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Bearing mechanisms of nodal piles in sand

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ABSTRACT: Nodal piles, whose shapes are similar to multi-underreamed piles, are precast piles having multiple nodes or bulbs. Vertical compression loading tests for model piles are carried out in order to investigate bearing mechanisms of nodal piles. Model piles tested are nodal piles having different numbers of nodes. Straight-shafted smooth and rough piles 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 nodal piles in sand is mainly attributed to bearing resistance of nodes, and that nodal piles are more effective than straight-shafted piles with the same outer diameter.

1 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 & Watson, 1936). They have been driven with gravel as a sealing material. They can also be installed in pre-bored holes with gravel or other sealing materials as non-displacement piles in urban areas. Cast-in-situ concrete piles called multi-underreamed piles have been extensively used for structures on Indian black cotton soils (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).

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

In order to investigate bearing mechanisms considering the above-mentioned effects of nodes, vertical compression loading tests for model nodal piles having different numbers of nodes are carried out. Straight-shafted smooth and rough piles 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 bearing mechanisms of nodal piles in sand.

2 TEST PILES, APPARATUS AND PROCEDURES

2.1 Model piles

The shapes of model piles are shown in **Fig. 1**. Three nodal piles having 3 to 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 one node along the middle of its shaft (**Fig. 1(d)**) is also tested in order to investigate mechanisms of the node which is affected by the lower shaft and not affected by the lower nodes. Straight-shafted smooth and rough piles and a corrugated pile are also tested to compare shaft resistance characteristics with those of nodal piles.

The piles are made of stainless steel, and strain gauges are instrumented inside of each hollow shaft. They are 100cm in length and 10cm in maximum diameter. Shaft diameters of nodal piles (**Fig. 1(a)-(d)**) are 6.82cm. Shaft surface profiles of the smooth pile (**Fig. 1(e)**) measured by a roughness gauge with a stylus indicate that maximum heights of asperities along a reference length of 2.5mm range from 9 to 15 μm. The rough pile shown in **Fig. 1(f)** is roughened by sticking 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 0.25cm and 1cm, respectively.

2.2 Test apparatus and procedures

Tests are carried out in a triaxial pressure chamber, 158cm inner diameter and 178cm high. Air-dried quartz sand which has the following properties is used for tests: D_{50}=0.360mm, D_{10}=0.195mm, U_c=1.85, ρ_{max}=1597kg/m^3, ρ_{min}=1264kg/m^3.

Uniform sand layers are prepared by a sand-rainer method, or a multiple sieving method (e.g., Miura & 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 values of relative density of sand mass prepared are about 80% after compression under σ_v=98kPa and σ_h=49kPa.

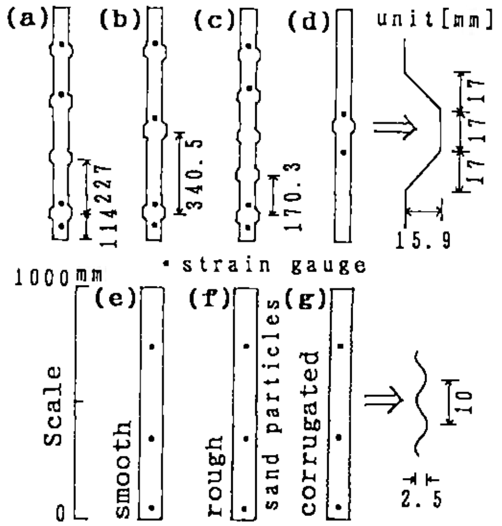


Fig. 1. Model piles tested.

Piles are settled up to 20cm. 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 being constant during each test. Two tests are carried out for each pile. 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 strain gauges instrumented. Strain-gauge readings are zeroed when a piles is fixed to the chamber. Before the vertical pressure is applied, the fixing device has to be removed and then reading is stopped until reconnecting electric wires. Since the strain increments measured during sand preparation are negligible, instrumentation is zeroed before applying vertical and horizontal pressures to evaluate initial residual stresses (Hanna & Tan, 1973).

Pressure sensitive paper is attached onto the shaft in each one extra test, which is settled up to 10cm, of the one-node pile and three-node pile.

3 TEST RESULTS

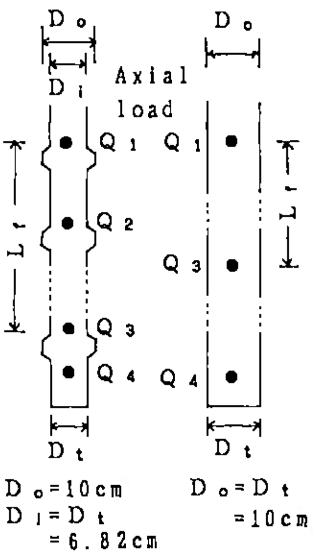
The results of loading tests are summarized from two viewpoints on shaft resistance of nodal piles: shaft friction resistance and shaft bearing resistance. The values of f, q_u, q_l and q_t are defined as shown in **Fig. 2**. Unit shaft skin friction vs. settlement, or f-S relationships, compared with the straight-shafted piles and corrugated pile are shown in **Fig. 3**. The results of q_u-S, q_l-S and q_t-S are shown in **Fig. 4**.

The deformation behaviour of thin coloured-sand layers observed during digging out 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. It can be observed in sand about 3mm from the outer surface (i.e. 10cm diameter) of the corrugated pile. 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 pressures have acted from the bottom of the node to about 10cm below the node. The changes on the three-node pile indicate similar patterns although acted pressures below upper two nodes have been less than those of the one-node pile.

4 BEARING MECHANISMS OF NODES IN SAND

Fig. 3 indicates that mechanisms of shaft resistance of nodal piles are basically different from those of straight-shafted or corrugated piles as far as settlements are limited within practical values; for instance, settlement equals to 10% of diameter is 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 mechanisms although the enlarged shape of the corrugation is similar to the node. It is suggested, therefore, that shaft resistance of nodal piles should be called shaft bearing resistance to contrast with shaft friction resistance.



$Q_f = Q_1 - Q_3$

$Q_u = Q_1 - Q_2$

$Q_l = Q_3 - Q_4$

$Q_t = Q_4$

$A_f = \pi D_o L_f$

$A_n = \dfrac{\pi (D_o^2 - D_i^2)}{4}$

$A_t = \pi D_t^2 / 4$

$f = Q_f / A_f$
$q_u = Q_u / A_n$
$q_l = Q_l / A_n$
$q_t = Q_t / A_t$

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

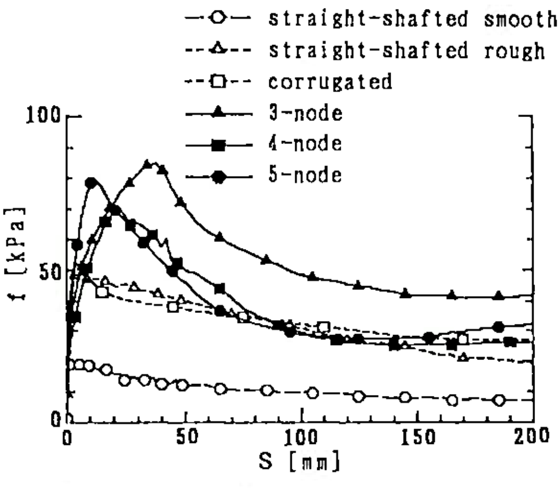
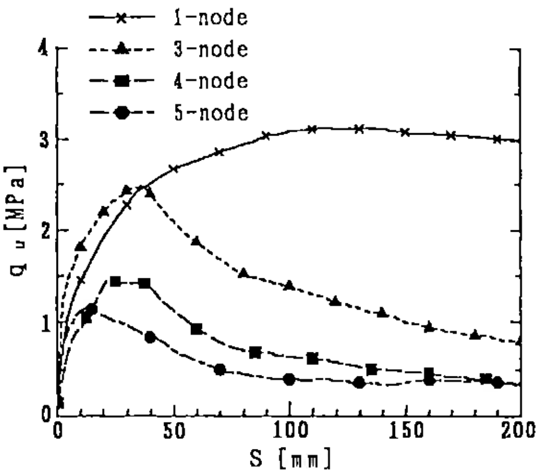
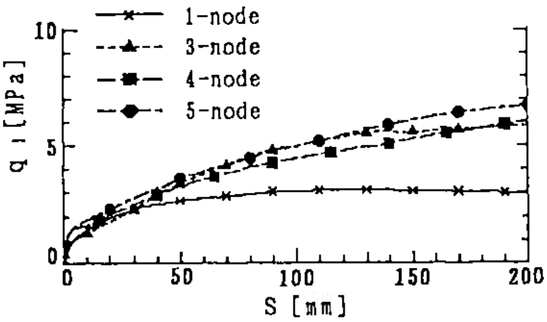


Fig. 3. Results of relationships between unit shaft skin friction and settlement.

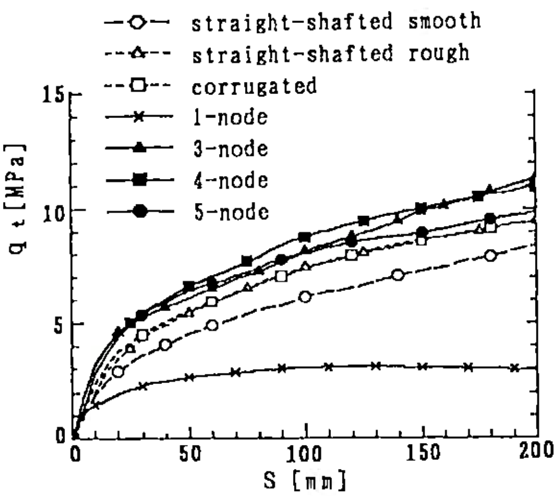
Fig. 4 is summarized to investigate bearing characteristics of nodes. **Fig. 4(a)** shows how the bearing resistance of an upper node of multiple nodes is influenced by the lower node, compared with the isolated node of the one-node pile. The shorter the distance to a lower node is, the less an upper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



(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.

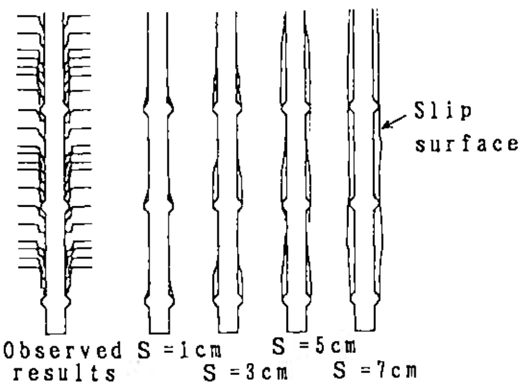


Fig. 5. Deformation behaviour of soil around the three-node pile.

Deformation behaviour shown in **Fig. 5** illustrates how the loosening due to lower nodes extends. A continuous cylindrical slip surface whose diameter is nearly equal to nodal diameter is formed due to loosening caused by the lower nodes. Then shaft resistance drops down from a peak value. The settlement where peak resistance is mobilized depends on distance between nodes and soil conditions. It seems that nodal piles whose shape is similar to the four-node or five-node pile is reasonable in general.

Figs. 4(b)(c) show the bearing characteristics of lowest nodes. The effect of the lower shaft can also be seen in the result of the one-node pile. The lowest node basically works as a part of toe. If the shaft under the lowest node is longer than a high-stress region, which is about 10cm in this case judged from colour changes of the pressure sensitive paper described in the last part of the preceding section, 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 nodal piles or toes of straight-shafted piles. As far as settlements are in a practical range, however, the difference is not significant.

Bearing mechanisms of a nodal pile are schematically illustrated compared with those of the toe of a straight-shafted pile in **Fig. 6**.

5 CONCLUSIONS

Shaft resistance of nodal piles in sand under ideal non-displacement conditions is mainly attributed to bearing resistance of nodes. A continuous cylindrical slip surface whose diameter is nearly equal to the nodal diameter does occur. However, settlements at which it does are usually much larger than allowable settlements, and thus nodal piles are different from straight-shafted piles with the same outer diameter in shaft resistance mechanisms.

When precast nodal piles are installed with gravel in cohesionless soil, they are effective because of not only their bearing mechanisms but also liquefaction resistance as a kind of gravel drains.

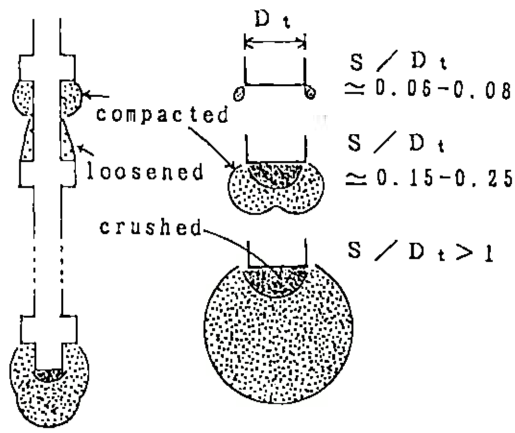


Fig. 6. Bearing mechanisms of a nodal pile compared with those of a pile toe.

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