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# Considerations in shaft excavation and peripheral ground deformation

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ABSTRACT: In recent years, as the scale and depth of underground structures have grown, there has been a growing engineering interest in deep shafts. This paper first investigates relatively large-scale shaft construction projects carried out in Japan in an effort to grasp their current state. Using measurement data about typical deep cylindrical shafts, a detailed study is then made on lateral working pressure, diaphragm wall displacement and ground surface settlement during excavation. In addition, measurement data obtained at some shaft construction sites is analyzed to investigate ground deformation characteristics common in shaft excavation.

## 1 INTRODUCTION

With the recent increase in underground space development in metropolitan areas, shaft construction projects have been increasing in Japan. From an engineering viewpoint, a shaft is defined as a structure with a depth larger than width, as distinct from earth retaining structures by open cutting of a long and narrow shape or those having a large planar shape. There is an additional definition of a shaft as a structure for providing access between underground and aboveground structures. This structure is also broadly called a shaft and is discussed in this paper. Although there have been many shafts constructed, no particular attention has been paid to them because of their small scale, most of which were on the ten meter scale in depth.

In recent years, however, underground structures have become greater in both scale and depth. Because of a recent shaft of the ground type to be excavated from soft alluvial deposits to diluvial deposits and soft rock, there also has been an increasing need for a detailed study on design and evaluation techniques for excavating shafts in a more safe and rational manner. For instance, in the respect that some control is exerted on the deformation of earth retaining walls and peripheral ground by three-dimensional shape effects of shafts during excavation.

This report first makes an analysis of the current track record of relatively large-scale shaft construction projects. A close study is then made on measurement data concerning typical cylindrical shafts. Finally, the characteristics of shafts with depth larger than width during excavation such as diaphragm wall displacement and peripheral ground deformation are made clear.

## 2 CURRENT STATE OF SHAFT CONSTRUCTION PROJECTS

Twenty four typical shaft construction projects out of the track record in shaft construction are summarized below, including underground tank construction records as examples of cylindrical earth retaining structures.

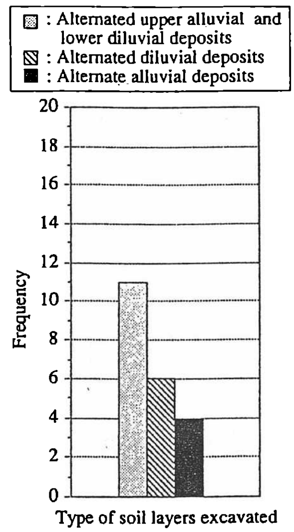


Figure 1. Type of soil excavated

Figures 1 through 4 summarize type of peripheral soil layers and relationships between excavation scale and depth. The most frequent type of soil excavated for shafts is alternating layers of sand, clay, and silt. The frequency of excavation for cylindrical shafts in relatively hard soil such as hardpan strata is also increasing in recent years.

The data exceeding 60 m in excavation width plotted in Figure 2 is the track record in cylindrical tank construction. When viewing ordinary shafts from an excavation scale, most of them are 20 m or less in excavation width (diameter) without regard to excavation depth.

For the relationship between wall length ($L_0$) and excavation depth (L) shown in Figure 3, most data fall within the bounds of $L = 0.6\text{-}0.7L_0$. In regards to the relationship between wall thickness and wall length, although there is a correlation when the wall thickness is less than 1 m, scattering increases when the wall thickness is greater than 1 m, depending on the type of earth retaining walls.

## 3 TYPICAL MEASUREMENTS OF CYLINDRICAL SHAFTS

### 3.1 *Outline of the cylindrical shaft*[1)]

The typical shaft described in this paper is a deep shaft of 28.2 m inside diameter and GL-60.3 m in excavation depth constructed together with a regulating reservoir of

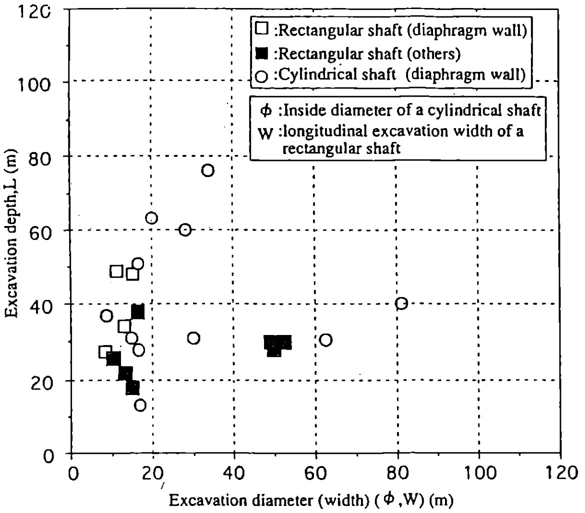


Figure 2. Relationship between excavation width (diameter) and excavation depth (L)

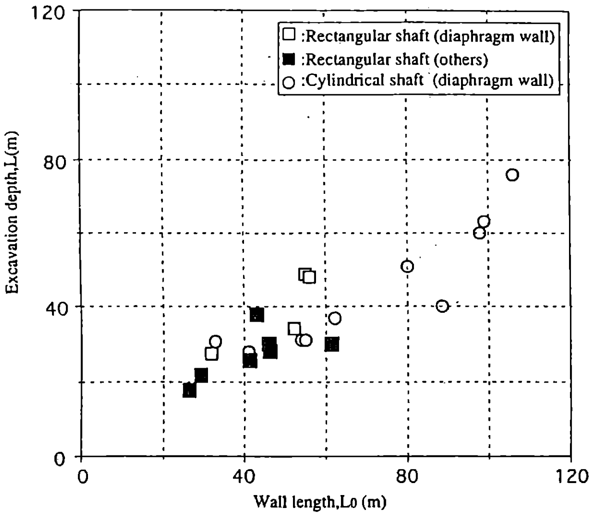


Figure 3. Relationship between wall length ($L_0$) and excavation depth (L)

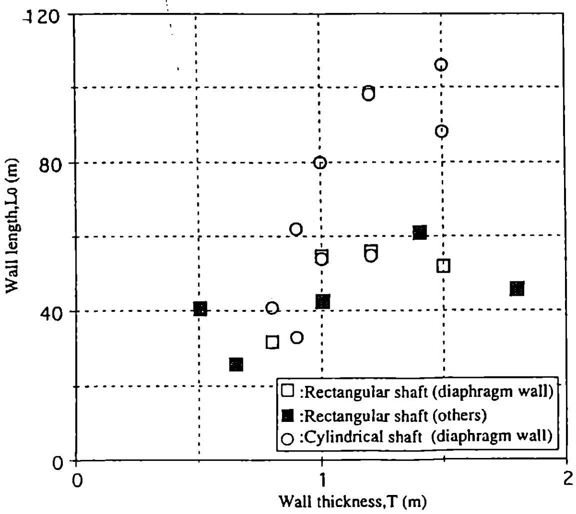


Figure 4. Relationship between wall thickness and wall length ($L_0$)

underground river type (of 12.5 m in inside diameter by shield tunnelling). Figure 5 shows the longitudinal section of the shaft. The diaphragm wall of 98 m in depth and 1.2 m in wall thickness forms a cylinder with 28 elements in total. Excavation was carried out in 6 excavation steps, ranging from the first excavation level to the final floor bedding level, and at the same time the wall was constructed by inverted lining method, in the steps shown (with circled numbers) in the figure. To prevent swelling, the shaft bottom was improved by chemical injection from the fourth excavation level as shown in the figure.

### 3.2 *Geological profile*

Figure 6 shows the soil boring log. At the project site situated on the Musashino plateau, Musashino and Tachikawa loam layers are distributed to a depth of 8 m from the surface, with the N-value nearly equal to zero. The younger Musashino gravel layer (Dg1) of relatively low consolidation is distributed at the depth between GL-9 to -23 m. Under the gravel layer is the Tokyo layer group, having consolidation higher than the above and N-value nearly equal to 50 or more, consisting mainly of bay sediments (such as consolidated silt, sand and gravel), and overlaying the Joso layer group.

### 3.3 *Measurement items and methods*

The following three measurement items were set up for the earth retaining wall.

(1) Earth pressure and hydrostatic pressure acting on the diaphragm wall

(2) Sectional stresses developed in the wall (stresses in concrete and steel reinforcement)

(3) Deformation of the wall

Besides the above, measurements were made on the

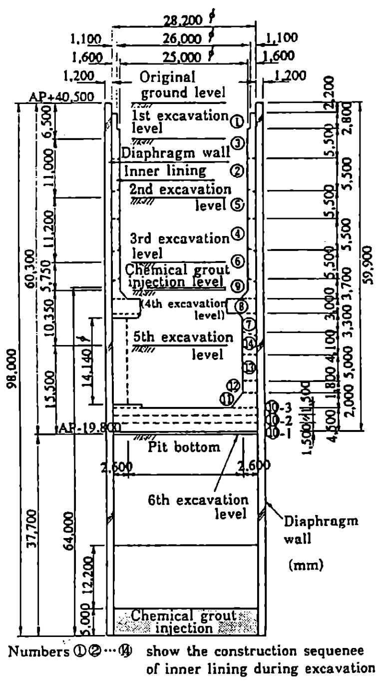


Figure 5. Longitudinal section of the shaft[1)]

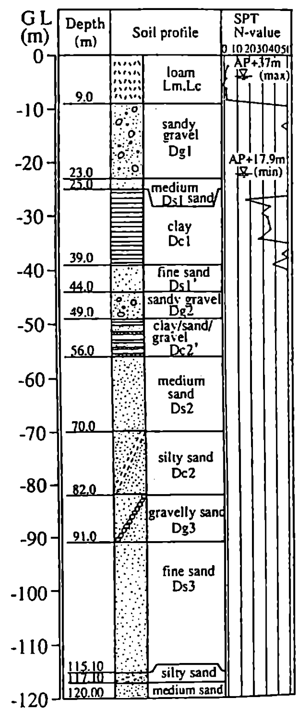


Figure 6. Geological profile and soil conditions near the shaft

settlement and horizontal displacement of the wall at the ground surface level (on measuring lines A to E in Figure 9.) Levels were taken and distances surveyed at points established on measuring lines (① to ③ in the figure) to measure ground surface settlement and horizontal movement around the shaft.

### 3.4 *Measurement results*

1) Earth pressure and hydrostatic pressure acting on the diaphragm wall

Figure 7 shows the changes in the total lateral pressure (earth pressure + hydrostatic pressure) and hydrostatic pressure measured on the measuring line E at every excavation step. It is clear from the figure that there was no variation in hydrostatic pressure during excavation, and the hydrostatic pressure measured was almost the same order of magnitude as established in the design stage. On the other hand, the earth pressure acting on the wall decreased steadily as excavation proceeded. In the final excavation stage, the earth pressure at rest used for design (the design coefficient of earth pressure at rest, $k_0 = 0.5$) dropped to about 0.1 on the coefficient basis at some points on the measuring lines. This indicates that hydrostatic pressure forms an increasing proportion of lateral pressure, as is often said to be the case for ordinary earth retaining walls in diluvial deposits[2].

Incidentally, usingan internal friction angle, $\phi = 37.8°$, which was obtained from a triaxial compression test on specimens taken from the Dgl layer, the coefficient of earth pressure at rest is given $K_0 = 1 - \sin\phi = 0.39$ by Jaky's equation, and the coefficient of active earth pressure is given $\tan^2(45° - \phi/2) = 0.24$ by Rankine's equation. The reason the earth pressure measured was lower than Rankine's active earth pressure with a cohesion factor, C, assumed to be zero is that the ground at the project site consisting mainly of diluvial deposits is on a fairly high consolidation level due to the effects of consolidation and age. Another reason is that the earth pressure acting on the wall was fairly lower than the value given by general earth pressure theories because of the three-dimensional shape effects of shafts.

2) Deformation and sectional stresses of the wall

Figure 8 shows the change in horizontal displacement of the wall with depth on measuring line E. The data indicates that the horizontal wall displacement was maximum and inward in the fifth excavation step and went back outward in the sixth excavation step. Since these wall deformation characteristics, which are not explained by general concepts, were also seen in the data measured on other measuring lines, it seems reasonable to consider that the soil pressure made uneven by the chemical injection into the bottom carried out before the fifth excavation step caused the lower part of the wall to be displaced and the inclinometer reference points to fluctuate.

The displacement of the wall was maximum on the ground surface as is the case with ordinary plane earth retaining structures. It was about 10 mm inward at all monitoring points when the fourth excavation step was completed (GL-35.0 m).

As shown in the distribution of wall displacement at the ground surface level in Figure 9, the circular wall is slightly deformed flat in the A-C direction. This corresponds to the horizontal ground surface

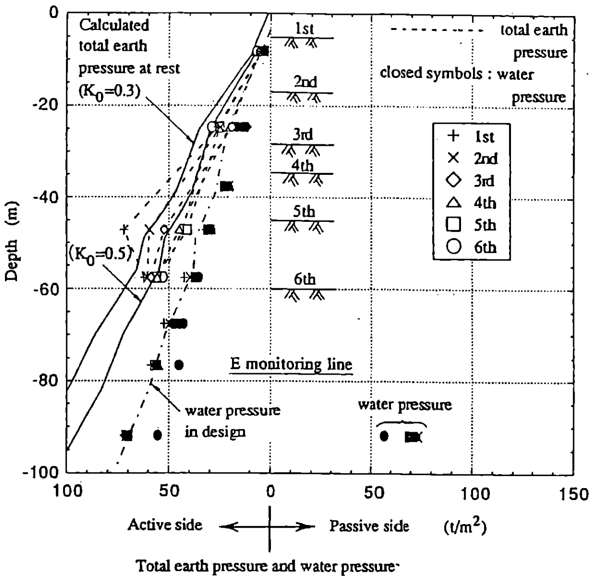


Figure 7. Lateral pressure and hydrostatic pressure measured (on measuring line E)[1]

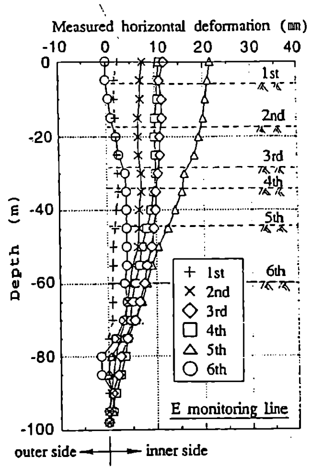


Figure 8. Changes in measured horizontal wall displacement with depth[1]

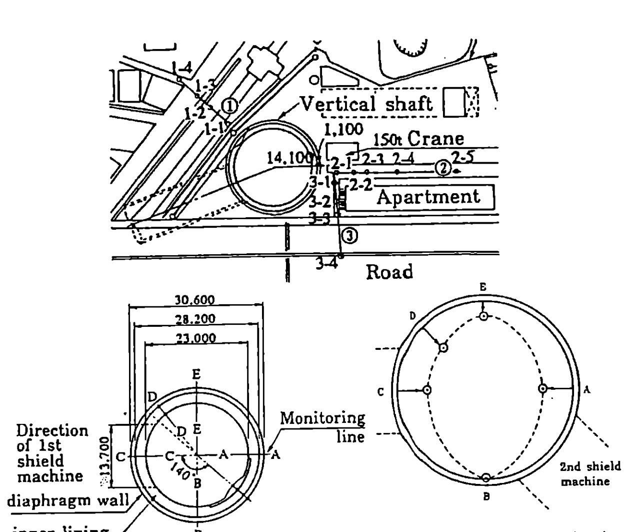


Figure 9. Wall deformation at ground surface on measuring lines

displacement obtained on three monitoring lines (①-1, ②-1, and ③-1 shown in Figure 12) around the shaft described later.

This project made an analysis to predict the deformation and sectional stresses of the wall during excavation with a cylindrical model. As described previously, the earth pressure at rest ($k_0 = 0.5$) was used for the lateral pressure acting on the wall. Figure 10 shows the predicted displacement of the wall. The results of the analysis predicted a deformation mode that loads acting on the wall and the deformation of the wall would increase with depth, taking into account the effects of inverted lining method; that is, the stiffness of the wall increases from the top of the shaft. In contrast to this, the measurement data (in Figure 8) shows a deformation mode where displacement was maximum on the ground surface, as is the case with ordinary plane earth retaining structures mentioned before. Since insertion-type inclinometers were used for the measurement, the data plotted in the figure indicates relative displacement after letting displacement at the lowest part of the wall be zero. Although it is impossible to compare measured values directly with analyzed ones, the two deformation modes are completely inverse.

Table 1 lists the maximum concrete stresses, both measured and predicted. The table shows that measured concrete stresses developed in concrete are about 40-60% of predicted values.

The possible causes of the difference in wall displacements and stresses in concrete between measurement and prediction can be considered as follows. First, for the reasons mentioned above, the earth pressure acting on the wall was overestimated. Second, thin mud films existed between wall elements were compressed as excavation advanced. Third, the action of unbalanced pressure and the effects of the method of evaluating embedded ground.

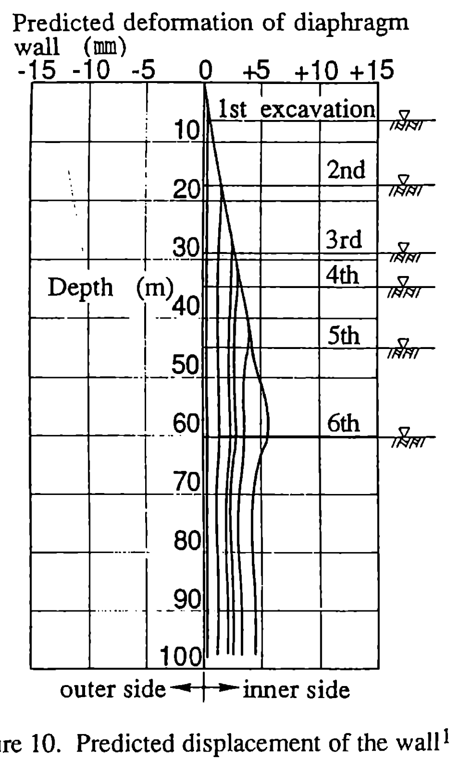


Figure 10. Predicted displacement of the wall[1)]

Table 1 Changes in maximum circumferential stresses measured and predicted with excavation steps[1)]

| | monitoring line | Excavaton Step | | | |
|---|---|---|---|---|---|
| | | 4th | | last | |
| | | measured values | predicted values | measured values | predicted values |
| concrete stresses (kg/cm2) | A | 40.8 | | 59.5 | |
| | B | 23.3 | | 75.0 | |
| | C | 32.9 | 66.0 | 82.0 | 124.7 |
| | D | 36.9 | | 72.0 | |
| | E | 24.5 | | 76.0 | |

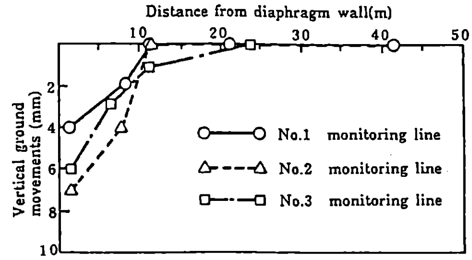


Figure 11. Ground surface settlement around the shaft after the completion of excavation

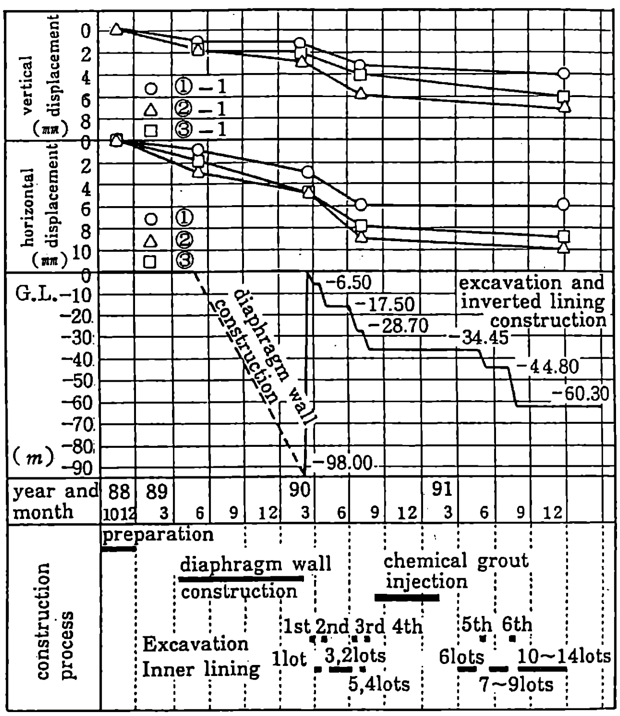


Figure 12. Construction progress records and changes in ground surface displacement with the passage of time[1)]

3) Peripheral ground surface deformation

Figure 11 shows the ground surface settlement on monitoring lines ① to ③ after the completion of the excavation. The 4-7 mm settlement near the wall extended up to 10 m, and no settlement occurred on the ground surface 50 m or more away from the shaft.

Figure 12 shows the construction progress records and the changes in settlement with the passage of time. Settlement began as the wall construction started and increased as excavation proceeded. Most of the settlement were observed when the excavation level reached the midway point of the design depth (GL-34.5 m), and afterwards the increase in settlement was only a little.

## 4 CHARACTERISTICS OF SHAFT EXCAVATION

As compared with earth retaining structures by open cutting to a long and narrow shape or those having a large planar shape, the three-dimensional shape effects of shafts on wall displacement and peripheral ground surface deformation are not negligible. In this regard, the wall displacement and peripheral ground surface deformation around shafts are studied from engineering aspect, emphasizing the differences from ordinary earth retaining structures.

### 4.1 *Wall displacement characteristics during shaft excavation*

Figures 13 and 14 show the relationship between excavation depth and the maximum horizontal wall displacement based on measurement results obtained in past shaft construction projects. There is little tendency in this relationship in Figure 13 that can be approximated by linear equations because the wall displacement is affected by the type of supporting. Insofar as cylindrical shafts are concerned, their wall displacements are relatively smaller than those of rectangular shafts, regardless of scale.

According to the relationship between the aspect ratio (a ratio of excavation width to excavation depth) and the maximum horizontal wall displacement as summarized in Figure 14, the displacement of rectangular shafts tends to increase with an increase in the aspect ratio. In contrast, it is of interest that the wall displacement of cylindrical shafts and underground tanks is relatively small without regard to the aspect ratio. It indicates that cylindrical earth retaining structures have advantages.

As mentioned above, such a characteristic is made clear from Figures 13 and 14 that the wall displacement of cylindrical shafts (including underground tanks) and shafts with a small aspect ratio becomes smaller than ordinary earth retaining structures.

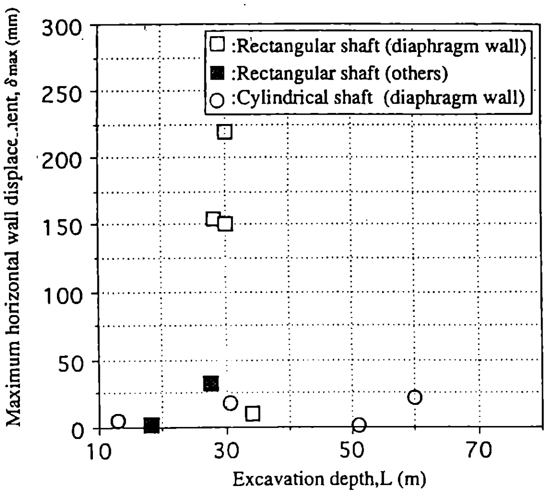


Figure 13. Relationship between excavation depth and maximum horizontal wall displacement (shaft)

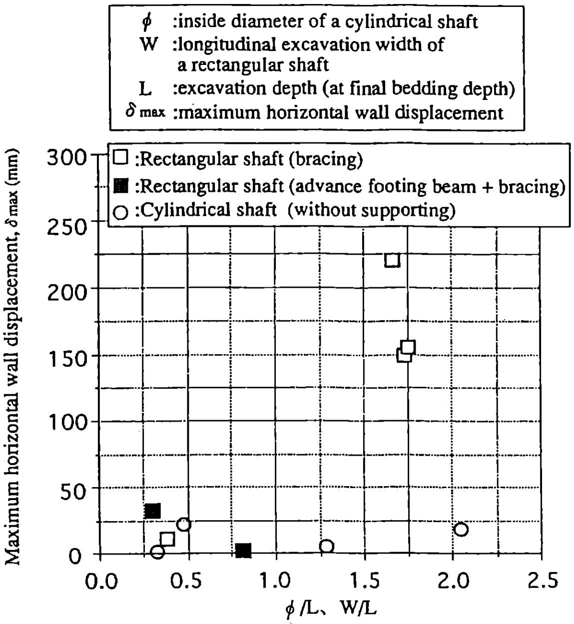


Figure 14. Relationship between aspect ratio and maximum horizontal wall displacement by shaft shape

### 4.2 *Peripheral ground surface settlement and wall displacement during shaft excavation*

Figure 15 shows the ground surface settlement measured at six rectangular shaft construction projects during excavation on a Peck settlement characteristic chart[3]. These data in the figure are within the bounds of 0.5% without regard to the distance from an earth retaining wall.

In addition, Figure 16 shows the relationship between the maximum horizontal wall displacement and the maximum ground surface settlement during the steps of excavating a rectangular shaft which is 6 m by 10 m in cross section, 17.35 m in excavation depth, and 21.5 m in wall length. It can be read from the graph that there is a tendency of ground surface settlement to be small, as

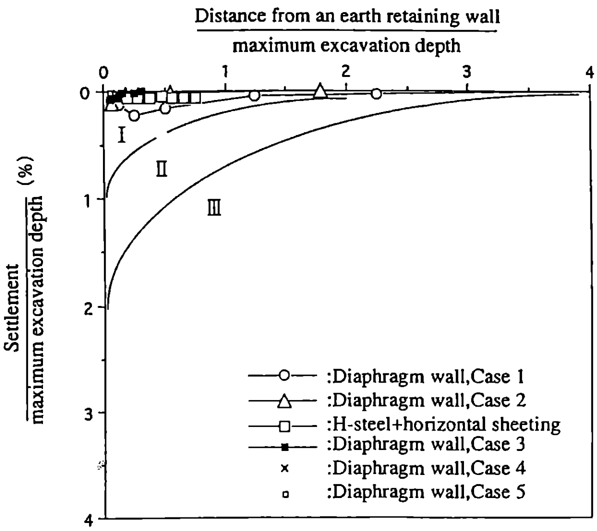


Figure 15. Peripheral ground surface settlement during shaft excavation

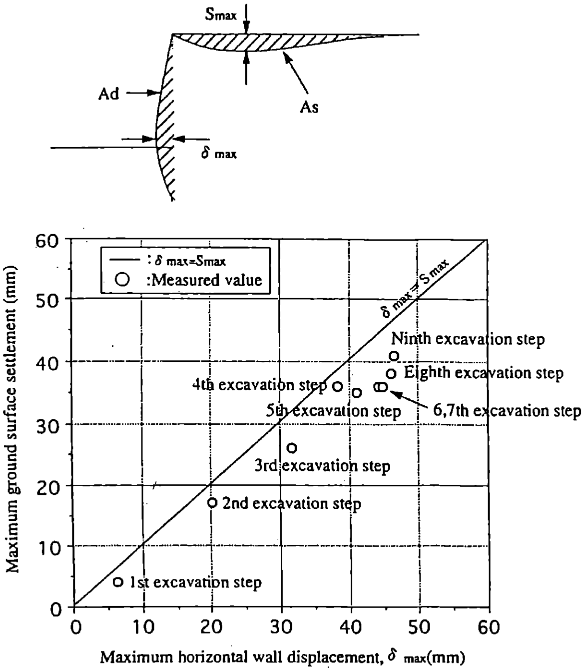


Figure 16. Relationship between maximum horizontal wall displacement and maximum ground surface settlement

compared with wall displacement, during shaft excavation. This points to the idea that ground surface settlement is controlled more than wall displacement during shaft excavation, as compared with ordinary earth retaining structures. This agrees well with the characteristics shown in Figure 15.

## 5 CONCLUSIONS

The results of this analysis made on the track record in shaft construction projects and measurements can be summarized as follows.

(1) In open cutting, such as excavating shafts, there is a tendency of both diaphragm wall displacement and ground surface settlement to decrease because of the three-dimensional shafts.

(2) It was made clear that cylindrical shafts tend to decrease in diaphragm wall displacement more than rectangular earth retaining structures on the same scale without regard to the aspect ratio of a shaft or the hardness of the ground excavated.

(3) It is theoretically and empirically well known that the diaphragm wall displacement and peripheral ground surface settlement around cylindrical shafts are controlled. Structural advantages of cylindrical shafts particularly in deep excavation were once again confirmed.

(4) More rational design would be made possible by taking into account shaft shape effects. In this case, two methods can be considered: one taking into account the three-dimensional effects of shaft structures; another taking into account the three-dimensional effects in setting up lateral pressure. As matters now stand, the former should be adopted because of difficulty in defining the latter quantitatively.

(5) An accurate prediction analysis on the effects of excavation on peripheral structures would be made possible by taking into account ground deformation characteristics specific to shafts construction.

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