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Ground movement, earth and water pressures due to shaft excavations

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SYNOPSIS: A deep diaphragm wall construction and a deep excavation performed by the inverted lining method in diluvial deposits were carefully monitored, and their observed behaviour was compared with design predictions. The results of the field monitoring have shown an approximate coincidence in lateral earth pressure at rest but less ground surface displacement than that predicted by the design.

1 INTRODUCTION

The design of a vertical shaft by multi-level excavation involves the ability to predict with reasonable accuracy the bending moments in the diaphragm wall, the earth pressures acting on the wall of the excavated side, and the likely magnitude of ground surface displacements. Recently the authors have had the opportunity to monitor the behaviour of a vertical shaft as well as ground surface displacements around the shaft, and to compare its actual performance with that predicted by the design.

The deep vertical shaft wall with an outer diameter of 30.6m, a depth of 98m and a thickness of 1.2m was constructed by excavation machines, and the 60m deep multi-level excavation, which was retained by this vertical shaft, was performed by using the inverted lining method. A cross-section of the vertical shaft is shown in Fig.1. This vertical shaft was built to accommodate TBM for shield tunnelling in the construction of an underground regulating reservoir in Tokyo.

This paper presents some results of the field monitoring and draws some preliminary conclusions from the observations. The vertical shaft is surrounded by already existing structures, apartment building (reinforced concrete structure - four story), main road etc. In particular, this apartment building is only about 10m away from the edge of the outer vertical shaft at the ground surface. However, no significant ground movement occurred even during very deep excavation.

2 GROUND CONDITIONS

The soil profile and geotechnical parameters are also shown in Fig.1. The ground conditions at the site comprise some 9m loam layer with almost zero N-values, and diluvial deposits of clay, sand and gravel with more than 50 of N-values except upper diluvial clay about 25m to 40m below ground level. The water table were hydrostatic below a level of between about AP+37.0m and AP+17.9m. Extensive ground investigations were carried out there earlier, including shear wave velocity tests as shown in Fig.1.

3 VERTICAL SHAFT CONSTRUCTION

3.1 Vertical shaft

The vertical shaft consists of a diaphragm wall and inner lining as shown in Fig.1. This inner lining was

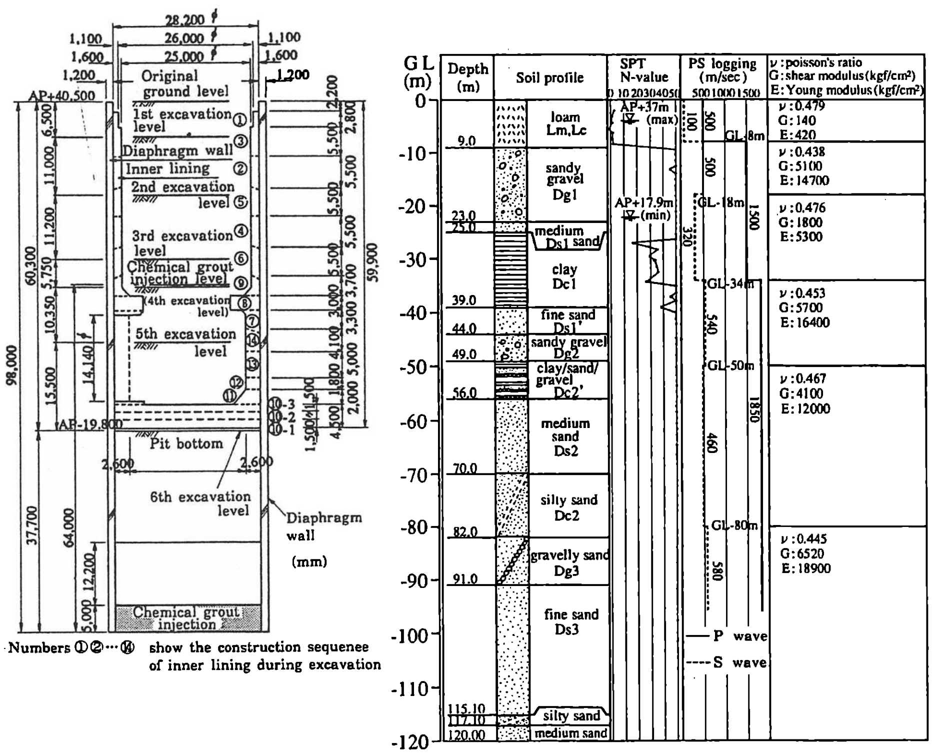

Fig.1 Cross-section of vertical shaft, soil profile and the results of PS logging.

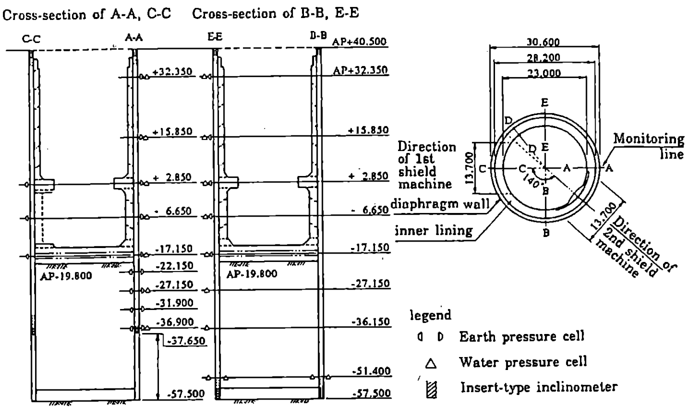

Fig.2 Locations of earth pressure cells, water pressure cells and insert-type inclinometers.

divided into fourteen lots as designated by the numbers shown in Fig.1. A 60m deep multi-level excavation was retained by a 98m deep 1.2m thick diaphragm wall and divided inner lining which was constructed by the inverted lining method as the numbers ①～⑭ in Fig.1 show the sequence of construction.

Total construction period was about 3 years and consisted of the diaphragm wall construction, chemical grout injection to prevent the heaving of the pit bottom, multi-level excavation and inner lining construction.

3.2 Design

At the start of the project reference was made to the observed behaviour of the vertical shaft in diluvial deposits. A number of analyses of the vertical shaft were carried out using a shell model which treats the soil as a series of Winkler springs and using the finite element method. In this paper, the behaviour of vertical shaft and ground surface displacements predicted by the shell model are compared with the monitoring ones. The stiffness and the coefficient of subgrade reaction were derived from SPT (Standard Penetration Test) and uniaxial compression tests as routine design method suggested.

The outline of the shell model is as follows;

1. The vertical shaft is modeled as an axisymmetric shell structure. Therefore, there is no need to separate the horizontal cross-section of the vertical shaft for hoop compression and vertical cross-section for bending moments.

2. Total earth pressure acting on the outside (active side) of the vertical shaft is assumed to be the earth pressure at rest. And total earth pressure acting on the inside (excavated or passive side) of the vertical shaft is calculated by this shell model as in the normal retaining wall design method, the so- called "elasto-plastic method" by Yamagata et al.(1969). This "elasto-plastic method" can predict the passive earth pressure which shows the reaction of the subgrade of soil but cannot exceed the passive Rankine stress.

3. The main deformation of this shell model will occur in the horizontal direction due to the hoop compression by lateral earth pressure. Deformation along the vertical shaft hardly occurred due to the high rigidity in the vertical direction.

4 INSTRUMENTATION

The instrumentation installed at the site was used to measure ① total earth pressure acting on the diaphragm wall, ② water pressure acting on the diaphragm wall, ③ deformation of the diaphragm wall and ④ ground surface displacements. Total earth pressure and water pressure were monitored by LVDT-type pressure cell (Linear Variable Difference Transducer) of which the nonlinearity was 0.5% and the diameter of these cells was 192mm. The locations of total earth pressure and water pressure cells are shown in Fig.2. Total earth pressure and water pressure were mainly monitored at A and E lines. Deformation of the diaphragm wall was monitored by insert-type inclinometers. These inclinometers were installed at all monitoring lines (A to E).

Ground surface displacements were monitored throughout the construction using precise leveling equipment, a theodolite, and precise horizontal taping.

5 OBSERVED BEHAVIOURS

5.1 Total earth and water pressures

Figs.3 (a) and (b) show the total earth pressure and water pressure profiles after each multi-level excavation along E and A monitoring lines. Total earth pressure includes water pressure. It is shown that the measured water pressure lies on the hydrostatic line used in the design.

Measured total earth pressure in Fig.3(a) during multi-level excavation indicates approximate agree-

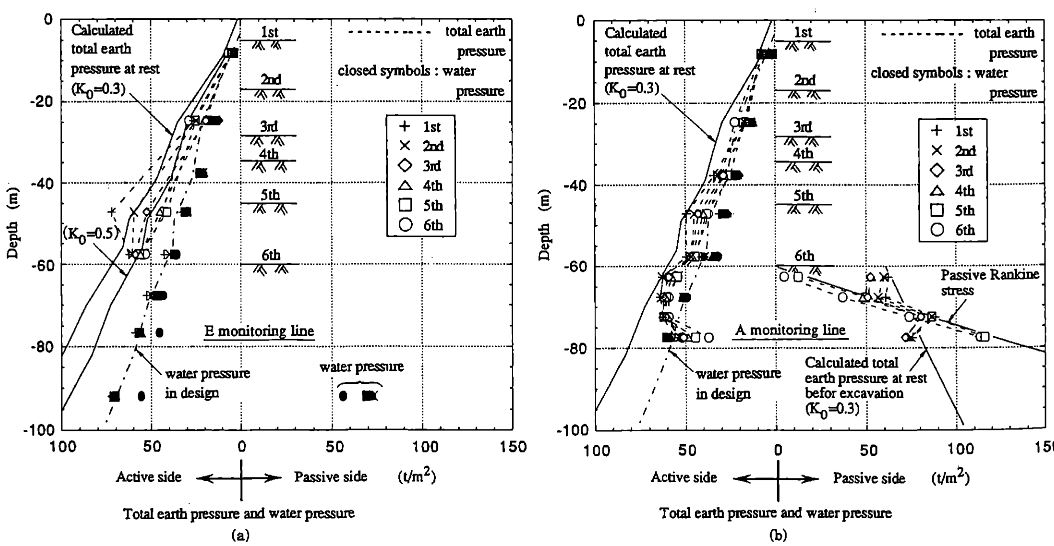

Fig.3 Total earth pressure and water pressure profiles after each multi-level excavation stage.

ment with the calculated total earth pressures at rest using a K_0 value between 0.3 and 0.5. It is also shown that the measured total earth pressure decreased with the decrease of the ground level at the passive side during multi-level excavation. Initial total earth pressure at rest might be changed to the active earth pressure as a result of the deflection of diaphragm wall. On the other hand, measured total earth pressure at the active side in Fig.3(b) was smaller than calculated total earth pressure at rest using a K_0 value of 0.3. It is also shown that the measured total earth pressure more than 70m below the ground surface was smaller than the measured water pressure. The setting of earth pressure cells on the diaphragm wall in these areas may have been imperfect.

Measured passive earth pressure distributions at the excavated side in Fig.3(b) show some interesting features; namely, (1) measured passive total earth pressures during the first and 4th excavation stages agree approximately with the earth pressure at rest calculated by a K_0 value of 0.3. (2) Measured passive total earth pressures during the 5th and 6th excavation stages show a remarkable change from the measured ones during the first and 4th excavation stages. (3) These measured passive earth pressures show an approximate agreement with the passive Rankine stress calculated by using the angle of internal friction of 46.6 (deg.) and assuming zero cohesion below the pit bottom. The reason for this remarkable change in the passive earth pressures during multi-level excavation is not clear at present. Some arching effect of the soils at the excavated side might be the reason.

5.2 Deformation of the diaphragm wall

The deformation profile of the diaphragm wall at various stages of excavation along E monitoring line is given in Fig.4. The horizontal deformation of the diaphragm wall was measured by insert-type inclinometers assuming that the deformation of the bottom of the diaphragm wall was zero. It is shown that the horizontal deformations of the diaphragm wall occurred on the inner (excavated) side at each excavation stage. In particular, horizontal deformation at the 5th excavation stage was the largest. Chemical grout injection was performed at the end of the 4th excavation stage, so the horizontal wall deformation at the 5th excavation stage in Fig.4 might be influenced by the pressure of this chemical grout injection.

Fig.5 shows the horizontal deformation of the diaphragm wall during the first and 6th excavation stages predicted by the shell model used in the design. The large part of the deformation of the axsymmetric shell model is attributed to the hoop compression by the lateral earth pressure which is dependent on the overburden earth pressure. Theoretically, the axial force to the circumferential direction of the diaphragm wall is calculated by the product of the lateral earth pressure and the radius of the shell model where axial force is considered. Therefore, the deformation of the diaphragm wall at the ground surface is nearly zero as shown in Fig.5. The theoretical deformation of the bottom of the diaphragm wall is proportional to the total change of the lateral earth pressure acting on the bottom of the wall during multi-level excavation as shown in Fig.5. However, measured horizontal deformations of the diaphragm wall in Fig.4 are completely different from the predicted ones in Fig.5. This is because the deformation of the diaphragm wall was measured by insert-type inclinometers assuming that the deformation of the bottom of the diaphragm wall was zero as explained before.

Fig.6 is prepared to show the horizontal deformation of the diaphragm wall at the ground surface after the 6th excavation stage. The wall deformation after excavation is not perfectly circular if examined in detail. The discussion relating to the ground surface displacements around the vertical shaft is in the next section.

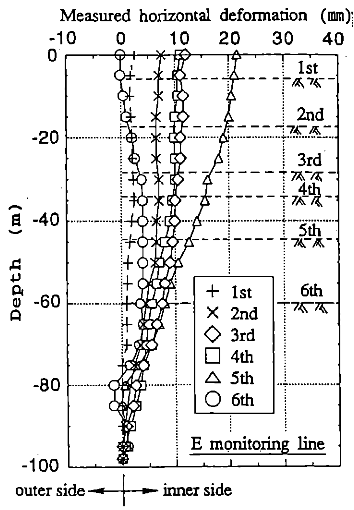

Fig.4 Measured deformation profiles of the diaphragm wall after each excavation stage along E monitoring line.

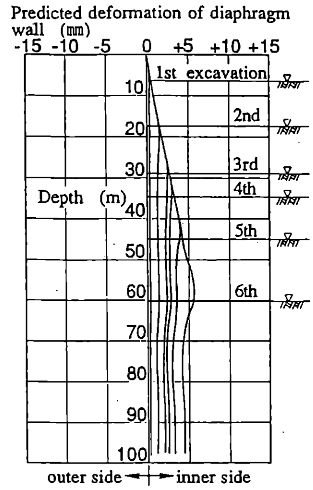

Fig.5 Deformation of the diaphragm wall predicted by the shell model used in the design.

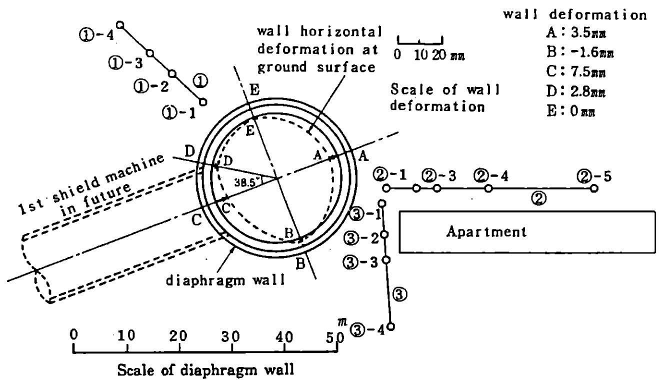

Fig.6 Wall horizontal deformation at the ground surface after the 6th excavation.

5.3 Ground surface displacements

Fig.7 shows the measured vertical and horizontal ground surface displacements associated with the diaphragm wall construction, multi-level excavation and inverted lining construction. The ground surface displacements were measured ; (1) at the start of this project, (2) just before the diaphragm wall construction, (3) just after the diaphragm wall construction, (4) after the 3rd excavation stage, and (5) after the 6th excavation stage. The vertical displacements of measuring points (①-1, ②-1, ③-1) and total horizontal displacements along the measuring lines (①, ②, ③) as shown in Fig.6 are drawn. A large part of the ground surface displacements occurred up until the 3rd excavation stage.

Figs.8 (a) and (b) show the relation between measured vertical and horizontal ground surface displacements and the distance away from the outer diaphragm wall at the ground surface after the 6th excavation stage. It is shown that the area of influence of the diaphragm wall construction and excavation was between about 10m and 15m away from the diaphragm wall at the ground surface. Very few displacements occurred in the vicinity of the apartment building as shown in Fig.6. From the monitored values in Fig.8(b) and Fig.6, we can estimate an approximate correlation between the horizontal ground surface displacements (10mm for No.③ and 9mm for No.②) and the diaphragm wall deformation at the ground surface (3.5mm for A monitoring line in Fig.6).

Moreover, Fig.8(c) shows the relationship between vertical and horizontal ground surface displacements for various stages. In particular, approximated straight lines in this figure indicate the directions of the displacement vector of the soil along the monitoring line at the ground surface. It is shown that the directions of the displacement vector at the ground surface were almost independent of the distance from the diaphragm wall. It is also shown that these directions were about 35 degrees to the horizontal direction. Therefore, the alluvial soil (loam) between GL-0m and GL-9m in Fig.1 might affect the are of the influence of the horizontal ground displacements as described in Fig.8(b). That is to say the deformation of diluvial deposits below GL-9m might be very small. Moreover, there was very little influence of the diluvial deposits on the ground surface displacements.

The shell model was used in the design to estimate the deformation of the diaphragm wall as explained before. Then the vertical ground surface displacements can be estimated by assuming that the moved volume of the soils at the active side due to the deformation of the diaphragm wall equals the settled volume of the ground surface (Peck(1969)). About 2.0mm maximum settlement at the ground surface about 30m away from the diaphragm wall was calculated by using the deformation of the diaphragm wall shown in Fig.5. The results of the field monitoring at this point in Fig.8(a) have shown less ground surface settlements than that predicted by the design. However, if the deformation of diaphragm wall calculated by the shell model is in conflict with the monitoring values as shown in Figs. 4 and 5, then this maximum predicted settlement (about 2.0mm) may be considered.

6. CONCLUSIONS

1. Measured total earth pressure during multi-level excavation indicates an approximate agreement with calculated total earth pressures at rest using a K_0 value between 0.3 and 0.5.
2. Measured passive total earth pressures during the 5th and 6th excavation stages show a remarkable change from the measured ones during the first and 4th excavation stages.
3. Horizontal deformation of the diaphragm wall at the ground surface occurred on the inner (excavated) side and was not perfectly circular in detail.
4. Measured horizontal deformations of the diaphragm wall were very different from the predicted ones.
5. The area of influence of the diaphragm wall construction and excavation was between about 10m and 15m away from the diaphragm wall at the ground surface.
6. The directions of the displacement vectors at the ground surface were almost independent of the distance from the diaphragm wall.

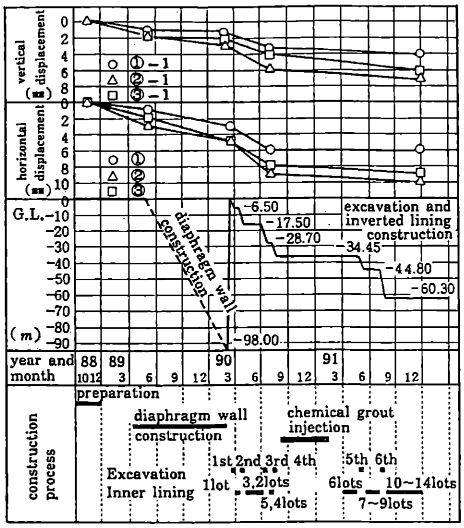

Fig.7 Ground surface displacements associated with the vertical shaft construction and the relating construction process.

ACKNOWLEDGEMENTS

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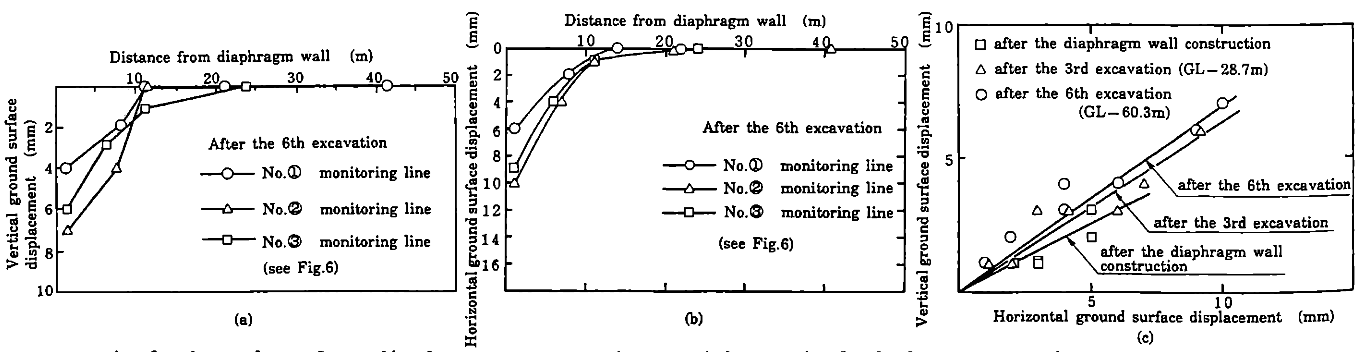

Fig.8 Ground surface displacements associated with vertical shaft construction and excavation.