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Earth and water pressures acting on the excavation side of a braced wall in soft ground

T. Tamano – *Osaka Sangyo University, Japan*
S. Fukui – *Osaka City, Japan*
S. Mizutani – *Pacific Consultants Co., Ltd, Tokyo, Japan*
H. Tsuboi – *Fudo Construction Co., Ltd, Osaka, Japan*
M. Hisatake – *Kinki University, Osaka, Japan*

ABSTRACT: The factors affecting the earth and water pressures acting as passive resistance on a braced wall on its excavation side include the earth load removed by excavation, lowering of the groundwater table, deformation of the braced wall, deformation and strength characteristics of the ground, and construction time. The mechanical behavior occurring is thus considerably more complex than that on the back of the wall.

This paper presents detailed observations of the mechanical behavior of earth and water pressures acting on the excavation side of a braced wall, obtained during excavation in soft clay. Next, with respect to the mechanical behavior of the passive resistance, the changes in earth pressure were considered separately for the two factors of the earth load removed by excavation and the wall displacement, as a result of which the following were found:

1) Water pressure decreases in correspondence with the progression of the excavation. Meanwhile, the earth pressure increases up to a wall displacement of 30–45 mm; thereafter it decreases as the wall displacement increases.
2) The maximum earth pressure at a wall displacement of 30–45 mm is not due to the ground reaching the ultimate passive state, but occurs because of the difference between a decrease in the earth pressure caused by the removal of earth load, and an increase in earth pressure caused by wall displacement. The initial coefficient of ground reaction K_h is about 1,100 kPa/m, and becomes non-linear along with the wall displacement. The coefficient of earth pressure at rest K_0 changes to about 0.45–1.8 for an overconsolidation ratio OCR of 1–6.7.

1 INTRODUCTION

The earth and water pressures acting on a braced wall (hereinafter referred simply as earth and water pressures) during excavation in soft clay change in association with each other and have rarely been measured accurately; hence much is still unknown about the mechanical behavior of each.

The evaluation of earth and water pressures significantly affects the stress and deformation of braced wall, and is thus an extremely important issue when considering the safety of excavation work. Generally, the stress and deformation occurring in a braced wall as a result of excavation are basically proportional to changes in the lateral pressure, i.e. the combined earth and water pressures acting on the back of the wall. On the excavation side, however, the situation is much more complex, and strongly affects the mechanical behavior of the braced wall.

The factors affecting the earth and water pressures on the excavation side can include the amount of earth load removed during excavation, lowering of the groundwater table, deformation of the braced wall, the deformation and strength characteristics of the ground, and excavation time, thus presenting much more complex mechanical behavior compared to the back. Hence much is unknown about the mechanical behavior of the earth and water pressures, in terms of passive resistance on the excavation side; case studies based on detailed field observations are required (Tanaka 1994, Fukui et al. 1994, Tamano et al. 1995).

This paper presents observations of mechanical behavior, based on detailed field measurements of earth and water pressures on the excavation side of braced work in soft clay, and the mechanical behavior of passive resistance is studied.

2 GROUND AND WORK CONDITIONS

The excavation work case studies taken up in this paper are from two sites for sewerage pumping stations in the Osaka region (henceforth referred to as Excavation Work A and B). A sectional view of the Excavation Work A is shown in Figure 1, and the ground conditions are shown in Figure 2. The excavation ground is a layer of clay 10.5–23.0 m below the surface; it is normally consolidated soft alluvial clay with undrained shear strength 30–70 kPa, natural water content 40–50%, liquid limit 50–70%, and plastic limit 20–27%. The dimensions of the excavation work are length 85.5 m, width 58.5 m, and excavation depth 20.8 m. The braced wall is 1.0 m thick and 38.25 m deep, and is a reinforced-concrete diaphragm wall constructed by means of the slurry-trench method. Down to 15.9 m below the surface, concrete was cast in three stages by reverse construction (top-down) method; bored piles by circulation method and structural columns (for supporting beams and floor slabs) were cast first. Thereafter beams and floor slabs were cast, and to support the braced wall while the excavation proceeded. In the deeper level, up to 20.8 m below the surface, the excavation was carried out while three rows of earth anchors supported the braced wall. The measuring instruments were positioned in the horizontal lateral middle.

A sectional view of Excavation Work B is shown in Figure 3. The ground conditions are largely the same as those for Excavation Work A. Excavation Work B involved circular excavation with an external diameter of 84.2 m, for an excavation depth of 40.9 m. The braced wall, a reinforced-concrete diaphragm wall, was 1.5 m thick and 89 m deep. The excavation was carried out by successively excavating and casting the inner wall, which also functioned as a support for the ring beam. As a result, compared to the Excavation Work A, the work was characterized by a smaller displacement of the braced wall (referred to as the "wall displacement"). At both sites, the groundwater table within the excavation area was lowered during the excavation, through the installation of deep wells.

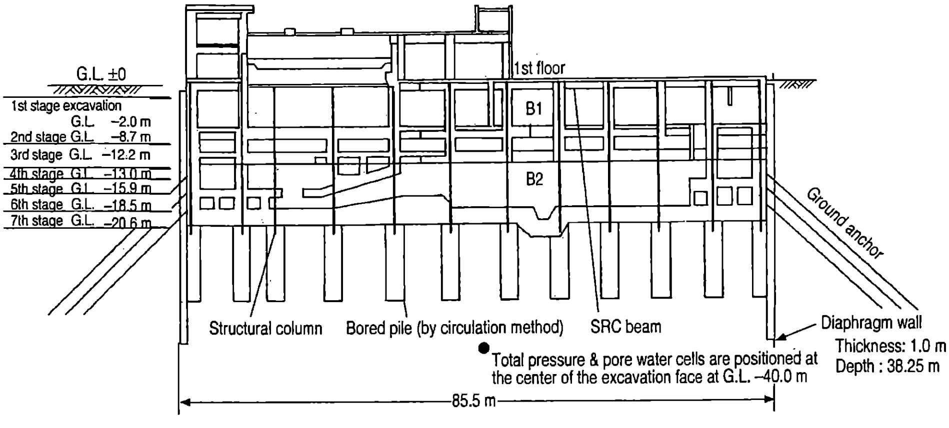


Figure 1. Sectional view of the excavation work (Excavation Work A)

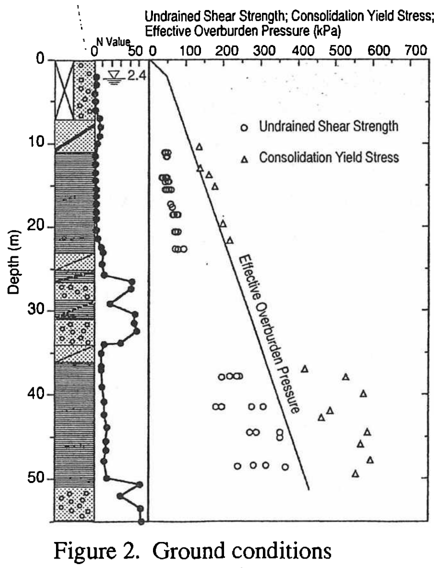


Figure 2. Ground conditions (Excavation Work A)

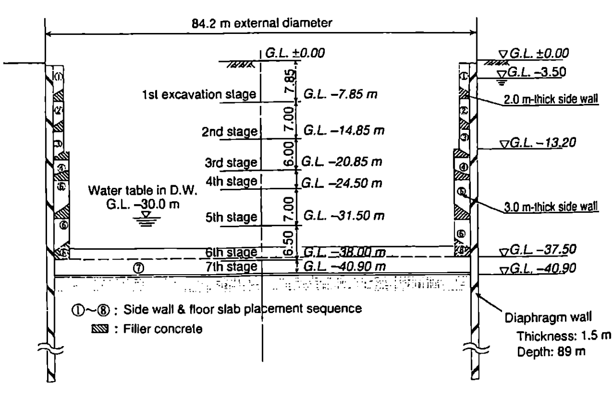


Figure 3. Sectional view of the excavation work (Excavation Work B)

3 OBSERVATION RESULTS

The distributions of lateral, water, and earth pressures as well as wall displacement for Excavation Work A are given in Figures 4 and 5, and in Figure 6 for Excavation Work B. The earth pressure shown here is a calculated value, derived from the difference between the observed lateral pressure and the observed water pressure.

Figure 7 gives the relationships between wall displacement and the lateral, water, and earth pressures acting on the excavation side. Lateral and water pressures have decreased at all measurements points. Earth pressure, though, does not decrease as the excavation proceeds; it rises together with the wall displacement until the wall displacement

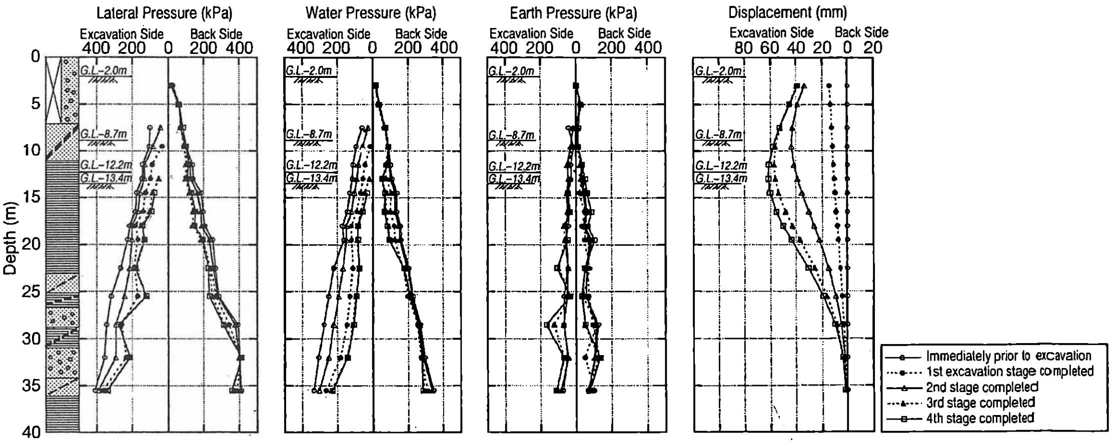


Figure 4. Distributions of lateral pressure, water pressure, earth pressure, and displacement at the braced wall (Excavation Work A, Stages 1-4)

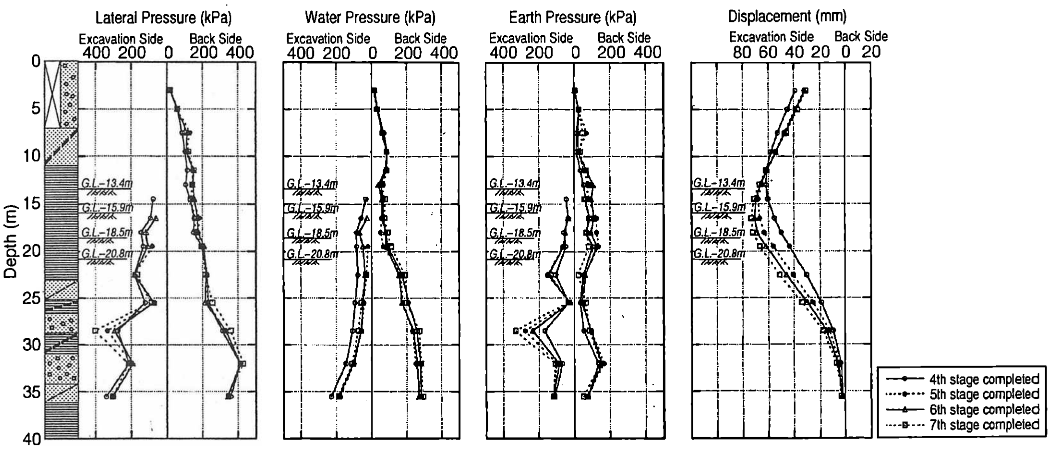


Figure 5. Distributions of lateral pressure, water pressure, earth pressure, and displacement at the braced wall (Excavation Work A, Stages 4-7)

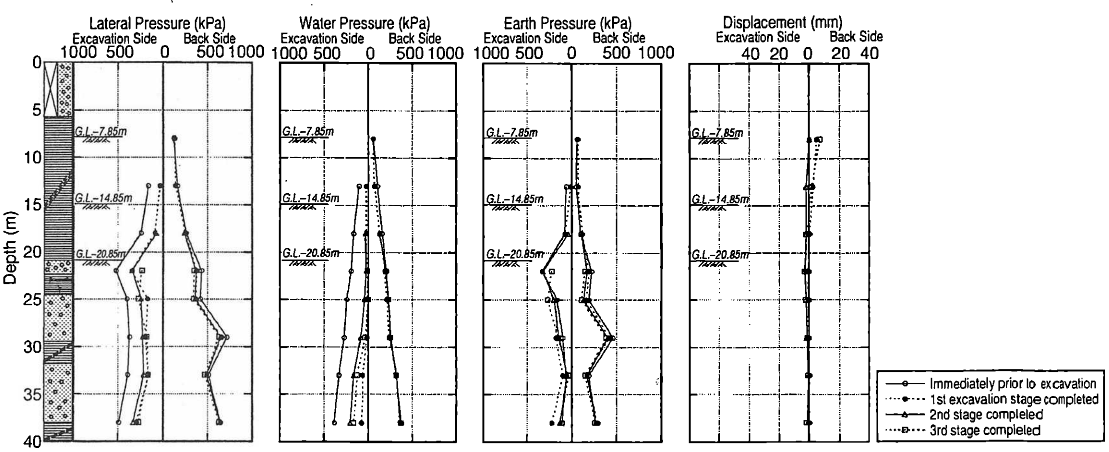
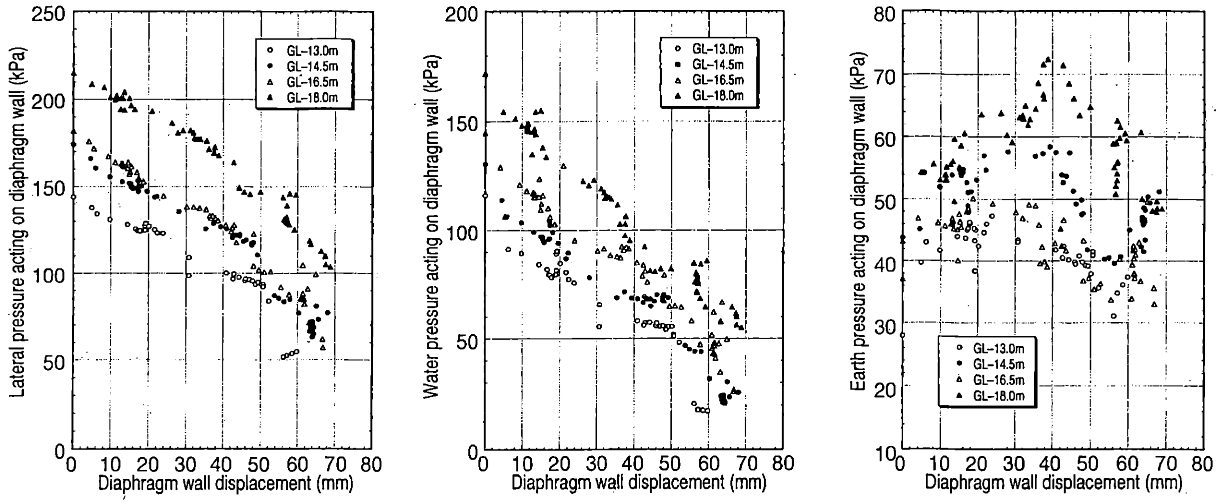
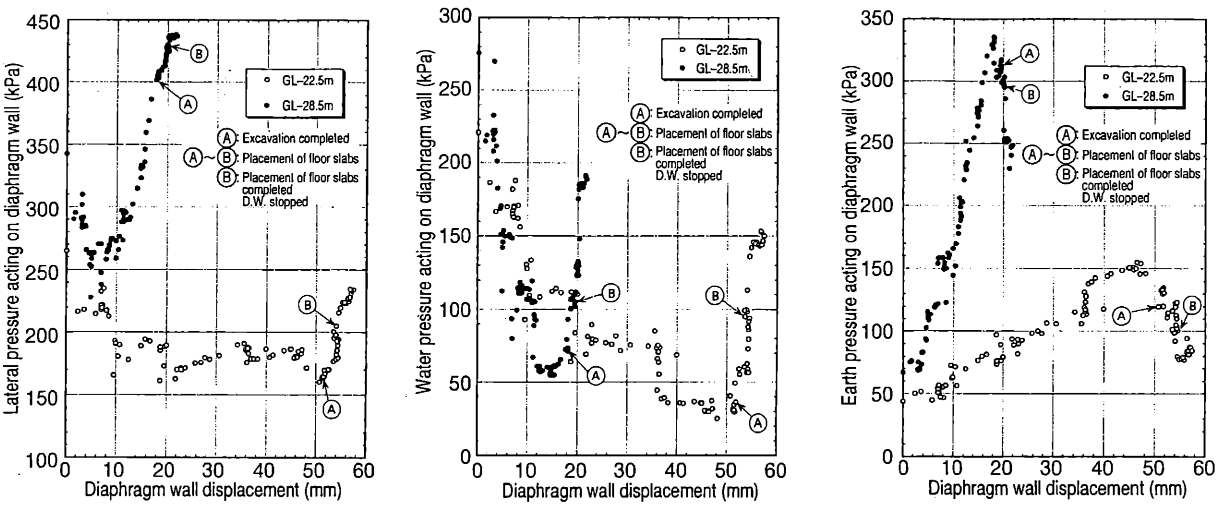


Figure 6. Distributions of lateral pressure, water pressure, earth pressure, displacement at the braced wall (Excavation Work B, Stages 1-3)



(a) (b) (c)

Figure 7. Relationships between displacement and lateral pressure, water pressure, and earth pressure at the braced wall (Excavation Work A, for G.L. -13.0 m – G.L. -18.0 m)



(a) (b) (c)

Figure 8. Relationships between displacement and lateral pressure, water pressure, and earth pressure at the braced wall (Excavation Work A, for G.L. –22.5 m & G.L. –28.5 m)

reaches 30–45 mm, after which it exhibits a tendency to decrease. Note that at the final stage of the excavation at 20.8 m below the surface, all the measurement points are exposed.

Figure 8 shows the relationships between wall displacement and lateral, water, and earth pressures, at the two points of 22.5 m below the surface, in the clay layer, at the lowest point of the alluvial clay below the final excavation depth, and 28.5 m below the surface, in the layer of alluvial sand. These figures indicate that the resultant passive resistance varies considerably according to soil conditions, being a maximum at a displacement 45 mm in the layer of clay and 18 mm in the layer of sand. Point A in the figures is the point at which the excavation has been completed, at 20.8 m below the surface, and Point B is when the deep wells are stopped, after the concrete for the floor slabs has been poured. The water pressure decreases up to Point A, and increases thereafter. The water pressure increase from Point A to Point B is because of the increased load brought about by the casting of the floor slabs. The revival in water pressure after point B is due to the stoppage of the deep wells. Whereas the change in water pressure can be evaluated with relative clarity, the mechanical behavior of the earth pressure is more complex.

4 PASSIVE RESISTANCE ON THE EXCAVATION SIDE OF THE WALL

The resultant passive resistance on the excavation side of the wall is not affected only by wall displacement, but also by the removal of the earth load due to excavation. The passive resistance is a combination of the earth pressure arising as the ground is displaced towards the excavation side, the

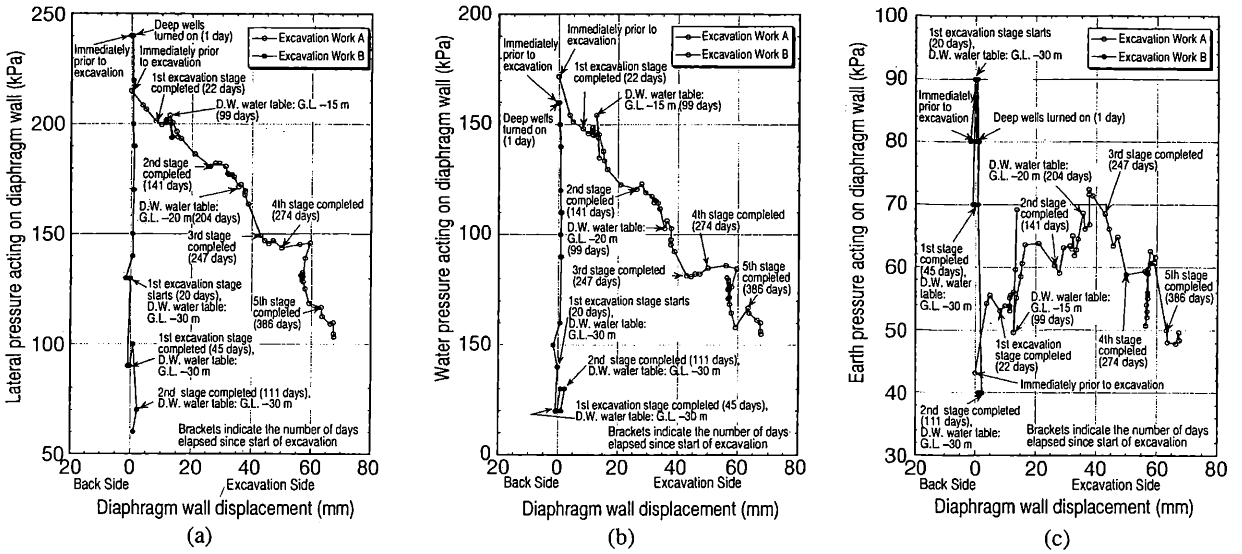


Figure 9. Relationships between displacement and lateral pressure, water pressure, and earth pressure at the braced wall (Excavation Works A & B, at G.L -18.0 m)

earth pressure acting on the wall as a result of the earth load within the excavation area, and the water pressure; it is expressed by the following equation.

$$P_P = K_h \cdot \delta + K_O \cdot \sigma'_z + P_W \tag{1}$$

where P_P is the passive resistance (kPa), K_h is the coefficient of ground reaction (kPa/m), δ is the wall displacement (m), K_O is the coefficient of earth pressure at rest, σ'_z is the effective overburden pressure (kPa), and P_W is the water pressure (kPa).

The passive resistance given in Equation (1) can be measured as the lateral pressure by the earth pressure cell. Taking a depth of 18 m below the surface as an example and using Equation (1), the relationship between the earth pressure occurring as a result of displacement of the ground towards the excavation side, and the earth pressure acting on the wall as a result of the earth load within the excavation area, is examined.

Generally, the change from a state at rest to the ultimate active state in clay is due to a strain of 1%, and a 20% strain is required from a change from the state at rest to the ultimate passive state (Lambe and Whiteman 1964). Previously the authors have shown that in the alluvial clay of Excavation Work A, a change from a state at rest to the ultimate active state occurs due to a wall displacement of only around 20 mm (Tamano et al. 1995). From this it can be deduced that a 20 times larger wall displacement of 40 cm will be required in order to reach the ultimate passive state, and it is unlikely that a wall displacement of only 30–45 mm will lead to an ultimate passive state.

Hence each of the forces of $K_h \cdot \delta$ and $K_O \cdot \sigma'_z$ will be considered separately, as follows: The relationships between wall displacement and lateral, water, and earth pressure at Excavation Works A and B are shown in Figure 9. The outstanding characteristic of Excavation Work B is that the wall displacement, at 1–2 mm, is extremely small. It is extremely difficult to obtain the exact relationship between the overconsolidation ratio OCR and K_O at each excavation stage. Hence the wall displacement at Excavation Work B was approximated to zero, and the relationship between OCR and K_O shown in Figure 10 was obtained. K_O at each excavation stage was determined as a ratio of the earth pressure given in Figure 9(c) and the effective overburden pressure, namely the overburden pressure or total stress less the water pressure given in Figure 9(b). The OCR increases from the pre-excavation value of 1.0 as the effective overburden pressure decreases while the excavation proceeds. Immediately prior to excavating the stage at 18.0 m below the surface, the value has reached 6.7. Meanwhile, the K_O increases from 0.45 to around 1.8. The figures show both the results from a variety of studies on the relationship between the OCR and K_O (Kulhawy and Mayne 1990) and the relationship between

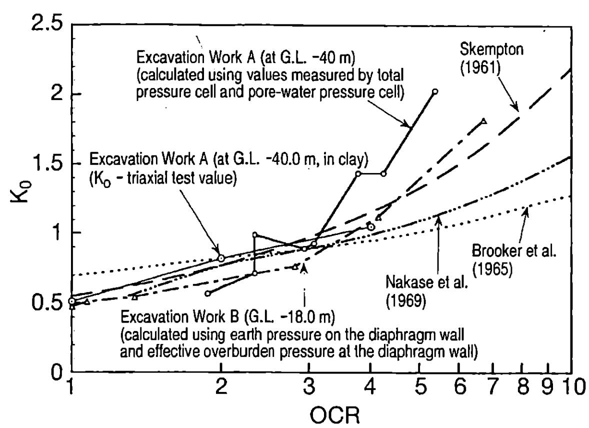


Figure 10. Relationship between OCR and K_O in clay

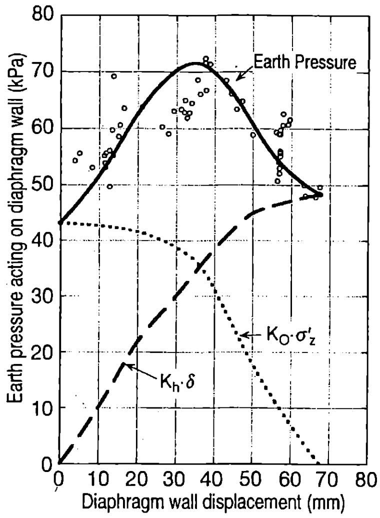


Figure 11 Relationships of $K_O \cdot \sigma'_z$ and $K_h \cdot \delta$ with earth pressure (Excavation Work A, at G.L. −18.0 m)

OCR and K_O determined using the values measured by the total pressure cell and pore-water pressure cell installed in the layer of diluvial clay at 40 m below the surface at the horizontal center of the excavation in Excavation Work A. From these relationships it can be assumed that the relationship between OCR and K_O found for 18.0 m below the surface at Excavation Work B was largely correct.

Using the relationship between the OCR and K_O at 18.0 m below the surface in Excavation Work B, $K_O \cdot \sigma'_z$ at Excavation Work A were calculated; subtracting $K_O \cdot \sigma'_z$ from the earth pressure results in $K_h \cdot \delta$. The relationships between these is shown in Figure 11. $K_O \cdot \sigma'_z$ decreases as the excavation proceeds, and $K_h \cdot \delta$. increases with the wall displacement; as the wall displacement exceeds 20 mm, however, the rate of increase subsides somewhat, and K_h becomes non-linear. Initially K_h is 1,100 kPa/m, up to a wall displacement of 20 mm. The maximum value of the earth pressure for a wall displacement of 30–45 mm in alluvial clay shown in Figures 7(c) and 8(c) is not due to the ground reaching the ultimate passive state; Figure 11 indicates that it is the result of a difference between a decrease in earth pressure caused by the removal of earth load, and an increase of earth pressure due to wall displacement.

5 CONCLUSION

This paper describes the mechanical behavior of lateral, water, and earth pressures acting as passive resistance on a braced wall during excavations for excavation work in soft clay. The paper can be summarized as follows:

1) Lateral and water pressures, in their relationship with wall displacement in soft clay, decrease as the excavation progresses. Earth pressure, though, increases up to a wall displacement of 30–45 mm, and thereafter decreases as the wall displacement increases.
2) The change in earth pressure was considered separately for the two factors of earth load removed and wall displacement. The maximum value of resultant earth pressure for a wall displacement of 30–45 mm is not due the ground reaching the ultimate passive state, but because of the difference between the decrease in earth pressure caused by the removal of earth load, and an increase in earth pressure caused by wall displacement.
3) The coefficient of ground reaction K_h is initially 1,100 kPa/m; thereafter it becomes non-linear along with the wall displacement. The coefficient of earth pressure at rest K_O changes from 0.45 to around 1.8 for an overconsolidation ratio OCR of 1–6.7.

REFERENCES

Brooker, E.W. and Ireland 1965. Earth pressures at rest related to stress history. *Canadian Technical Journal*, Vol.1, No.1: pp. 1-15.

Fukui, S., T. Tamano, and H. Suzuki 1994. Long-term measurements of lateral pressures acting on brace walls in soft clay. *Proc. of the Int'l Symp. on Underground Construction in Soft Ground*: pp. 199-202.

Kulhawy, F.H. and P.W. Mayne 1990. *Manual on estimating soil properties for foundation design, Final Report, Project 1493-6, EL-6800*. Electric Power Research Institute, Palo Alto, CA.

Lambe, T.W. and D.V. Whiteman 1964. *Soil Mechanics*: pp. 162–194. John Wiley & Sons Inc.

Nakase, A., M. Kobayashi and M. Katsuno 1969. Change in undrained shear strength of saturated clays through consolidation and rebound. *Report of the Port and Harbour Research Institute*, Volume 6, No. 4: pp. 103–143 (in Japanese).

Skempton, A.W. 1961. Horizontal stresses in an overconsolidated Eocene clay. *Proc. of 5th Int'l Conf. SMFE*, Vol. 1: pp. 351–357.

Tamano, T., S. Fukui, H. Suzuki, H. Matsuzawa, and K. Ueshita 1995.Mechanical behavior of earth and water pressures acting on outside of braced walls in soft clays. *Proc. of JSCE*, No. 516, Vol. 27: pp. 53-61 (in Japanese).

Tanaka, H 1994. Behavior of a braced excavation in soft clay and undrained shear strength for passive pressure. *Soils and Foundations*, Vol. 34, No. 1: pp.53–64.