# Static Axial Reciprocal Load Test of Cast-In-Place Nodular Concrete Pile and Nodular Diaphragm Wall

K. Watanabe[1], H. Sei[2], T. Nishiyama[1] and Y. Ishii[1]
[1]*Geotechnical Engineering Department, Technical Research Institute, Obayashi Corporation, Tokyo, Japan, Corresponding Author, E-mail*: watanabe.koji.ro@obayashi.co.jp
[2] *Technical Solution Department, Technical Research Institute, Obayashi Corporation, Tokyo, Japan*

**ABSTRACT:** In recent years, both tension force and compression force occur in foundation such as pile foundation or wall foundation due to earthquake and wind loads with increasing building height and building weight. In addition, tension loads on foundation can increase also as groundwater table rises. This trend is noticeable especially in urban central areas of Japan. From these backgrounds, it is necessary to develop new types of foundations for high-rise superstructures. New types of foundation are nodular cast-in-place concrete pile or nodular diaphragm wall with one- or two-bell shaped enlargements to increase both bearing capacity and tension resistance. The main purpose of this study is to confirm the resistance of nodular cast-in-place concrete pile and nodular diaphragm wall in clayey soils. The paper reports the investigation of construction methods of nodular cast-in-place concrete pile and nodular diaphragm wall, and the results of static axial reciprocal load tests carried out to develop the nodular cast-in-place concrete pile and nodular diaphragm wall. According to the ultrasonic measurement during the construction of piles or wall and the investigation of pile shape or wall shape after the load tests, the nodular cast-in-place concrete pile and nodular diaphragm wall were constructed as designed. As a result of load tests, the nodular cast-in-place concrete pile and nodular diaphragm wall have large tension and compression resistance. The tension resistance at the nodular part and under-reamed part shows a large value.

**Keywords:** Nodular Cast-in-place Concrete Pile, Nodular Diaphragm Wall, Reciprocal Load Test, Bearing Pressure, Clayey Soil

## INTRODUCTION

In recent years, both building height and building weight increase. This trend is noticeable especially in urban central areas of Japan. Both tension force and compression force occur in foundation such as pile foundation or wall foundation due to the overturning moment due to earthquake and wind loads. Tension loads on foundation can increase also when groundwater table rises, because buoyancy force acting on basement structure increases. From these backgrounds, it is necessary to develop new types of foundations for high-rise superstructures.

There exist little researches on nodular cast-in-place concrete pile and nodular diaphragm wall in sand and/or gravel deposits. However, there exist a little research on nodular cast-in-place concrete pile and nodular diaphragm wall constructed in clayey soils. Mohan (1961) carried out a series of load tests on under-reamed piles both in clayey and in sandy soils in Deccan Plateau, India. The test results indicate that the load-settlement behaviour is considerably improved by providing more than one bulb. This is mainly due to a substantial increase in their frictional resistance component. One additional bulb increases the bearing capacity by more than 50%. Thus, a very high pile capacity is achieved by providing a number of bulbs at suitable intervals and the main concern of the pile design is the limiting load.

Under-reamed piles for highway bridges foundations, which had knots at the pile shaft, were studied by Clisby and Mattox (1971). They confirmed increase of vertical bearing capacity in compression from field load tests, and examined the factures of under-reamed piles by excavating the constructed piles.

Akino and Kanatani (1983) carried out pull-out (tension) load tests on model under -reamed piles at 1g acceleration field. This

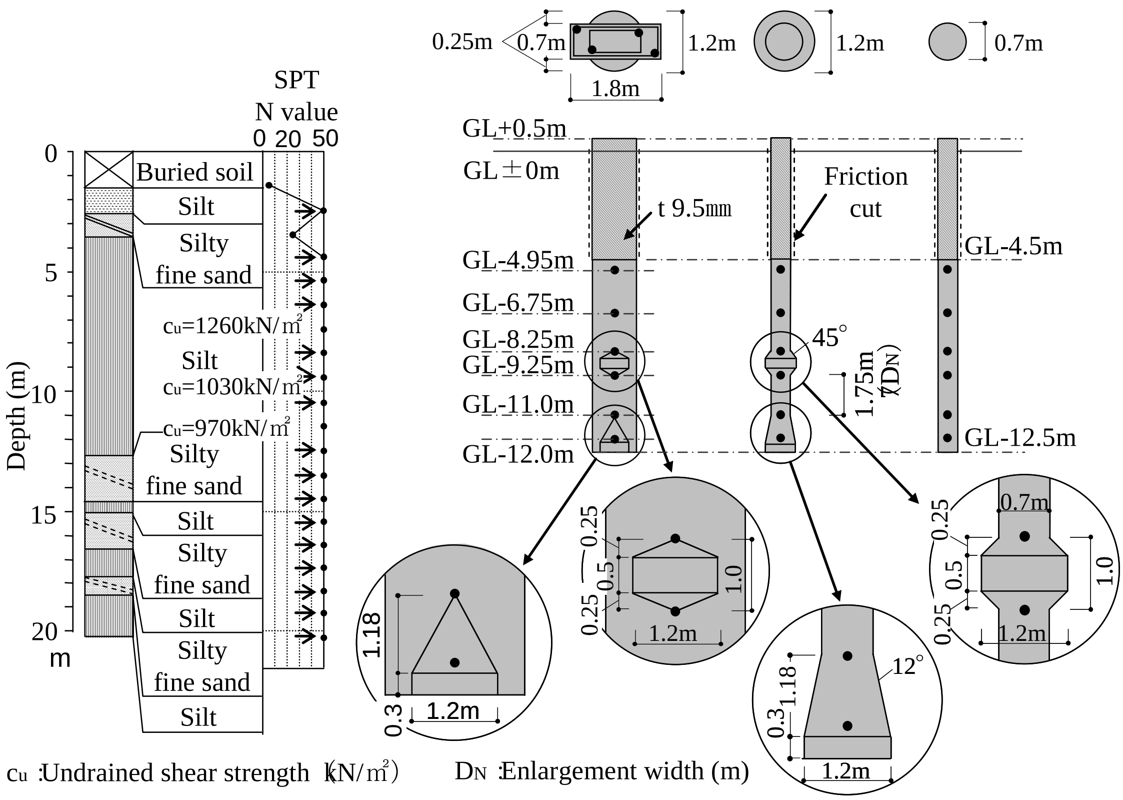



Figure 1 Soil profile and test piles

observation confirmed development of slip lines in the ground around the under-reamed part. They concluded that spherical expansion theory is applied to estimation of the tension resistance of under-reamed part.

There are several researches on cast-in-place concrete piles with one- or two-bell shaped enlargements to increase both bearing capacity and tensile resistance. Sudo et al. (2005, 2008 and 2009) carried out a series of load tests on nodular cast-in-place concrete piles and nodular diaphragm walls. They confirmed the tension and compression resistance of nodular part and under-reamed part. They concluded that tension resistance and compression resistance increase due to the existence of nodular part. Hirai and Aoki (2008) reported a series of in-situ full-scale tension load tests on cast-in-place concrete piles with one- or two-bell shaped enlargements in order to investigate the characteristics of tension resistance behaviour. The test results indicated that the uplift tension resistance of a belled pile embedded within stiff deposit is larger than that of a corresponding straight pile.

The purpose of this study is to confirm the resistance of nodular cast-in-place concrete pile and nodular diaphragm wall in clayey ground. This paper firstly describes the investigations of construction method for the nodular cast-in-place concrete pile and nodular diaphragm wall, and then presents the results of static reciprocal load tests carried out to develop the nodular cast-in-place concrete pile and nodular diaphragm wall.

## LOAD TESTS DESCRIPTION

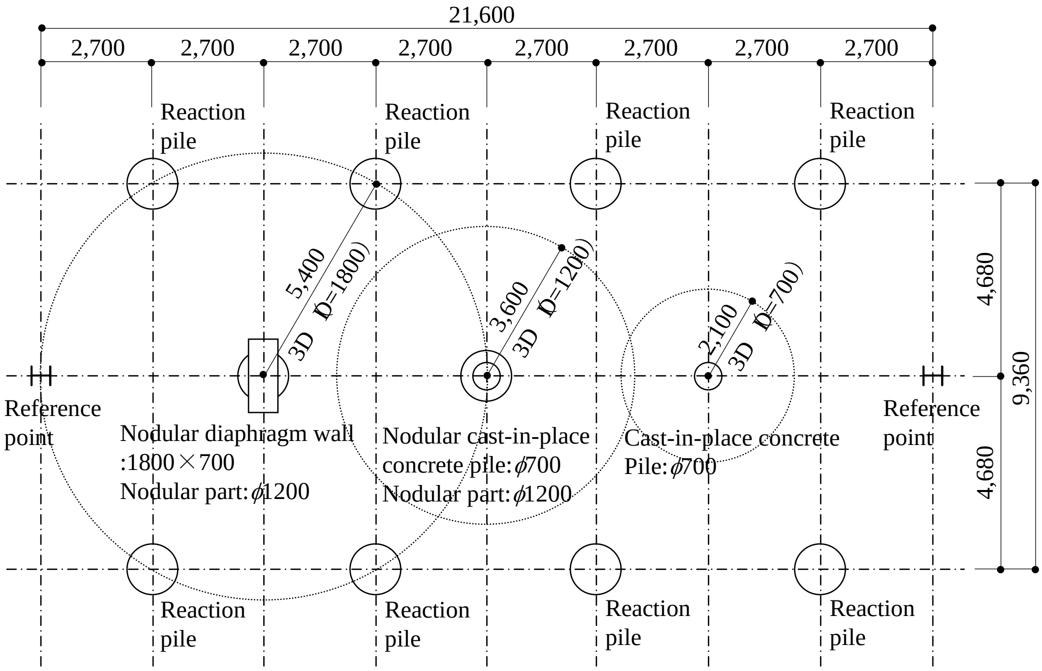



Figure 2 Arrangement of test piles and reaction piles

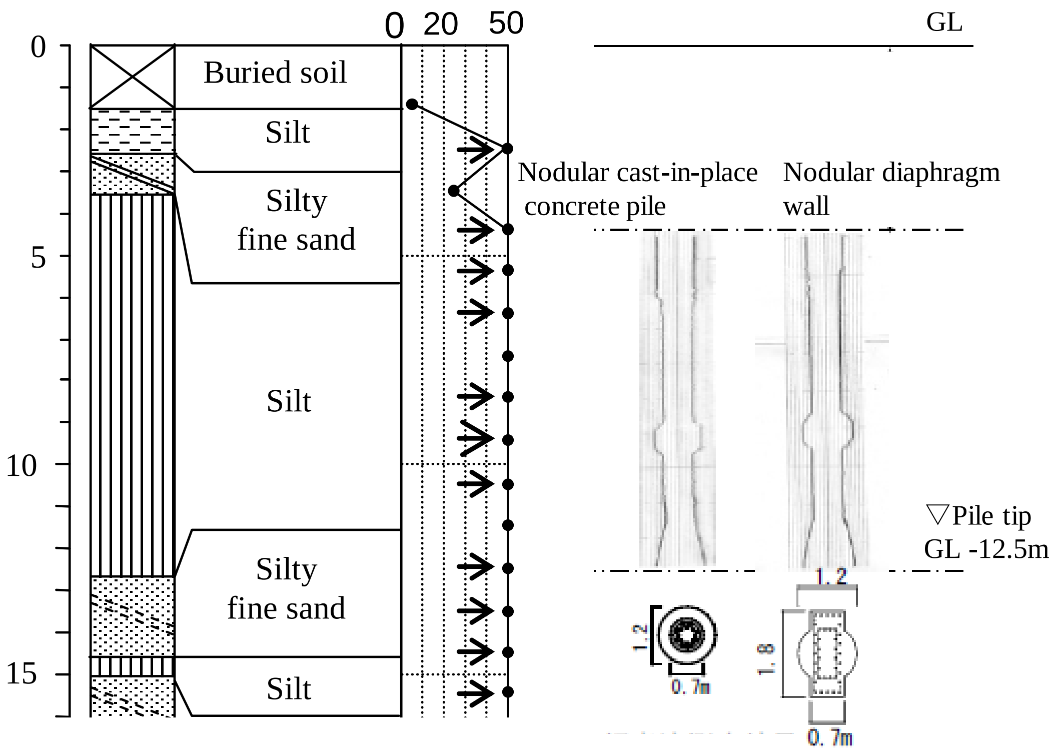



Figure 3 Results of ultrasonic measurement

The profiles of soil layers and SPT *N*-values at the test site are shown in Figure 1, together with the seating of the test piles and the test wall. Three types of test piles, 1) cast-in-place concrete pile (straight pile), 2) nodular cast-in-place concrete pile and 3) nodular diaphragm wall were constructed. The nodular cast-in-place concrete pile and the nodular diaphragm wall have not only nodular part but also under-reamed part. The reason of constructing three types of test piles was to confirm the increase of pile resistance by constructing nodular part. The test piles had a diameter of 700mm and the test wall had a cross section of 700-by-1200mm. The inclined angle of nodular parts and under-reamed parts were 45 degrees. The test nodular pile and test wall had nodular parts and under- reamed parts as shown in Figure 1 and Photo 1. The ground at the test site consisted of buried soil, hard silt and clayey sand at depths of 0 to 3.5m, consolidated silt more than SPT *N*-value of 50 at depths 3.5m to 12.5m, and silty sand and consolidated silt at depths deeper than 12.5m. The nodular parts were located at a depth of around 9m where consolidated silt having SPT *N*-value greater 50 existed, while the pile and wall base were also sat on the silty sand layer below 12.5m depth. Friction cut by a double pipe method was carried out from the ground level to a depth of 5m to examine the resistance at the embedded point of consolidated silt layer having SPT *N*-value greater 50.

Reaction beam and reaction pile system were employed to apply loads on the test piles and the test wall. Table 1 shows the maximum load in each load test. Reaction piles were constructed away from the test piles and the test wall so that centre-to-centre distance between the reaction piles and the test piles or the test wall was greater than 3 times of the diameters of the test piles or test wall, following JGS standard of vertical load test method (2002). All the load tests were carried out following JGS standard of vertical load test method (2002). Loading method was multiple cycle method with stepwise loading. Holding time for each loading step was 30 minutes for new loading steps and zero load steps and 2 minutes at repeated loading steps. Displacement and load at pile head (ground level), and strains of PC steel rods at six levels of the test piles and test wall were measured. The measured strains were used for estimating axial forces and local displacement in the test piles and test wall.

## CONSTRUCTION OF TEST PILE AND TEST WALL

The nodular cast-in-place concrete test piles and the nodular diaphragm wall were constructed by the following process;

The axial part of pile was excavated, after that the nodular part and the under-reamed part were excavated by the similar method used for constructing the under-reamed parts of cast-in-place concrete pile. Note that the underground continuous wall method was used for excavation of nodular diaphragm wall. After the excavation, installation of rebar cage and concreting were carried out.

Confirmation of the construction method and the shape of the constructed piles or wall is one of the important purposes of the load tests. So, the ultrasonic measurement was carried out with the excavation of ground, and the test piles and test wall were dug from the ground to investigate the shape of piles after the completion of the load tests.

The results of ultrasonic measurement are shown in Figure 3. According to Figure 3, the test pile and test wall were constructed as designed. There was no collapse of ground at nodular parts and under-reamed part.

Photo 1 shows the test pile and test wall dug from the ground after the load test. From Photo 1, it has been observed that there was no slime at the nodular parts and under-reamed parts, and the concrete was filled in the entire part of the pile.

Thus, it is possible to construct the nodular cast-in-place concrete pile and the nodular diaphragm wall adopting the above-mentioned construction method.

## RESULTS OF LOAD TESTS

The static axial reciprocal load tests were carried out for two types of test piles and test diaphragm wall such as cast-in-place concrete pile, nodular cast-in-place concrete pile and nodular diaphragm wall to confirm the resistance of them. The results of these load tests are described in this section.

(a) Nodular cast-in-place concrete pile

(b) Nodular diaphragm wall

Photo 1 Test piles after digging

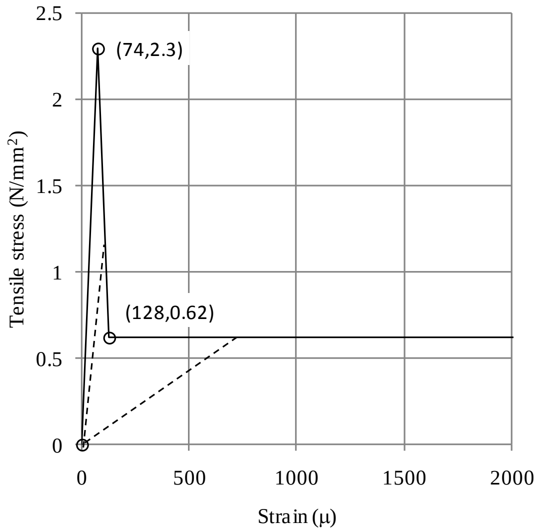
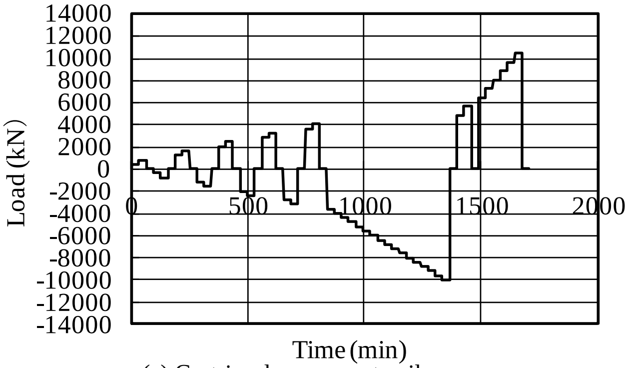



Figure 4 Relationship between tension stress and strain on concrete

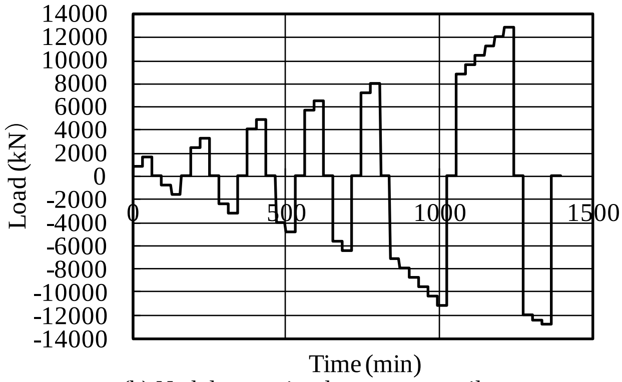
### Method for Estimating Tensile and Compressive Axial Forces

In order to estimate tensile axial forces from the measured strains of PC steel rods in the test piles and the test wall, Young's modulus and cross-sectional area of each cross-section indicated in Table 2 were used. In order to take into account non-linear stress-strain behaviour of the concrete material, the relationship between tension axial stress, $\sigma$, and tension axial strain, $\varepsilon$, shown in Figure 4 was employed. Naganuma and Yamaguchi (1990) reported the softening characteristics of concrete in tension loading. The cyclic behavior of reinforced concrete was summarized by Naganuma and Ohkubo (2000). Based on these works, the relationship between tension stress and tension axial strain of the test piles and test diaphragm wall was estimated as shown in Figure 4. The tension stress (or force) of the test piles and test wall was estimated from the measured strain using the stress-strain curves in Figure 4. The relation indicated by the solid line was used for new loading steps, while the relations indicated by the dashed lines were used for repeated loading steps. When the compressive strain is measured, Young's modulus of the concrete was estimated from the relation shown in Figure 4. Specifically, the initial gradient of the relationship between tension axial stress and tension axial strain was calculated and used as the Young's modulus for estimating the axial force in compression side.

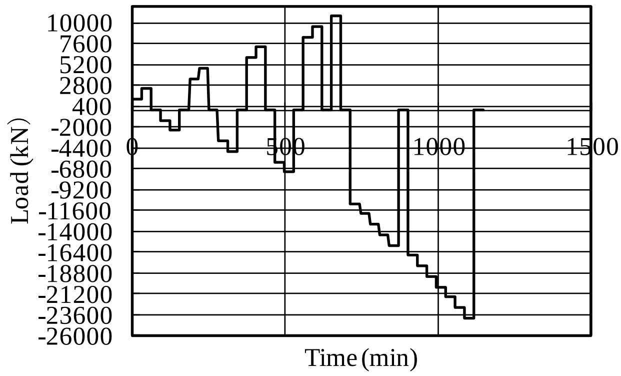
**Method for Calculating Local Displacement of Pile**




(a) Cast-in-place concrete pile




(b) Nodular cast-in-place concrete pile




(c) Nodular diaphragm wall

Figure 5 Load cycles

Table 1 Maximum load and loading step

| | Maxumum load | | Loading |
|---|---|---|---|
| | Compression load (kN) | Tension load (kN) | step (kN) |
| Cast-in-place concrete pile | 10400 | 10000 | 400 |
| Nodular cast-in-place concrete pile | 12800 | 12800 | 800 |
| Nodular diaphragm wall | 10800 | 10800 | 1200 |

Table 2 Calculation conditions

| | Elastic modulus ($N/mm^2$) | Sectional area ($mm^2$) | |
|---|---|---|---|
| | | Pile | Wall |
| Concrete | Function | $3.69 \times 10^5$ | $1.22 \times 10^6$ |
| PC steel rod | $2.12 \times 10^5$ | $1.63 \times 10^4$ | $4.07 \times 10^4$ |

In order to obtain local displacement of pile from the measured displacement at pile head and strains of PC steel rods in the test piles and test wall, the length from the measurement point of displacement (pile head) to each level of strain measurement (see

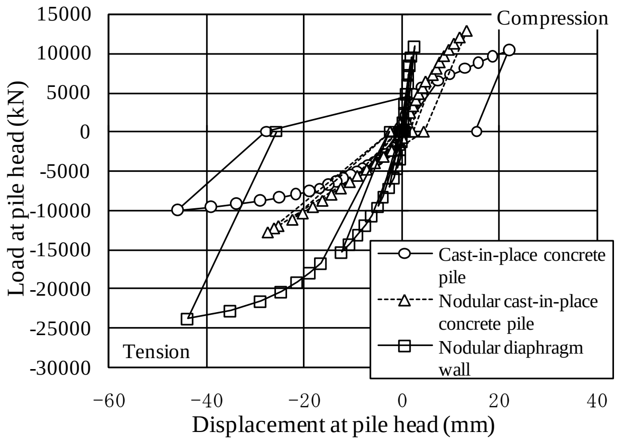



Figure 6 Relationships between load and displacement at pile head

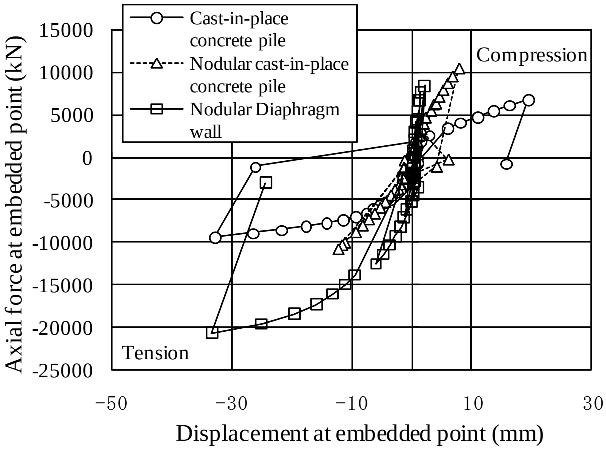



Figure 7 Relationships between axial force and displacement at embedded point

Fig. 1) was used. The displacement of each level was calculated by Eq. (1).

$$\delta_i = \delta_{at\ pile\ head} - \varepsilon_{i\ ave} * L_i \qquad (1)$$

$\delta_i$: Displacement of each level

$\delta_{at\ pile\ head}$: Displacement at pile head (measured displacement)

$\varepsilon_{i\ ave}$: Average strain of pile section from pile head to level where displacement is calculated

$L_i$: Length from pile head to the pile level

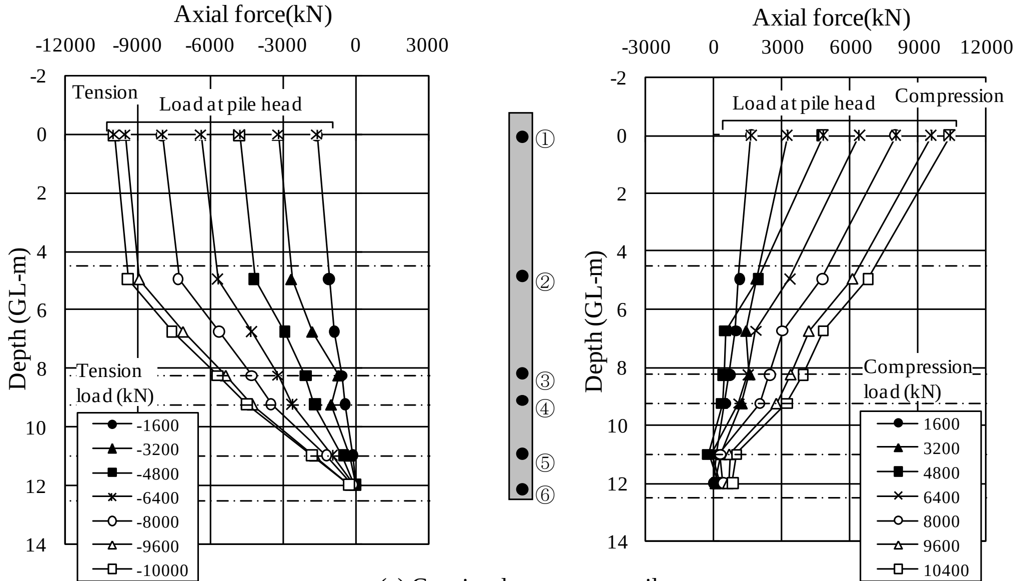
**Relationships between Tension and Compression Load and Displacement**

The loading sequence of each reciprocal load tests is shown in Figure 5. The maximum load and loading steps in each load test are summarized in Table 1.

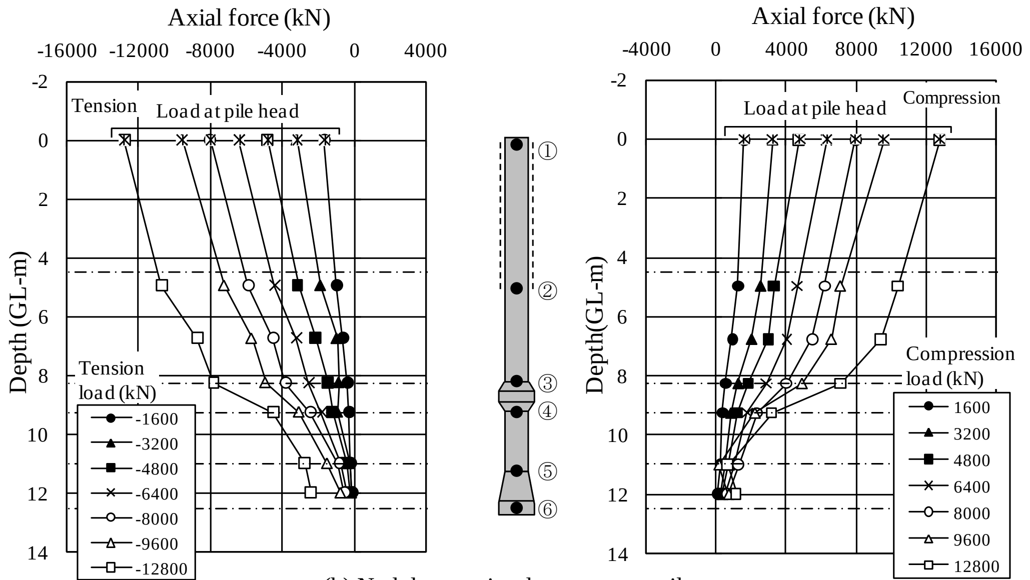
Figure 6 shows the relations of tension and compression loads at loading point and displacements at loading point measured in the three tests. Note that tension force and upward displacement are taken as negative (compression force and downward displacement as positive) in this paper. Figure 7 shows the relationships between reciprocal load and displacement at below the friction cut by the double pipe method (embedded point). It is inferred from Fig. 7 that the cast-in-place concrete pile reached the yielding and indicated the plastic behaviour in both compression side and tension side. The nodular cast-in-place concrete pile was applied 1.3 times load compared to the cast-in-place concrete pile, but the behaviour showed elastic state in the compression and tension sides. Comparing the axial forces in the cast-in-place concrete pile and that in the nodular cast-in-place concrete pile at a displacement of 10mm, the axial force of the nodular cast-in-place concrete pile is almost 1.3 times axial force of the cast-in-place concrete pile. The nodular diaphragm wall has the large resistance because the sectional area is large. A load of 14000kN was mobilised at a displacement of 10mm. It can be also seen that the stiffness in the compression side was larger than that in tension side. The reason of this phenomenon is attributed to occurrence of cracks in the wall in the tension side. The distributions of axial force are shown in Figures 8 (a) to (c).

**Distributions of Axial Force and Shaft Friction**

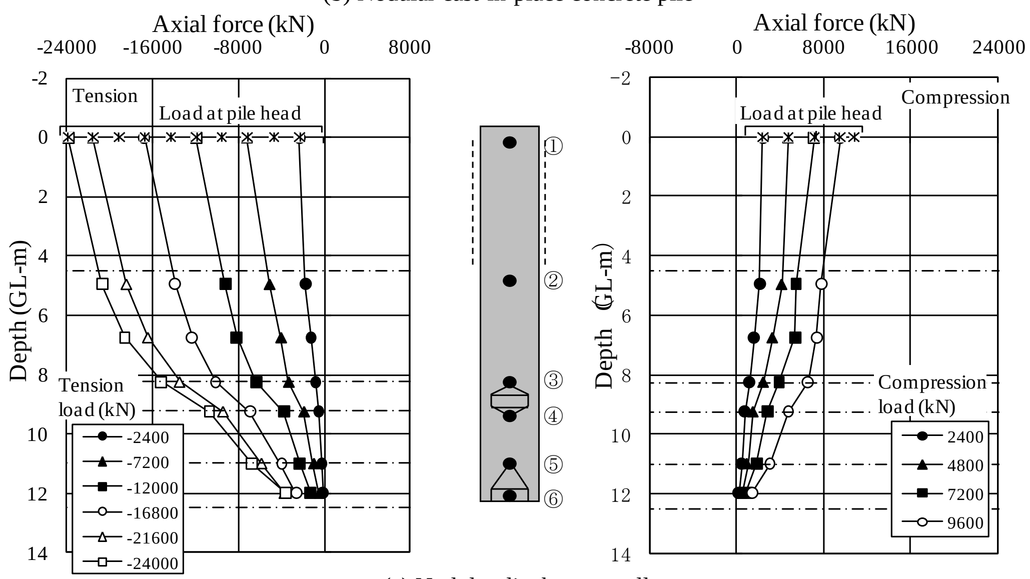
In the case of the cast-in-place concrete pile (Figure 8 (a)), the




(a) Cast-in-place concrete pile




(b) Nodular cast-in-place concrete pile




(c) Nodular diaphragm wall

Figure 8 Distributions of axial force

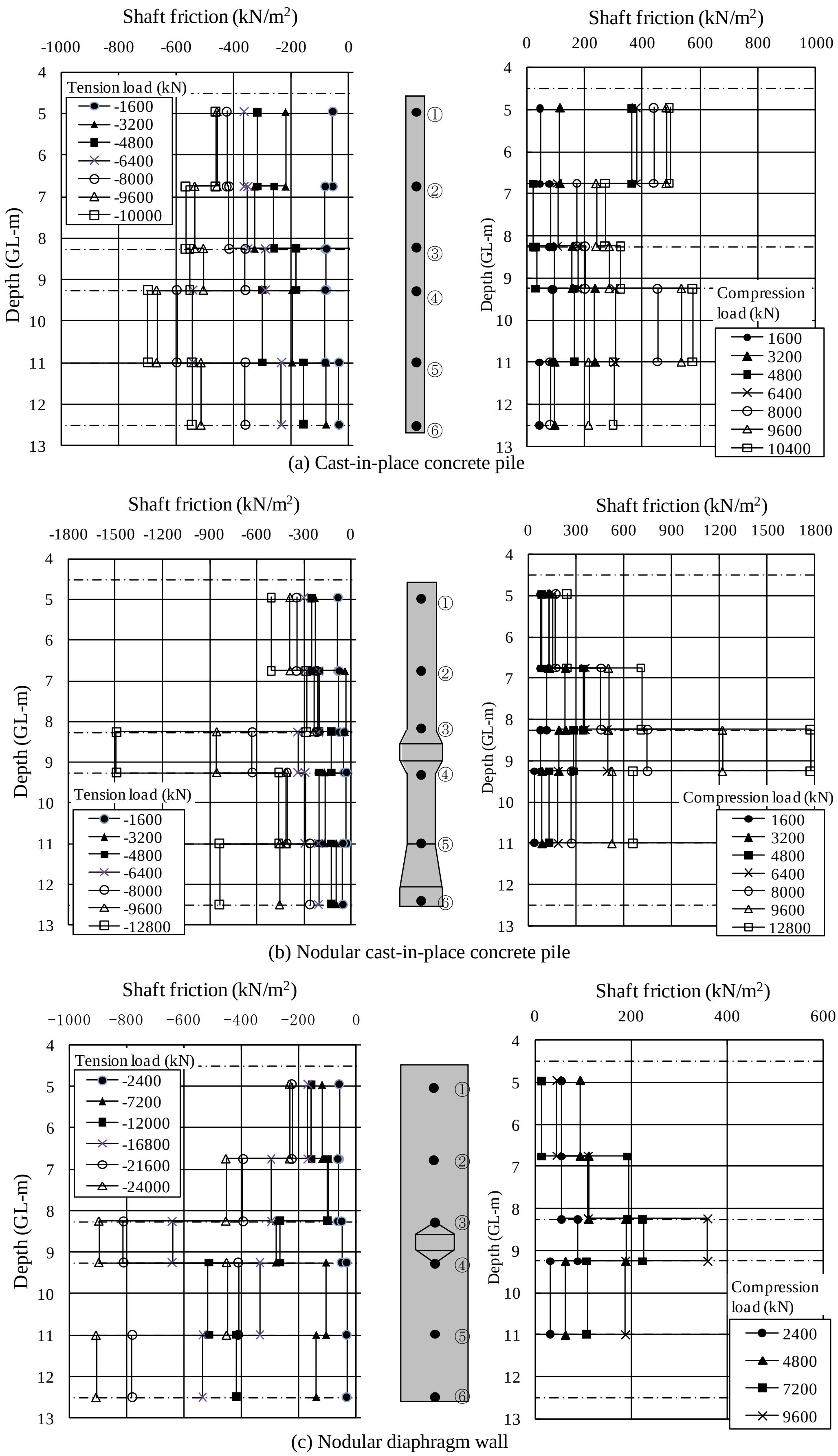
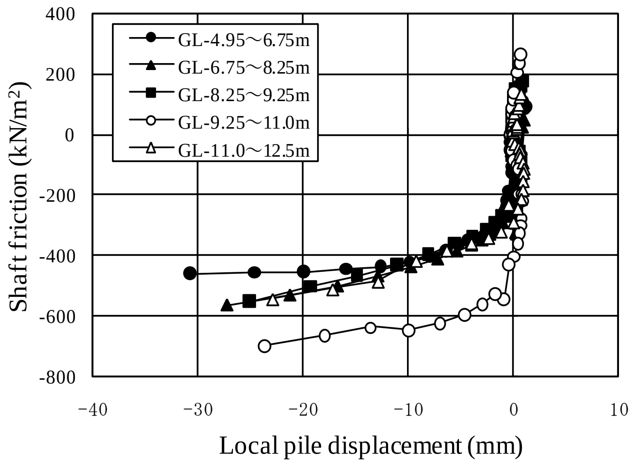


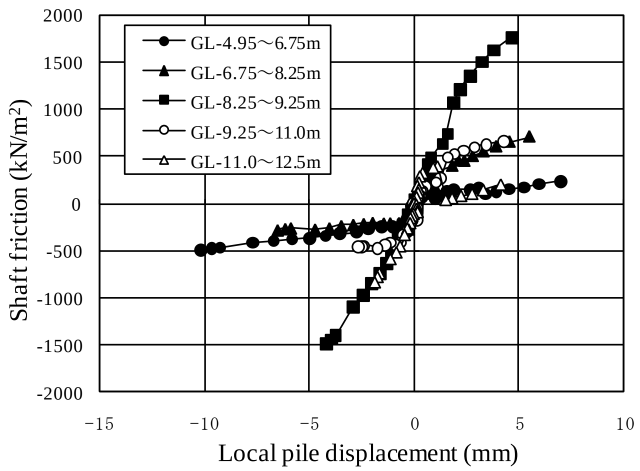

Figure 9 Distributions of axial force

amplitude of pile axial force below the tension cut decreases almost linearly with increasing depth in the compression and tension sides, indicating uniform mobilisation of shaft resistance along the embedded section below the tension cut at each loading step.

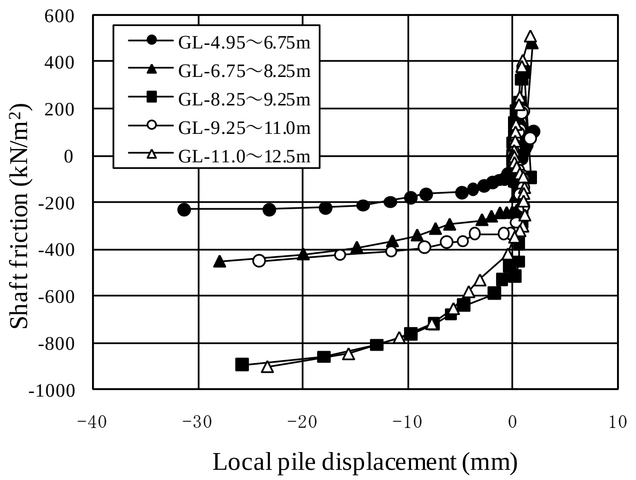
In case of the nodular cast-in-place concrete pile as shown in Figure 8 (b), the amplitude of axial force decreases with increasing




(a) Cast-in-place concrete pile



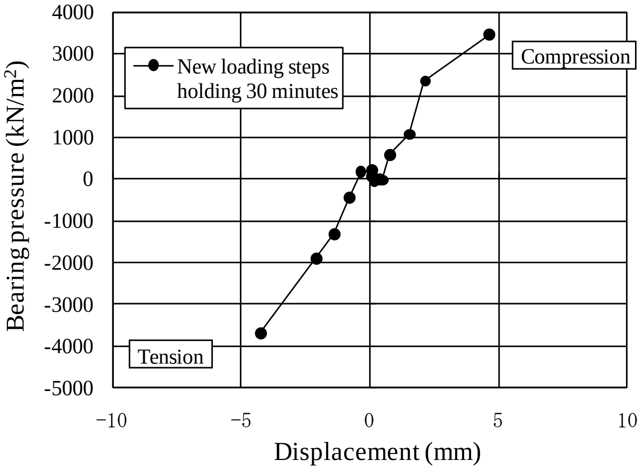

(b) Nodular cast-in-place concrete pile



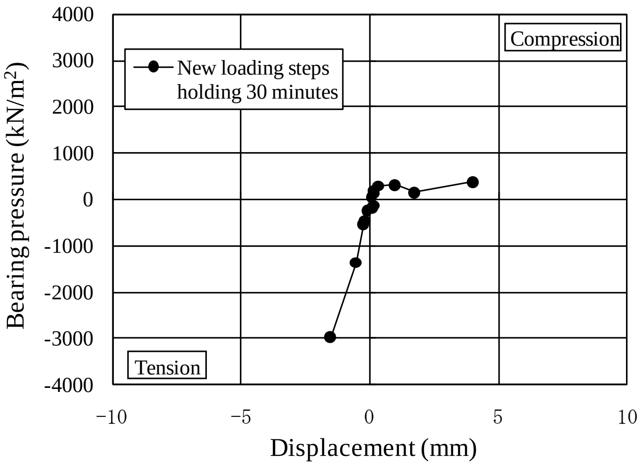

(c) Nodular diaphragm wall

Figure 10 Relationships between shaft friction and displacement

depth in both tension and compression sides. However, the rate of decrease is not constant and sudden decrease in axial force occurs at the nodular part. This trend is predominant when the amplitude of axial force becomes large. Thus, the resistance at the nodular part is much larger than that at the axial part (general part), and the resistance at the nodular part increases as the load at pile head increases. It is said that the difference of axial force at the under-reamed part is small because the load transferred to the pile tip is small. This fact implies that the soil around the under-reamed part




(a) Nodular part




(b) Enlargement part

Figure 11 Relationship between bearing pressure and displacement on nodular cast-in-place concrete pile

has a large resistance.

According to Figure 8 (c), the axial force of nodular diaphragm wall has the similar trend to the nodular cast-in-place concrete pile. The axial force decreases as the depth becomes deeper, and the rate of decrease in the axial force is large at the nodular part. It is also said that this trend dominates when the load at pile head is large. From this fact, it can be seen that the resistance of soil increases by constructing the nodular part and the resistance at the nodular part increases as the load increases. The shaft resistance exists along the section of friction cut because the friction cut by double pipe method did not work well.

Figures 9 (a) to (c) show the distributions of shaft friction. The shaft friction of each test pile and test wall section was calculated as difference of axial forces divided by the corresponding surface area. Surface area of the nodular part or under-reamed part was allowed for, if it existed.

The maximum shaft friction of cast-in-place concrete pile shows 500 to 700kN/m$^2$ in tension side and 300 to 600kN/m$^2$ in compression side, respectively. The shaft friction at the section of GL-9 to -11m is larger than that at the other section. The pile at this section expanded about 100mm from the investigation of ultrasound measurement.

The maximum shaft friction at the nodular part from Figure 9 (b) is 1800kN/m$^2$ in tension side and 1500kN/m$^2$ in compression side, respectively. The shaft friction at the under-reamed part is larger than that of the axial part (general part). Here, the shaft friction at the under-reamed part in compression was removed from the distributions of shaft friction because the friction at inclined part of under-reamed part cannot be considered. It is difficult to estimate the shaft friction at inclined part.

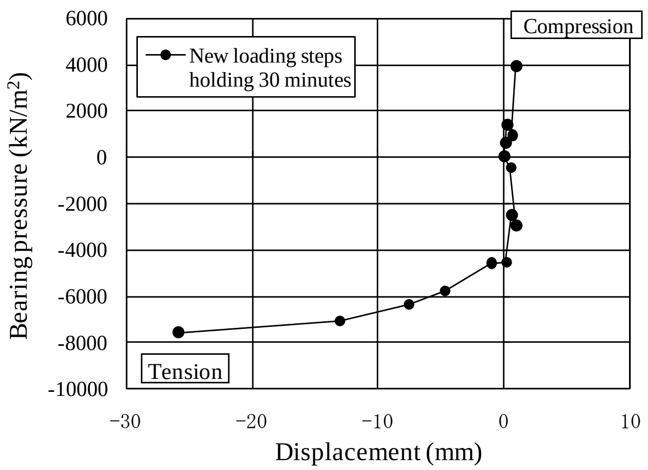
The trend similar to the nodular cast-in-place concrete pile was observed in the nodular diaphragm wall. The shaft friction at the nodular part and under-reamed part of the nodular diaphragm wall shows large value compared to the axial part. The maximum value of shaft friction at the nodular part and under-reamed part is 900kN/m$^2$ in tension side. The shaft friction is small value in compression side because the applied load is small. However, compared to the shaft friction at nodular part and that at axial part, the former part shows large value.

The relationships between the shaft friction and the local pile displacement for each section of the test piles and the test wall are summarised in Figures 10 (a) to (c). From these figures, the following findings were obtained. The shaft friction of the cast-in-place concrete pile (see Figure 10 (a)) was fully mobilised for all sections, and the shaft friction reached the ultimate state in tension side. The shaft resistance exhibited a nearly elastic-perfect plastic behaviour.

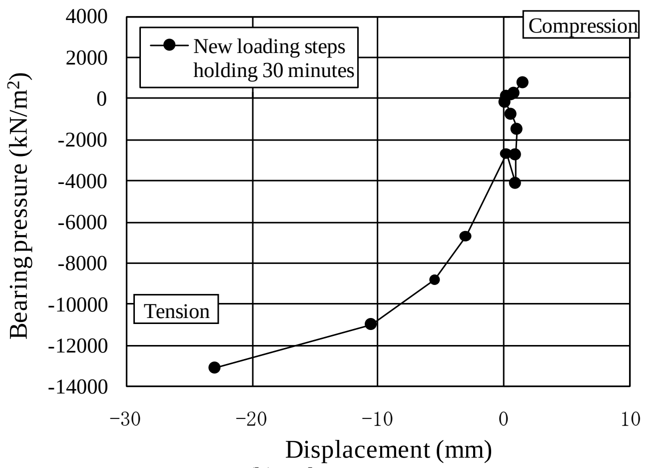
The shaft friction of the nodular cast-in-place concrete pile and nodular diaphragm wall did not reach limit values and tended to increase much more if larger tension and compression load would had been applied.

**Bearing Pressure of Nodular Part and Under-Reamed Part**

The relationships between bearing pressure and displacement of the



(a) Nodular part



(b) Enlargement part

Figure 12 Relationship between bearing pressure and displacement on nodular diaphragm wall

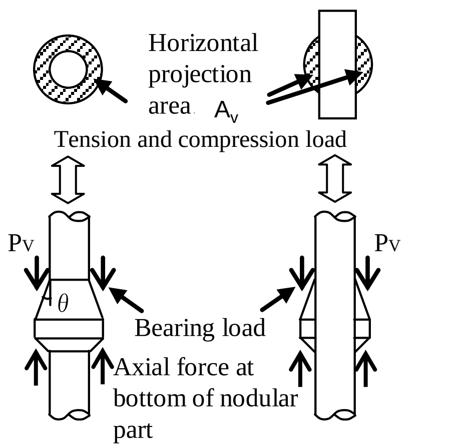
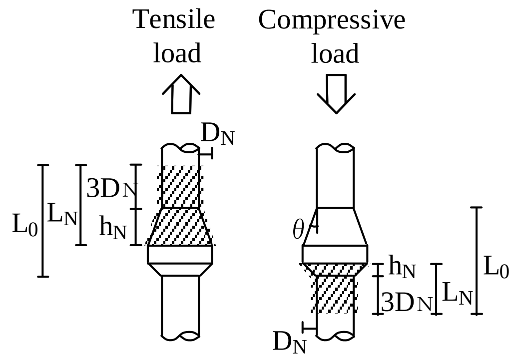
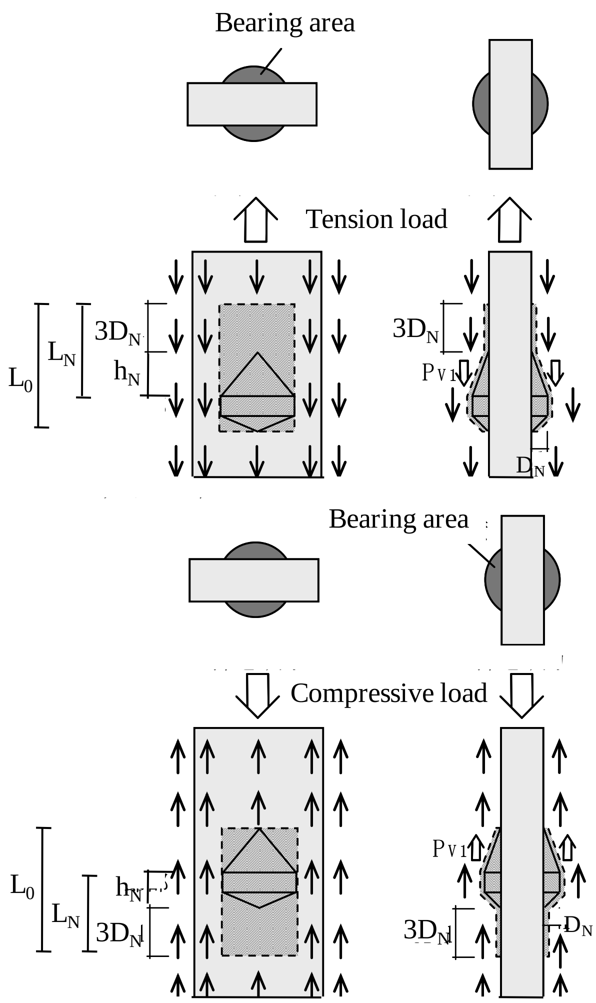



Figure 13 Projection areas of nodular part for nodular pile and nodular wall



(a) Nodular cast-in-place concrete pile



(b) Nodular diaphragm wall

$L_N$: Calculation range of average N value and undrained shear strength

$L_0$: Neglected range of shaft friction

Figure 14 Calculation area of bearing pressure nodular cast-in-place concrete pile and the nodular diaphragm wall are shown in Figures 11 and 12, respectively. Figures 11 and 12 involve bearing pressure at nodular part and that at under-reamed part.

The difference of axial force above and below the nodular part or under-reamed part is divided by the projection area (bearing area) of the nodular part or the under-reamed part as shown in Figure 13 to estimate the bearing pressure, $p_v$. Figure 14 indicates the calculation area of bearing pressure involving neglected range of the shaft friction. The hatched area in Figure 14 shows the assumed influential zone on the bearing pressure of nodular part.

From Figure 11, the bearing pressure, $p_v$, for the nodular part of the nodular cast-in-place concrete pile reached -3700kN/m$^2$ and 3400kN/m$^2$ at displacements of -4.2mm and 4.6mm in tension side and compression side, respectively, and that of under-reamed part reached -3000kN/m$^2$ and 370kN/m$^2$ at displacement of -1.5mm and 4.1mm in tension side and compression side, respectively. These bearing pressures did not reach limiting values and trended to increase when the maximum tension and compression loads were applied.

According to Figure 12, the bearing pressure, $p_v$, for the nodular part of the nodular diaphragm wall reached -7600kN/m$^2$ and 3900kN/m$^2$ at displacements of -25.9mm and 1.0mm in tension side and compression side, respectively, and that of under-reamed part are -13000kN/m$^2$ and 780kN/m$^2$ at displacement of -23.0mm and 1.6mm in tension side and compression side, respectively. These values are greater than those in the load test of the nodular cast-in-place concrete pile (Figure 11), especially for tension resistance. However, the same trend was obtained that the bearing pressure in compression side is small value. It may be concluded that as the displacement is small, the bearing pressure does not mobilise fully.

## CONCLUSIONS

The purposes of this study were to develop new types of foundations and to examine the resistance of them. The following findings were obtained.

1) The ultrasonic measurement was carried out during the excavation of ground, and the test piles and test wall after the load test were dug from the ground to investigate the shapes of the piles and the wall. From these investigations, it can be said that it is possible to construct the nodular cast-in-place concrete pile and nodular diaphragm wall by the construction method proposed in this paper.

2) Three types of test piles or wall were constructed, and the static axial reciprocal load tests were carried out to obtain the tension and compression resistance. It is found from these load tests that the nodular cast-in-place concrete pile and nodular diaphragm wall have large tension resistance. However, the compression resistance could not mobilise enough.

3) The tension and compression resistance of nodular part and under-reamed part for nodular cast-in-place concrete pile were investigated. It was confirmed that both tension and compression resistance could not fully mobilise because the displacement was not enough.

4) The tension and compression resistance of nodular part and under-reamed part for nodular diaphragm wall were also examined. It was observed that the bearing pressure at the nodular part and under-reamed part is large in tension loading.

## Notations

The following symbols were used in this paper.

$\delta_i$: Displacement at each level

$\delta_{\text{at pile head}}$: Displacement at pile head (measured displacement)

$\varepsilon_{\text{i ave}}$: Average strain of pile section from pile head to level where displacement is calculated

$L_i$: Length from pile head to the pile level

$p_v$: Bearing pressure

$L_N$: Calculation range of average SPT N-value or undrained shear strength

$L_0$: Neglected range of shaft friction

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