Point resistance of piles in sand

Résistance de pointe des pieux dans le sable

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SYNOPSIS The point resistance of piles in sand is mainly considered from the viewpoint of the particle-crushing energy around the pile tip. It is shown that the work dissipated in the particle-crushing of sand is as much as 80 - 90% of the total work done by the external force and that the point resistance of piles in sand greatly depends on the particle-crushing property of the sand.

INTRODUCTION

Past studies on the bearing capacity of piles in sand (De Beer, 1963, BCP Committee,1969, Takano et al., 1974) suggest that the point resistance of piles closely relates to the particle-crushing of sand around the pile tip. This study makes it clear how the particle-crushing affects the point resistance of piles by the detailed investigations on model pile tests.

EXPERIMENTS

Main properties of the sand used in this study are as follows: Maximum diameter ≈ 2.00 mm, fifty percent diameter = 0.84 mm, specific gravity=2.66, maximum void ratio = 1.07 and minimum void ratio= 0.627, respectively. Figure 1 is the schematic diagram of the sand container used for the model pile test. This apparatus is an assembly of two pieces of cylindrical walls, a bottom plate and a ceiling plate and a steel pile of 5 cm in diameter and 32 cm in length. The wall friction was decreased by coating a small amount of grease on the inner wall of the cylinder and by attaching double layers of polyvinyl sheets with soapy water between them to the wall.

Air-dried sand of water content of 0.3 to 0.5 percent was compacted in 28 cm thick in a dense state (void ratio is 0.60 and wet density is 1.66 g/cm^3) and the model pile was placed on the sand surface using a supporting frame. After that, a sand layer of 13 cm thick was filled additionally, and thereby a buried model pile of 13 cm depth was prepared. A ceiling plate was set and two rubber bags were inserted through the holes as shown in Fig. 1, for applying the vertical pressure σ_v to the sand surface.

For the pile loading test, the sand container was set on a compression machine, and pile stress was applied in controlled steps, with each step being approximately one-twentieth of the contemplated maximum stress. At each step, the stress was sustained until the rate of settlement became 0.01 mm/min, and then the incremental stress for the next step was applied. After the pile loading test, water was supplied to the container so that the sand sample can stand itself by the capillary force for the convenience of extruding the sample from the container. A CBR mold attached a cutter head was then pushed into the sand sample as illustrated in Fig. 2. For sectional sampling, the CBR mold was placed on a sample-extruder and thin-wall rings of diameters 10 cm, 6 cm and 4 cm were inserted in order, as seen in Fig. 3. The sampling sections are shown later in Fig. 5.

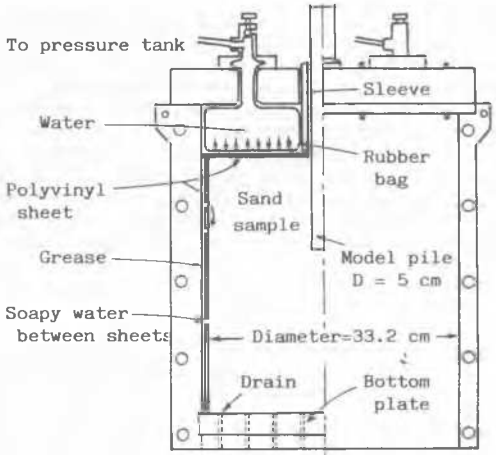


Fig. 1 Sand Container for Pile Test.

Fig. 2 Sampling of Sand Around the Pile Tip

Fig. 3 Sectional Sampling Using Thin-Wall Rings

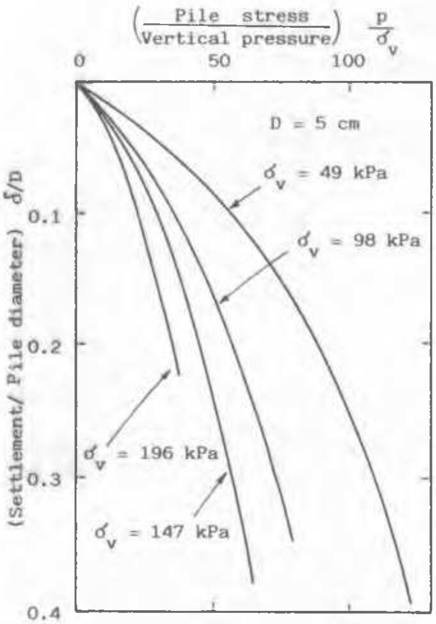


Fig. 4 Normalized Pile Stress - Settlement Curves

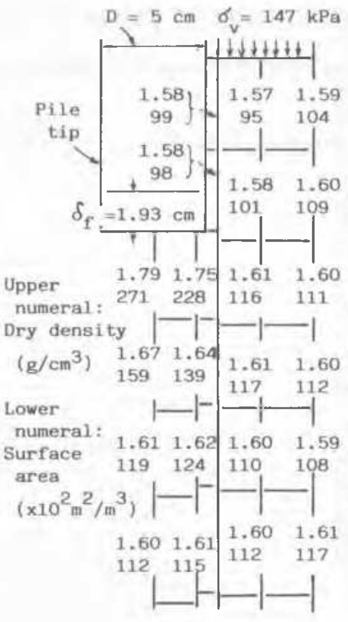


Fig. 5 Measured Dry Density and Surface Area in Each Section

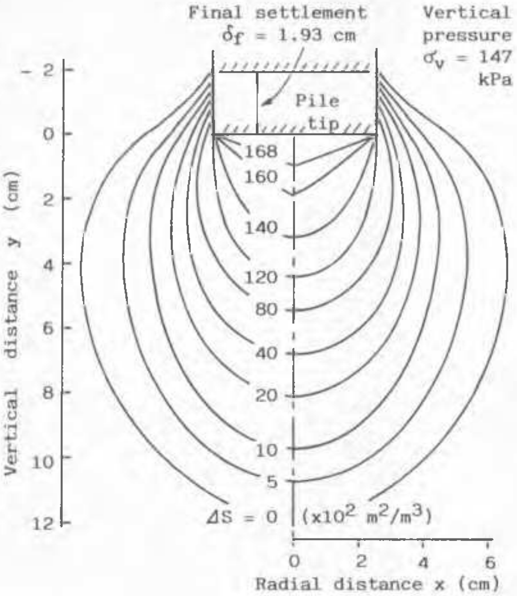


Fig. 7 Surfaces of Equi-Amount of Particle-Crushing

PARTICLE-CRUSHING REGION

Figure 4 shows the normalized pile stress and settlement relationships of four cases of different vertical pressures, explaining that all the curves continue to slope as the case of actual pile load tests and that the characteristics of these curves are of local shear failure. In the previous study, where the experiments were carried out using the model pile of 3.5cm, the author pointed out that the pile stress - settlement curve could be simulated reasonably by a mathematical model proposed by Shioi et al. (Miura, 1983). Situation is the same for the present data, but here the discussion is not made on this problem.

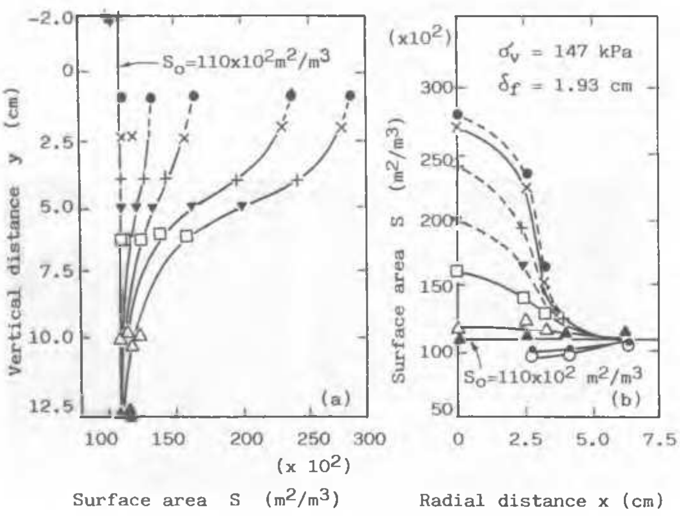


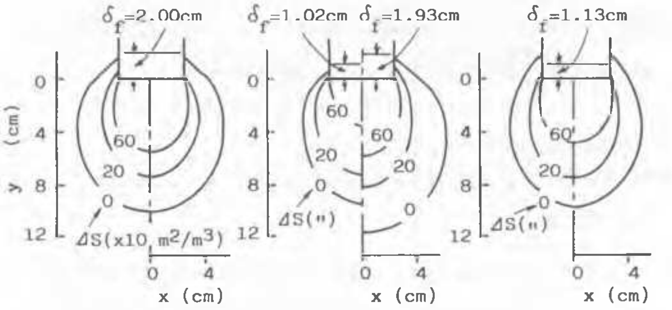
Fig. 6 Distribution of the Amount of Particle-Crushing (Surface Area S) Around the Pile Tip

Now, for investigating the effect of particle-crushing on the point resistance of piles in sand, it is necessary to know the particle-crushing distribution around the pile tip in detail. Previous study proved that the amount of particle-crushing could be evaluated reasonably by the surface area S, which is calculated by $S = S_w \times \rho_d$, where S_w and ρ_d indicate specific surface area (m^2 /g)and dry density. The value of S_w can be obtained through the sieving test and the Blaine test, and the details of them appear elsewhere (Miura et al. 1977).

Assuming that S value determined by the above-mentioned method represents the value at the center of each sampling section depicted in Fig. 5, the changes of surface area in vertical direction below the pile tip (y direction) and the radial direction (x direction) can be depicted as shown by Fig. 6, which is for the case of vertical pressure of 147 kPa and the final settlement δ_f of 1.93 cm. The broken lines in the figure represent the curves obtained by extraporation or interporation.

Based on the y - S curve and x - S curve, we may depict the contour lines of equi-amount of particle-crushing around the pile tip as illustrated in Fig. 7, where ΔS means an increase of surface area from the original value of S_o = 110 x 10^2 m^2/m^3. It can be seen that the cone, the strongly crushed region, grows just below the pile, and that the surfaces of equi-amount of particle-crushing extend spherically around the cone. It is also known that the diameter of the bulb-shaped particle-crushing zone is two to three times of the diameter of the model pile.

Figure 8 comparably indicates the development of particle-crushing zone for various vertical pressures and settlements. The outermost line of ΔS being zero indicates the particle-crushing regions which essentially the same with the plastic region. As for the shape of the plastic



a) σ_v = 49 kPa b) σ_v = 147 kPa c) σ_v = 196 kPa

Fig. 8 Comparison of the Particle-Crushing Regions for Various Test Conditions

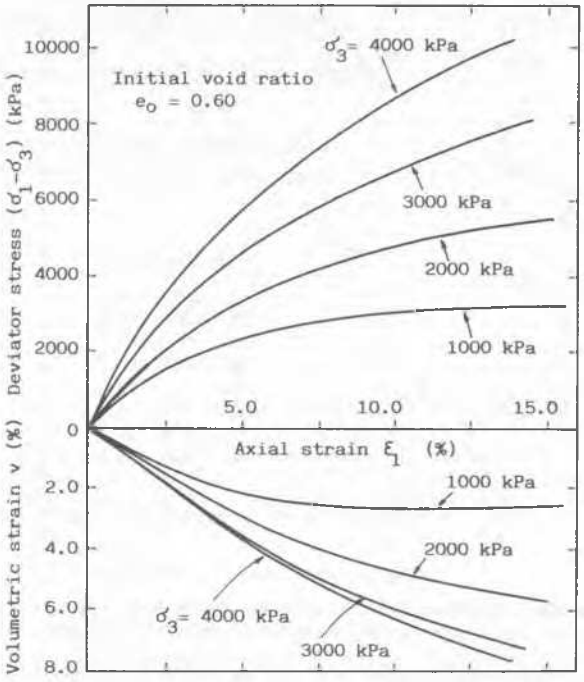


Fig. 9 Stress-Strain Curves in Drained Triaxial Compression Tests at σ_3 = Constant

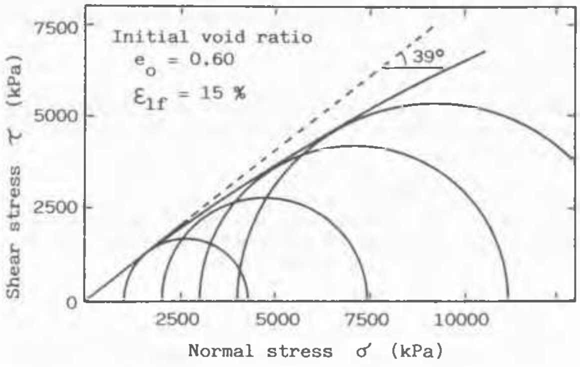


Fig. 10 Failure Envelope of the Tested Sand

zone that develops around the pile tip, several ideas have been proposed, and among them we can find a bulb-shaped one (Vesić, 1967). Aboshi(1975) also found experimentally the plastic zone around the tip of deep pile to be bulb-shaped. These investigations stated above support the present shape of the plastic region, i.e., the particle-crushing region.

CONSIDERATION ON ENERGY BALANCE

The point resistance of piles in sand is discussed in the following from the viewpoint of energy balance by evaluating the energies dissipated in the particle-crushing around the pile tip and also in the friction between the pile shaft and sand. First, the energy dissipated in particle-crushing can be estimated on the basis of S - w relationship, where w is plastic work done per unit volume (kN·m/m^3) (Miura et al., 1977). The S - w curve for the present sample was determined through drained triaxial compression tests carried out on the sand specimen of 5 cm diameter and 12.5 cm height with a void ratio of 0.61 to 0.65, being the nearest possible to the void ratio of the pile test sample. The conditions of the triaxial compression tests are:strain rate = 0.2%/min and confining pressure of 500 kPa to 4000 kPa.

Stress-strain curves obtained are represented in Fig. 9, showing that no peak appears even at an axial strain of 15 percent when the confining pressure is higher than 2000 kPa. Fig. 10 shows the failure envelope; the convexity of the failure envelope may be caused by the particle-crushing. The internal friction angle at confining pressures under the particle-crushing region, i.e. $\sigma_3 \leq$ 300 kPa is determined as 39.0°. The sample experienced various axial strains were taken out from the triaxial chamber for measuring the specific surface area S_w. The dry density ρ_d corresponding to the S_w value was determined on the basis of the volume change during the shear, and the product of these values gives the surface area per unit volume, S. The plastic work done per unit volume w is given from the stress-strain curves, q - ε and p - v, i.e.,

$$w = \int (\sigma_1 d\varepsilon_1 + 2\sigma_3 d\varepsilon_3)$$
$$= \int (q d\varepsilon + p dv) \quad (1)$$

where, $q = \sigma_1 - \sigma_3$, $p = (\sigma_1 + 2\sigma_3)/3$, $d\varepsilon = d\varepsilon_1 - (dv/3)$ and $dv = d\varepsilon_1 + 2d\varepsilon_3$. The above-mentioned equation neglects the elastic component since it occupies only a few percent of the total work. The author found in the previous study that there was a unique relationship between the surface area S and the plastic work done w independent of the stress level and the magnitude of the confining pressure (Miura et al., 1977). This is also true for the present sample as seen in Fig. 11.

Now, the plastic work done per unit volume w_i corresponding to each value of ΔS in Fig. 7, can be read on the curve in Fig. 11. For example, ΔS_1 = 168 x 10^2 m^2/m^3 (S=168+110=278 ") in Fig.7 corresponds to w_1 = 12.3 N·m/m^3 in Fig. 11. While, the volume of each section of Fig. 7 is measured graphically and denoted by v_1. Hence, the summation of the products of w_i and v_i might be the total work dissipated in particle-crushing,

$$W_c = \sum w_i \times v_i \quad (2)$$

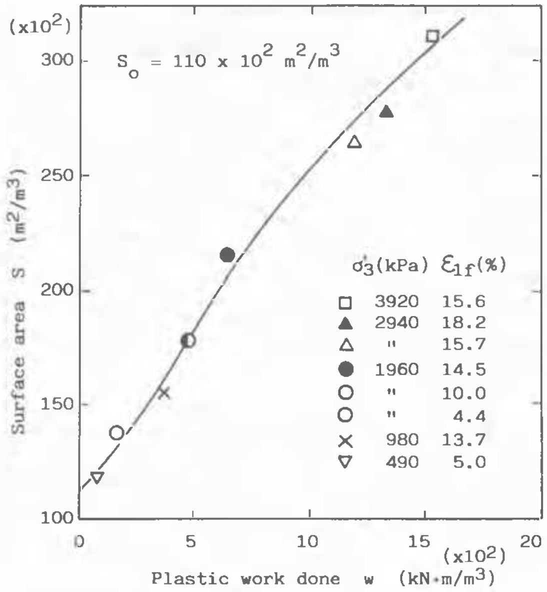


Fig. 11 Relationship between Surface Area S and Plastic Work Done w per Unit Volume

The value of W_c for the experiment shown in Fig.7 is W_c = 190.2 N·m. Next, the frictional work dissipated at the contact face of the pile shaft and sand, W_f, may be evaluated in the following ways. The horizontal stress acting on the pile shaft σ'_h, is expressed using Jaky's equation for the coefficient of lateral pressure at rest, $K_o = 1 - \sin \phi_d$, as

$$\sigma'_h = \sigma'_v \times K_o \quad (3)$$

Assuming that the frictional angle between the pile and sand is $\phi_f = 2\phi_d/3$, then the coefficient of friction is

$$\mu = \tan(2\phi_d/3) \quad (4)$$

The diameter of the pile being D, the buried length L and the final settlement δ_f, the frictional work W_f is calculated by

$$W_f = \sigma'_h \mu \pi D L \delta_f \quad (5)$$

Substituting D = 5 cm, L = 13 cm and ϕ_d = 39° for the case of σ'_v = 147 kPa, we obtain W_f = 9.9 N·m.

The total work done by the external force W_e was evaluated by the enclosed area of the pile stress-settlement curve and for the case of σ'_v = 147kPa and δ_f = 1.93 cm, W_e was 239.0 N·m. Therefore, the work done by the external force at the pile tip,

$$W = W_e - W_f = 229.1 \text{ N·m} \quad (6)$$

To this value, the rate of the work dissipated in particle-crushing W_c (= 190.2 N·m) becomes a high percentage of 83%. Figure 12 summarizes the experimental results of four cases, indicating that the particle-crushing energy covers in fact as much as 80 to 90% of the total energy. The results stated above clearly indicate that the point resistance of piles in sand greatly depends on the particle-crushing property of sand below the pile tip to a depth of several times of the pile diameter.

CONCLUSIONS

The point resistance of piles in sand was mainly

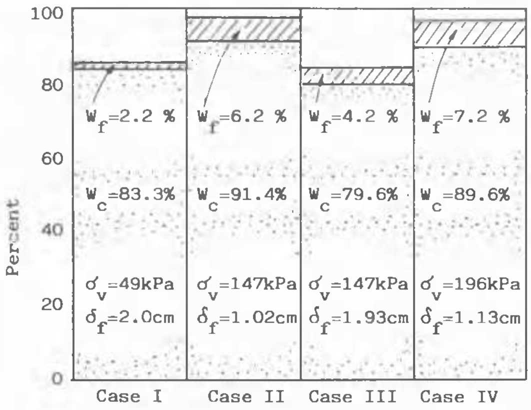


Fig. 12 Percentage of the Dissipated Energy for Particle-Crushing W_c and Shaft Friction W_f

investigated from the viewpoint of particle-crushing by carrying out model pile tests, and the following conclusions were derived.

(1) A bulb-shaped particle-crushing region of a dimension of two to three times of the diameter of piles develops around the pile tip.

(2) The work dissipated in the particle-crushing of sand is as much as 80 to 90 percent of the total work done by the external force.

(3) The point resistance of piles in sand greatly depends on the particle-crushing property of sand below the pile tip to a depth of several times of the pile diameter.

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