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ABSTRACT

Although the ground supporting the foundation can be regarded as three-dimensional nonlinear continuous body, in design, grounds are modeled as linear elastic springs. However, in reality, grounds exhibit nonlinear load-displacement (p-δ) characteristics. In Specifications for Highway Bridges (Japan Road Association, 1994), ground reaction coefficient is defined as the secant slope of noticeable displacement and load intensity on p-δ curve corrected according to width of foundation. For the purpose of examining the scale effect of large-diameter pile, this paper presents a study on scale effect of lateral ground reaction coefficient based on results of lateral loading tests performed using large loading plate in the pit of a large-diameter deep pile.

KEYWORDS

lateral loading test, lateral ground reaction coefficient, scale effect, large-diameter deep pile, calcareous sandy ground

INTRODUCTION

In designing pile foundations, the ground is considered as elastic springs and the piles as elastic beams. This means that when ground is subjected to a certain load p the displacement δ formed and the acting load are linearly proportional with each other. Therefore evaluation for lateral ground reaction coefficient which expresses this p-δ curve would be essential in foundation design. But ground reaction coefficient cannot be expressed alone by deformation modulus of ground but also in terms of shape, dimensions, and stiffness of loading surface of foundation. Moreover, there is a need to consider and determine the inconsistency, in the direction of depth, and inelastic property of ground, which are quite difficult to evaluate. As indicated in Specifications for Highway Bridges (Japan Road Association, 1994), the lateral ground reaction coefficient for pile foundation is taken as the secant slope on load-displacement curve within range of displacement suitable for foundation structures corrected according to loading width of the foundation. This correction, based on the outcome of studies by Public Works Research Institute (Ministry of Construction, 1967), is proportional to -3/4th power of loading width (refer to Japan Road Association, 1994) as indicated in equation (1),

$$k_H = k_{H0}\,(B_H/30)^{-3/4} \qquad (1)$$

where k_H (kgf/cm^3) is the lateral ground reaction coefficient, k_{H0} (kgf/cm^3) is the lateral ground reaction coefficient determined from plate bearing test using 30-cm-diameter rigid circular plate, and B_H (cm) is the equivalent loading width of foundation perpendicular to direction of load.

It is clear from equation (1) that the larger the diameter of pile the smaller the lateral ground reaction coefficient. Meanwhile, recent foundations are being designed as large-scale structures because of the growing number of huge bridges as well as for labor-saving construction; piles with diameter larger than 2 to 3 meters are also becoming common for pile foundations. This suggests problems about the amount of decrease in lateral ground reaction coefficient due to scale effect in relation to displacement limit for design. Three-meter-diameter pile corresponds to that of 30-centimeter-diameter decreased by approximately 18%. On the other hand, according to Technical Standards for Port and Harbour Facilities in Japan (Ports & Harbour Bureau, Ministry of Transport, 1979), there is hardly any decrease by load width for 30-cm-diameter piles or larger. This disagreement may be due to the difference of ground conditions considered in the experiment.

The actual structure considered in this paper is the foundation of a prestressed concrete rigid-frame bridge (see Fig. 1) with 2.5-m-diameter deep piles. This bridge is constructed by cantilever method from both ends towards the center. In order to coincide the girder according to plan its deflection during construction must be forecast. Particularly in the case of pile foundation, lateral displacement of pile and rotational displacement of pile head should also be estimated in addition to girder's displacement. This implies the importance of determining lateral ground reaction coefficient k_H to execution management. In this experiment, lateral loading tests in the pit for a deep pile is performed to know in-situ lateral ground reaction coefficient k_H, scale effect of k_H is examined, and the actual k_H used in calculating displacement is determined.

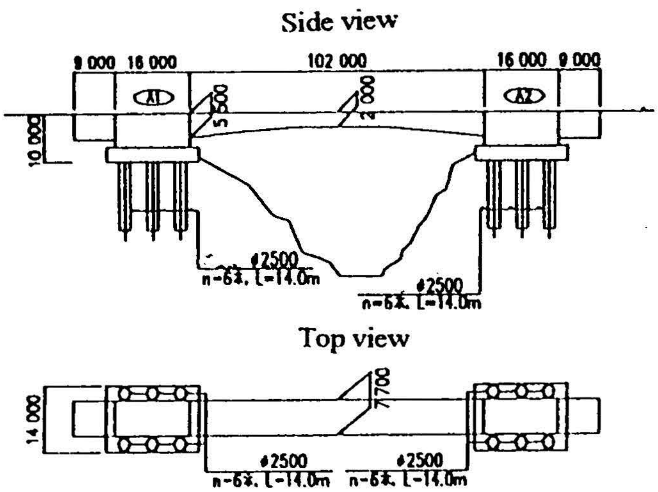

Fig. 1 General view of the bridge

LOADING TEST APPARATUS

Loading test site

The location of the loading test is shown in Fig. 2. The borehole of the pile in the second column which is quite away from the slope was selected as test site to eliminate any effects that slope would cause to the tests. Tests were conducted one meter above the bottom of excavation hole after constructing the 14- m-long pile. Sample blocks were collected after reaching the calcareous sand layer at the bottom of deep pile. Table 1 shows the physical properties of the samples, where W, W_s, V, ρ_t, ρ_d, e, and w represent the wet weight, dry weight, volume, wet density, dry density, void ratio, and water content, respectively.

Table 1 Physical properties of samples

sample	No.0-1	No.0-2	No.0-3	No.1-2	No.1-3
W(gf)	412.39	385.80	401.40	486.14	490.99
W_s(gf)	398.66	351.25	370.44	463.55	455.85
V(cm^3)	214.41	208.90	198.40	214.64	220.53
ρ_t(g/cm^3)	1.923	1.847	2.021	2.265	2.226
ρ_d(g/cm^3)	1.859	1.680	1.865	2.160	2.067
e	0.519	0.680	0.514	0.307	0.366
w (%)	3.44	9.84	8.36	4.87	7.71

The liner plate was removed and shaped into a 2.5-m-diameter circle to clear the gap between the loading plate and loading surface. The loading surface was also flattened.

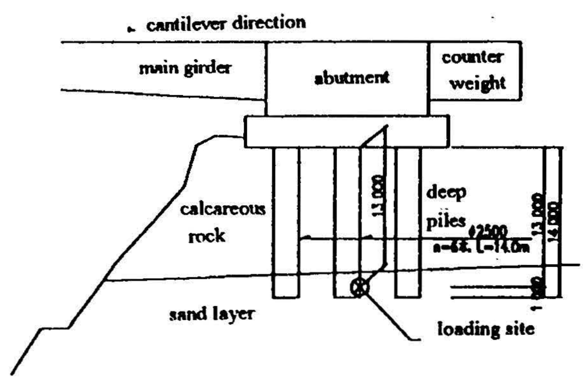

Fig. 2 Loading test position

Loading plate

As shown in Fig. 3, there were four types of loading plate and one anchor plate used. Size of loading plate was established, in regards to scale of the field, with 50-cm minimum width. Maximum width was set to 2 m, which is a little bit smaller than pile diameter (2.5 m), for proper installation. Furthermore, to obtain a consistent shape factor for the loading plates, the ratio of lateral width L to longitudinal width B, L/B, was fixed to 2.0. These widths correspond to the dimension of lateral projection plane.

The width in the middle was determined so that the equivalent loading widths are logarithmically at even interval. In designing the loading plates, the design reaction is uniformly distributed throughout the plate. Using SM490 as material for the plate, its allowable stress is similar to that of temporary structures which is 1.5 times of usual structures, i.e. σ_{ca}=2850 kgf/cm^2.

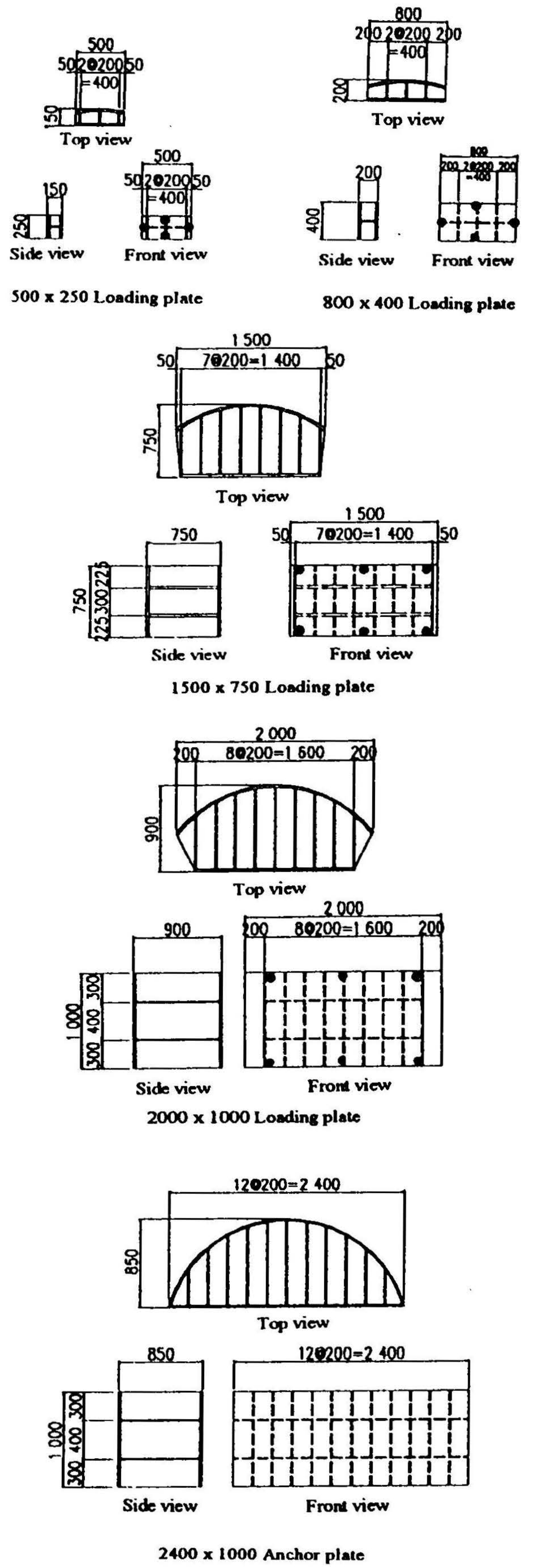

Fig. 3 Shape and dimensions of loading plates

Load and apparatus

The apparatus was set up in such a way that it would not settle at the bottom of the pile as shown in Fig. 4.

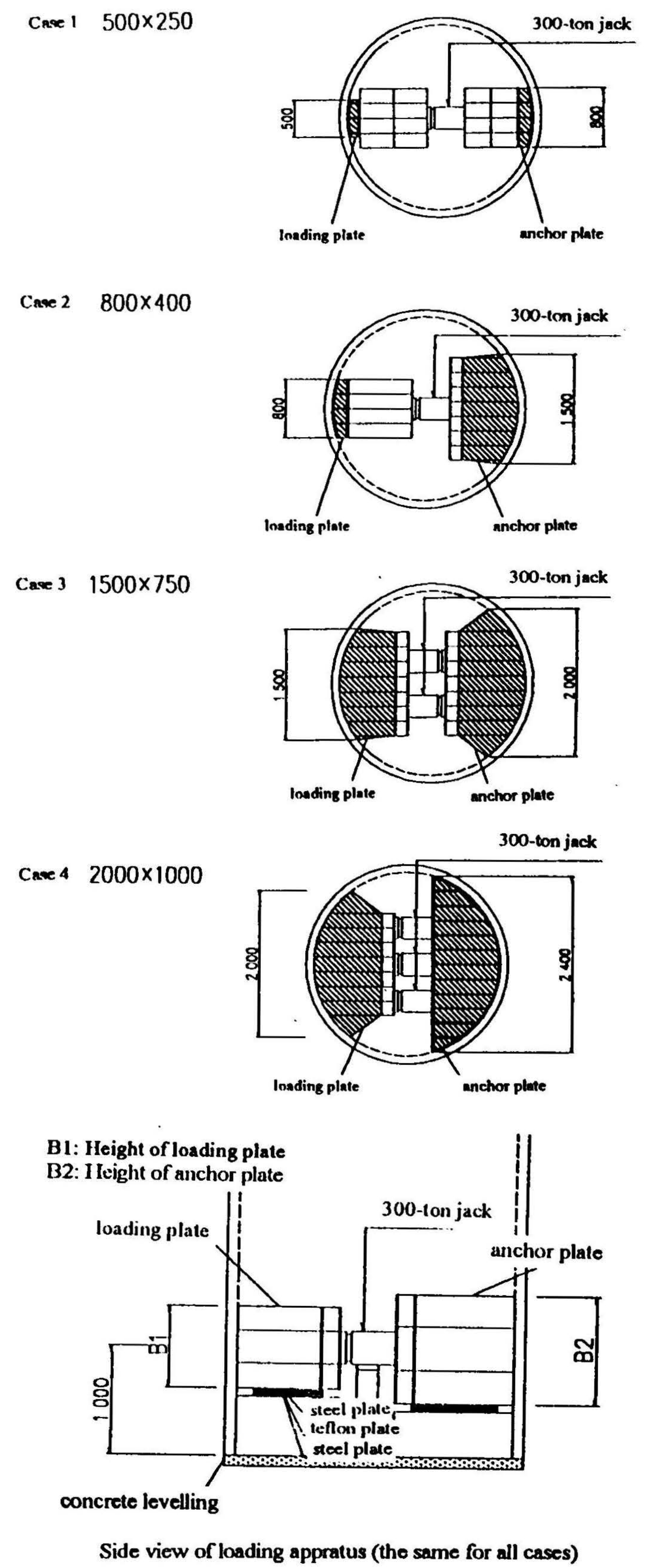

Fig. 4 Loading apparatus

Concrete was cast placing H-beam scaffold on top of it, then Teflon-lined steel plate was laid with loading plate set over it so that the jack directly acts on the loading surface.

There were three 300-tf jacks prepared which were combined according to strength of load. The order of loading was considered such that previous tests would have no effect on the later as much as possible. As shown in Fig. 4, case 1 and case 2 have the same direction, and case 3 and case 4 were adjusted transversal to it.

Displacement meters were attached to station beams which consist of round pipe and steel pipe struck into bottom of foundation. Four were fixed for case 1 and case 2, and six for case 3 and case 4. Their average reading would be the displacement of loading plate. In the detail drawing of loading plate, shown in Fig. 3, big round dots indicate the position of displacement meters.

Figure 5 shows the loading apparatus used for case 3, where on the left side is the loading plate of case 3 and on the right is that of case 4 used as anchor plate.

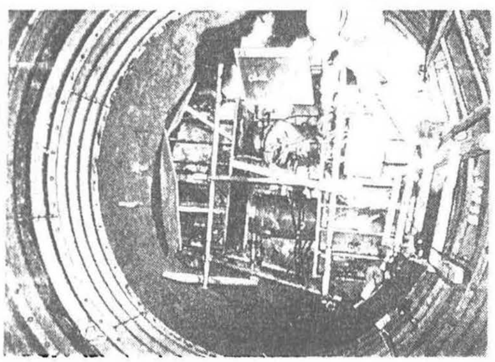

Fig. 5 Loading apparatus for case 3

The maximum load considered in the test is calculated, as standard value, according to the formula for passive earth pressure of caissons (see eq. 2) indicated in Specifications for Highway Bridges, since the form of ground failure is unknown.

$$p = K_P \gamma h + 2c\sqrt{K_P} \qquad (2)$$

$$K_P = \frac{\cos^2\phi}{\cos\delta\left[1-\sqrt{\dfrac{\sin(\phi-\delta)\sin(\phi+\delta)}{\cos\delta\cos\alpha}}\right]^2} \qquad (3)$$

In equation 2, K_P represents coefficient of passive earth pressure, γ (tf/m³) is density of soil, ϕ is angle of internal friction, α (=0 degree) is angle of inclination of ground surface, δ (=-ϕ/3) is angle of wall friction, c is cohesion of soil, and h (=10 m) is depth. Table 2 shows the yield loads calculated based on c, ϕ, and γ of sample blocks No.0, No.1 and the block composed of both. Herein, P and P_y represent ultimate and yield loads, respectively. Also, the density of soil γ is taken as the average value of corresponding wet densities in Table 1.

Table 2 Yield loads

(a) Case 1

sample block	No.0	No.1	No.0+No.1
K_p	3.565	3.316	3.244
p (tf/m²)	208.5	547.9	398.1
P (tf)	26.1	68.5	49.8
$P_y = P/1.5$ (tf)	17.4	45.7	33.2

(b) Case 2

sample block	No.0	No.1	No.0+No.1
K_p	3.565	3.316	3.244
p (tf/m²)	208.5	547.9	398.1
P (tf)	66.7	175.3	127.4
$P_y = P/1.5$ (tf)	44.5	116.9	84.9

(c) Case 3

sample block	No.0	No.1	No.0+No.1
K_p	3.565	3.316	3.244
p (tf/m²)	208.5	547.9	398.1
P (tf)	234.6	616.4	447.9
$P_y = P/1.5$ (tf)	1564	410.9	298.6

(d) Case 4

sample block	No.0	No.1	No.0+No.1
K_p	3.565	3.316	3.244
p (tf/m²)	208.5	547.9	398.1
P (tf)	417.0	1095.8	796.2
$P_y = P/1.5$ (tf)	278.0	730.5	530.8

Table 3 shows the computed maximum loads. Herein, ultimate loads were found where, for safety assumption, working area of resisting earth pressure is assumed as the area of loading plate. Maximum loads were obtained by considering half the capacity of the jack as standard, although yield load was basically adopted. The hatched parts in Fig. 4 show the loading plates.

Table 3 Maximum test loads

	Case 1	Case 2	Case 3	Case 4
$L \times B$ (cm)	50 x 25	80 x 40	150 x 75	200 x 100
P_{max} (tf)	35	120	350	520

Loading method

Loading method is based on multi-cycle system (see Fig. 6 to Fig. 9) indicated in JGS Standard (JGS, 1983). Maximum loads were classified into eight stages where loading was performed by load control system in either third or fourth cycle. Case 2 and case 4 were used temporarily as loading plates of case 1 and case 3. This means that discontinuity with respect to time exists between the current working load and the next load. Nevertheless, continuity in load-displacement curve is roughly maintained. Case 4 shows the working load in anchor plate of case 3 and its load cycle following case 3.

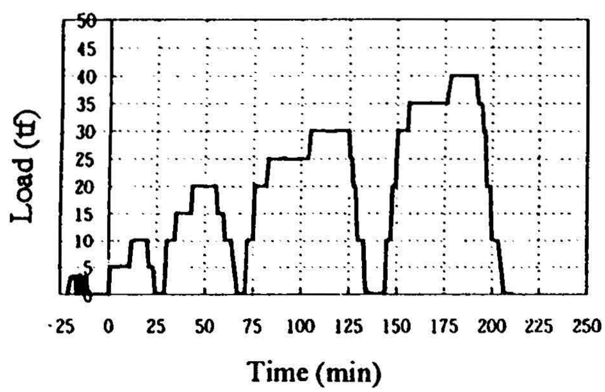

Fig. 6 Loading cycle for case 1

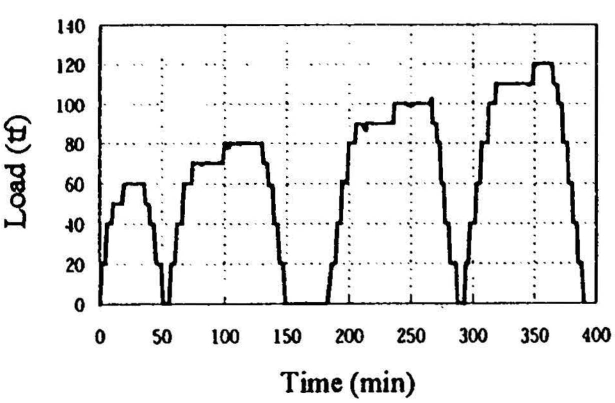

Fig. 7 Loading cycle for case 2

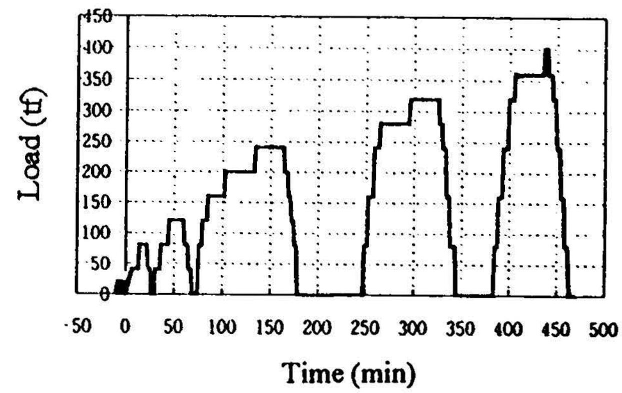

Fig. 8 Loading cycle for case 3

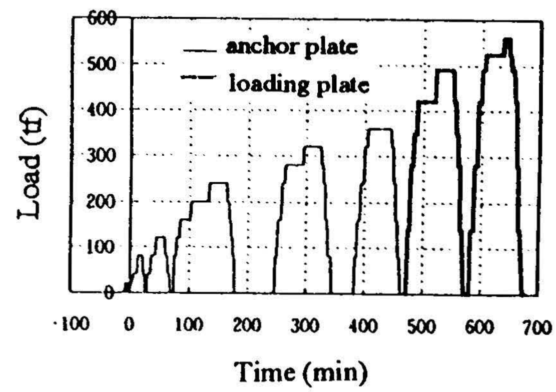

Fig. 9 Loading cycle for case 4

TEST RESULTS

Load-displacement curve

Load-displacement curves of case 1 to 4 are shown in Fig. 10 where displacement of loading plate is taken as the average record of all meters installed in the plate. Meters were installed as shown in Fig. 3, that is, 4 for case 1 and 2, and 6 for case 3 and 4. Yield loads are estimated using the logP-logS curves in JGS Standard (JGS, 1983) as shown in Fig. 11 to Fig. 14. The points indicated in these figures represent the yield loads according to logP-logS curves. When yield load is exceeded, ground displacement above loading plate becomes larger than below causing torque in the plate and making it impossible to measure post-yield displacements. It appears that ground failure occurred forming sliding surface under the ground and creating loading plate to expand.

In case 4, the displacement corresponding to maximum load of case 3 is obviously larger than the record observed in anchor plate of case 3. Since later load-displacement curve was not obtained in case 4, the load-displacement curve of case 3 before its maximum load is also adopted. In case 2, load-displacement curve of anchor plate and the one due to later reloading were arranged independently from each other.

The yield loads obtained from Fig. 11 to Fig. 13 are compared with that used as maximum loads of test. It reveals that for case 1 to 3 yield loads calculated from material property of entire ground are nearly equal to values determined from the figures; in case 1, the former is 33.2 tf and later is 30 tf, in case 2, these are 84.9 tf and 90 tf, and in case 3, 298.6 tf and 250 tf. In case 4, the yield load taken from Fig. 14 is 350 tf which lies halfway between the values computed from material property No.0, 278 tf, and from material property of entire ground, 530.8 tf.

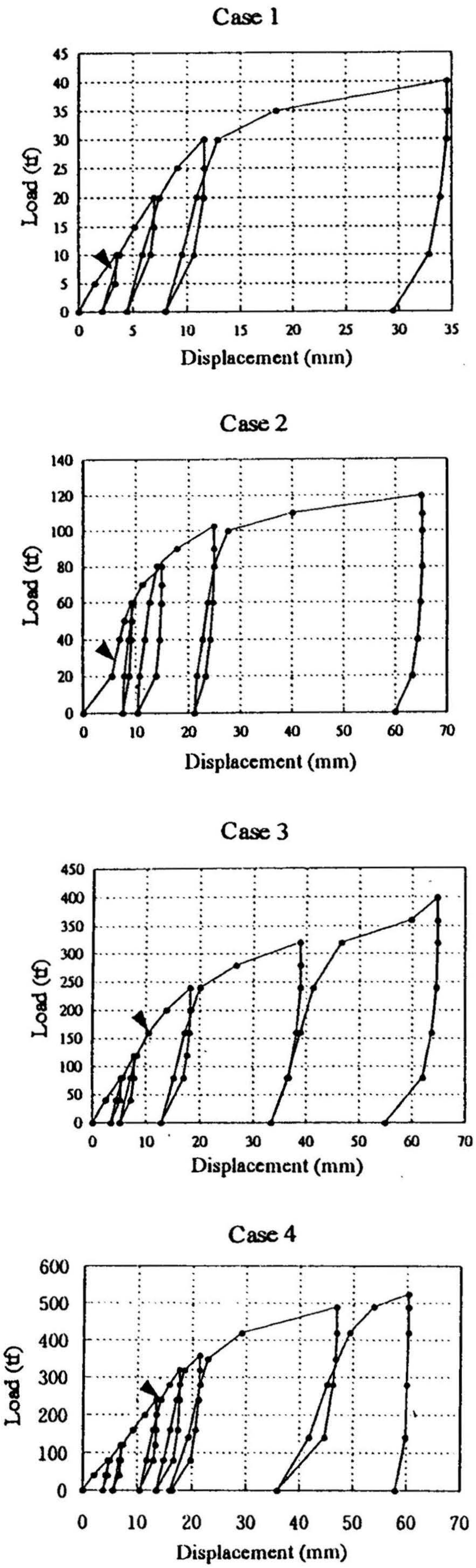

Fig. 10 Load-displacement curves

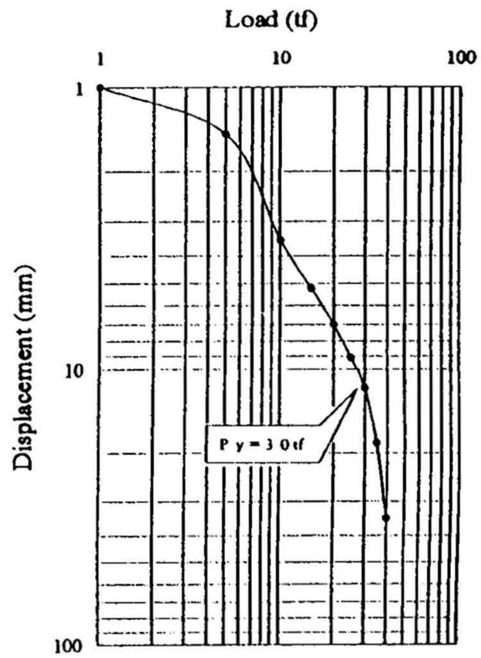

Fig. 11 Yield load for case 1 based on Log P~Log S graph

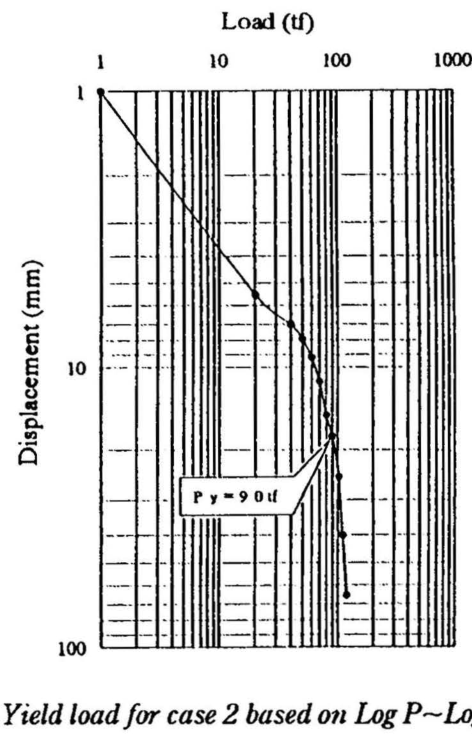

Fig. 12 Yield load for case 2 based on Log P~Log S graph

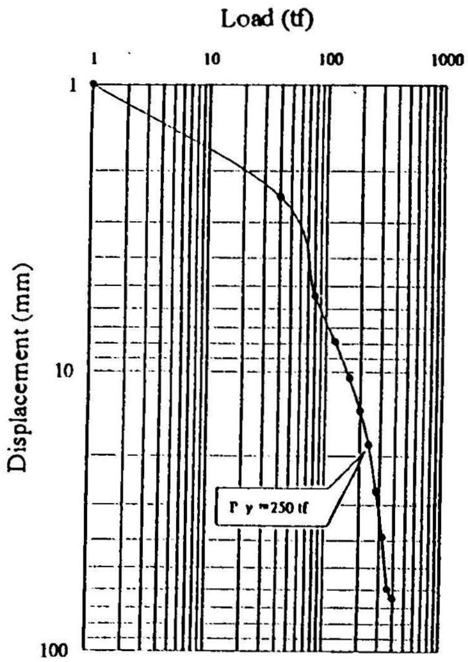

Fig. 13 Yield load for case 3 based on Log P~Log S graph

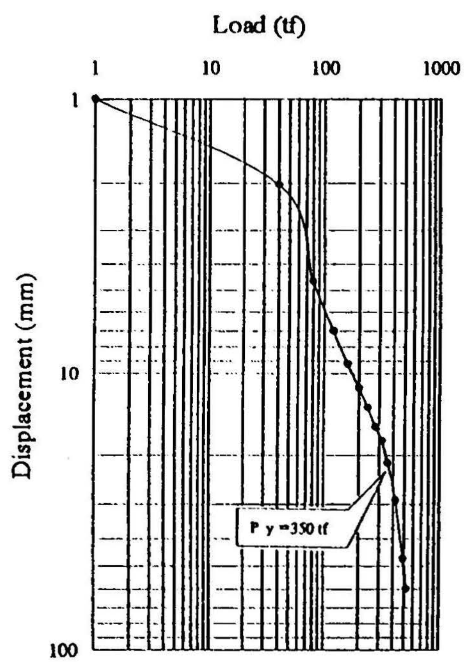

Fig. 14 Yield load for case 4 based on Log P~Log S graph

Although spread of resisting earth pressure is not taken into account in establishing test loads, strength of samples are almost evenly distributed as seen from scales of loading plates used. Thus, the ground can be considered, as it appears to be, uniform. Moreover, load-displacement curves used in examining lateral ground reaction coefficient k_H are also obtained from test results.

Scale effect of ground reaction coefficient

The standard displacement usually used in design of pile foundation, that corresponds to 1% of pile diameter, is determined so that residual displacement will not occur (Japan Road Association, 1994). In conformity to this, standard displacement at initial stage of loading test used in computing lateral ground reaction coefficient k_H is considered to be the displacement which corresponds to 1% of loading width.

Loading width is regarded as equivalent loading width, i.e. $B_0=(LxB)^{1/2}$. Table 4 shows the lateral ground reaction coefficients k_H which are calculated from load-displacement curves that correspond to 1% strain of equivalent loading width.

Table 4 k_H corresponding to 1% strain of loading width

	Case 1	Case 2	Case 3	Case 4
Loading surface area, A (cm^2)	1250	3200	11250	20000
Equivalent loading width, A$^{1/2}$ (cm)	35.4	56.6	106.1	141.4
Standard displ., δ (mm)	3.54	5.66	10.61	14.14
Load (tf)	7.143	30.0	160.0	240.0
Ground reaction, $\sigma=P/A$ (kgf/cm^2)	5.714	9.375	14.222	12.000
$k_H=\sigma/\delta$ (kgf/cm^3)	16.140	16.564	13.404	8.487

It can be recognized that as loading width becomes larger k_H becomes smaller. Suppose that ground displacement follows the theory of elasticity, then k_H would be inversely proportional to loading width (Japan Road Association, 1994). According to Specifications for Highway Bridges, this is proportional to -3/4th power of loading width based on laboratory test results for Kanto loam and wet sandy ground (Public Works Research Institute, 1967). On the other hand, according to Technical Standards for Port and Harbour Facilities in Japan (Ports & Harbour Bureau, Ministry of Transport, 1979), scale effect for loading width of 30 cm or larger, i.e. k_H due to loading width, does not decrease for sandy grounds. These suggest that scale effect varies with respect to ground conditions.

Figure 15 shows the lateral ground reaction coefficient expressed as function of equivalent loading width based on the test results. The small squares in the Fig. 15 marks the values obtained from test results. Results which correspond to Specifications for Highway Bridges and theory of elasticity are also indicated in the same figure.

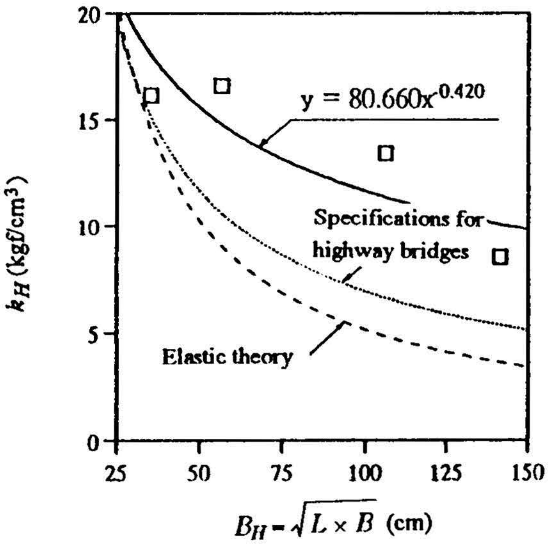

Fig. 15 k_H coefficient of calcareous sandy ground

In the test ground, i.e. calcareous sand bed, the scale effect of lateral ground reaction coefficient k_H obtained from large curved loading plate varies, as equivalent loading width increases, in proportion to loading width raised to -0.42 power. Therefore, the decrease of k_H becomes smaller compared with that of Specifications for Highway Bridges, where loading width is raised to -0.75 power.

CONCLUSIONS

Lateral loading tests in the pit for a 2.5-m-diameter deep pile in calcareous sand bed were performed. The physical and mechanical characteristics of calcareous sandy ground were investigated based on sample test results.

The following summarizes the results of sample tests and undisturbed samples of calcareous sandy ground.

- Undisturbed samples were formed after freezing using core bit for decomposed granite soils.
- Calcareous sandy grounds have different degree of solidifications as well as physical and mechanical properties corresponding to location of sampling.

Moreover, below reveals the results concerning the scale effect of lateral ground reaction coefficient k_H for the test ground.

- Lateral ground reaction coefficient k_H calculated from load-displacement curve that corresponds to 1% strain of equivalent loading width tends to become smaller as loading width becomes larger.
- By comparing k_H with those obtained from the past test results, it is found that scale effect have an inclination to change with ground characteristics.

The performed test presented just one example of scale effect of k_H but it is believed that studies on lateral resistance of underground structures having large loading width, like large-diameter piles and diaphragm walls, contributes significant informations in the future. Hence, further study will be presented in the future by performing simulations of loading tests and investigating k_H for foundations with large loading width.

The lateral resistance observed from the test results is used in examining adjustments of vertical displacements of girder during construction of the rigid-frame bridge. The k_H obtained from test results is used in regulating deflections of girder during cantilever installation since it is larger than the prescribed safe value in Specifications for Highway Bridges. Since there is risk of overestimating vertical displacement in using Specifications for Highway Bridges, control value based on k_H of test results is applied.

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