A numerical study on ground displacement and stress during and after the installation of deep circular diaphragm walls and soil excavation

Yasushi Arai a,*, Osamu Kusakabe b, Osamu Murata c, Shinji Konishi d

a Railway Technical Research Institute, Structure Technology Division, 2-8-38, Hikari-cho, Kokubunji-shi, 185-8540, Tokyo, Japan
b Department of Civil & Environmental Engineering, Tokyo Institute of Technology, Japan
c Marketing and Business Development Division, Railway Technical Research Institute, Japan
d Railway Technology Promotion Division, Railway Technical Research Institute, Japan

Received 31 May 2006; received in revised form 5 November 2007; accepted 5 November 2007
Available online 21 February 2008

Abstract

Three-dimensional total stress elasto-plastic FEM analysis was conducted to examine ground movement and stress after the installation of circular diaphragm walls and soil excavation within the walls.

Combinations involving three different wall thicknesses and two different excavation sequences within the wall were adopted to investigate differences in the final ground movement and the lateral stress in the ground after wall installation and excavation within the wall in multi-layered ground.

The analysis results showed that the construction sequence significantly affects ground displacement and lateral stress behind the wall, implying that the situation even before excavation within the wall is no longer axisymmetric.

Reducing the wall thickness also reduced the vertical and circumferential section forces of the wall after excavation within it.

© 2007 Elsevier Ltd. All rights reserved.

Keywords: Circular shaft; Excavation; Diaphragm wall; Installation effects; Three-dimensional FEM analysis

1. Introduction

Any large-scale excavation requires retaining structures (such as diaphragm walls) to be installed before soil excavation is commenced. Although the influence of excavation work on the surrounding ground and on existing structures has been commonly evaluated through numerical simulation, the main interest focuses on the influence of the excavation process on these areas after retaining structures are installed in the soil. In other words, numerical simulation of the excavation process has generally been carried out under the assumption that the construction of retaining structures prior to excavation will not affect in situ stress conditions. The corresponding numerical technique is sometimes referred to as wished-in-place, where the wall is placed without any change to the in situ stress (e.g. De Moor and Stevenson [1]). This common assumption, however, has been questioned in practice as the influences of wall installation (referred to as installation effects) are thought to affect the subsequent behavior of the wall and the final overall condition.

The process of constructing diaphragm walls is rather complicated. The wall normally consists of a series of panels whose full construction sequence includes excavation under bentonite slurry followed by concreting and hardening.

Gunn and Clayton [2] and Kutmen [3] stressed the importance of the effects of installing the retaining wall. Gunn et al. [4] performed two-dimensional FEM analysis,
modeling the full construction sequence of the diaphragm wall followed by concreting and subsequent hardening. De Moor [5] carried out two-dimensional FEM analysis series on a plan (horizontal) section through a series of wall panels for a given depth. Ng et al. [6] conducted pseudo three-dimensional FEM analysis on the effects of diaphragm wall installation to examine load transfer mechanisms, horizontal arching and vertical load transfer. Ng and Yan [7] performed three-dimensional finite difference analysis of a single-diaphragm wall panel construction of 15 m deep, 8 m long and 0.6 m wide, and later extended this to three-panel construction (Ng and Yan [8]). Gourvenec and Powrie [9] published the results of three-dimensional FEM analysis on the effects of diaphragm wall installation to examine load transfer mechanisms, horizontal arching and vertical load transfer. Ng et al. [10], Ariizumi et al. [11]. Muramatsu and Abe [12] carried out field measurements focusing on the peripheral ground deformation when a diaphragm wall was installed and when soil within the wall was excavated.

In this research, we performed three-dimensional total stress elasto-plastic FEM analysis to examine ground movement and stress in the ground after installation of circular diaphragm walls and soil excavation within the walls. We selected a notional prototype for this analysis to model a previous deep circular diaphragm wall construction in Tokyo, with 32 m diameter, 85.5 m wall length and 1.2 m wall thickness. The ground conditions selected are those typically encountered in the Tokyo Bay area. Two factors considered are the thickness of the diaphragm wall and the type of soil excavation within the wall, and we discussed the results to examine the effect due to construction sequence.

In the foregoing project, earth and water pressures, as well as stresses in the diaphragm wall are being monitored to verify and improve the current design calculations.

The monitoring data has attracted the attention of those designing the future Central Linear Shinkansen and Out-Ring expressway projects, and this study will provide further insight into the properties of circular diaphragm wall construction.

2. Numerical modeling of diaphragm wall construction and soil excavation within the wall

2.1. Aims of this research

Numerical modeling of the full construction sequence for diaphragm walls and subsequent soil excavation involves at least three numerical modeling phases. The first phase is a modeling process to construct a single wall panel, including excavation under bentonite slurry, followed by concreting and hardening. The second phase involves installing the other wall panels and joining several single panels to form a complete diaphragm wall structure. The third phase is the main soil excavation in front of or within the wall.

2.2. Notional prototype

The notional prototype for the wall adopted in this study involves a circular diaphragm wall constructed in typical ground conditions in the Tokyo Bay area, where a layer of soft, normally consolidated clay is underlaid by a stiff sand layer on base mud rock.

The dimensions and soil parameters used in the analysis were selected on the basis of previous experience and the current design practice for axisymmetric shafts in Japan. The notional reference prototype has a circular shaft with an internal diameter of 32 m, a wall thickness of 1.2 m and an embedded depth of 85.5 m. The depths of the clay and sand layers are 25.6 m and 40.8 m respectively, and the layer below the sand layer is base mud rock. The underground water level is assumed to be the surface ground level referred to in previous cases of construction.

In this analysis, the circular wall was composed of twelve initial panels and twelve subsequent panels, and the circular wall was modeled as a polygonal shape with 48 sides. The initial panels consist of three gutters while the subsequent ones are comprised of a single gutter, meaning that the circular diaphragm wall consists of 48 gutters in total. Each gutter has a length of 2.09 m, a depth of 85.5 m and a typical thickness of 1.2 m. Japanese practice is to construct the subsequent panels (which join the initial panels to form a diaphragm wall) using an effective concrete cutting method. This results in a joint so efficient at transferring circumferential forces that the circumferential stiffness of the wall (both axial and bending) can be assumed to match the vertical stiffness, referring to Japanese Standard Design Code [13]. Consequently, such an assumption has been made in the examples of analysis presented in this paper, and the wall was modeled with isotropic stiffness properties.

2.3. FEM analysis

2.3.1. Outline of FEM model

Three-dimensional numerical simulations were carried out using a commercially available FEM analysis code.
named MARC. Fig. 1a shows the FEM mesh with a volume of 200 m in depth and 400 m × 400 m in area, and the circular shaft with an internal diameter of 32 m is located in the center of the analysis zone (see Fig. 1b and c). Such a large zone was selected to avoid any measurable effects from the boundary in the final results. In this research, we use hexahedral elements for three-dimensional FEM. These elements have eight nodes and eight integration points, and the Gaussian integration method was applied to them. The analyzed zone has 23,775 nodes and 21,075 elements in total. The displacement of nodes along the side boundaries is fixed in the X-direction, while the displacement of those along the bottom boundary is fixed in the Z-direction. The clay and sand were assumed to behave as an elasto-perfectly plastic body with the Mohr–Coulomb failure criterion, obeying the associated flow rule. The base mud rock was assumed to be a linear elastic body.

The ground is divided into 14 horizontal layers whose soil properties are listed in Table 1. These properties were selected to represent realistic values on the basis of previous literature (Waseda University [14]).

The way in which multiple wall panels are connected is also an important factor to consider. Large-scale circular diaphragm walls are typically formed by first placing a number of initial panels with equal spacing, and then connecting them with subsequent panels to fill the spaces (schematically illustrated in Fig. 2).

Each initial panel is commonly composed of three gutters, and is constructed in four stages as shown in Fig. 3. The first gutter (Gutter 1) is excavated and filled with slurry, the third gutter (Gutter 3) is formed in the same way, and the second gutter (Gutter 2) is then used to connect the three gutters. A reinforced steel cage is then inserted, and concrete slurry is poured into it. The subsequent panel (consisting of a single gutter) is made in such a way that the gutter is excavated and filled with slurry,
and then a reinforced steel cage is inserted and concrete slurry is poured into it.

2.3.2. Modeling the wall panel construction

In the numerical simulation, the construction sequence of the initial panel is modeled in the following stages:

Stage 1 (Ben1): Soil elements in Gutter 1 are removed, and bentonite slurry with a pressure increasing linearly with depth is applied along the excavated area. The slurry has a unit weight of 11.0 kN/m³.

Stage 2 (Ben13): Soil elements in Gutter 3 are removed, and the slurry pressure is applied along the excavated area.

Stage 3 (Ben123): Soil elements in Gutter 2 are removed, and the slurry pressure is applied along the excavated area.

Stage 4 (Con123): The slurry pressure is removed, and elastic elements are placed in the excavated area to model the solid concrete wall. The self-weight of a unit weighing 24.0 kN/m³ with a Young's modulus of 27 MN/m² and a Poisson ratio of 0.2 is then defined in the elastic elements.

From Stage 3 (Ben123) to Stage 4 (Con123), the pressure along the excavated wall may vary with time. Lings,
Ng and Nash [15] adopted bi-linear distribution with depth, concrete slurry pressure at the upper part and bentonite slurry pressure at the lower part using the concept of critical height suggested in CIRIA report 108 (Clear

Fig. 4. Installation of panels at selected steps of the diaphragm wall.

(Legends)  I: Initial Panel, S: Subsequent Panel

(Step F: Initial panels complete  Step L: Diaphragm wall complete)
and Harrison [16]). In the present simulation, this method was not adopted as the concept of critical height is considered applicable only up to a depth of 30 m. From experience gained in Japan, the critical height may also change with the pouring rate of the concrete slurry, the slump value and the temperature when concreting is carried out (Arii [17], JSCE [18]).

The construction sequence of the subsequent panels is modeled only in Stages 1 (Ben1) and 4 (Con123). In Stage 4, the boundaries between the concrete elements and the surrounding soil elements are assumed to be continuous.

**Fig. 4** shows the status of panel installation at selected steps for discussion of the FEM analysis. The diaphragm wall of this shaft is composed of 12 initial panels and 12 subsequent panels, meaning that 24 steps are required to complete the structure. In determining the installation sequence of each panel, the area of $360^\circ$ was divided into the three areas of I, II and III as shown in **Figs. 2 and 4**.

**Table 2**

<table>
<thead>
<tr>
<th>Diaphragm wall thickness (index)</th>
<th>Soil excavation type (index)</th>
<th>Case index</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.2 m (t12)</td>
<td>Type A</td>
<td>t12-A</td>
</tr>
<tr>
<td>0.6 m (t06)</td>
<td>Type B</td>
<td>t06-B</td>
</tr>
<tr>
<td>0.3 m (t03)</td>
<td>Type A</td>
<td>t03-A</td>
</tr>
<tr>
<td></td>
<td>Type B</td>
<td>t03-B</td>
</tr>
</tbody>
</table>

**Fig. 6** shows the geometry of the initial and subsequent panels and selected elements for lateral stress examination (not to scale).
In the first phase, the initial panels were installed in a clockwise direction maintaining an interval of 120° for each one. In the second phase, subsequent panels were installed in a similar way to avoid concentrating the installation effects.
of each panel locally as in actual diaphragm wall construction.

2.3.3. Modeling soil excavation within the diaphragm wall

Once the diaphragm wall is installed in the ground to an embedded depth of 85.5 m, soil excavation within the wall is carried out up to a depth of 52.7 m in nine layers as illustrated in Fig. 1c. The numerical simulation of the excavation process is to remove the elements of each layer. The type of soil excavation may affect the final condition of the surrounding soil, and two possible types were considered. Type A involves excavating a quarter of each layer in a clockwise direction, while in Type B two opposite quarters of each layer are excavated at the same time, as illustrated in Fig. 5.

2.3.4. Cases analyzed

Analysis was carried out for the two major possible controlling factors of wall thickness (1.2 m, 0.6 m, 0.3 m) and the type of excavation within the wall (Types A and B). These three different wall thicknesses and two different excavation types (totaling six cases) were examined, as summarized in Table 2.

3. Results and discussion

3.1. Lateral stress changes during initial panel construction

One of the issues in terms of the effects of the installation process is its influence on lateral stress distribution along the wall panel depth (as previously examined by Ng and
Yan [8] and Gourvenec and Powrie [9]). The soil stresses and those of the diaphragm wall are the mean values of the stresses at each integration point in the selected elements. Fig. 6 shows detailed element meshes around an initial panel. Lateral stress was examined on three selected elements behind gutters at each ground layer (Layers C3, S3 and B1). Fig. 6 shows the geometry of the initial and subsequent panels in question, and Fig. 7 shows the total lateral stress distribution with depth at various stages of initial panel construction behind each gutter. The figure shows that along Gutter 2 the lateral stress at Layers C3 and B1 is less than the initial total horizontal stress, while the lateral stress at Layer S3 is greater than the initial total horizontal stress. Incidentally, before executing the analysis of the diaphragm wall installation, vertical stress $\sigma_v$ corresponding to the force of gravity was set at each integration point of the finite element of the soil, and horizontal stress $\sigma_h$ corresponding to the Poisson ratio was set at the same integration point. In this research, the horizontal stress was assumed to be the initial lateral stress, and this analytical process was defined as the initial stress FEM analysis.

When the stress distribution patterns along the three gutters are compared, it is clear that those along Gutters 1 and 3 are more or less identical, while the pattern along

---

**Fig. 10. Change in horizontal displacement distribution with depth during installation of the first initial panel: effect of construction sequence.**

---

**Fig. 11. Change in horizontal displacement distribution with depth during installation of the first initial panel: effect of wall thickness and construction sequence.**
Gutter 2 (located in the middle) differs, particularly above the toe of the wall panel. This implies that stress redistribution and concentration occurs behind Gutter 2 during the construction process from Ben13 to Ben123. Specifically, lateral stress decreases slightly in the construction process from Ben1 to Con123 in the upper clay layer, and suddenly increases in the construction stage from Ben13 to Ben123 in the sand layer. Fig. 8 summarizes the effects of initial panel construction on lateral stress in terms of the earth pressure coefficient (lateral total stress/vertical total stress) along Gutter 2. The reason for choosing Gutter 2 is that the major influence of the initial panel construction process appears behind the middle gutter of the wall panel. Initial panel construction causes a decrease in lateral stress in the clay layer and an increase in the sand layer, and these trends become more marked when the panel wall is thicker, as seen in Fig. 8. It should be noted here that the lateral stress distribution in multi-layered ground is different from that in single-layer ground.

It is also important to identify the zone that is affected by wall panel installation. Fig. 9 plots the lateral stress at Layers C3, S3 and B1 normalized by the initial total horizontal stress (i.e. the lateral stress ratio) with distance from the outer surface of Gutter 2. The lateral stress ratio varies with the soil layer; the change is less marked during concreting (from Ben123 to Con123), as shown in Fig. 9. The lateral stress ratios at Layers C3 and B1 decrease from 1.0 to 0.65 and 0.80 respectively, and the ratio at Layer S3 increases from 1.0 to 1.7 towards the outer surface of Gutter 2 at the time of wall panel installation. These lateral stress ratios change rapidly with distance at about 0.2D (where D is the depth of the wall panel) from the outer

![Graph](image-url)

**Fig. 12.** Difference in the vertical displacement profile on the ground surface along Lh1 and Lh2: effect of wall thickness and construction sequence.

![Graph](image-url)

**Fig. 13.** Increase and decrease of lateral stress behind existing panel at Layer C3 during the whole process of panel construction.
surface of Gutter 2 for Layers C3, B1 and S3. This is consistent with the previous results obtained by Ng and Yan [8] showing that the zone of rapid change is within $0.2D$. The distance required to recover the initial stress condition in the present analysis is about $0.5D$ for Layers C3 and B1, and $0.2D$ for S3. These results are not always the same as those found by Ng and Yan [8], which show that the distance is about $1.0D$. This finding shows that the previous results of two-dimensional analysis may not be wholly applicable to circular diaphragm walls in multi-layered ground.

3.2. Horizontal and vertical displacement profiles during initial panel installation

There must be horizontal and vertical displacement in the ground associated with changes in stress near the panels. The selected positions of horizontal and vertical displacement are shown in Fig. 14 and Fig. 15. The legends in the figures indicate the status of panel installation:

- I: Initial Panel
- S: Subsequent Panel
- (): Newly installed panel
- : Already installed panel

Fig. 14. Increase and decrease of lateral stress behind existing panel at Layer C3 during adjacent panel construction.

Fig. 15. Horizontal displacement profiles with depth along Lv19 and Lv20 during the construction of initial and subsequent panels: effect of wall thickness.
displacement for the initial panel are indicated as explanatory notes on each related figure (see Figs. 10–12). Lv1, Lv2, Lv3 and Lv4 are the lines for the horizontal displacement profile behind the panel, while Lh1 and Lh2 are for the vertical displacement profiles. Figs. 10 and 11 show the change in horizontal displacement distribution with depth during installation of the initial panel. Fig. 11 shows the effect of wall panel thickness on horizontal displacement distribution with depth, particularly in the clay layer. Corresponding to the lateral stress distribution shown in Figs. 7 and 8, the soil in the clay layer moves inward, whereas that in the sand layer moves outward.

The magnitude of horizontal displacement is significantly greater along Lv2 and Lv3 and smaller along Lv1 and Lv4, regardless of the layers. Increased wall thickness requires wider excavation, causing larger horizontal displacement in the clay layer as seen in Fig. 11.

A clear difference in the vertical displacement profile on the ground surface along Lh1 and Lh2 is also seen in Fig. 12, implying that settlement may be observed behind the middle of the wall panel, and a slight heave may occur behind the outer surface of the wall panel. In particular, Fig. 12 indicates the effects of wall panel thickness on the vertical displacement distribution with distance.

---

![Fig. 16. Vertical displacement profiles on the ground surface along Lh19 and Lh20 during the construction of initial and subsequent panels: effect of wall thickness.](image1)

![Fig. 17. Horizontal displacement profile on the ground surface during the construction of initial and subsequent panels.](image2)
It is of practical importance to know the zone affected by the installation of the wall panel. In this analysis, the influence of diaphragm wall construction ceases at a distance approximately equal to one wall-panel depth \(1.0D\), which is consistent with the results of the centrifuge model tests reported by Powrie and Kantartzi [19]. The results obtained by Gourvenec and Powrie [9] indicated that avoiding the influence of wall installation requires a distance of up to 40 m from the wall face. This corresponds to more than 2.0\(D\), which is much less than the results obtained from two-dimensional plane strain finite element analysis.

![Lateral stress distribution diagram](image-url)

**Fig. 18.** Maximum and minimum lateral stress distribution inward and outward from the wall with depth after completion of diaphragm wall: effect of wall thickness.

<table>
<thead>
<tr>
<th>Layer index</th>
<th>t03-B</th>
<th>t06-B</th>
<th>t12-B</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Maximum</td>
<td>Minimum</td>
<td>Maximum</td>
</tr>
<tr>
<td>C3</td>
<td>1.13</td>
<td>0.90</td>
<td>1.19</td>
</tr>
<tr>
<td>S3</td>
<td>1.03</td>
<td>0.98</td>
<td>1.01</td>
</tr>
</tbody>
</table>
3.3. Lateral stress distribution and horizontal and vertical displacement profiles during the installation of initial and subsequent panels

Fig. 13 demonstrates how the lateral stress ratios behind Gutters 16-20 fluctuate in the upper clay layer (Layer C3) during the whole process of wall panel construction. The reason for this fluctuation is considered to be the local formation of arching and stress transfer during the process of construction, as is schematically illustrated in Fig. 14. In the construction of initial panel No. 5, Gutter 17 is excavated first, followed by Gutters 19 and 18. At Step A indicated in Fig. 14, the lateral stress ratio behind Gutter 18 decreases from 1 to 0.6, while the ratio behind Gutters 17 and 19 increases from 1 to 1.1. At this stage there is no influence from lateral stress in neighboring areas (the lateral stress ratio is 1 at the location of Gutters 16 and 20). At Step B, initial panel No. 6 is constructed, resulting in an increase in the lateral stress ratio only behind Gutter 19, the nearest gutter. Similarly, at Step G, subsequent panel No. 5 is constructed, resulting in an increase of the lateral stress ratio only behind Gutter 20, the nearest gutter. In the final step (Step L), the lateral stress ratio finally becomes 1.2 behind Gutter 17, 1.1 behind Gutters 19 and 20, 0.9 behind Gutter 16 and 0.6 behind Gutter 18.

The displacement at initial panel No. 5 shown in Figs. 4 and 14 is to be examined. The locations of the line of interest in this consideration are indicated as explanatory notes on each related figure (see Figs. 15-17). Fig. 15 shows horizontal displacement profiles with depth along Lv19 and

![Fig. 19. Lateral stress distribution behind the wall with depth at the center of initial panel No. 5 after soil excavation: effect of wall thickness.](image)

![Fig. 20. Maximum and minimum lateral stress acting on the outside wall face during the soil excavation stage: effect of soil excavation type.](image)
Lv20 during initial and subsequent panel construction for various wall thicknesses.

The general trends at Lv20 on the outer surface of wall panel No. 5 are similar to those of Lv4 (see Fig. 10), and the trends at Lv19 in the middle are similar to those of Lv3 (see Fig. 10). The main differences in the displacement profile are seen in the clay layer and in the increased horizontal displacement with thicker walls. Fig. 16 shows the vertical displacement profile with various wall thicknesses at the ground surface level. The profile is largely dependent on the relative location of the wall panel. Settlement is observed at Lh19, and heave is seen at Lh20. It is interesting to note that the magnitude of the differential displacement between Lh19 and Lh20 remains the same for different wall thicknesses, suggesting that wider wall excavation leads to larger heave, compensating for the potentially large settlement.

Muramatsu et al. [12] reported the results of field measurements for displacement during circular shaft construction. Although the ground and construction conditions were different from those used in this study, comparison of the order of magnitude may be useful for verification of the present study. The thickness of the soft ground was 8 m from the surface in the field, while the present study assumed a thickness of 25 m from the surface. The predicted vertical displacement was 2.0 mm (see Fig. 16 at Lh20 (t12)) compared to the corresponding field value of 3.0 mm.

The prediction in this study for horizontal displacement at 5.5 m from the outer surface of the wall at the time of diaphragm wall installation was 15.0 mm (see Fig. 17 at Lh20), which is comparable to 5.0 mm of horizontal displacement at the corresponding location in the field measurement.

3.4. Lateral stress distribution and horizontal displacement distribution after the completion of diaphragm walls

The values of maximum and minimum lateral total stress distribution with depth inward and outward for the circular diaphragm wall are presented for various wall thicknesses in Fig. 18. The value of the initial total horizontal stress with depth is also plotted in the figure, and is found to be almost the average of the maximum and minimum lateral stress levels both inward and outward. The
influence of the wall thickness is noticed in the clay layer. The thicker the wall is, the greater the difference between the maximum and minimum lateral stress values.

Table 3 summarizes the range of ratios of lateral stress on the internal wall face to the lateral stress on the outer wall face for various wall thicknesses at the clay and sand layer. It can be seen that the thinner the wall, the smaller the range of the ratio.

3.5. Lateral stress changes during and after the soil excavation stage

No literature is available relating to the numerical study of installation effects, including the installation stage and the subsequent soil excavation stage. Fig. 19 shows the lateral stress distribution with depth for various wall thicknesses behind the center of initial panel No. 5, indicating that the value of earth pressure differs considerably from that of the initial total horizontal stress, and that the effect of the wall thickness is as small as 20 kN/m². The maximum and minimum lateral stresses acting on the outer wall face during the soil excavation stage for a wall thickness of 1.2 m are plotted with depth for the two types of soil excavation in Fig. 20. It is noted that the type of soil excavation has no effect on the lateral stress distribution for either the maximum or minimum values. The initial total horizontal stress of each soil layer is also close to the maximum value for the soft clay layer, and gives approximately the mean value of the maximum and minimum values for stiff-layer ground. The type of excavation is also predicted to have no effect on the internal horizontal displacement profile with depth.

Fig. 21 shows the internal horizontal wall displacement divided by the shaft diameter with depth at the lines of L_x and L_y indicated as explanatory notes on the figure after soil excavation for various wall thicknesses. The magnitude of the maximum inward movement is in approximate inverse proportion to the wall thickness.

Fig. 22 shows the changes in horizontal displacement distribution with depth at x1, x2, y1 and y2 indicated as explanatory notes on the figure at the times when the diaphragm wall construction stage and soil excavation stage were completed. In these cases, during the construction stage the horizontal displacement gradually accumulates towards the inside of the wall in the clay layer and the base mud rock layer, whereas horizontal displacement in the sand layer occurs in the opposite direction. However, once the excavation stage starts, horizontal displacement only occurs toward the inside of the wall at all depths. The magnitude of the accumulated displacement in the clay layer is in the order of y2, x2, y1 and x1, clearly indicating that the magnitude of such displacement depends on the construction sequence. The ratios of the displacement after diaphragm wall completion to the accumulated displacement in clay are 0.15 at x1 and 0.1 at x2, x3 and x4.

Corresponding to the wall deflection, the vertical bending moment changes with depth. Fig. 23 shows the vertical bending moment (M_v) distribution with depth for various wall thicknesses, and indicates that thinner walls have a smaller bending moment, although the overall pattern of the bending moment distribution remains similar.

4. Conclusions

The processes of installing a circular diaphragm wall and excavating soil within the wall were analyzed as three-dimensional events. The main findings on lateral stress in the ground and ground movements, examined by three-dimensional FEM analysis, are as follows:

(1) Numerical evaluation using FEM analysis was successfully carried out to investigate the effects of
installing circular diaphragm walls, including the detailed installation stage and the subsequent soil excavation stage. The realistic multi-layered ground used has a more complicated lateral stress distribution. Results from single-layer ground may not have provided an overall picture of this complexity.

(2) The results of the analysis showed that the situation even prior to excavation within the wall is no longer axisymmetric. This non-uniform characteristic with periodic fluctuations was formed at an early stage of the initial panel construction.

(3) The influence of the type of soil excavation within the wall may be negligible.

(4) The maximum value of lateral stress after excavation within the wall was greater than the initial total horizontal stress, and the minimum was smaller than the initial total horizontal stress. The mean of the maximum and minimum values was found to be close to the initial total horizontal stress.

(5) Reducing the wall thickness resulted in a decrease in the vertical section forces of the wall after excavation within it.

Acknowledgements

The authors are grateful to Dr. Shikai Du for his help with finite element analysis using MARC, and to Dr. Motoi Iwanami and Keiji Oishi for their help with the outline of the construction sequence for the circular shaft.

References


