphragm wall was utilized as the support scheme. Currently, there are very few engineering examples of this type of support structure both in China and abroad. Through the geotechnical finite element analysis software MIDAS GTS NX, a 3D finite element model was constructed to study the deformation and internal stresses of the support structure and adjacent ship lock, during the new ship lock’s foundation pit excavation, under different wall spacing. Based on the engineering case simulation results under different double diaphragm wall spacing, conclusions are reached on the influence and behaviour of the wall spacing double diaphragm wall structural parameter.

Keywords: double diaphragm wall; support structure; ship lock; wall spacing; sensitivity analysis

1. Introduction
The standard practice for ship lock expansion is for a new ship lock to be built laterally next to the original ship lock it will complement or replace [1]. Before construction, an appropriate and effective foundation pit support scheme should be adopted to meet the deformation control requirements during the foundation pit excavation process and guarantee the protection of the adjacent ship lock and surrounding environment.

Qingyuan’s new second-line ship lock was arranged adjacent on the right side of the existing first-line ship lock. The new ship lock was designed to support vessels up to 1000t vessels. It has 3 main segments, an upper gate of 50 m, lock chamber 220 m and lower gate 56 m in length. The first and second-line ship locks are designed to be at a 90 m distance from their center axis. Ground elevation neighboring 5 m with foundation pit maximum excavation depth of 15.5 m. The new ship lock foundation pit width was of 65.5 m for the upper gate and, lock chamber segments; and lower gate’s 60 m. The upper gate is located at the right bank of the Qingyuan Water Control Project (WCP) dam; the lock chamber and lower gate are located to the right of the first line ship lock. The stratum is poor, and geological conditions are complex.

Given the proximity to the existing ship lock and geological and hydrological conditions, the Shenzhen Water Planning and Design Institute and Zhongshan Design Group Co., Ltd chose the double diaphragm wall with horizontal reinforced concrete brace as the support scheme between the first-line ship lock and second-line ship lock foundation pit, figure 1 (right) as reference. The wall nearest to the first-line ship lock (rear wall) is 1000 mm thick and the wall next to the excavation (front wall), right of the rear wall, has a thickness of 1200 mm, the design distance between diaphragm walls (wall spacing) was 12
Utilizing MIDAS GTS NX software, a 3D finite element strain model of the new ship lock double diaphragm wall supported foundation pit excavation was constructed. At the time of writing this paper only 2 reports in China and abroad were found on the application of double row diaphragm walls in deep foundation pits with adjacent ship locks. Luu N and Pham Q\(^2\) (2020) made a report on the design and construction experience of a double diaphragm wall supported foundation pit for a high-rise building. In their report the double diaphragm wall spacing was 200 mm, small in contrast to the wall spacing of 12 m present in the present research engineering case. Luo Xiang\(^3\) (2018) provided a detailed report a ship lock expansion project that utilized a double diaphragm wall support scheme, the analysis displayed a wall spacing of 15 m with cement reinforced soil.

In actual engineering practice double row diaphragm support structure design is only carried out by reference to similar engineering projects and previous engineering experience. In each observed engineering case, the wall spacing form one case to another varied considerably\(^1\)-\(^2\). The present research has certain value for improving the basic theory of double row diaphragm wall supported engineering projects with an adjacent ship lock.

**Figure 1.** Upper view (right) and upper gate cross section view (left) of Qingyuan ship lock expansion project.

2. Finite Element Simulation of Double Row Diaphragm Wall

The engineering case design parameters and relevant geological conditions of the environment were the basis for the construction of the MIDAS GTS NX finite element model. All concrete slabs have a strength rating (SR) C30. A two-row concrete bream truss 4.25 m apart vertically was applied as horizontal support across the foundation pit, between the diaphragm walls. The beams have steel reinforced C40, with a 1.2 m H x 1.1 m W cross section. The beams are supported by 5 rows of steel columns spanned 13.5 m, that are inserted into the concrete piles not less than 3 m, as displayed in figure 1(left). The excavation was divided into 3 stages. After first layer of brace horizontal concrete support is constructed, the first stage of excavation was executed reaching a height of 0.52 from 2.25 m (with 1.73 m of vertical excavation). Promptly after the second layer of brace horizontal concrete support was constructed, the second stage of excavation was performed. The second stage reached a depth of 6.01 (with 6.53 m of vertical excavation). Finally, the third stage of excavation consisted of 9.49 m of vertical excavation reaching a depth of 15.5 m.

2.1. Geological Conditions

According to the engineering survey data, the second-line ship lock is located on an erosion and accumulation valley plain. The Quaternary cover of the project area is thick and composed mainly of sandy soil. Cohesive soils, mixed silt clays, tend to provide less stability in large excavations. The surrounding silt content and piping increase the probability of geological failure. This in turn can lead to unfavourable deformations, settlement (such as geological collapse) and possible cracking in
neighbouring structures. The cover layer is composed of quaternary rushing and flooding. The soil layer distribution are as follows:

**Table 1.** Soil layer distribution in geological section between first-line ship lock and double row diaphragm wall.

| Soil No. | Soil Name               |
|----------|-------------------------|
| 1b       | Sand Filling            |
| 1-1      | Coarse Sand             |
| 1-3      | Muddy Silty Clay        |
| 2-2      | Mixed Silt              |
| 2-3      | Fine Sand               |
| 4-3      | Round Gravel            |
| 6-3      | Weathered Limestone     |

**Figure 2.** Geological section between first-line ship lock and double row diaphragm wall (drill points ZK6018 to ZK161).

2.2. *Construction of Finite Element Model*

To improve the calculation accuracy, efficiency, and convergence of the finite element model, a three-dimensional (3D) strain model of the upper gate foundation pit section with its surrounding environment and adjacent ship lock section was constructed, as seen in figure 3.

**Figure 3.** 3D Finite element model of new ship lock upper gate section foundation pit excavation.

To improve the calculation reliability and convergence of the finite element calculation, a three-dimensional (3D) strain model was established. The foundation pit width of the project is 65.5m and the depth is 16m. To eliminate the influence of the model boundary conditions on the foundation pit as much as possible, the model size was 290m×51m×85.5m (width × length × height), in comparison to the actual case boundary conditions 190m×50m×40m. Given the scale of the project the analysis focused on the deformations in terms of the cross-section width and height.

Based on Schanz and Vermeer\(^4\) (1999) report on the features of the Hardening Soil (HS) model and its ability to simulate soil hardening behavior, the HS model was considered to be the most accurate
constitutive soil model to calculate the deformation and stress of the soil. Lei Wang and Hsein Zhuang\cite{5} (2014) by considering the hardening effect and non-linearity of the soil in its elastic stage, determined the most accurate model for optimization design of excavation supporting structures was the hardening soil model, whilst for the concrete and steel elements the linear elastic model (LEM). The constitutive model adopted for concrete and steel elements was the linear elastic model, whereas for rock and soil the hardening soil model was adopted.

3. Analysis of Double Diaphragm Wall under Different Wall Spacing

The presence of two diaphragm walls caused the rear wall and front wall to experience different types of soil-structure interactions. Through single factory sensitivity analysis, the resulting deformation of the supporting structure and displacement of the adjacent ship lock are studied under different wall spacings as to determine the influence of wall spacing on the foundation pit support structure.

3.1. Single Factor Sensitivity Analysis

Utilizing the established finite element model, the influence of wall spacing was analysed based on the principle of single factor sensitivity analysis. Through multiply simulations, the wall spacing was sequentially taken as 3 m, 6 m, 9 m, 12 m, 15 m, and 18 m. Aside of wall spacing, all the remaining parameters were consistent with the established model and original engineering case design parameters.

3.1.1. Sensitivity Analysis of Wall Spacing Results. The finite element analysis results showed that the displacement of the front and rear walls will be reduced to a certain extent with the increase in wall spacing of the DRDW, as see in figure 6 and figure 8. The reduction in displacement was larger for the rear wall. The front wall bending moment was not significantly affected by changes in wall spacing, as shown in figure 7.

![Figure 4. Front diaphragm wall displacement simulation and monitoring data results.](image1)

![Figure 5. Rear Wall Displacement simulation and monitoring data results.](image2)

![Figure 6. Front Wall Displacement Under Different Wall Spacing.](image3)

![Figure 7. Front Wall Bending Moment Under Different Wall Spacing.](image4)
4. Comprehensive Influence Analysis of Wall Spacing

As the wall spacing increased from 3m to 18m, the maximum horizontal displacement of the adjacent ship lock decreased from 6.43mm to 5.82mm with a change of 0.61mm (figure 10). The deformation of the front wall did not appear to be affected by the wall spacing. The deformation of the rear wall changed drastically from an initial 12.61 mm at a 12 m wall spacing, to an increased 27.97 mm when the wall spacing was 3 m. Conversely, the rear wall deformation decreased to 8.56 mm when the wall spacing was increased to 18m, as displayed in figure 8.

Based on figure 9, it is clear that wall spacing has a large influence on the rear wall maximum bending moment. The maximum bending moment of the front was marginally increased with the increase of the wall spacing (figure 7). From the analysis, it can be seen that with the increase of wall spacing, the overall lateral resistance of the DRDW supporting structure, can be fully exerted; the mechanical characteristics of the rear wall were greatly improved, and the horizontal displacement and bending moment increase the anchoring effect on the front wall. Larger wall spacing can cause greater reduction of the adjacent ship lock displacement.

5. Concluding Remarks

It was observed that as the surface area of the active soil between the front and rear wall increased the overall deformation of the rear wall decreased considerably, and adjacent ship lock displacement decreased marginally and front wall displacement was virtually unaffected.
Increase in wall spacing also had a positive effect in the reduction of maximum bending moment of both front and rear wall. This can be attributed to the active soil area between the diaphragm walls absorbing a portion of the shear forces during the pit excavation process.

For adjacent structures, increased wall spacing appeared to cause an overall reduction in maximum displacement. In similar projects, the deformation of the supporting structure and the deformation of the adjacent structure should be comprehensively weighed.

This paper was able to establish the wall spacing influence on deformation and internal stresses of double diaphragm wall.

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