Bearing mechanisms of multi-node piles

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ABSTRACT

Multi-node piles are piles having multiple nodes or bulbs along their shafts. Vertical compression loading tests for model piles are carried out in order to investigate bearing mechanisms of multi-node piles. Model piles tested are multi-node piles having different numbers of nodes. Piles with straight-shaft having smooth or rough surfaces and a corrugated pile are also tested for comparison. These piles are set up in a large triaxial chamber filled with dry sand under nearly ideal non-displacement conditions. It is shown from the test results that shaft resistance of multi-node piles in sand is mainly attributed to bearing resistance of each nodal base and friction resistance of shaft below it where high normal stresses act, and that multi-node piles are more effective than straight-shaft piles with the same outer diameter.

KEY WORDS: pile, shaped pile, bearing capacity, shaft resistance, model test, sand.

INTRODUCTION

Piles having multiple nodes or bulbs have been used in some countries. Precast concrete piles called 'nodal pile', which used to be called 'Takechi pile', have been widely used in Japan for more than 60 years (Clarke and Watson, 1936). When they are driven into the ground, gravels are used as a sealing material to fill the void between the pile shaft and the ground. They can also be installed in pre-bored holes with gravel or other sealing materials as non-displacement type piles in urban areas. Cast-in-situ concrete piles called multi-underreamed piles have been extensively used for structures on Indian black cotton soils where upward movement of piles due to soil expansion is important (Mohan et al., 1969). In the field of ground anchors, multi-underreamed anchors whose shapes are similar to these piles have been used (e.g., Hunt, 1986). Therefore, multi-node piles may be effectively used for offshore structures where uplift resistance of pile is an important design factor.

In multi-node piles of the non-displacement type and multi-underreamed piles, each node works as a kind of pile base until a continuous cylindrical slip surface whose diameter is nearly equal to that of the nodes is formed. However, the resistance of the node is different from that of the pile base, which is usually modeled by a spherical cavity expansion theory (Hirayama, 1988), due to the existence of the adjacent shaft and the node below. The adjacent shaft below may prevent surrounding soil from being fully compacted, and the adjacent node causes loosening of the soil.

In order to investigate bearing mechanisms of the pile nodes, vertical compression loading tests for model multi-node piles having different numbers of nodes are carried out. Piles with straight-shaft having smooth or rough surfaces and a corrugated pile are also tested for comparison. These piles are set up in a large triaxial chamber filled with dry sand under nearly ideal non-displacement conditions. This paper summarizes the test results, and discusses fundamental bearing mechanisms of multi-node piles in sand.

TEST PILES, APPARATUS AND PROCEDURES

The shapes and dimensions of model piles are shown in **Fig. 1**. Three multi-node piles having 3, 4 and 5 nodes are tested. The four-node pile shown in **Fig. 1(a)** is a 1/4-scale model of one of the current 'GEOTOP nodal piles'. A pile which has a single node at the middle of its shaft (**Fig. 1(d)**) is also tested in order to investigate the mechanism of the node which is affected by the shaft lower and free from the effect of the node below. Straight-shafted smooth and rough piles and a corrugated pile are also tested to compare shaft resistance characteristics with those of multi-node piles.

The piles are made of stainless steel, and strain gauges are instrumented inside of each hollow shaft. They are 1000mm in length and 100mm in maximum diameter. The shaft diameter of multi-node piles (**Fig. 1(a)-(d)**) is 68.2mm. Shaft surface profile of the smooth pile (**Fig. 1(e)**) measured by a roughness gauge indicates that maximum height of asperities along a

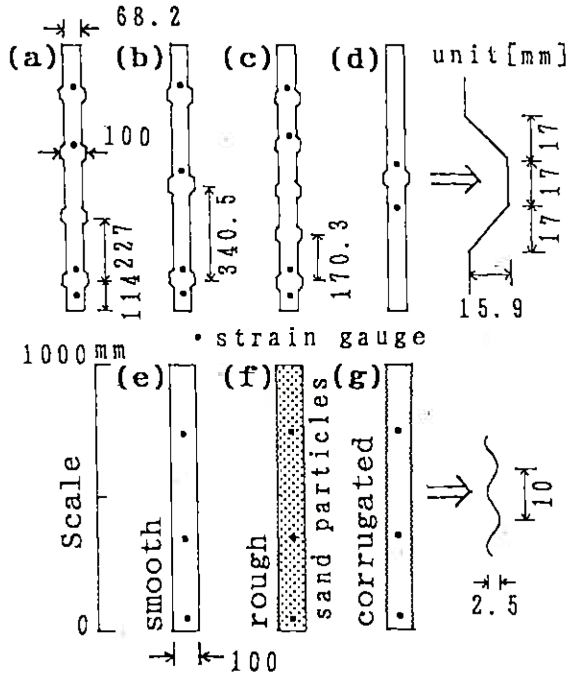


Fig. 1. Model piles tested.

reference length of 2.5mm ranges from 9 to 15 μm. Multi-node piles have the same order of asperities. The rough pile shown in **Fig. 1(f)** is roughened by pasting sand particles used in tests on the shaft surface of the smooth pile. The height and pitch of corrugations of the corrugated pile (**Fig. 1(g)**) are 2.5mm and 10mm, respectively.

Tests are carried out in a triaxial pressure chamber, 158cm of inner diameter size and 178cm in height. Air-dried quartz sand which has the following properties is used for tests:
mean grain size or 50% diameter D_{50} = 0.33mm,
effective grain size or 10% diameter D_{10} = 0.20mm,
uniformity coefficient U_c = 1.8,
maximum dry density ρ_{max} = 1597kg/m^3,
minimum dry density ρ_{min} = 1264kg/m^3.

Uniform sand layers are prepared by a sand-rain method, or a multiple sieving method (e.g., Miura and Toki, 1982). When the thickness of the layers becomes 70cm, a test pile is installed fixing its top to the chamber with a fixing device. Then preparation of sand layers is continued up to the top level of the chamber interbedding very thin coloured-sand layers to observe the behaviour of the surrounding soil when a pile is dug out after testing. After removing the fixing device, vertical and horizontal pressures are applied. Thus the pile is considered to be embedded in nearly ideal non-displacement conditions. The relative density of sand mass prepared is about 80% after compression under σ_v=98kPa and σ_h=49kPa.

Piles are loaded up to 200mm displacement. Loading is displacement-controlled with a loading speed of 1mm/min, while the initial part of loading is load-controlled. The values of σ_v (=98kPa) and σ_h (=49kPa) applied to soil mass are kept constant during each test. Two tests are carried out for each type of the piles. Test results shown in the following section are the average values of two tests.

Unit shaft skin friction or other unit resistances are calculated from the measurements of strain gauges instrumented. Strain-gauge readings are zeroed when a pile is fixed to the chamber. Before the vertical pressure is applied, the fixing device has to be removed and the reading is stopped until reconnecting electric wires. Since the strain increments measured during sand deposition are negligible, instrumentation is zeroed before applying vertical and horizontal pressures to evaluate initial residual stresses (Hanna and Tan, 1973).

Pressure sensitive paper is attached onto the shaft to evaluate the normal stress acting on the shaft for two extra tests, in which the one-node pile and three-node pile is loaded up to 100mm.

TEST RESULTS

The results of loading tests are summarized from two viewpoints on shaft resistance of multi-node piles: shaft friction resistance and node bearing resistance. As shown in **Fig. 2**, the value of f which represents conventional shaft friction resistance, and the values of q_u, q_1 and q_t which represent node bearing resistance are defined. Unit shaft skin friction vs. settlement, or f-S relationships, compared with the straight-shafted piles and corrugated pile are shown in **Fig. 3**. The results of q_u-S, q_1-S and q_t-S are shown in **Fig. 4**.

The deformation behaviour of thin coloured-sand layers observed during digging out the piles indicates that a slip occurs at the pile-sand interface in the case of the smooth pile while it does in sand about 3mm from the interface of the rough pile. For the corrugated pile, the slip surface is observed in sand about 3mm from the outer surface (i.e., 10cm diameter). The deformation behaviour, which is evaluated from coloured-sand layers, of soil around the three-node pile is illustrated in **Fig. 5**.

Colour changes of the pressure sensitive paper on the one-node pile indicate that high normal pressures have acted along the shaft from the bottom of the node to about 10cm below the node. The colour changes on the three-node pile indicate similar patterns although the pressures on the shaft below upper two nodes have been less than those of the one-node pile. Many scratched lines, which indicate interface slip under high normal pressures, are observed in a coloured zone.

BEARING MECHANISMS OF NODES IN SAND

Fig. 3 indicates that the patterns and amounts of shaft friction resistance of multi-node piles are very different from those of straight-shafted or corrugated piles. It should be noted that settlements are limited within some value in practice; for instance, settlement equals to 10% of diameter (i.e., 10mm for all the piles in this study) has been employed as a reference settlement for non-displacement piles in Japanese design codes. The corrugated pile shows almost the same shaft resistance with the rough straight-shafted pile. The nodes and corrugations are different in resistance mechanisms although the enlarged shape of the corrugation is similar to the node as shown in **Fig. 1(g)**. Therefore, both nodal base resistance and shaft friction resistance under high normal pressures along the shaft below each node, which is described in the last part of the preceding section, play an important role in so-called shaft resistance of multi-node piles (Yabuuchi et al., 1993b).

Fig. 4 summarizes the load bearing characteristics of nodes. **Fig. 4(a)** shows how the load bearing resistance of an upper node of multiple nodes is influenced by the distance between nodes, compared with the isolated node of the one-node pile. The shorter the distance between upper and lower nodes is, the less an upper node resists.

Deformation behaviour shown in **Fig. 5** illustrates how the loosening of soil develops from the lower node to upper node. A continuous cylindrical slip surface whose diameter is nearly equal to multi-node diameter is formed after a complete loosening is developed from the lower nodes (Yabuuchi et al., 1993a). Then shaft resistance drops down from a peak value. The settlement where peak resistance is mobilized depends on the distance between the nodes and soil conditions. It seems that multi-node piles whose

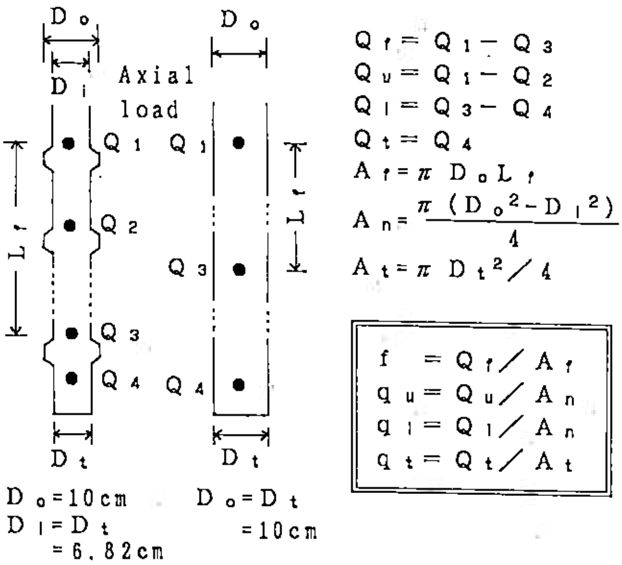


Fig. 2. Definitions of f, q_u, q_l and q_t.

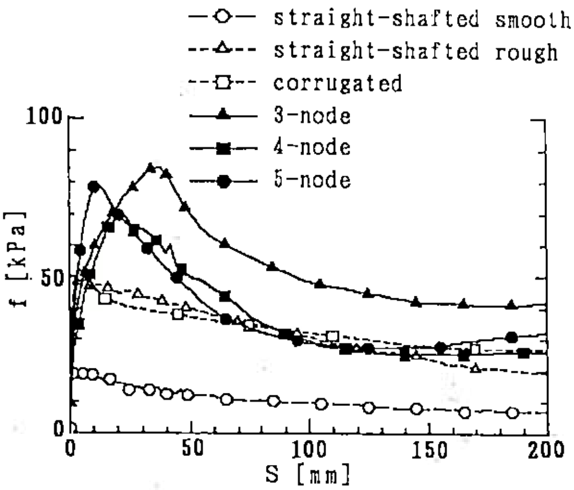
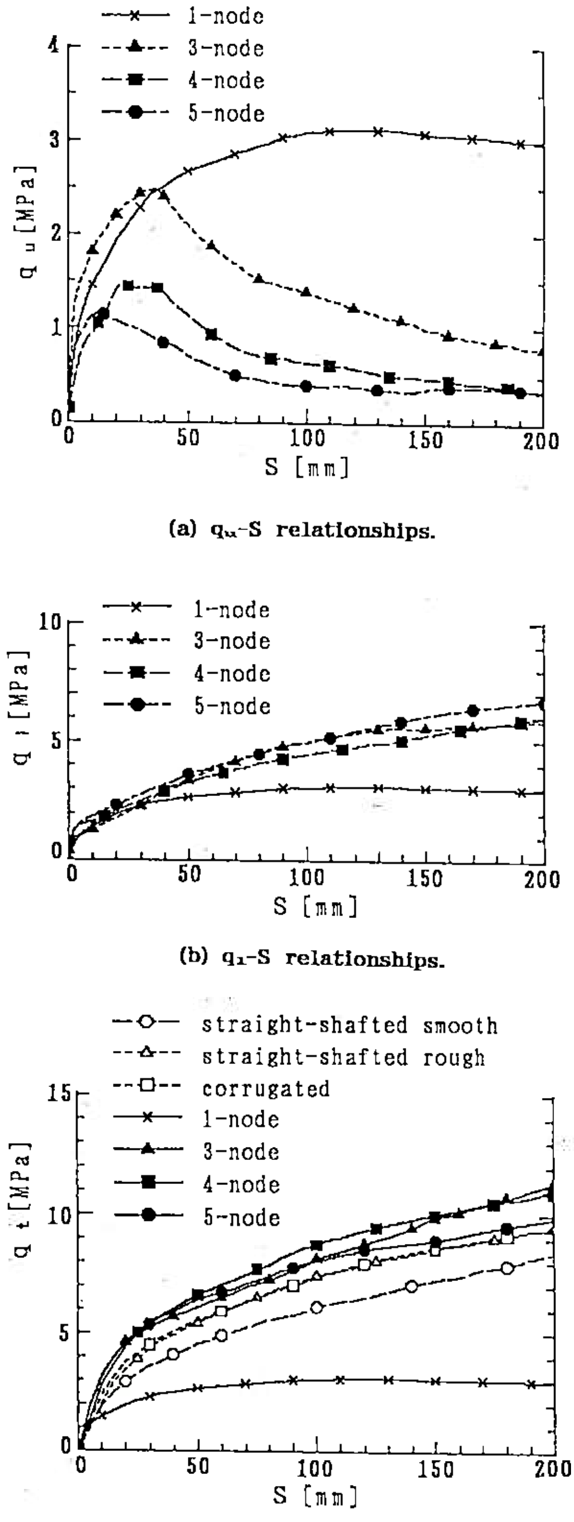


Fig. 3. Relationships between unit shaft friction and settlement.



(a) q_u-S relationships.

(b) q_l-S relationships.

(c) q_t-S relationships.

Fig. 4. q_u-, q_l- and q_t-S relationships.

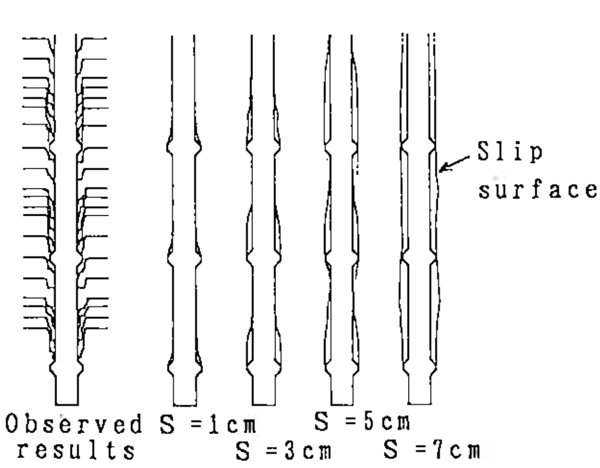


Fig. 5. Deformation behaviour of soil around the three-node pile.

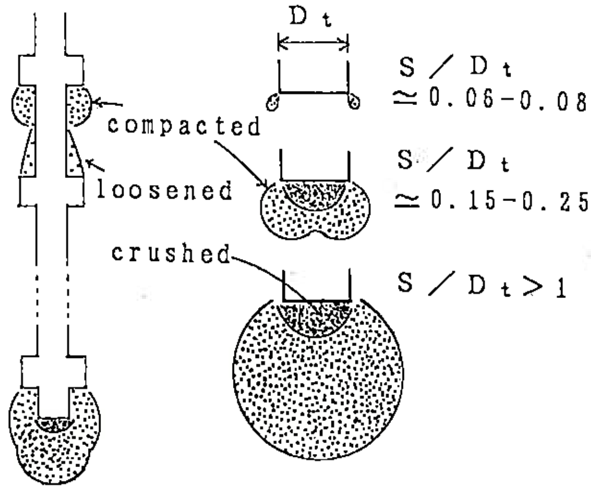


Fig. 6. Bearing mechanism of a multi-node pile compared with those of a pile base.

configuration is similar to the four-node or five-node pile yields reasonable load bearing characteristics in general.

Figs. 4(b)(c) show the bearing characteristics of lowest nodes. The result of the one-node pile also shows a detrimental effect of the lower shaft. The lowest node basically works as a part of pile base. If the shaft under the lowest node is too long to keep a highly stressed region on the shaft, which is about 10cm in this case as judged from colour changes of the pressure sensitive paper, the lowest node cannot fully compact the lower soil (Hirayama, 1988). Then physical ultimate base bearing capacity, which requires settlements more than base diameter (Hirayama, 1990), of the node of the one-node pile is much smaller than the lowest nodes of the other multi-node piles or toes of straight-shafted piles. As long as settlements are in a practical range, however, the difference is not significant. Thus each node in a multi-node pile may be as efficient as its pile base if loosening of soil does not occur within an allowable settlement.

Load bearing mechanism of a multi-node pile is schematically illustrated in comparison with that of the base of a straight-shafted pile in Fig. 6.

CONCLUSIONS

Shaft resistance of multi-node piles in sand under ideal non-displacement conditions is mainly controlled by the load bearing resistance of nodes and friction resistance of shaft below where high normal stresses act. A continuous cylindrical slip surface whose diameter is nearly equal to the multi-node diameter does occur. However, settlements at which a continuous slip surface develops are usually much larger than allowable settlements, and thus multi-node piles show different load-settlement curves as compared with straight-shafted piles having the same outer diameter.

Judging from the above-mentioned test results, multi-node piles are more effective than straight-shafted piles for resisting compressive load as well as uplift load.

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