Behavior of a pile under horizontal cyclic loading

Comportement d'un pieu sous chargement horizontal cyclique

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SYNOPSIS Model pile tests are carried out to investigate the behavior of a pile under horizontal cyclic loading. The new subgrade reaction model is proposed on the basis of model tests. The analyses using this model are compared with the field test results of piles.

INTRODUCTION

In a previous paper (Nakai & Kishida : 1982) the behavior of a pile under horizontal load was discussed considering the non-linear behavior of soil and pile shaft. Properties of soil near a pile is changed by movements of pile. Gap between soil and a pile occurs in some cases.

In order to study this problem, the new subgrade reaction model was proposed on the basis of model pile test results. The results of field test of a pile under horizontal cyclic loading are summarized and analyzed by the proposed model.

MODEL TEST

Model tests were carried out to investigate the behavior of a pile under horizontal cyclic loading. The model pile is an acrylic resin pipe being 2cm in diameter and 40cm in length. The thin lead sheet is attached inside the pile shaft so that the deflection of the pile can be taken in the X-ray picture.

Two kinds of tests were made, one for the dry dense sand of relative density of 95% and the other for Kawasaki clay. The clay was remolded and reconsolidated so that the plasticity index was 27.2% and the value of undrained shear strength was 9.8KPa. These soils were placed in the test box being the 40cm in length, 20cm in width and 40cm in depth. The pile and the lead shot were placed in the soils, and the horizontal cyclic load was applied at the top of the pile. The X-ray pictures were taken during the tests, and movements of the soils and the pile were observed by shadows of the lead shot and the pile shaft in the X-ray film.

The relationships between load and displacement at the top of the pile are shown in Fig.1(a) and Fig.1(b). The test result in the sand(Fig.1(a)) indicate that the hysteresis curves under cyclic loadings show about the same shape, and that the area enclosed by the curve increases with the increment of load. The test result in the clay(Fig.1(b)), however, indicates the different shape of the hysteresis curves compared with the test result in the sand, and the areas enclosed by the curves are much smaller than the ones in the sand.

Movements of the sand and the pile in Fig.2(a) show that the sand in front of the pile is compacted due to movements of the pile, and that the sand in back of the pile moves down to the pile shaft decreasing its density. No gap between the sand and the pile was observed. The sand near the pile shaft is compacted during horizontal cyclic loading. When the partially saturated sand has the apparent cohesion, the

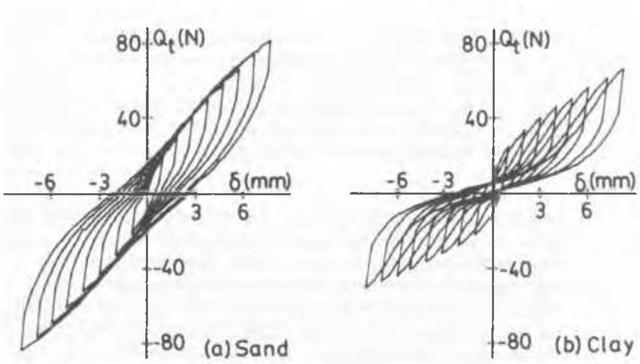


Fig.1 Load-Displacement Relationships

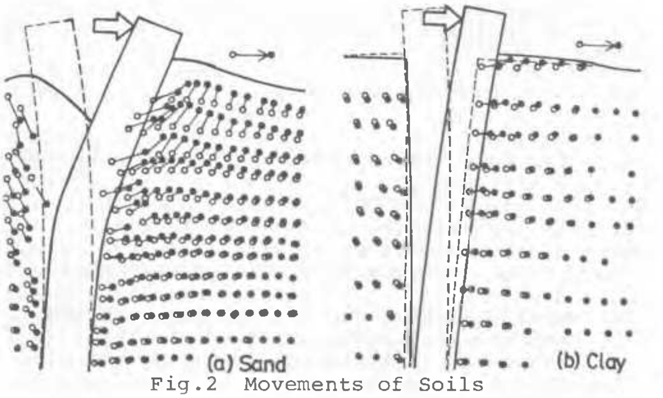


Fig.2 Movements of Soils

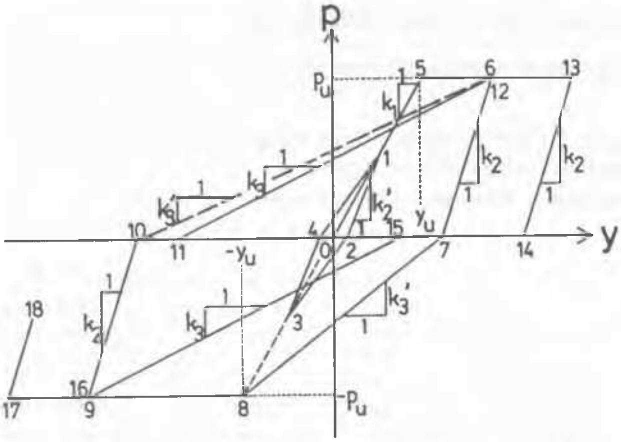


Fig.3 Proposed Subgrade Reaction Model

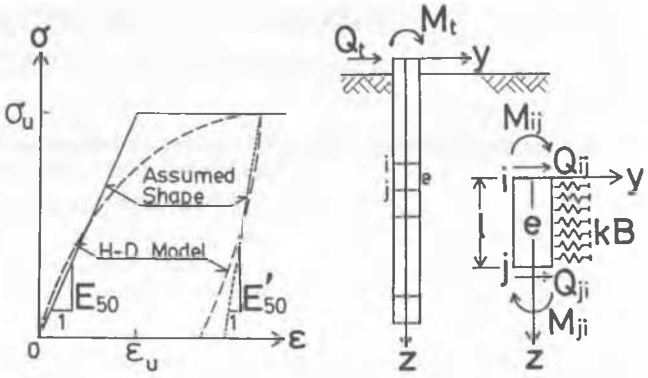


Fig.4 Relation between E_{50} and E_{50}'

Fig.5 Analytical Model

sand may have the critical height due to the apparent cohesion. In this case, gap between the sand and the pile occurs, and such phenomena can be observed in field tests. Movements of the clay and the pile in Fig.2(b) show that the gap between the clay and the pile was clearly observed in back of the pile. The height of the gap is a part of the critical height due to cohesion. The clay in front of the pile is remolded and decreases its strength significantly.

The difference of the hysteresis curves between the dry sand and the saturated clay is mainly due to the change of soil properties near the pile and also due to the presence of the gap between the soil and the pile shaft.

THE RELATIONSHIP BETWEEN SUBGRADE REACTION AND DISPLACEMENT UNDER HORIZONTAL CYCLIC LOADING

Based on the model test results, the authors propose a new subgrade reaction model as can be seen in Fig.3, which considers the change of soil properties and the gap between the soil and the pile under horizontal cyclic loading. The explanation of the proposed model is as follows.

(1) P_u in Fig.3 is the ultimate horizontal soil resistance calculated by theory of plasticity (Nakai & Kishida : 1982)

(2) The slope of the line $\overline{05}$ is the initial subgrade reaction coefficient(k_1) given by the following equation.

$$k_1B = 1.3\ \frac{E_s}{1-\nu_s^2}\sqrt[12]{\frac{E_sB^4}{E_pI_p}} \qquad (1)$$

E_s, E_p : elastic coefficients of soil and pile
ν_s : Poisson's ratio of soil
I_p : moment of inertia of pile
B : diameter of pile
k_1 : subgrade reaction coefficient

(3) When the value of the subgrade reaction reaches the ultimate value(P_u), the displacement increases following the line $\overline{56}$.

(4) The slope of the reverse line(k_2 at $\overline{67}$) is determined by Hardin-Drnevich model of soil. The ratio of E_{50}' to E_{50} is approximately 1.33. By substituting E_{50}' instead of E_{50} into Eq.(1), the approximate value of k_2 is expressed as follows.(Fig.4)

$$k_2 \fallingdotseq 1.4k_1 \qquad (2)$$

(5) When the subgrade reaction is less than the ultimate value, the slope of the reverse line $\overline{12}$ is dependent on the value of the displacement, and is expressed as follows,

$$k_2' = k_1 + (k_2 - k_1)y/y_u \qquad (3)$$

y_u : the value of the displacement at P_u

(6) When the value of displacement y is smaller than y_u, the hysteresis curve($\overline{12}$, $\overline{23}$, $\overline{34}$ or $\overline{41}$) is easily determined by putting the point 1 and 3 at equal distance from the point 0.

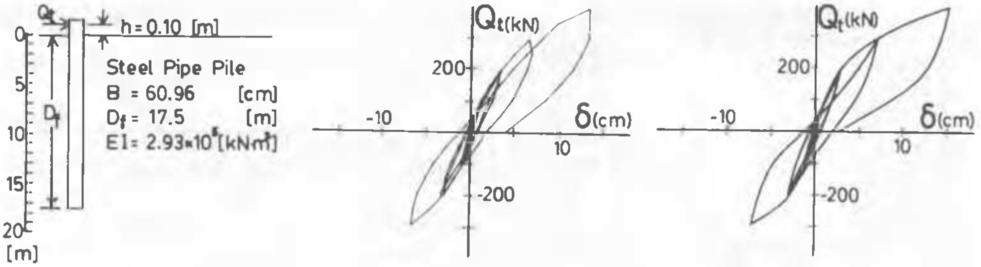
(7) When the value of displacement y is greater than y_u, the slope of the reverse line $\overline{67}$ is k_2 until the value of the subgrade reaction reaches zero. When the subgrade reaction is less than zero, that means the pile is moved to the opposite direction, the reverse line $\overline{78}$ is determined to pass the negative maximum displacement point 8 recorded in the preceding loadings. The slope of the reverse line is determined by the following expression.

$$k_3' = P_u/(Y_{max} - Y_{min} - P_u/k_2) \qquad (4)$$

Ymax : Maximum displacement recorded in the preceding loadings in positive direction (6 in Fig.3)
Ymin : Maximum displcement in negative direction recorded in the preceding loadings (8 in Fig.3)

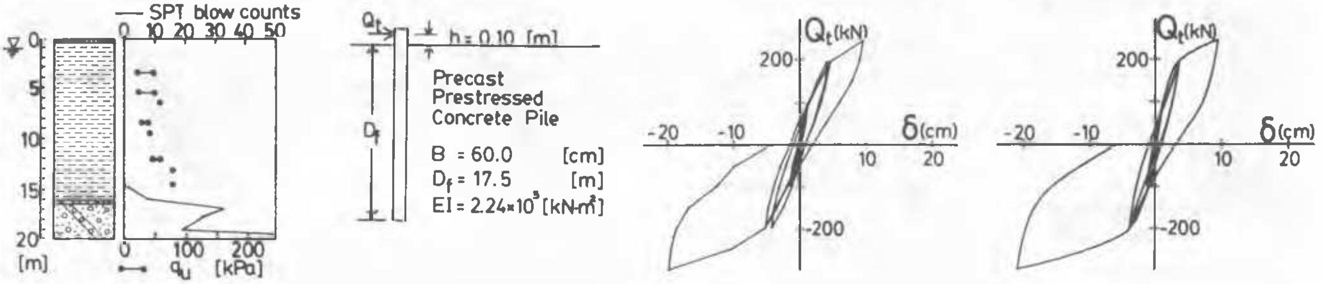
(8) The elastic modulus of the alluvial soil in Tokyo area decreases its value to about one third of the initial value due to disturbance of soil. The decrease of subgrade reaction due to disturbance of soil is evaluated by decreasing the value of E to one third of the initial one in Eq.(1). The effect of disturbance is expressed as follows,

Fig.6 Symbols of Soils



(a) Size and Stiffness of Pile (b) Test (c) Calculation

Fig.7 Test at Shiki (Open-Ended Steel Pipe Pile)



(a) Soil Profile (b) Size and Stiffness of Pile (c) Test (d) Calculation

Fig.8 Test at Shiki (Precast Prestressed Concrete Pile)

$$k_3 \fallingdotseq 0.3k_1 \quad (5)$$

(9) The case that k_3' is equal to or greater than k_3 means that no gap occurs between the soil and the pile. In this case, the slope of the reverse line is equal to k_3' as shown $\overline{78}$ in Fig.3.

(10) The minimum value of subgrade coefficient is k_3. The case that calculated k_3' (the broken line $\overline{10\ 12}$ in Fig.3) is smaller than k_3 ($\overline{11\ 12}$) has no physical meaning. The real phnomenon is the line $\overline{10\ 11\ 12}$. The line $\overline{10\ 11}$ means the gap and no subgrade reaction occurs. The slope of the line $\overline{11\ 12}$ is k_3. The point 12 is the maximum displacement in the preceding loadings. Thus, the line $\overline{10\ 11\ 12}$ is obtained.

The successive load-displacement relationships can be determined by the aforementioned procedures.

METHOD OF ANALYSIS

The method of analysis is based on the subgrade reaction theory appling the proposed model under horizontal cyclic loading. The pile is divided into small elements as shown in Fig.5. The deformation of the element is expressed in the form of series.

The relationship between deformation and the nodal force in each element can be calculated by Rayleigh-Ritz method. The nodal force is obtained by minimizing potential energy of the pile-soil system satisfying compatibility condition of displacements and equilibrium of forces at the boundary of each elements. The detailed method of this subgrade reaction theory that can include the non-linear characteristics of both soil and pile is published previously (Nakai & Kishida : 1982).

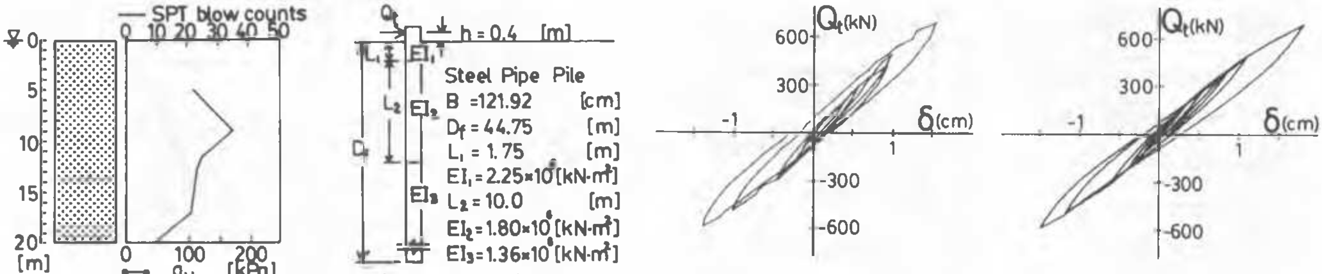
COMPARISON BETWEEN CALCULATED AND FIELD TEST RESULTS

Full scale pile loading tests were carried out at four construction sites to compare the test results with calculated ones by the proposed theory. The symbols of soils are shown in Fig.6. The open-ended steel pipe pile and the precast prestressed concrete pile tests were carried out at Shiki in Saitama. The soil is mostly clay and its profile is shown in Fig.8(a). The test and calculated results of the open-ended steel pipe piles are shown in Fig.7. The test and calculated results of the precast prestressed concrete pile are shown in Fig.8. In Figs.7-11, Q_t means the horizontal load and δ means the horizontal displacement at the top of the pile.

The test on the open-ended steel pipe pile is also carried out at Ishikari in Hokkaido. The soil profile, size and stiffness of pile, the test and calculated results are shown in Fig.9.

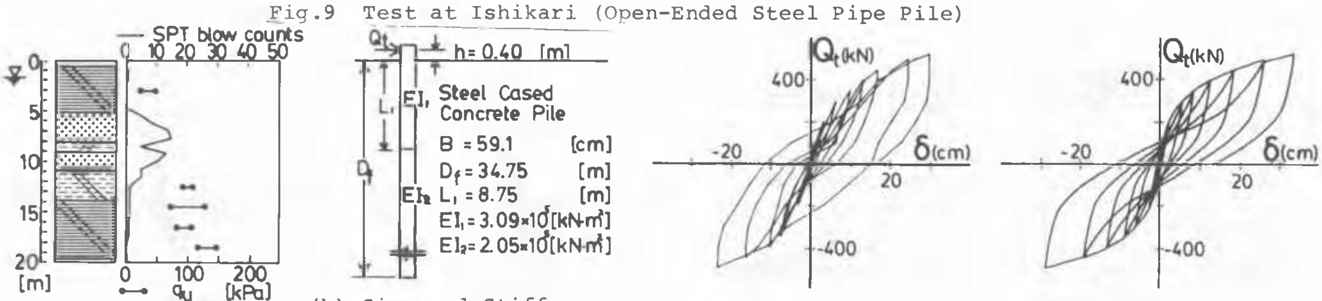
The tests on the steel cased concrete pile is carried out at Ichikawa in Chiba. The soil profile, size and stiffness of pile, the test and calculated results are shown in Fig.10. The test on the bored concrete pile is also carried out at Sendai in Miyagi. The soil profile, size and stiffness of pile, the test and calculated results are shown in Fig.11. All the tests except at Sendai were carried out under the condition of the pile top being free to rotate.

In the tests of steel pipe piles shown in Fig.7



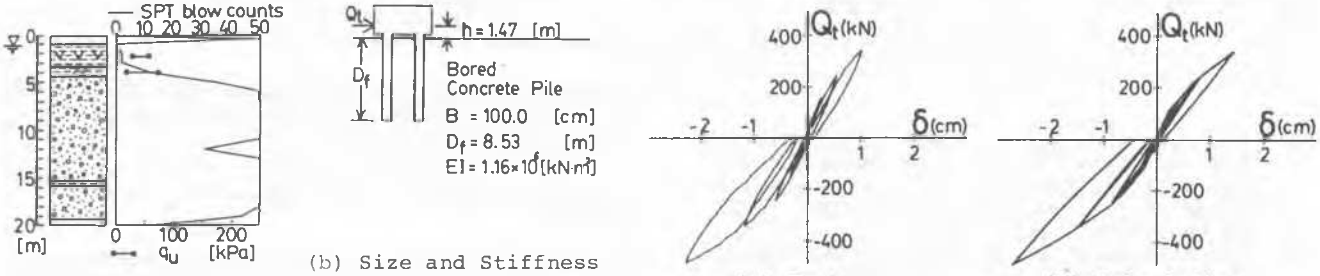
(a) Soil Profile (b) Size and Stiffness of Pile (c) Test (d) Calculation

Fig.9 Test at Ishikari (Open-Ended Steel Pipe Pile)



(a) Soil Profile (b) Size and Stiffness of Pile (c) Test (d) Calculation

Fig.10 Test at Ichikawa (Steel Cased Concrete Pile)



(a) Soil Profile (b) Size and Stiffness of Pile (c) Test (d) Calculation

Fig.11 Test at Sendai (Bored Cast-in-place Concrete Pile)

and Fig.9, the calculated results show fairly good agreement with the test results. In the tests of the precast prestressed concrete and the steel cased concrete piles shown in Fig.8 and Fig.10, the concrete in the pile shaft develops cracks due to large deformation of the pile shaft. Though the non-linear properties of concrete is included in the proposed method, it is difficult to obtain the accurate behavior of concrete in the pile shaft. The difference between the calculated and test results is mostly due to the change of pile stiffness under large deformation of the pile shaft.

In the test of the bored concrete pile, the top of two piles are connected by the reinforced concrete pile cap so that the top of the piles are restrained from rotating. Though the change of stiffness of the reinforced concrete pile shaft is difficult to estimate, the calculated result shows fairly good agreement with the test result. It is due to the reason that the deformation of the pile shaft is rather smaller than the case of Fig.8 and Fig.10.

CONCLUSIONS

The behavior of a pile under horizontal cyclic loading can be explained by the subgrade reaction theory using the proposed model.

The effect of change of soil properties near a pile shaft and the gap between soil and pile are important factors to be considered when a pile is subjected to horizontal cyclic loading.

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REFERENCE

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