Modern Tunneling Science and Technology, Adachi et al (eds), © 2001 Swets & Zeitlinger, ISBN 90 2651 860 9

Diaphragm wall stability during excavation in alluvial sand deposit

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ABSTRACT: Diaphragm wall is frequently used as the retaining wall or the cut-off wall for open cut excavation. The trench wall stability is the key issue for the design and construction method of diaphragm wall. The aim of this study is to investigate the trench wall stability during excavation in saturated sand. Field measurement of the pore-water pressure variation during diaphragm wall excavation were carried out. The mechanism for the variation of pore-water pressure and its effect upon the factor of safety for trench wall stability is quantitatively evaluated using the limit equilibrium method. The results obtained from this study will be introduced into the control for the trench wall stability during excavation.

1 INTRODUCTION

Diaphragm wall, which is very stiff and can be constructed with low noise and vibration, is used for various purposes, including as a retaining wall or cut-off wall for open-cut excavations, or as a foundation for superstructures. In particular, with the increase in the scales and depths of such projects as the improvement of sewer facilities and construction of artificial underground rivers in urban areas, the use of diaphragm walls as retaining structures is increasing.

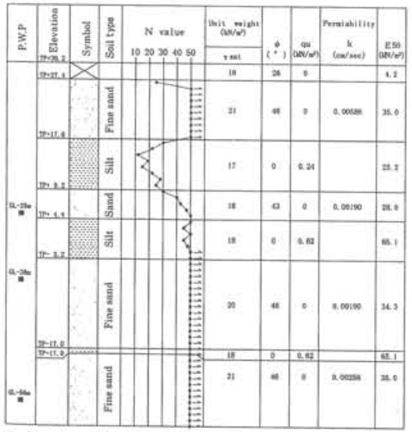

Figure 1. Profile of the ground and soil parameters.

Diaphragm wall is constructed while keeping a trench filled with slurry with a relative density large enough to withstand earth and water pressures that may cause a collapse of trench surfaces. This means that retaining the stability of the trench surfaces by slurry is an important factor. Once the trench surfaces collapse, this collapse may cause not only the need for filling and re-excavation, but also problems such as settlement of the ground in the vicinity and adverse effects on subsequent construction activity, depending on the extent of the collapse. Therefore, the utmost attention is required during the construction of this type of structure.

Focusing on excess pore-water pressure occurring in nearby ground during the excavation of diaphragm walls in sandy soil at a construction site, the authors measured this pressure and quantitatively evaluated its effects on the stability of trench surfaces.

2 MEASUREMENT OF GROUND BEHAVIOR DURING DIAPHRAGM WALL EXCAVATION

2.1 *Outline of measurement*

The profile of the ground in which the diaphragm wall was driven is shown in Figure 1. As shown in the figure, the ground typically consists of alternating layers of sandy soil and clay. The clay forms solid layers and is not considered to affect the stability of the trench surfaces. This indicates that the stability of the sandy soil layers is an important factor during diaphragm wall construction. The authors therefore focused on the pore-water pressures in the sandy soil layers and installed pore-water pressure transducers in a boring hole at three different depths: GL-25 m, -36 m, and -56 m (Fig. 1). Five diaphragm wall elements bordering the transducers were selected for measurement during construction. The layout of the five elements is shown in Figure 2.

When the excavation depths of the five elements neared the elevations of the transducers, the pore-water pressures were automatically measured at intervals from 2 to 10 seconds: the water pressure data were automatically recorded together with excavator data (e.g. depth, location, and torque of the cutter) obtained using the excavation accuracy control system developed by Nishimatsu Construction Co., Ltd.

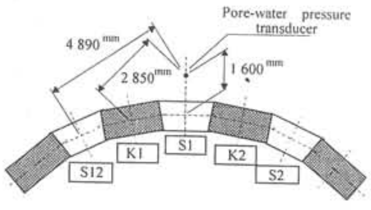

Figure 2. Layout of the measured elements.

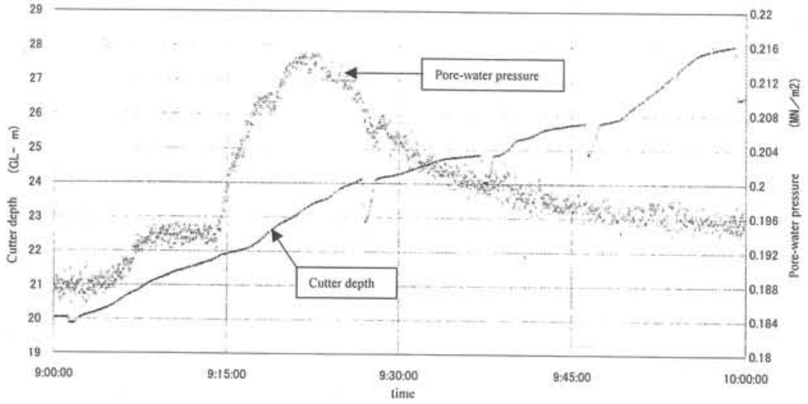

Figure 3. Pore-water pressure and cutter depth when the S 2 element was excavated (GL -25 m) .

2.2 *Measurement results*

Excavation of the five elements started with S 12, followed by in the order of S 1, S 2, K 1, and K 2, in order ,and the changes in the pore-water pressures in the five elements were measured at three different depths.

Representative measurement results are given in Figure 3 . Table 1 shows the maximum pore pressure for each element during excavation derived from the results in Figure 3. Table 2 shows the cutter depth at the time when the maximum pore-water pressure occurred, and Table 3 the cutter depth at the time when the pore-water pressure began to increase.

Figure 4 is a conceptual depiction of the relationship between the cutter depths and pore-water pressures, with the left vertical axis showing the cutter depths (depths of the ground being excavated measured from the ground surface), the right vertical axis showing the measurements of pore-water pressures, and the horizontal axis showing time. As shown in this figure, the pore-water pressure starts to increase when the cutter arrives at the upper boundary (point A) of the previous layer (sandy soil layer) in which the pore-water pressure transducer is provided and reaches its maximum value (point B) with excavation progress. After passing this point, however, this pressure starts to decrease in spite of the continuation of excavation, coming close to the initial value. The discontinuity in the curve for the cutter depths corresponds to the period during which the diaphragm wall excavator is left idle for measuring the excavation accuracy and the machinery adjustment.

Table 1. Maximum pore pressure (MN/m^2) .

Element NO.	GL-25m	GL-36m	GL-56m
S12	0.210	0.290	0.456
K1	0.214	0.286	0.458
S1	0.220	0.309	0.468
K2	0.218	0.290	0.462
S2	0.216	0.287	0.460
Initial value	0.189	0.257	0.450

Table 2 Cutter depth with time and the maximum pore-water pressure (m) .

Element No.	GL-25m	GL-3om	GL-56m
S12	-23.000	-33.500	-56.500
K1	-23.000	-33.810	-55.200
S1	-22.850	-33.280	-54.100
K2	-23.240	-33.300	-54.000
S2	-23.020	-33.980	-51.300

2.3 *Discussion*

Analysis of the relationship between the measurement data and the locations of the cutter and the pore-water pressure transducers revealed the following:

1. As shown in Figure 5, the pore-water pressure recorded by the transducer at GL-25 m started to increase when the cutter neared the upper boundary surface (at a depth of approximately GL-20 m) of the sandy soil layer in which the transducer was provided. The pore-water pressure in sandy soil layers with a high permeability is sensitive to disturbance and increases as diaphragm wall excavation progresses.

Table 3 Cutter depth at the time when the pore-water pressure begins to increase.

Element No.	GL-25m	GL-36m	GL-56m
S12	-22.100	-32.600	indistinct peak
K1	-22.100	-32.600	indistinct peak
S1	-22.100	-32.600	indistinct peak
K2	-22.000	-32.600	indistinct peak
S2	-21.800	-32.600	indistinct peak

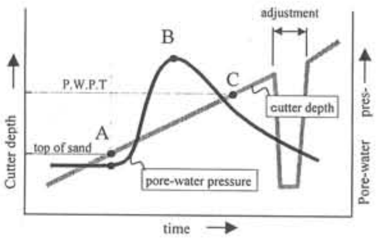

Figure 4. Schematic diagram of the relationship between the cutter depths and pore-water pressures.

2. As shown in Table 3, the pore-water pressure recorded by the transducer installed at GL-36 m began to increase when the cutter reached a depth of 32.6 m from the ground surface. This depth corresponds to the elevation of the upper surface of a sandy soil layer detected by a boring test. This means that this layer is also sensitive to disturbance and, in fact, increases in the pore-water pressure due to excavation were observed. As excavation proceeded further, the pore-water pressure showed an abrupt increase,but sharply decreased after reaching its maximum value with a larger gradient than that recorded by the transducer at a depth of GL-25 m.

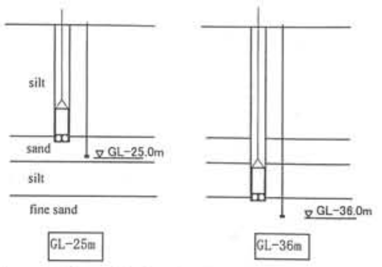

Figure 5. Cutter depth when the maximum pore-water pressure occur.

3. Changes in the pore-water pressures observed by the transducer at a depth of GL-56 m were less than those observed by the other two transducers. Some curves for the changes in pore-water pressures did not show a distinct peak value. Although the layer at this depth is composed primarily of sandy soil, the description for the boring test states that it contains some consolidated clay, indicating that increases in pore-water pressures are prevented by this clay with a low permeability.

4. When the pore-water pressures measured by the transducers at GL-25 m and GL-36 m reached maximum values, the depth of the cutter was shallower than the transducer's elevation.

The relationship between the maximum pore-water pressure increment ΔUmax and the mechanical properties of the nearby ground, as shown in Figure 6, was obtained by classification of the results of measurement by the authors and by Hosoi et al. The pore-water pressure increase ratio, calculated by dividing ΔUmax (maximum pore-water pressure increment) by U (natural groundwater pressure), was at maximum 0.2, and was found to be in good relation to the effective overburden pressure at that location σ'.In contrast, as shown in Figure 7, ΔUmax was found to be approximately proportional to the ratio of the excavation torque T to the square of the distance from the cutter L^2.where

ΔUmax: maximum pore-water pressure increment
T: Cutter torque
L: Horizontal distance between the center of the trench and the pore-water pressure transducer

Furthermore, if the effects due to the type of the soil are taken into consideration together with the permeability coefficient k, which is considered to affect the pore-water pressure increase rate, the following equation can be obtained (Fig. 8):

$$\Delta U_{max} = 0.0106\,(T/kL^2) + 1.55 \qquad (1)$$

The increase in the pore-water pressure calculated using the differential pressure by the natural groundwater level and the in-trench wall slurry level is given in Table 4: as shown in this table, the maximum pore-water pressure increase was approximately 70 % of the differential pressure.

3 EFFECTS OF THE PORE-WATER PRESSURE INCREASE ON THE STABILITY OF TRENCH WALL SURFACES

3.1 *Evaluation of partial stability*

Pore-water pressures near the bottom of trench surfaces tend to increase during diaphragm wall excavation. In this section, the effects of the pore-water pressure increase on the stability of trench surfaces are discussed.

The factors affecting the stability of trench surfaces are complicated. Previous studies indicate that the following are important factors:

1) Soil characteristics
2) Groundwater level
3) Diaphragm wall profile (e.g. thickness, width, and element shape)
4) Characteristics of stabilizing slurry
5) Surcharge load on ground surface
6) Duration of work interruption

Taking into consideration these factors, along with the records on trench-surface collapses and the results of model tests and analyses previously conducted, many methods for predicting trench surface stability have been proposed (Uchida & Mizutani, 1971), (Kanaya & Akino, 1984), (Yoshida, 1985), (Piaskowski & Kowalewski, 1965), (Higuchi et al., 1994). Each of these methods evaluates the stability based on the mechanical equilibrium of a large soil mass whose slip surface extends up to the ground surface, but does not take into consideration the partial increase in pore-water pressures mentioned in the former section. In actual construction, partial flaking of trench surfaces as well as collapse of the soil block near the ground surface frequently occurs. In addition, records on some cases, in which the trench surfaces of small-scale diaphragm wall foundations have collapsed, show that excess pore-water pressure can occur during excavation (Hosoi et al., 1994a). These findings clearly indicate that factors other than the above 1) to 6) such as changes in the stresses acting on the nearby ground and trench surfaces during excavation could adversely affect the stability of trench surfaces.

Excess pore-water pressures occur only near the bottom of trench-wall surfaces. This means that the increase in pore-water pressures affects the stability of only trench surfaces near the bottom of the diaphragm wall. To evaluate the stability of such a partial area, Hosoi et al (Hosoi et al., 1994b) have proposed equation (2), which is based on the mechanical equilibrium of a wedge-shaped sliding soil block.

$$F_S = \frac{\{(W+\Delta u\,b)\cos\theta + M\sin\theta - \Delta u L\}\tan\phi + cL}{(W+\Delta u\,b)\sin\theta - M\cos\theta} \qquad (2)$$

where,
Fs: factor of safety
W: weight of sliding soil block (= 1/2 b h γ')
Δu: excess pore-water pressure
M: resultant of differential pressure between stabilizing slurry pressure and groundwater pressure (= differential pressure Δp × h)
ϕ: angle of the shearing resistance of soil
c: cohesion of soil
γ': unit weight of submerged soil
b, h: width and height of the sliding soil block
L, θ: length and angle of the slip surface

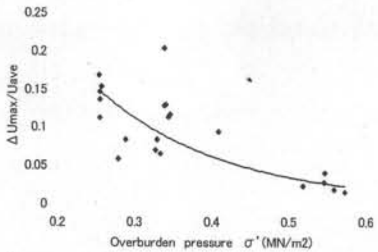

Figure 6. Relationship between the pore-water pressure increase ratio and the effective overburden pressure.

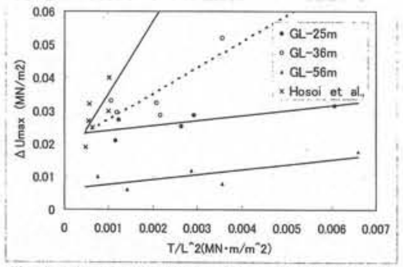

Figure 7. Relationship between the maximum pore-water pressure and the distance (1) .

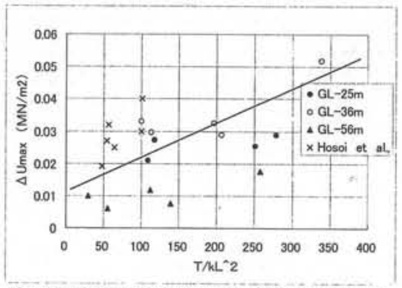

Figure 8. Relationship between the maximum pore-water pressure and the distance (2) .

Table 4. Maximum pore-water pressure increment (MN/m^2) .

Element No.	GL-25m	GL-36m	GL-56m
S 12	0.021	0.033	0.006
K1	0.025	0.029	0.008
S1	0.031	0.052	0.018
K2	0.029	0.033	0.012
S2	0.027	0.030	0.010
initial p.w.p. ①	0.189	0.257	0.450
slurry pressure ②	0.230	0.340	0.540
②−①: α	0.041	0.083	0.090
Δ Umax/②−①	0.76	0.63	0.2

Although equation (2) is a simplified formula and does not take into consideration the resistance on the sides of the sliding soil block, a trial calculation by this equation using the dimensions of the partial collapse of the trench surfaces of an actual diaphragm wall give a factor of safety Fs smaller than 1.0, indicating the effectiveness of this equation.

The relationship between the angle of the shearing resistance of soil ϕ and the height of a sliding soil block h was calculated using α (ratio of Δp (differential pressure between the stabilizing slurry pressure and groundwater pressure calculated by equation (2)) to Δu (excess pore-water pressure)) as a parameter. In the calculation, the angle of the slip surface θ is assumed to be equal to the angle of active collapse, i.e. θ = 45° + ϕ/2, and cohesion (c) and the unit weight (γ') of submerged soil were set to 0 and 10 kN/m^3, respectively. Figure 10 shows that although the factor of safety Fs increases with the increase in the angle of the shearing resistance of soil, Fs starts to decrease and the possibility of the partial collapse of trench surfaces increases when the water pressure ratio α exceeds approximately 0.6. Figure 12 shows the relationship between the factor of safety and the differential pressure for typical sandy soil with a ϕ of 30°, when the sliding soil block height is 3.0 m. A similar tendency to that of the measurement results in actual diaphragm walls is observed in this figure: i.e. where the excess pore-water pressure increases to a value giving a water-pressure ratio α of approximately 0.7, the stability of the trench surfaces cannot be assured unless the head difference between the slurry and groundwater levels is more than approximately 2 m. This finding agrees with both the records on trench-surface collapse in actual construction projects and the results of calculations regarding the stability of soil near the ground surface, so this value (a head difference of 2 m) is used as the standard requirement for diaphragm wall excavation. At locations near the bottom of the diaphragm wall, however, the water pressure ratio could exceed 0.7, which makes the trench surfaces susceptible to collapse. Figure 12 indicates that where the head difference is more than 2.5 m, the stability of a 3m-high soil block can be assured, even if the water-pressure ratio α exceeds 0.8. On the other hand, Figures 10 and 11 show that where the water pressure ratio is more than 0.8, the factor of safety is almost the same, regardless of the sliding soil block height and the angle of shearing resistance. These results suggest that a head difference of approximately 2.5 m would suffice. However, a margin of safety is necessary, since the slurry level could decrease with excavation progress, and the groundwater levels could fluctuate unless the slurry is automatically replenished.

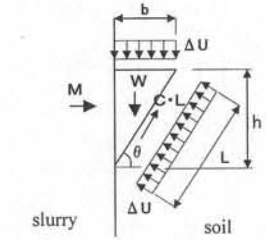

Figure 9. Limit equilibrium for soil block.

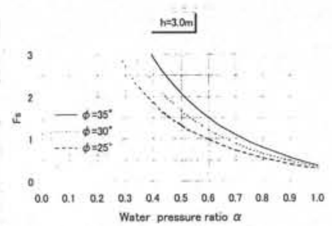

Figure 10. Evaluation of partial stability at the height of 3 m.

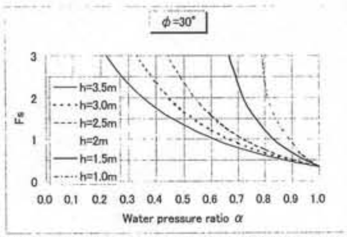

Figure 11. Relationship between the differential pressure and factor of safety.

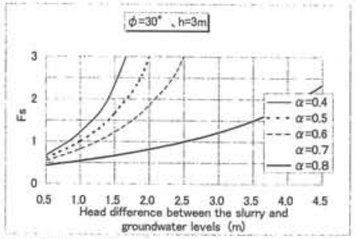

Figure 12. Head difference and the factor of safety of a partial area.

4 CONCLUSION

In this study, excess pore-water pressures, which occur in nearby sandy soil layers during diaphragm wall excavation using a horizontal multi-shaft excavator, were measured, and the mechanism of pore-water pressure increase and the partial stability of trench surfaces were investigated. As a result, the following findings were obtained:

1. With the progress of diaphragm wall excavation, pore-water pressures in the ground near the trench surfaces increase.

2. The increment in pore-water pressure in the area 1.6 to 4.9 m from the center of the trench is at maximum 70 % of the differential pressure between the in-trench slurry pressure and groundwater pressure.

3. The increment in pore-water pressures is a closely related to the distance from the trench, the torque of the excavation cutter, and the permeability coefficient.

4. Although the partial stability of trench surfaces decreases with increases in pore-water pressures, the possibility of the slide of a soil block with a height of less than 3 m decreases where the difference between the in-trench slurry level and the groundwater level is maintained at more than 2.5 m.

The stability of trench surfaces is, in general, evaluated using equilibrium equations for the complete collapse of trench surfaces. However, when areas with a partial increase in pore-water pressures appear near the bottom of trench surfaces, as described in this paper, partial collapse can occur, which can then cause progressive failure that will finally result in a large-scale slip. Therefore, when diaphragm walls are constructed in ground containing sandy soil layers with a high groundwater level, it is necessary not only to carefully monitor increases in pore-water pressures, the duration of excavation, and the level of in-trench slurry during excavation, but also to consider the necessity of groundwater-level reductions and ground stabilization.

REFERENCES

Higuchi, Y., Higashida, A., Nagura, K. & Kawasaki, K. March 1994. New stability analysis method for slurry trenches constructed in sandy ground. *Tsuchi to Kiso*. 7-12. (in Japanese)

Hosoi, T., Hara, N., Tamakoshi, M. & Sakamoto, R. 1994b. Test report for thick diaphragm walls in underground space at great depth (No. 3). *Nishimatsu Corp. Technical Report*. 17:33-40. (in Japanese)

Hosoi, T., Nishi, T. & Fukuda, Y. 1996. Consideration on excess pore-water pressures occurred in ground when diaphragm walls are excavated. *Proc. 31st Conf. Japanese Geotechnical Society*: 1989-1990, 1996. (in Japanese)

Hosoi, T., Saito, K & Nishi, T. March 1994a. Excavation of thick diaphragm walls in underground space at great depth. *Tsuchi to Kiso*. 41-44. (in Japanese)

Kanaya, Y. & Akino, N. 1984. Full-size test for stability of groove face in excavating mud water. *Proceedings of Japanese Society of Soil Mechanics and Foundation Engineering (JSSMFE)*. 24-4:171-182. (in Japanese)

Piaskowski, A & Kowalewski, Z. 1965. Application of thixotropic clay suspensions for stability of vertical sides of deep trenches without strutting. *Proceedings of 6th ICSMFE*. 2:526-529.

Uchida, H. & Mizutani, H. 1971. Stability of excavated wall surface using bentonite mud water. *Kajima Corp. Institute Report*. 4:95-107. (in Japanese)

Yoshida, Y. 1985. Stability of excavated mud wall surface in non-cohesive soil ground. *Proceedings of JSSMFE*. 25-4:159. 167. (in Japanese)