

EVALUATION OF HEAVING RESISTANCE FOR DEEP SHAFT USING NODULAR DIAPHRAGM WALL

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ABSTRACT: In recent years, an increasing number of plans in Japan have been proposed for large-scale railway structures to be built deep underground. To construct a large-scale railway structure, it is necessary to construct vertical shafts that serve as the starting and ending point for the shield machine during the construction as well as the air vents once it goes into operation. In such situations, it is expected that there will be an increase in the cases where the vertical shafts will be built to reach deep underground. If typical diaphragm walls were used to construct these deep shafts, the embedment depth of the diaphragm walls would have to be made substantially significant in order to control the heaving. Heaving as stated here is a phenomenon in which pressurized water contained in the permeable layer below the impermeable layer close to the bottom of the excavated ground breaks through the impermeable layer owing to the upward force of the water pressure during the excavation process, which then causes the vertical shaft to lose its stability. Using nodular diaphragm walls that have nodular part on the diaphragm walls of the deep shaft could be relied upon for the purpose of supporting the embedment depth of the diaphragm walls. In this research, the influence the nodular part resistivity was examined in resisting heaving when nodular diaphragm walls are used for the deep shaft. The experiments at gravitational and centrifuge acceleration fields were conducted, and their effectiveness were confirmed.

Keywords: Deep Shaft, Heaving Resistance, Nodular Diaphragm Wall, Model Test

1. INTRODUCTION

In recent years, an increasing number of plans have been proposed for large-scale railway structures to be built deep underground. To construct a large-scale railway structure, it is necessary to construct vertical shafts that serve as the starting and ending point for the shield machine during the construction as well as the air vents once it goes into operation. In such situations, it is expected that there will be an increase in the cases where the vertical shafts will be built to reach deep underground. When typical diaphragm walls were used to construct these deep shafts, the embedment depth of the diaphragm walls would have to be made substantially significant in order to control the heaving. Heaving as stated here is a phenomenon in which pressurized water contained in the permeable layer below the impermeable layer close to the bottom of the excavated ground breaks through the impermeable layer owing to the upward force of the water pressure (uplift force) during the excavation process, which then causes the vertical shaft to lose its stability.

There are two methods to construct deep shafts: the pneumatic caisson construction method and the diaphragm wall construction method. The pneumatic caisson construction method has demonstrated to reach a maximum depth of

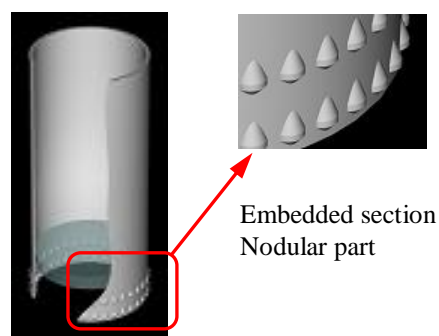


Fig. 1 Schematic View of Nodular Diaphragm Wall

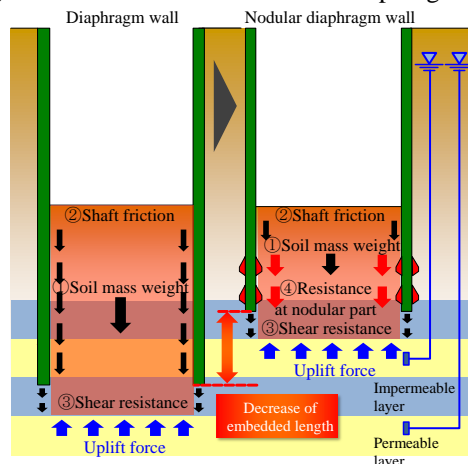


Fig. 2 Effect of Nodular Diaphragm Wall

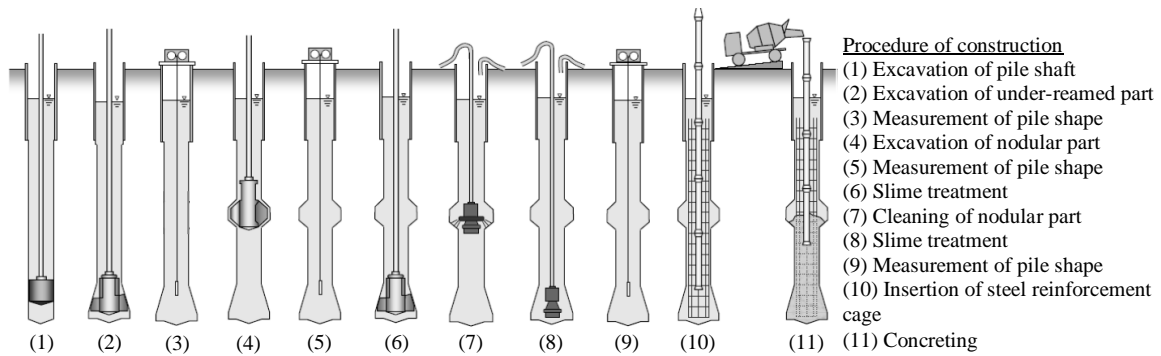


Fig. 3 Construction procedure of cast-in-place concrete pile

approximately 40 to 50m^[1], and as there is a need to highly pressurize the air during construction, there are challenges in applying this method to deep underground construction. On the other hand, the diaphragm wall construction method has shown it can reach a maximum depth of approximately 100 to 120m^{[2], [3]}, but concerning construction deep underground, as some have pointed out, there are chances of pouring deficiencies of concrete due to, for example, the tremie pipes clogging^[2]. Therefore, for this method, it is necessary to make the embedment depth as shallow as possible. Using nodular diaphragm walls that have nodules on the diaphragm walls of the deep shaft, as seen in Fig. 2), could be relied upon for the purpose of supporting the embedment depth of the diaphragm walls (Fig. 2). The nodules of the nodular diaphragm walls are expressively able to bear the pressure and thus possess greater resistance than normal diaphragm walls⁴⁾. In the construction of nodular diaphragm walls, a construction method that expands the mid-section of the diaphragm wall is used in order to create its nodular part. The above-mentioned construction methodology was developed by the Obayashi Corporation and has already been utilized in the field in a few construction projects such as architecture field^{[4], [5]}.

In this research, the influence the nodular part resistivity was examined in resisting heaving when nodular diaphragm walls are used for the deep shaft. The experiments at gravitational and centrifuge acceleration fields were conducted, and their effectiveness of heaving resistance were confirmed. This paper reports the results of the model experiment subjected to gravitational and centrifuge acceleration fields.

2. NODULAR DIAPHRAGM WALL

Figure 3 shows the construction process of the nodular diaphragm wall construction methodology. First, use the diaphragm wall construction method to excavate the trench, and then excavate the bottom of the trench to enlarge. Next, use a specialized bucket for the nodular section to

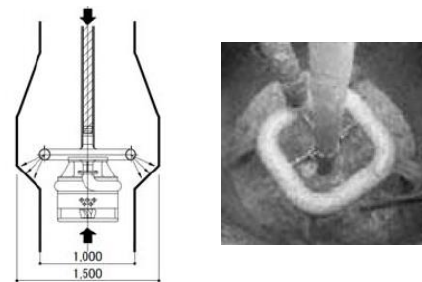


Fig. 4 Slime Cleaner for Nodular Part

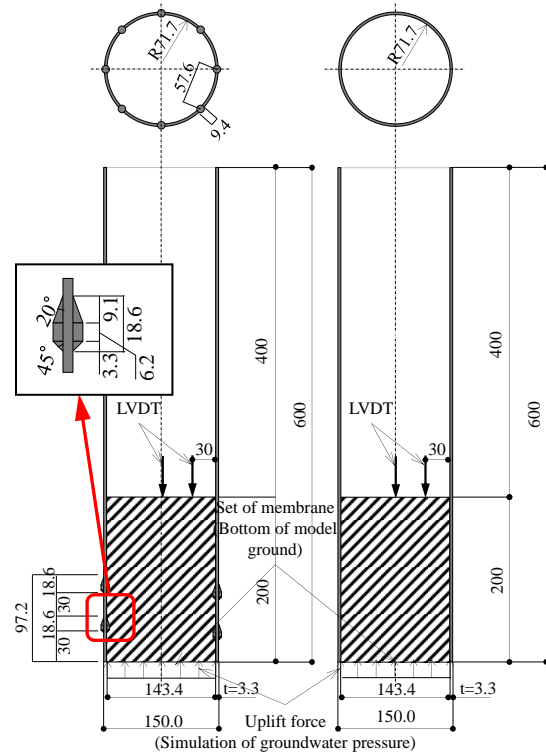


Fig. 5 Shaft Model for Uplift Experiment at Gravitational Acceleration Field

excavate the nodular section. After the excavation, the nodular part and the pile tips are treated for slime and the slurry in the cavity is replaced with good fluids. For the slime treatment of the knuckles, specialized slime cleaner designed for the nodules is used as seen in Fig. 4. After that, a steel reinforcement cage is inserted and set up

inside the tremie pipe to pour concrete. The shape of the nodular part is verified by the use of ultrasound measuring equipment. For the construction experiment conducted here, the result of the ultrasound was compared to the actual measurements of the part that was dug up, and it was verified that the nodular part were indeed in the specified shape⁴.

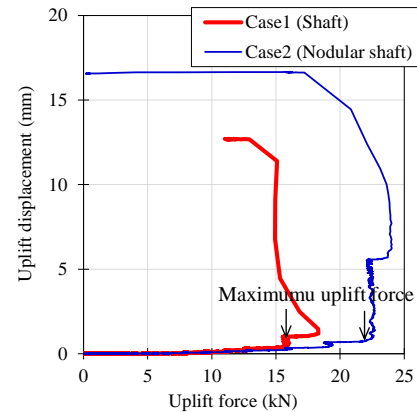
3. UPLIFT FORCE EXPERIMENT AT GRAVITATIONAL FIELD

3.1 Overview of Uplift Force Experiment

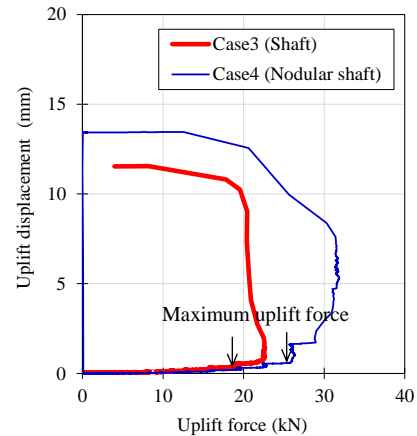
The uplift force experiment at a gravitational field was conducted to verify the heaving resistance of the regular and nodular diaphragm walls. As seen in Fig. 5, two models- one shaped with no nodular part (diaphragm wall model) and one shaped with nodular part (nodular diaphragm wall model) – were used in this experiment. A 200mm thick foundational ground layer was created in a 600mm deep cylindrical model. Additionally, the insides of the models were coated with silica sand No. 7 (0.3~0.08mm) to create roughness. The ground was created in the model had a solution injection layer and modified concrete ground layer to set up the experimental condition as stated in Table 1. It should be noted that the undrained shear strength in the Table 1 shows the actual strength during the experiment. The chemical grouting soil layer (Cases 1 and 2) was created by mixing soluble glass type chemical grouting to the silica sand No. 7. The target strength for the solution injection layer for the undrained shear strength was $c=100\text{kN/m}^2$. Additionally, the cemented improvement ground layer (Cases 3 to 6) was created by mixing, silica sand No. 7 and blast furnace slag cement type B. The two target strengths for the undrained shear strength were $c=300$ and 500kN/m^2 . The mix for the chemical grouting soil layer and the cemented improvement ground layer were determined through mixing experiments prior to this stage of the experiment. Furthermore, prior to the uplift force experiment, the same materials from the same batch were used that were used to create the ground layer of the models to perform the unconfined compression test to verify they were reaching the specified strength. For the uplift force experiment, the heaving behavior by incrementally applying the uplift force from the bottom of the improvement soil layer was verified. This uplift force mimics the upward water pressure from the pressurized water in the permeable layer below the impermeable layer. For this process, a membrane to simulate the impermeable layer was installed when activating the uplift force. By doing so, the destruction of the ground layer through seepage as

Table 1 Experiment Condition for Uplift Experiment at Gravitational Acceleration Field

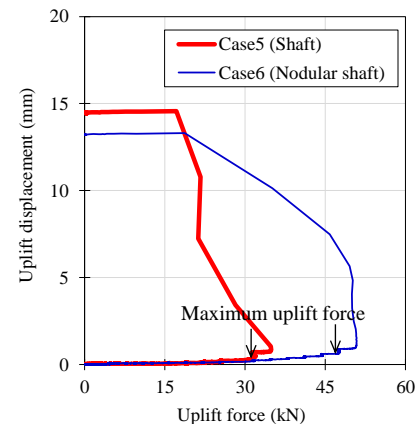
	Undrained shea strength c (kN/m ²)	Model shaft
Case 1	105	Diaphragm wall
Case 2	(Chemical grouting)	Nodular diaphragm wall
Case 3	297	Diaphragm wall
Case 4	(Cemented improvement)	Nodular diaphragm wall
Case 5	512	Diaphragm wall
Case 6	(Cemented improvement)	Nodular diaphragm wall



(a) Case 1, Case 2 ($c=100\text{kN/m}^2$)



(b) Case 3, Case 4 ($c=300\text{kN/m}^2$)



(c) Case 5, Case 6 ($c=500\text{kN/m}^2$)

Fig. 6 Relationships between Uplift Displacement and Uplift Force

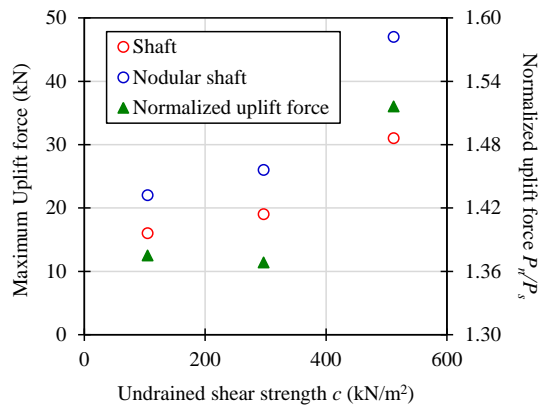


Fig. 7 Relationships between Maximum Uplift Force, Normalized Maximum Uplift Force and Undrained Shear Strength

well as water filling the interface between the ground and the model was prevented. Measurement items were the uplift displacement on the surface of the ground and the uplift force. The uplift displacement is measured by checking two-points in the radial direction (the center of the ground surface and 30mm from the wall) in order to see the distribution on the flat surface.

3.2 Results of Uplift Force Experiment

Figure 6 shows the relationship between uplift displacement and uplift force obtained through the study of each case. In these cases, two measurement points were used on the topside of the ground to measure uplift displacement, but the differences in the displacement amount were not that different from one another in each case; therefore, they were organized as the average displacement between two points. According to Fig. 6, there is a tendency for the uplift displacement to increase gradually as the uplift force increases. Especially in the case of the diaphragm wall model (no nodular part) which are represented with the red lines, it is seen that the element of resistance against heaving is the peripheral friction between the surfaces where the ground is up against the diaphragm wall model, it is said that once the peripheral friction is triggered, the uplift displacement increases. On the other hand, if the figure is looked upon at the blue line representing the nodular diaphragm walls in each of the figures, since the peripheral friction and nodular resistance is activated, it can be said that it has an improved performance in withstanding heaving. When the uplift force is further increased, then a much greater increase is seen in uplift displacement. This seems to be because the resistivity (bearing resistance) of the nodular diaphragm wall's resistance element against

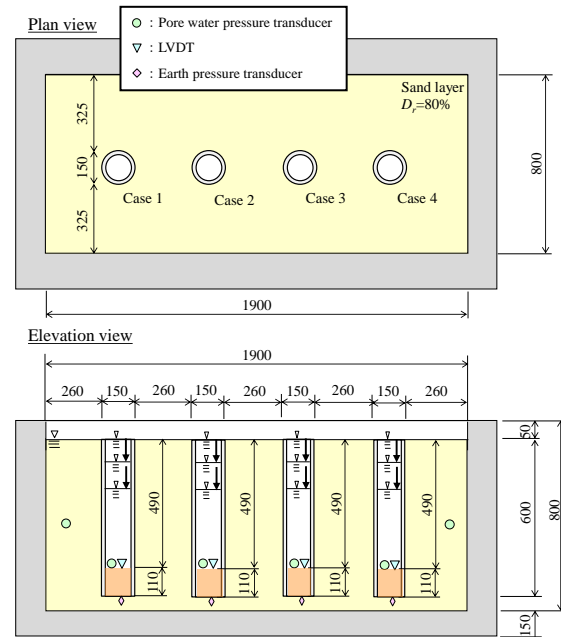


Fig. 8 Summary of Centrifuge Model Test

Table 2 Experiment Condition for Centrifuge Model Tests

	Model shaft	Strength of model ground c (kN/m ²)	Friction at embedded part
Case 1	Diaphragm wall	53	With friction
Case 2	Nodular diaphragm wall		
Case 3	Diaphragm wall		Without friction
Case 4	Nodular diaphragm wall		

heaving is being expressed in addition to the peripheral friction. The relationship among the maximum uplift force obtained in each of the cases, the normalized maximum uplift force, and the undrained shear strength is plotted in Fig. 7. Here, the normalized maximum uplift force for each case is calculated by dividing the diaphragm wall model's maximum uplift force, P_s , by the nodular diaphragm wall model's maximum uplift force, P_n . It is seen from Fig. 7 that the maximum uplift force increases as the undrained shear strength increases. This tendency is repeated in the diaphragm wall model and the model of the nodular diaphragm wall. From the normalized maximum strength in the Fig. 7, it is seen that each of the undrained shear strengths show a value of approximately 1.37 to 1.51. From this, it can be said that when nodular diaphragm walls are used, owing to the expression of the resistance of nodular part in addition to the peripheral friction, the heaving resistance becomes 30 to 50% greater.

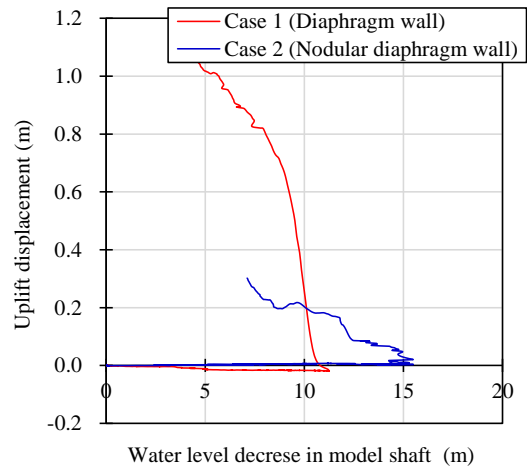
4. CENTRIFUGE MODEL TEST

4.1 Summary of Centrifuge Model Test

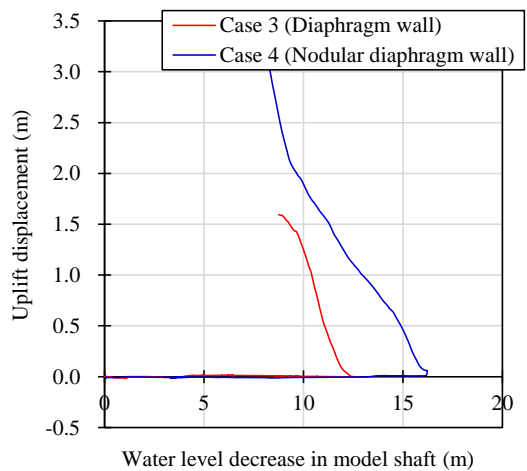
A centrifuge model test was conducted to verify the results of the nodular and the diaphragm wall's heaving resistance tested in the gravitational field. Figure 8 covers the overview of the centrifuge model test. The centrifuge model test was conducted by setting up four test pieces inside a large rigid model container (Width 1900mm x Depth 800mm x Height 800mm). The model ground was created by using silica sand No. 7 ($G_s = 2.645$) and using the air-pluviation method to achieve a relative density of $D_r = 82\%$, and then soaking the bottom side of the rigid model box in water to saturate the sand. The peripheral ground's ground water level is the same level as the ground surface. The models used in this experiment are the same two shapes as listed in Fig. 5 (diaphragm wall model and the nodular diaphragm wall model), and in a 600mm deep cylindrical model a modified ground layer that is 110mm thick layer was created. Additionally, for the cases where the friction is recreated inside, the model was coated using silica sand No. 7 to create its roughness. The cemented improvement ground placed inside the model used a mixture of silica sand No. 7 and blast furnace slag cement type B with the target of achieving undrained shear strength of $c=50\text{kN/m}^2$. The ratio to create the mixture for the modified ground was decided based on mixing experiments conducted prior to this stage of the study. Before the centrifuge model test was conducted, the same materials from the same batch that were used to create the modified ground in order to conduct the uniaxial compression test to verify when it reached the specified strength. The test was set up to first reach the predetermined centrifugal acceleration (80G) to then simulate the gradual excavation to verify the heaving behavior. To recreate the gradual excavation, the salt water (specific gravity of 1.05) was gradually drained that was covering the cemented improvement ground in the model. The measurement item were the uplift displacement on the surface of the cemented improvement ground, the decrease in the salt water's water level over the cemented improvement ground, and the water pressure of the cemented improvement ground. The experiment condition is shown in Table 2. The ground strength stated in Table 2 is the actual strength at the time of the test.

4.2 Results of Centrifuge Model Test

Figure 9 shows the relationship between the uplift displacement and the decrease in the water level. The uplift displacement measured here is the amount of displacement that was measured at the



(a) Case 1, Case 2 (With friction)



(a) Case 3, Case 4 (Without friction)

Fig. 9 Relationships between Uplift Displacement and Decrease of Water Surface in Shaft

center of the modified ground. Furthermore, both the uplift displacement and the drop in the water level are organized based on the real-life scale calculated by multiplying with the magnification of the centrifugal acceleration (80G). According to Fig. 9, no significant differences are seen in the diaphragm wall or the nodular diaphragm wall in their uplift displacement even when the water level starts to drop. However, there is a sudden increase in the uplift displacement once the water level drops between 10 and 13m. On the other hand, with the nodular diaphragm wall, an increase in uplift displacement is seen once the water level drops by 15 to 16m. From this phenomenon, it can be said that in the diaphragm wall model, the resistive element against the heaving behavior is only the cemented improvement ground self-weight and the peripheral friction between the cemented improvement ground and the diaphragm wall model, the uplift displacement occurred at a

relatively less significant drop in the water level compared to the nodular diaphragm wall. On the other hand, when it comes to the nodular diaphragm wall, it is said that since there was an additional element of resistance against heaving in the form of nodular part, heaving occurred only after the drop in the water level became significant. For this examination, it was only used the inside of the model's cemented improvement ground and considered the existence or the lack of friction in between the model's boundary surfaces as the parameter. It is said that the influence of the boundary surface's friction, or lack thereof, between the cemented improvement ground and the model have on heaving resistance is small.

5. CONCLUSION

The modeled experiments to examine the heaving resistance of nodular diaphragm walls to determine their suitability to be used as the deep shafts for railway structures were conducted. The following findings are obtained from this study:

1) Through the uplift force experiment at the gravitational field is confirmed that when the nodular diaphragm walls are used for the vertical shafts, there would be an increase in the heaving resistance due to the resistance of nodular part in addition to the peripheral friction.

2) It is concluded that in the centrifuge model test, which reproduces the full-scale stress and strain fields, that the vertical shafts using the nodular diaphragm walls had a greater heaving resistance.

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