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Characteristics of Multi-pile Foundation

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1. Introduction

Multi-pile foundations of the type that large diameter piles are founded into the desired bearing layer and are rigidly bound at their heads by a top-slab have been recently brought into gradual application starting from Great Bridge of Biwa Lake, because of their easy construction in water. Report on the technical investigation of the connecting bridges of Honshu and Shikoku also considers this type of technique as one of the objects, in the comparison design, in the same rank as other foundation types. However, since experience on this type of construction is still not enough and no experiment has been made with respect to this technique, much to be clarified is left on its mechanical properties, requiring a prompt investigation of the method of design. The present report describes part of the results investigated in the horizontal load test and vibration test of models of multi-pile foundation.

2. Outline of test

2-1 Structure and dimensions of models and the ground condition of test site.

The test models were installed in the compound of Chiba Branch, Public Works Research Institute. Their structure and dimensions are shown in Fig. 1 and the ground condition is shown in Fig. 2. The stiffness ratio of the top-slab to the pile is 52 and 7 at the top-slab of No. 1 and No. 11 respectively.

2-2 Testing Methods

Kinds, methods and measuring instruments of test carried are listed in Table 1.

Loads are imposed by connecting two test models with a PC steel rod and mutually pulling them with a jack. In parallel with this test, horizontal loading tests of single pile using piles of same diameter in the same compound have been made.

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Table 1 Testing method

Kind of test	Load	Position of load (denoted with symbols in Fig. 1)	Measuring instrument
Axis-centered horizontal load test at the top-slab position	Max. 30 ton 3 cycle	A	- o Wire strain-gauges (165 pieces) (overground part of steel pipes, steel pipes inside the top-slab, bottom surface of the top-slab, surface of concrete, reinforcing steel pipes, tower). - o Molded gauges (48 pieces) (inside the concrete of the top-slab) - o Dial gauges (18 pieces) - o Deflectometers (3 pieces) - o Water-pipe type inclinometers (4 pieces) (on the top-slab) - o Accelerometers (14 pieces) (on the top-slab, steel pipes)
Eccentric horizontal load test at the top-slab position	Max. 15 ton 2 cycle	B	
Axis-centered horizontal load test at the tower-top position	Max. 100 ton 5 cycle	C	
Axis-centered natural vibration test at the top-slab position	Initial load 10 ton	A	
Eccentric natural vibration test at the top-slab position	Initial load 5 ton	B	
Axis-centered natural vibration test at the tower-top position	Initial load 10 ton	C	
Forced vibration test at the top-slab position	Vibrational power 0.3, 0.6, 1.3, 1.8 ton	Vibrator set on the top-slab	
Single-pile horizontal load test	Max. 4.75 ton 2 cycle	58.5 cm above the ground	

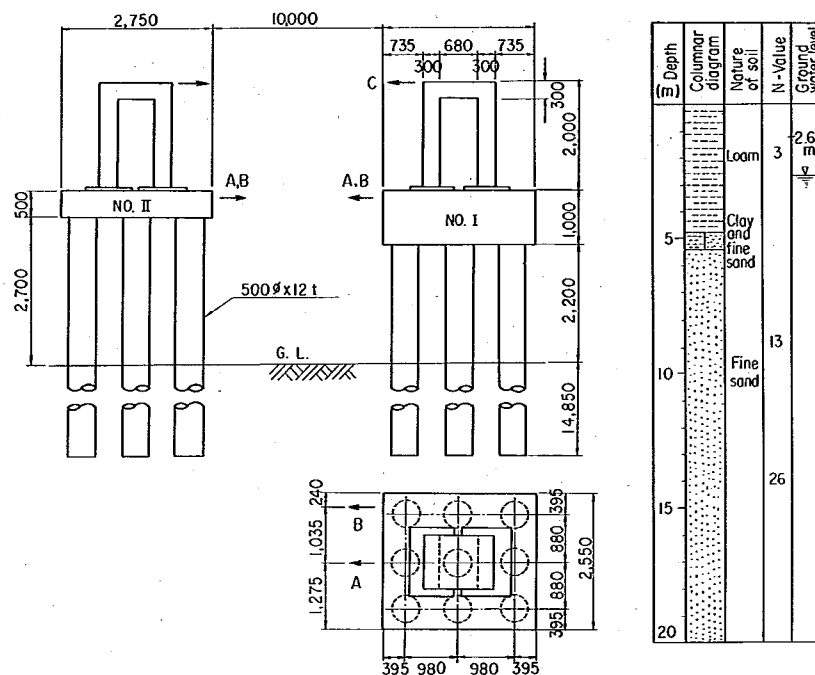


Fig. 1 Structure and dimensions of models

Fig. 2
Ground condition

3. Results of horizontal load test and discussion

Fig. 3 and Fig. 4 show examples of displacement and angle of inclination in the axis-center horizontal load test at the top-slab and the top-end of tower. The displacement of the test model is, in general, obtained from the spring constant of ground but here, on the contrary, mean lateral ground reaction coefficient K was obtained by a back calculation from the measured displacement and the angle of inclination, assuming the equal share of each pile. They are plotted against the magnitude of the displacement at the ground surface in Fig. 5, together with K -values obtained from the horizontal load test of single piles. The result indicates that the K -value of the model is smaller than that of single piles owing to group pile effect. Also different K -values depending on load positions may be considered to be influenced by the different deformation of piles even for equal ground surface displacement (The tower loading gives a larger rotation angle.).

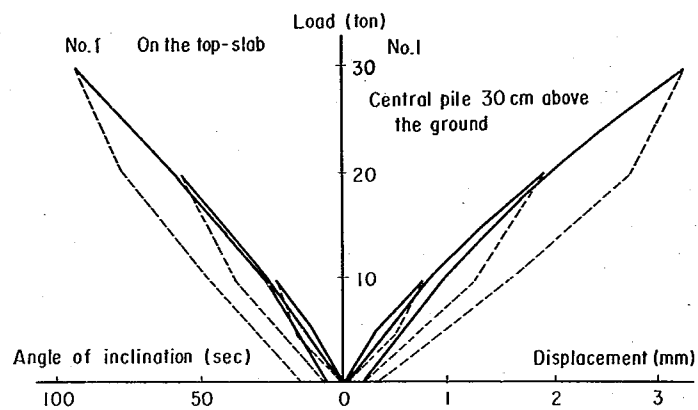


Fig. 3 Axis-centered horizontal load,
load vs. displacement
angle of inclination curve

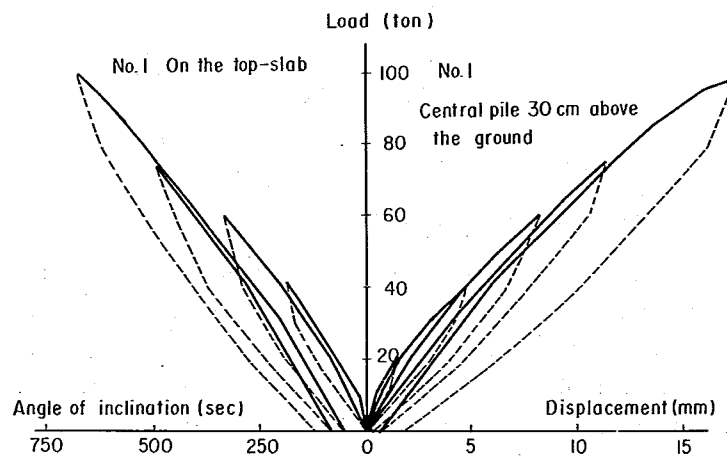


Fig. 4 Horizontal load on the top-end of the tower,
load vs. displacement
angle of inclination curve

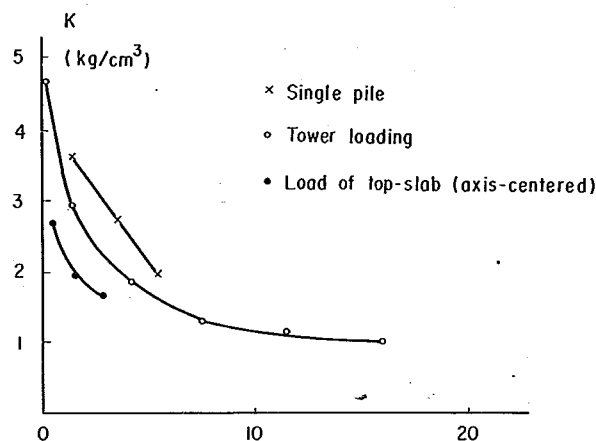


Fig. 5 Displacement of pile of the ground surface vs. lateral ground reaction coefficient K (mean)

Next, Fig. 6 shows the ground reaction coefficient of each pile in the form of ratio to that of the central pile, through backward calculation from the horizontal force and the bending moment shared at the head of the pile obtained by measured strains.

The figure shows that the K-values of the front row are 50 - 70% larger than that of the central pile and those of the rear row are approximately equal to it. Moreover, the K-values of the side piles and that of the central pile are little different. It is evident from a simple calculation formula that the share ratio of the K-value does not directly correspond to the share ratio of the horizontal force or bending moment and as the K-value increases, the influence of the share ratio of K-value on that of the force decreases. In the present experiment, the share ratio of force is 40 - 50% larger than that in the front row piles than that of the central pile.

As the relationship of the share ratio of spring constant with that of force varies with the strength of spring as is shown above, further investigation is needed which way is more universal in the expression of share ratio of pile group.

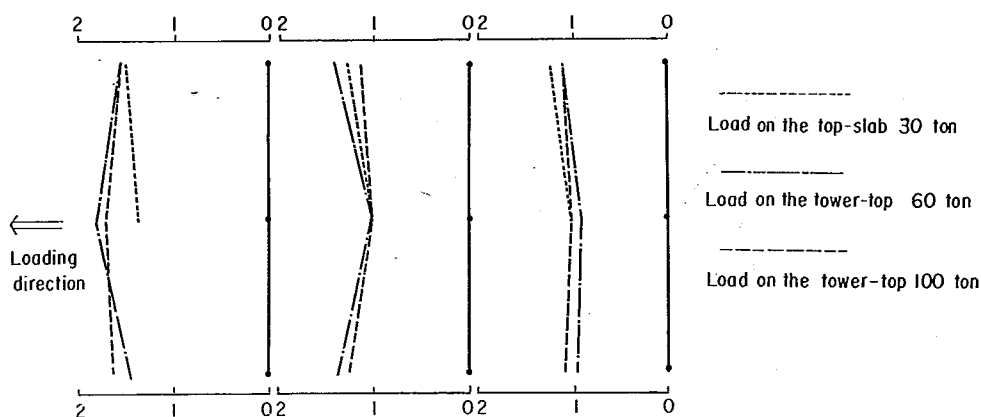


Fig. 6 Lateral ground reaction coefficient ratio of each pile on the basis of central pile (=1)

In the second place, Fig. 7 shows the plot of relationship of the torsion spring constant K_θ , which is designated for the ratio of the moment of the external force with respect to the center of the top-slab to the rotation angle of the top-slab, with the displacement of the top-slab in the eccentric load test. The tendency that K_θ decreases as the displacement increases can be seen probably due to the transfer of the share ratio of the horizontal load shared by the pile from the load side to the opposite side, causing the larger increasing rate of torsional moment exerting on the pile head than that of load weight. Calculation of the apparent fix point of pile from the measured value of the torsional moment and the torsional angle exerting on the pile head gives the position of 2.5 m below the ground for both of No. I and No. II. This result

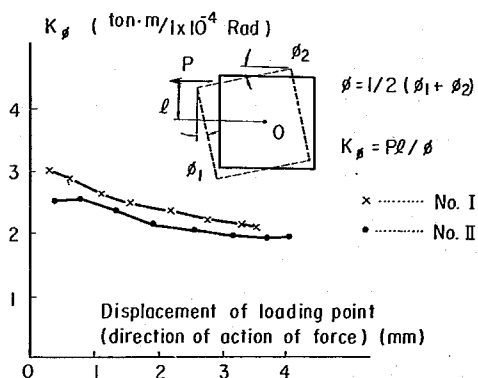


Fig. 7 Eccentric horizontal load on the top-slab, displacement vs. torsional spring constant on the top-end of the top-slab

shows that even Kanto loam layer can provide enough constraint if such extent of embedded length is allowed. In this case, of the total torsional resistance, 80% is due to the body of the pile and about 20% is due to the horizontal ground reaction. Accordingly, in the multi-pile type having low rigidity of the foundation, the check on "torsion" is required.

4. Results of vibration test and discussion

In Table 2 and Table 3, are shown the results on natural frequency and damping factor obtained in the natural vibration test and forced vibration test. By obtaining the natural frequency of the multi-pile foundation on the assumption of one degree of freedom system model and also taking the total mass on the ground as the mass contributing to vibration, the lateral reaction coefficient of the ground calculated backwards from the measured period will be

axis-center natural vibration of the top-slab $K = 1.23 \text{ kg/cm}^3$

axis-center natural vibration of the tower $K = 1.24 \text{ kg/cm}^3$

forced vibration $K = 1.08 \text{ kg/cm}^3$

which correspond to the values at fairly large displacement in comparison with the static K-values of Fig. 2.

Table 3 Resonance frequency
 $f' \text{ (C/S)}$

Damping factor h
Natural frequency $f \text{ (C/S)}$

$$f = f' \sqrt{1-2h^2}$$

(No. 1, central pile, from the measured strain, at the point 1.7 m above the ground)

Vibrational power	$f' \text{ (C/S)}$	h	f
0.3	7.3	0.073	7.85
0.3	7.85	0.078	7.9
0.6	7.85	0.078	7.9
0.6	7.85	0.080	7.9
1.8	7.65	0.087	7.7
1.8	7.50	0.066	7.55

Table 2. Natural frequency f (c/s), damping factor h (natural vibration)

Set position of Accelerometer		Axis-centered natural vibration test at the top-slab		Eccentric natural vibration test at the top-slab		Axis-centered natural vibration test at the tower-top	
		f	h	f	h	f	h
No. I	Axial direction on the center of the top-slab	8.5	0.074	8.5	0.088	7.8	0.068
	Perpendicular-to-axis direction on the center of the top-slab	-	-	9.5	0.058	-	-
	Axial direction on the upper corner of the top-slab	8.5	0.071	8.0	0.058	7.8	0.062
	Perpendicular-to-axis direction on the upper corner of the top-slab	-	-	15.2	0.064	-	-
	Axial direction at 2 m above the ground of the central pile	8.5	0.075	8.3	0.086	7.8	0.075
	Axial direction at 0.3 m above the ground of the central pile	8.5	0.088	8.3	0.097	7.8	0.071
No. II	Axial direction on the center of the top-slab	9.5	0.128	10.0	0.153	8.3	0.058
	Perpendicular-to-axis direction on the center of the top-slab	-	-	18.0	0.077	-	-

This calculation considers the part which appears on the ground as the vibrating mass but, in actual, the additional mass existing under the ground may be required to consider. The wave form of the natural vibration indicates the gradual decrease of the amplitude owing to damping but the period undergoes very little influence. It is considered from this fact that the dynamic spring of the ground is not so affected as the static spring by the magnitude of the deformation. Fig. 8 shows the mode of acceleration obtained in the natural vibration test at the top of the tower. On the assumption that of the results of acceleration measurement in the eccentric natural vibration, the frequency along the perpendicular direction to the axis at the upper corner of the top-slab is due simply to the torsional vibration (the influence of the coupled vibration is neglected, but it is recognized as about 10 - 20% from the result of axis natural vibration test), the torsional spring constant is obtained which agrees roughly with the static spring shown in Fig. 7.

5. Postscript

This paper reports on the large scale model experiment elucidating the characteristics of the multi-pile foundation and as its part, the test results from the viewpoint of spring of ground. While their outline is simply described, the more detailed

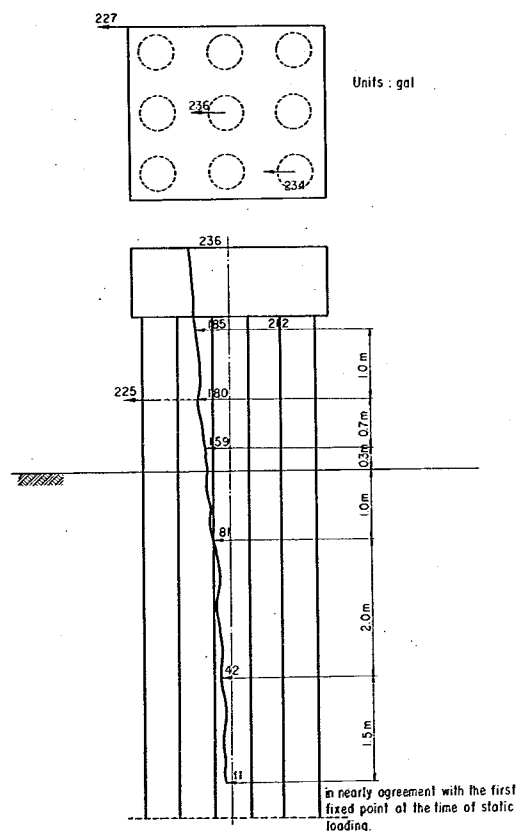


Fig. 8
Acceleration mode of natural
vibration at the tower-top position

investigation is in progress, for dissolving many problems left. For example, concerning the share ratio of load of each pile, the accumulation of the data is being obtained quantitatively under different conditions for gaining more universality.

Also as for the dynamic spring, its effective method of estimation is a future problem as being related to the concept of the additional mass of soil.

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