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Behavior and soil resistance of shaped cantilever diaphragm walls

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ABSTRACT: The cantilever method using diaphragm walls with shaped cross section was used to excavate very soft ground down to a depth of 12.2m and an area of 134m×96m in Tokyo, Japan. This paper clarifies the behavior of the walls in this excavation and compares with the design analysis result of the walls. Next this paper proposes a method for evaluating the soil resistance which supports the diaphragm walls with shaped cross sections and demonstrates the effectiveness of the proposed method.

1 INTRODUCTION

In the cantilever method, larger stresses and deformations occur in the earth retaining walls than the method with supports because of the supporting characteristics of the cantilever beam. Hence, the cantilever method only applies to shallow excavations of 3m to 5m depth in existing circumstances.However, the cantilever method doesn't need supports such as struts and anchors, and enhances the efficiency of underground work. Therefore, various attempts have been made to apply the cantilever method to deeper excavations such as using diaphragm walls of various shaped cross sections such as T and +; this type of walls has very high rigidity. The cantilever method using this walls has been used for excavations of depth over 10m. However, there are few construction examples and past studies.

This paper outlines large scale excavation using the above method in very soft ground and describes two kinds of analysis for designing the walls before the excavation. The design analysis result is compared with the measured behavior of the walls.Next, according to the measured behavior of the walls, this paper proposes a method for evaluating the soil resistance which has much influence on the behavior of the walls without supports.And simulations of the measured wall behavior are conducted to demonstrate the effectiveness of this evaluation method.

2 BEHAVIOR AND DESIGN ANALYSIS

2.1 *Excavation and measurement*

This construction site is located in Tokyo.The soil profile is shown in Figure 1. Soft clay layers extend from the ground surface to a depth of 26m. Gravel layers with more than 50N-value exist from a depth of 34m.

The scale of excavation is very large with an area of 134m×96m and a depth of 12.2m, as shown in Figure 2 and Figure 3. The cantilever method using diaphragm walls with T-shaped cross section, as shown in Figures 3 - 4, was selected. The T-shaped diaphragm walls consist of buttresses and flat walls, and those two kind of walls are connected to each other as structural one body. The length of the flat walls is 22m. And the buttresses are embedded into a gravel layer with more than 50N-value from a depth of 34m in order to be used for piles.

During the excavation, the lateral pressure acting on the T-shaped diaphragm walls, the deformations of the walls and the reinforcing bar stresses of the walls were measured. The transducers were mainly installed on the monitoring point shown in Figure 2.The position of these trans-

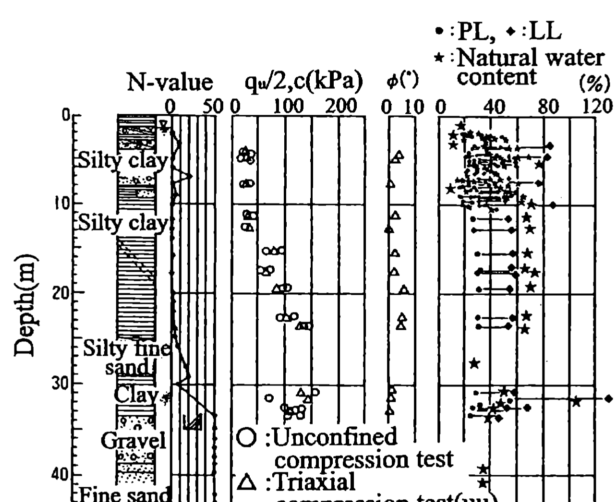


Figure 1. Ground condition.

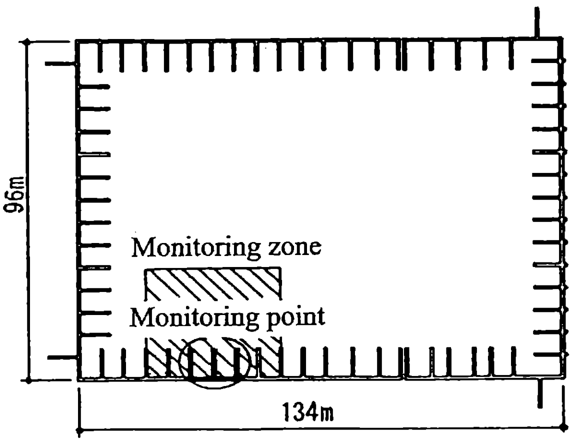


Figure 2. Layout of diaphragm walls and monitoring point.

ducers are shown in Figures 3 - 4. In the buttresses, 2-5 reinforcing bar stress transducers were installed on the same horizontal cross section in order to observe the vertical stress distributions.

This cantilever method didn't need any supports, therefore it was possible to excavate down to the final excavation depth at a stretch.However, taking safety into consideration, the final excavation depth was divided into three steps.In the each step, first, the monitoring zone in front of the monitoring point (Fig. 2) was excavated in order to make sure the safety. Next, the whole excavation area was excavated.

2.2 *Analysis method for design*

It is inappropriate to analyze the three-dimensional T-shaped diaphragm walls by the analysis method of generally-used two-dimensional earth retaining walls. Therefore, in designing the T-shaped diaphragm walls, two analysis methods as follows were selected (Sei et al. 1994).

1. Finite element method (A method). Taking symmetry of the T-shape into consideration, as shown in Figure 5, one half the size of the T-shaped diaphragm walls is used as the analysis model. The wall is treated as an elastic body.The assumed stress-strain relationship in the soils is as presented by the Duncan Chang method (1970). In the analysis, first, the initial stresses of soil before the excavation was calculated. Next, the soil elements of excavated parts in each excavation step were eliminated.

2. Beam-spring analysis method (B method). In this analysis model shown in Figure 6, the wall is treated as an elastic beam. And the soil resistance is evaluated by springs.The spring constants of the soil were determined by the effect of the frictional resistance acting on the buttresses added to the passive resistance acting on the flat walls. The lateral pressure used in the analysis is shown in Figure 6 (Miyazaki 1994).As the soil supporting condition in the bottom of the T-shaped diaphragm walls was not clear, the analyses were conducted by three types of bottom supporting condition, namely, fixed, pin and free.

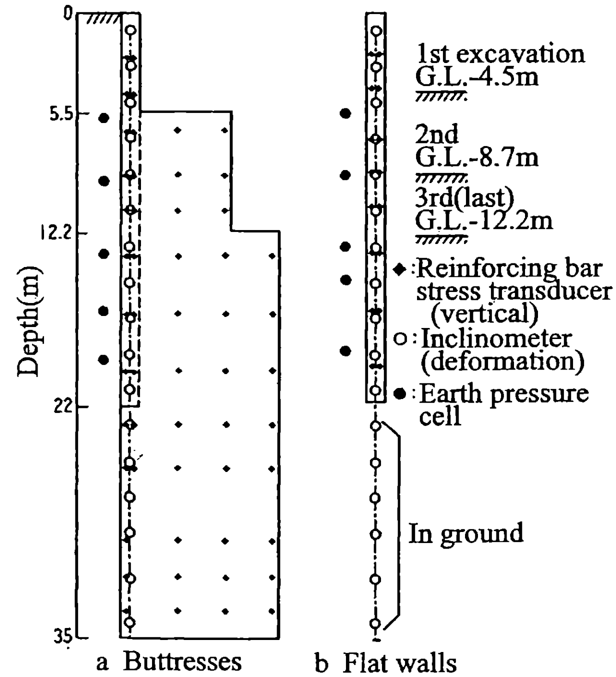


Figure 3. Section of diaphragm walls.

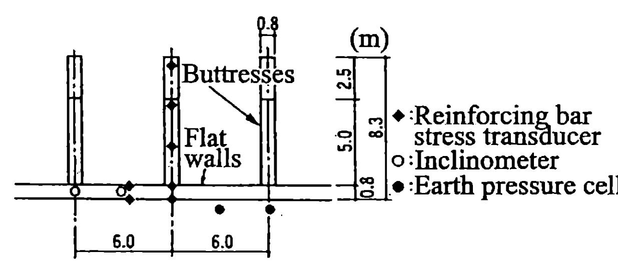


Figure 4. Plan of diaphragm walls.

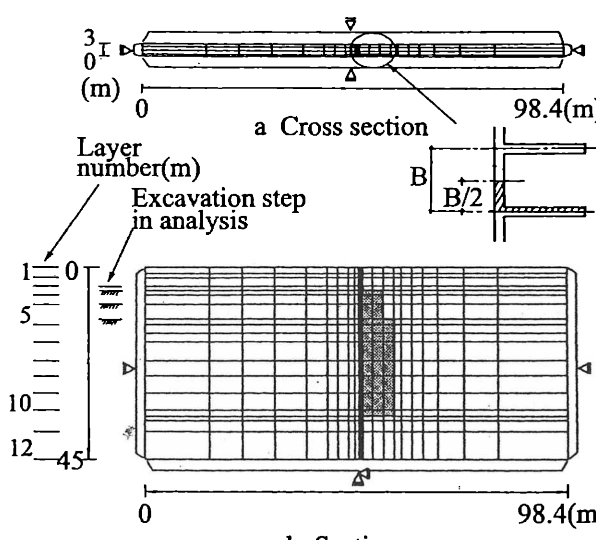


Figure 5. Analysis model for finite element method (A method).

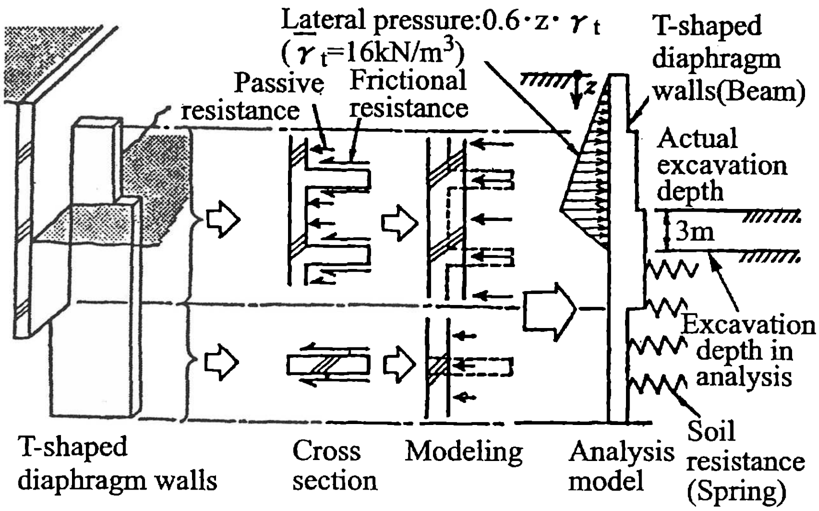


Figure 6. Beam - spring model (B method).

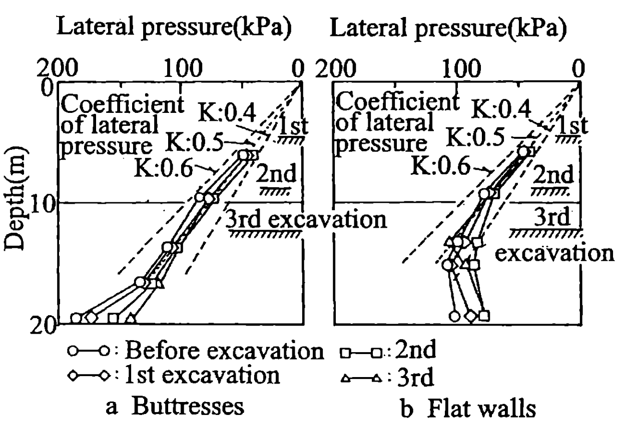


Figure 7. Measured lateral pressure.

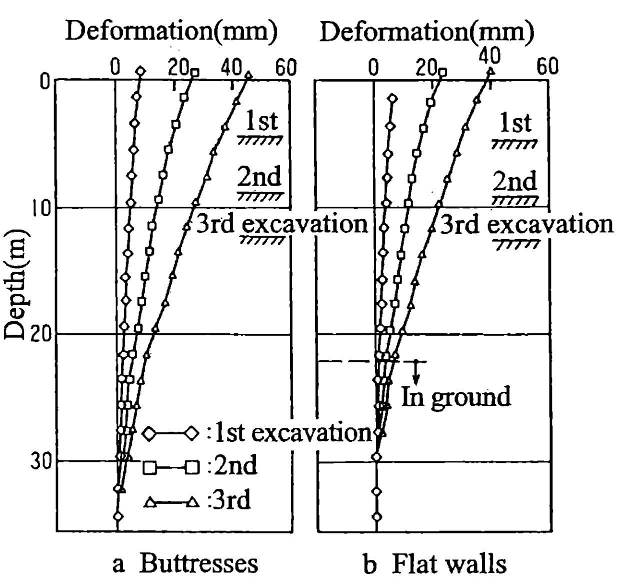


Figure 8. Measured deformation.

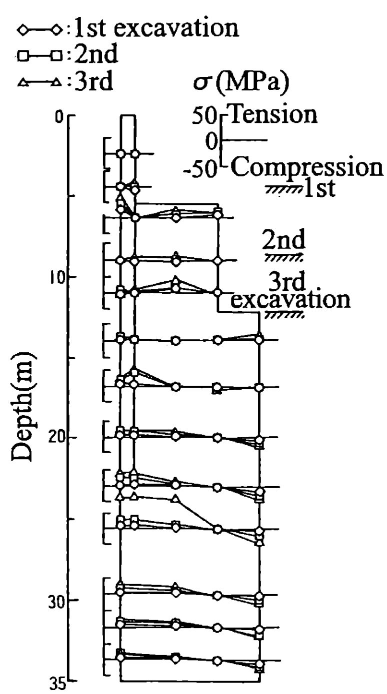


Figure 9. Measured reinforcing bar stress in buttresses.

2.3 *Behavior and design analysis result*

1. Lateral pressure. Figure 7 shows the measured lateral pressures acting on the buttresses and the flat walls. These pressures measured above the final excavation bottom show the triangular distribution. With the progress of the excavation, these pressures lower slightly. The coeficient of the lateral pressure used in the analyses is 0.6 but the measured one is about 0.5.

2. Deformation. Figure 8 shows the measured deformations of the buttresses and the flat walls. Though the embedded depth of the flat walls is 22m, the soil deformation below the flat walls bottom until a depth of the buttresses bottom was measured. The T-shaped diaphragm walls has high rigidity, the buttresses and the flat walls bend

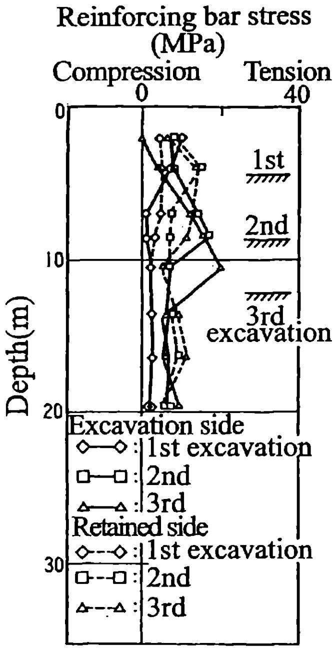


Figure 10. Measured reinforcing bar stress in flat walls.

little. And the whole walls rotated around the buttresses bottom.

3. Reinforcing bar stress. Figures 9 - 10 show the measured reinforcing bar stresses in the buttresses and the flat walls.The reinforcing bar stresses of the buttresses tend to increase suddenly at a depth of 5.5m and 22m where the cross section shape of the walls changes.The maximum tensile stress is about 100MPa and occurs at a depth of 25m.Stress distributions on horizontal cross sections are about a straight line.On the other hand, the flat walls locate on the tensile zone for the neutral axis of the T-shaped cross section. So, the stresses of the retained and the excavated side are tensile stresses. And the values of the stresses are small, about 20MPa at maximum.

4. Comparison of design analysis result with behavior. The measured deformation and bending moments in the final excavation step are compared with the result of the design analyses, as shown in Figure 11.And, for reference, the calculated values of shear force are also shown.

The deformation predicted by the A method fits well with the measured one. On the other hand, the calculated values of making the buttresses bottom condition fixed and pinned by the B method are smaller than the measured one. But the calculated values assuming a bottom free condition fit well. Considering the above, the actual supporting condition of the buttresses bottom is supposed to be an elastic one between a fixed and pinned condition.

The measured bending moments are calculated by the reinforcing bar stress (Fig. 9). The bending moments by the A method don't fit well the measured one. On the other hand, every value predicted by the B method above the depth of 25m fit well the measured ones. However, below a depth of 25m, the predicted values for the bottom fixed condition are larger than the measured ones. On the contrary, the values predicted for the bottom free and pin condition are smaller than the measured ones. These problems are considered to be due to the actual buttresses bottom supporting condition being elastic as mentioned above. So, in B method, if the support of the buttresses bottom is a spring support, the measured behavior is supposed to be fitted well.

3 SOIL RESISTANCE EVALUATION

In this section, at first, the method for evaluating the soil resistance supporting the diaphragm walls with shaped

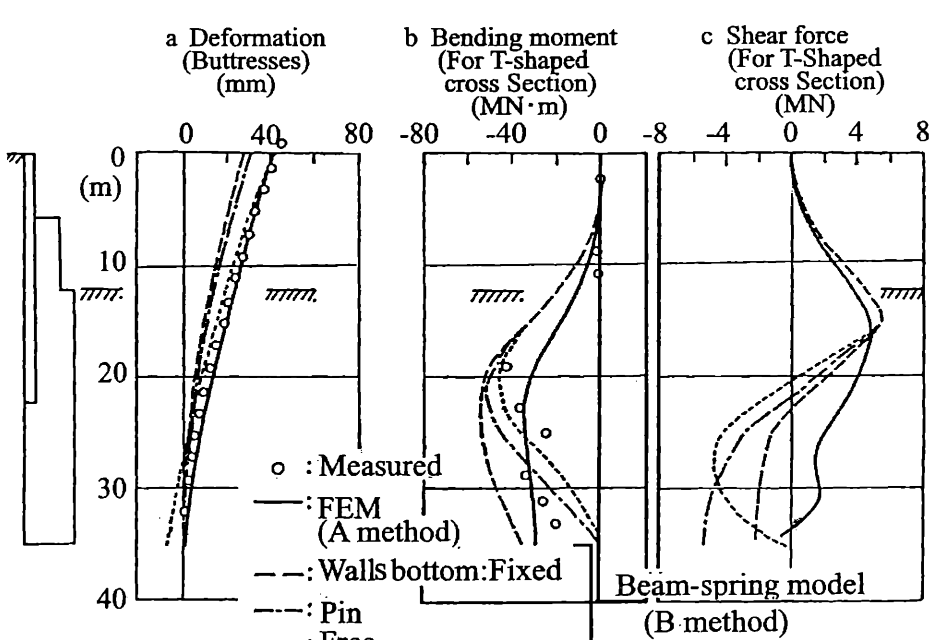


Figure 11. Design analysis result (3rd excavation).

cross section is proposed. Next, by this method, the soil resistance of the walls whose shapes have a possibility of being the adopted one are evaluated. This evaluating method can evaluate the passive resistance acting on the flat walls and the frictional resistance acting on the buttresses without separating the two resistance. The soil resistance is evaluated on the bottom of the shaped diaphragm walls as well as the embedded part of the walls.

3.1 *Method for evaluating soil resistance*

It was clarified that the shaped diaphragm walls having high rigidity bend little and rotate around the bottom. Therefore, as shown in Figure 12, the displacement of any horizontal cross section in the walls can be divided into three displacement components, namely, lateral, vertical, and rotational component. So, the soil resistance is evaluated using lateral, vertical, and rotational sprigs as shown in Figure 13. In this paper, these three springs are called "ground springs" generically. In this evaluation method, the soil resistance is evaluated by the finite element method.However, if the cross section of the walls and the ground conditions change, this method needs another analysis by finite element method. So, the ground springs for the embedded part of the walls are evaluated as the following process.

1. The ground springs per unit width for the diaphragm walls with typical shaped cross section in the thin soil layer having a certain elastic modulus are evaluated by finite element method. These ground springs cover only the thin soil layer, but above and below soil layers.

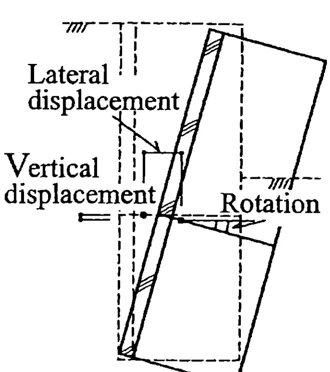


Figure 12. Displacement of shaped diaphragm walls.

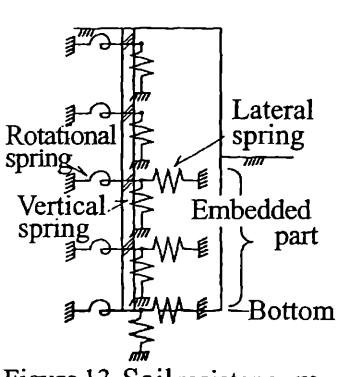


Figure 13. Soil resistance model.

2. The ground springs per unit width for the flat walls in the same condition of above 1. are evaluated by the finite element method. And the ratios of the ground springs for the shaped diaphragm walls : the ground springs for the flat walls are calculated.

3. The ground springs of optional shaped diaphragm walls in optional ground condition are evaluated as mentioned below.

At first, considering the ratio of the thin soil layer's elastic modulus (the above 1.): the optional ground's one, the ground springs of the flat walls per unit width in the optional ground condition are evaluated.Next, by using these ground springs for the flat walls and the ground spring ratio calculated in the above 2., the ground springs per width for the optional shaped diaphragm walls are evaluated.

The soil resistance on the bottom of the shaped diaphragm walls is evaluated in same way.

3.2 *Soil resistance acting on embedded part*

1. Analysis model and method. The shape and size of the diaphragm walls which are evaluated by the proposed method are shown in Figure 14 and Table 1. The length of the buttresses (D) and the interval of the buttresses (B) are varied.

As an example, the analysis model for the T-shaped diaphragm walls is shown in Figure 15 (for lateral spring) and Figure 16 (rotational spring). Both the walls and the soil are treated as elastic bodise. The soil resistance for tensile force is ignored. Therefore, in the analyses of the lateral springs, the soil in the retained side is not considered. And in the analyses of the rotational springs, film elements, namely, connecting an element surface with another one, are installed in order to prevent tensile stresses between the walls and the soil. Each directional ground spring is calculated with the forced displacement in each direction on the walls and the reaction for this forced displacement.

Besides, as mentioned above, the shaped diaphragm walls rotate around the bottom of the walls. Therefore, the vertical displacement of the walls is small, the vertical resistance of the soil affects the behavior of the walls little. So, the evaluation of the vertical spring is not shown here.

2. Analysis result. The relationships between the ground spring and the length of the buttresses (D), and the relationships between the ground springs and the interval of the buttresses (B) are shown in Figure 17 (lateral spring) and Figure 18 (rotational spring). In those Figures (a), making D longer hardens the ground springs of every shaped diaphragm walls. And making D (4m) longer by 3 times (12m) hardens the lateral springs by only 1.2 times, but the rotational springs by about 10 times. According to the above, making D longer is effective for increasing the rotational resistance.

In Figures 17 (b), 18 (b), widening B, the ground springs tend to soften except the T-shaped diaphragm walls. However, widening B from 6m to 12m, the amount of softening is only 10%, and the soil resistance does not decrease so much.

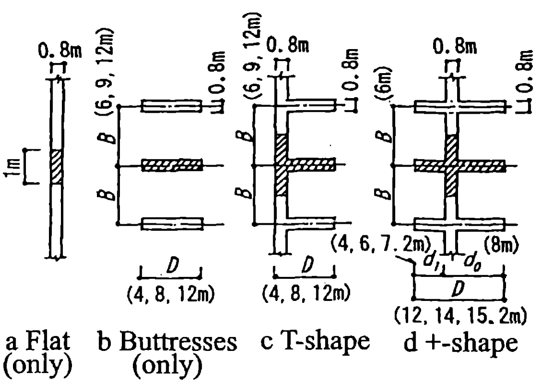


Figure 14. Cross section shape of evaluated diaphragm walls.

Table 1. Size of evaluated diaphragm walls.

Walls shape	Length of buttresses D (m)	Interval of buttresses B (m)
Flat(only)	-	-
Buttresses (only)	8	6,9,12
	4,(8),12	6
T - shape	The same as buttresses	
+ - shape	12,14,15.2 (d_0=8,d_1=4,6,7.2)	6

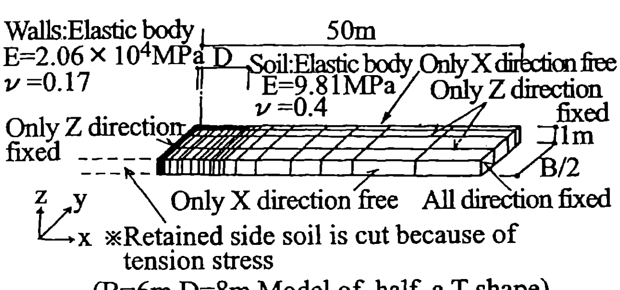


Figure 15. Analysis model for lateral spring of walls embedded part.

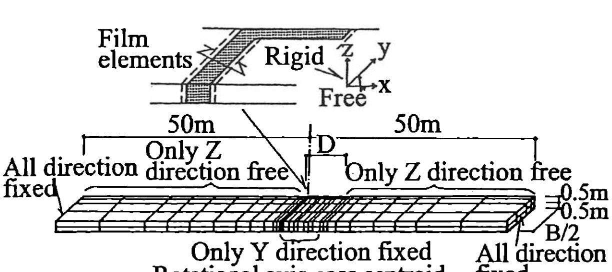


Figure 16. Analysis model for rotational spring of walls embedded part.

3.3 *Soil resistance acting on bottom*

1. Analysis model and method. The shape and size of the diaphragm walls which are evaluated are same as the embedded part of the walls (Figure 14 and Table 1).

As an example, the analysis model for T-shaped diaphragm walls is shown in Figure 19. This model presents the following condition. The shaped diaphragm walls are embedded in the hard layer. Other layers above this hard layer are soft enough to be ignored in evaluating the soil resistance on the walls bottom. Each directional ground spring is calculated with the forced displacement in each

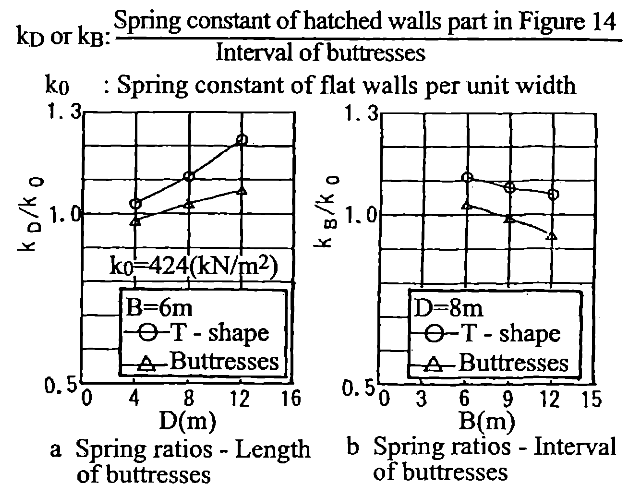


Figure 17. Lateral spring of embedded part.

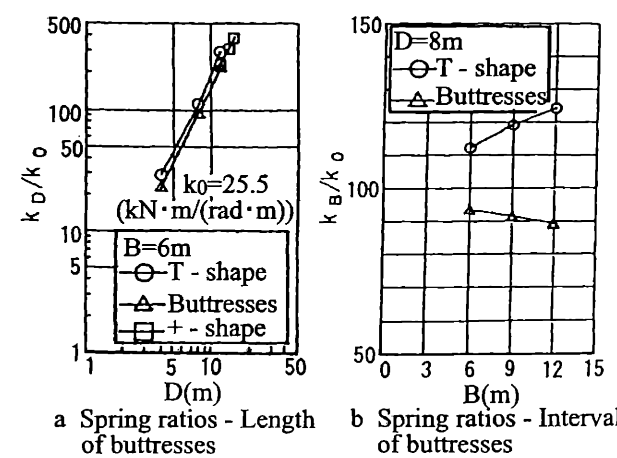


Figure 18. Rotational spring of embedded part.

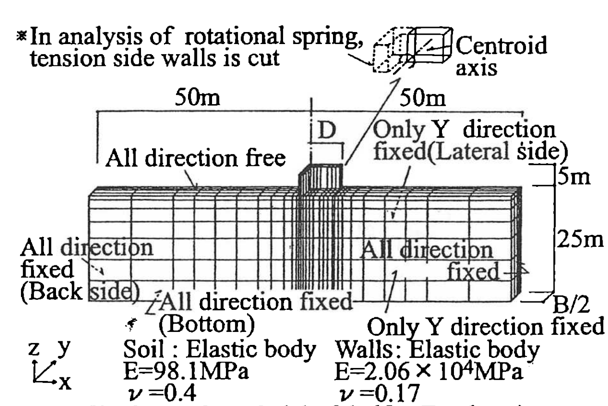
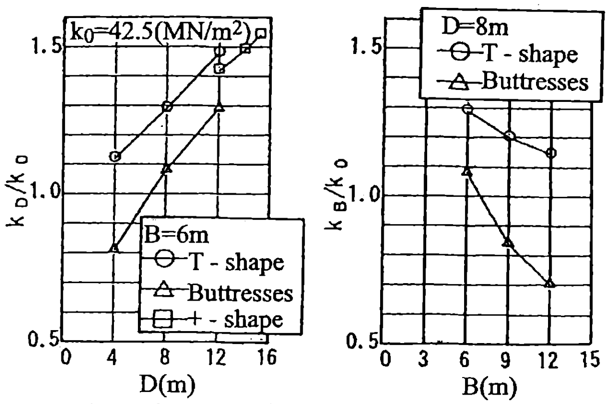
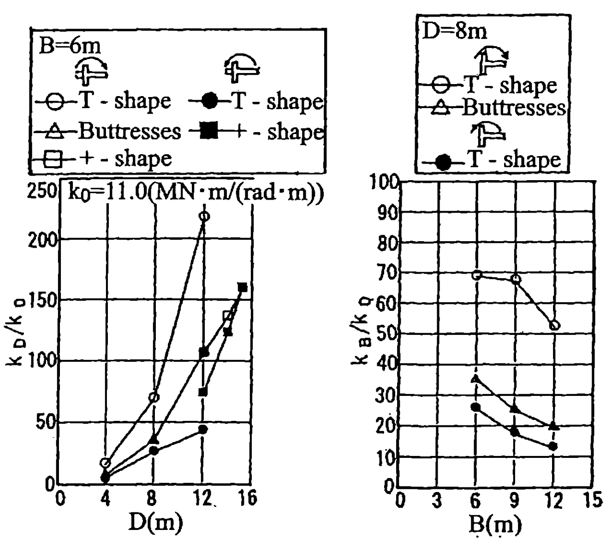


Figure 19. Analysis model for soil spring of walls bottom.



a Spring ratios - Length of buttresses
b Spring ratios - Interval of buttresses

Figure 20. Lateral spring of bottom.



a Spring ratios - Length of buttresses
b Spring ratios - Interval of buttresses

Figure 21. Rotational spring of bottom.

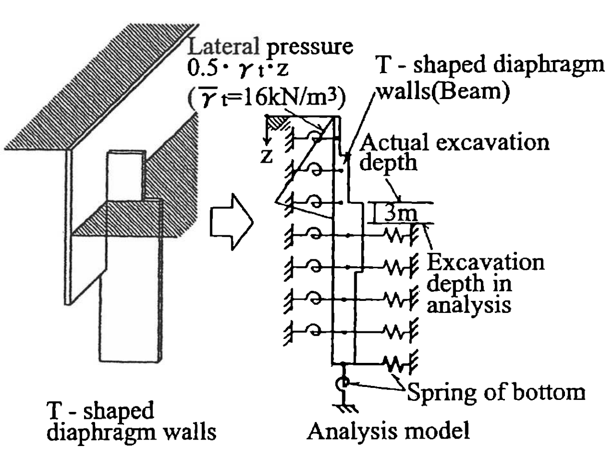


Figure 22. Beam - spring model.

direction on the walls and the reaction for this forced displacement. In evaluating the rotational spring, the soil tensile resistance acting on the wall bottom is ignored.

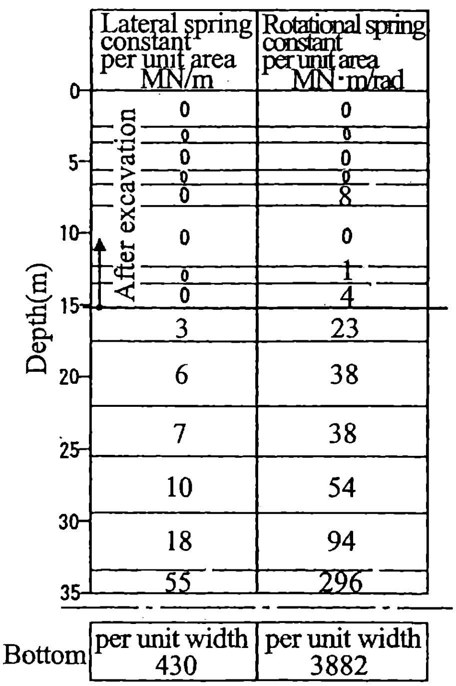


Figure 23. Soil spring constant for beam - spring model.

2. Analysis result. The same Figures as the embedded part of the walls are shown in Figures 20, 21. In those Figure (a), making D longer hardens the ground springs of every shaped diaphragm walls. And making D (4m) longer by 3 times (12m) hardens the lateral springs by only 1.5 times, but the rotational spring by about 10 times in the minimum case. According to the above, making D longer is effective for increasing the rotational resistance.

In Figures 20 (b), 21 (b), widening B, the ground springs tend to soften.

4 SIMULATION OF BEHAVIOR

4.1 *Analysis model and method*

Simulations of the measured behavior of the T-shaped diaphragm walls shown in section 2 have been conducted. The model for these simulations is shown in Figure 22. The T-shaped diaphragm walls is treated as an elastic beam. The soil resistance is presented by the lateral and the rotational springs. The constants of these springs shown in Figure 23 are obtained by the proposed method. The lateral pressure used is shown in Figure 22. The coefficient of lateral pressure is adopted as 0.5 according to the measured result.

4.2 *Comparison analysis result with behavior*

The calculated values are compared with the measured deformations and bending moments in Figure 24. Both calculated values fit well the measured values. Therefore, the proposed method is effective for evaluating the soil resistance which supports the shaped diaphragm walls.

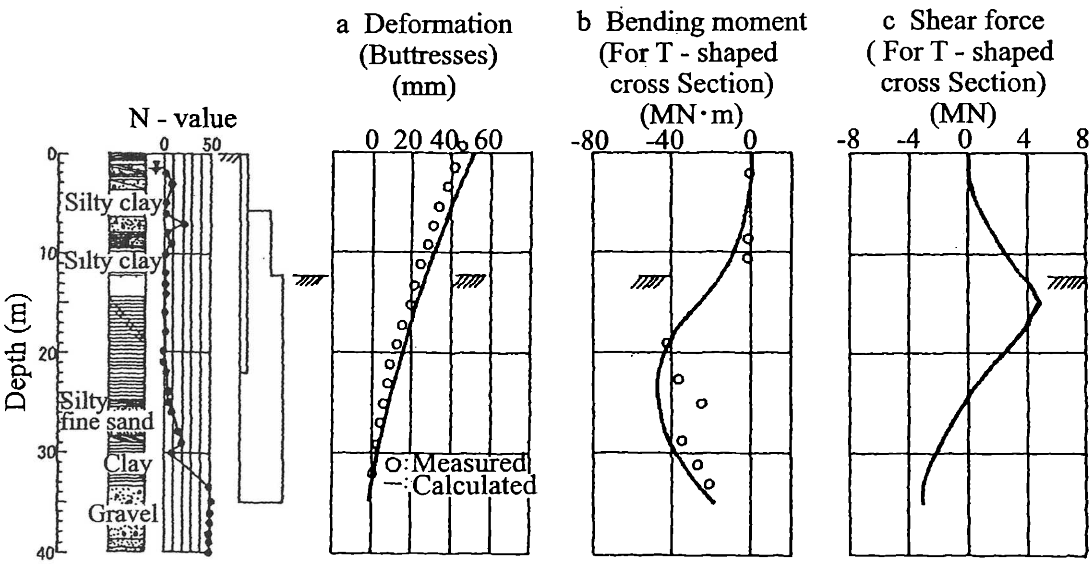


Figure 24. Comparison calculated values with measured values(3rd excavation).

5 CONCLUSIONS

This paper clarifies the characteristic behavior of the diaphragm walls with T-shaped cross section and compares this with the design analysis results. Next, this paper proposes the method for evaluating the soil resistance which supports the diaphragm walls with shaped cross section and demonstrates the effectiveness of the proposed method by the simulation of the measured behavior of the T-shaped diaphragm walls.

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