Dynamic experiments with model pile foundations

Expériences dynamiques avec des modèles de fondations sur pieux

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SYNOPSIS: A pile group with typical spacing subjected to either vertical or horizontal forces usually has a global stiffness less than the sum of stiffnesses of individual piles taken separately in the same embedment material. This is due to the phenomenon of pile-soil-pile interaction. Dynamic experiments conducted on rigid-fixed-cap model steel pile groups with small numbers provided data which allowed examination of effects of spacing and displacement amplitude on the dynamic behavior of pile groups. It was found that spacing has a dominant effect and a practical limit beyond which no interaction occurs was suggested. Response non-linearities were also observed and interpreted.

INTRODUCTION

For many heavy civil engineering structures such as modern urban buildings, off-shore platforms, nuclear power plants etc., deep foundations are selected to ensure safety by providing necessary resistance and stability. Electro-mechanical machinery which require strict limitations on foundation motion are also often supported on piles. These foundations could be subjected to different types of forces such as the static weight of structure, or dynamic loads like wind, sea waves, earthquakes, or machinery with unbalanced forces. To achieve sound design coupled with cost-effectiveness thorough understanding of the behavior of deep foundations is fundamental.

Studies on the behavior of pile groups under dynamic forces were first undertaken in the late 70's and were mainly numerical, Wolf et al. (1978). Several assuptions on the mechanical properties and configuration of the dynamic system components were adopted. Most of these studies agreed on the fact that interaction effects are of importance and identified the parameters which affect it. A limit on the spacing to diameter ratio varying between 30 and 100 for horizontal motion, and 10 and 20 for vertical motion beyond which interaction can be neglected was found for small groups. The uncertainties shown by these ranges of spacing to diameter ratios show that experimental data are of great value.

In this investigation data were obtained from carefully conducted dynamic experiments on model steel pile groups with spacing ratios ranging from 2 to 10. Groups of 2 and 4 piles embedded in granular soil were considered. The rigidity of the pile group cap and its fixity to piles were both ensured by careful design and execution of construction details. Response due to vertical and horizontal dynamic forces were obtained.

PREPARATION FOR TESTS

Testing facility and physical soil properties

Tests were conducted in the Geotechnical Engineering Testing Facility at the University of Michigan. It consists of a 6.70 m diameter and 2.13 m deep cylindrical bin filled with sand. Fig. 1 shows the sand bin along with some loading equipment used in performing the tests.

The soil was fairly homogeneous, fine to medium, poorly graded sand (SP) with small amount, 3.0 %, of fine particles with size less than 0.1 mm. It had a coefficient of uniformity C_u of 2.9 and an effective size of 0.13 mm. The minimum and maximum void ratios were 0.57 and 0.76 respectively and the specific gravity G_s was 2.67.

Fig. 1 Overview of Pile Testing Facility

Model piles and pile caps

The model piles were hollow steel pipes with a unit mass of 7.8 t/m^3, a compression modulus of $2*10^5$ MN/m^2 and a Poisson's ratio of 0.3. They have an outside diameter of 6.0 cm and a ratio of inside to outside diameter of 0.85. The embedded length was 1.98 m. These dimensions correspond to an aspect ratio of approximately 33 and a moment of inertia of 27.47 cm^4. The model piles were selected to be relatively flexible, to avoid bin side effects, and to ensure total embedment in a single homogeneous soil stratum.

Caps were designed to be rigid relative to the piles which were rigidly connected to them. Rigidity of connection ensured a head-fixity condition while rigidity of the cap itself is necessary to simplify analysis and interpretation. These conditions result in a maximum horizontal stiffness for the pile group. Fig. 2 illustrates different extreme combinations of cap and pile-cap connection and expected cap displacement for groups of 2 or 4. The condition shown by Fig. 2 (c) was the goal for these tests.

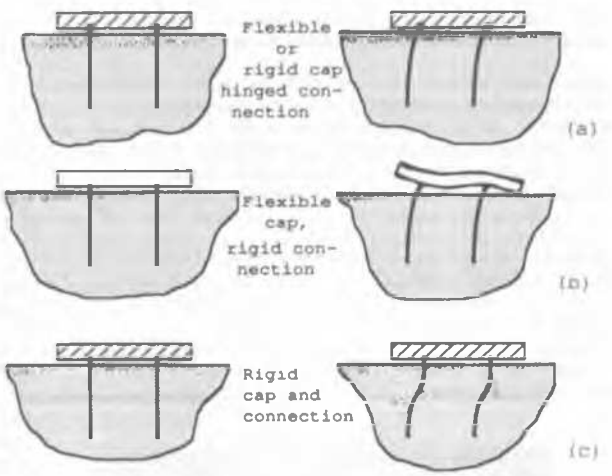

Fig. 2 Effects of pile-cap connection and cap rigidity

In practice a relatively rigid cap is easy to design and build. However the degree of fixity of the connection of piles to pile cap is quite difficult to control and evaluate although the overall stiffness of a pile foundation is very sensitive to it. It also depends on the amount of deformation. A criterion for practically ensuring rigid caps could be that the ratio of bending stiffness of cap (B_c) to that of pile [$4EI/l_e$] be greater than a certain limit where E is the Young modulus of steel, I the moment of inertia of one pile and l_e the effective length of pile.

In the present study l_e was taken as 14 times the outside pile diameter and the lower limit ratio was set at 55. For groups of two piles, pairs of structural steel channels (C5/6.7 or C6/8.2) were machined out and welded to opposite sides of piles. The amount and pattern of weld were selected in order for the connection to stiff. Thick, heavily reinforced concrete caps were adopted for groups of four. The steel reinforcement was made of no. 6 or 7 deformed bars placed near the bottom of cap. It was found through monitoring motion of the pile caps at selected locations that these cap systems reduced the cap rotation to a negligible amount for spacing ratios greater than 4. For smaller spacings, relatively small rotations occurred probably because of the fact that the group tend to behave as a single 'composite pile'.

Installation and mechanical soil properties

To ensure the desired precision in pile alignment and verticality, the piles were installed by first excavating a large pit and then replacing the soil around the piles by vibratory compaction in lifts. A hand auger was used to dig small holes about one meter deeper and at the predetermined pile locations. Piles were then carefully placed. Soil was backfilled in 13 cm thick lifts and compaction was performed for each lift. A Nuclear Density Meter was used to control unit weight the average of which was 16.95 KN/m^3. This value corresponds to a dense condition. Fig. 3 shows piles during the backfilling stage. After piles were installed,

Fig. 3 Piles During Installation Stage

caps were built and heavy steel plates were rigidly connected to the cap to provide for inertia and maintain resonance frequencies within the operating range of the forcing devices.

To use results of these tests in the evaluation of analytical approaches to the problem of dynamic behaior of pile groups, it is necessary to know the dynamic properties of the soil (i.e., shear modulus and damping). Cross-hole and resonant column tests were used to determine these two properties respectively. The former varied between 137 m/sec at a depth of 30.5 cm and 244 m/sec at 1.83 m, the latter between 3.0 % and 1.3 % at the same depths.

TESTING PROCEDURE

A series of low strain harmonic tests were first performed using an electro-magnetic type of exciter which generates forces with frequency-independent amplitudes. This shaker is quite versatile in that it can be used in various modes and is easy to connect to many types of test-structures and also easy to operate. Response and free vibration decay curves were obtained for forces ranging from 22 to 156 N for horizontal mode and 22 to 67 N for vertical mode. Velocity transducers were used to measure cap motion. After installation of piles, excitation was applied to the cap for a certain period of time before readings were taken. This is to allow for the system parameters to reach stationary values as these parameters usually change during the initial stage of vibration. For all groups tested, the maximum displacement reached was 1/100 times pile diameter. This value was for the group of 2 with spacing ratio 2. It was at resonance with the largest force amplitude. Fig. 4 shows a final test set-up for a group of four. Subsequent to the above tests

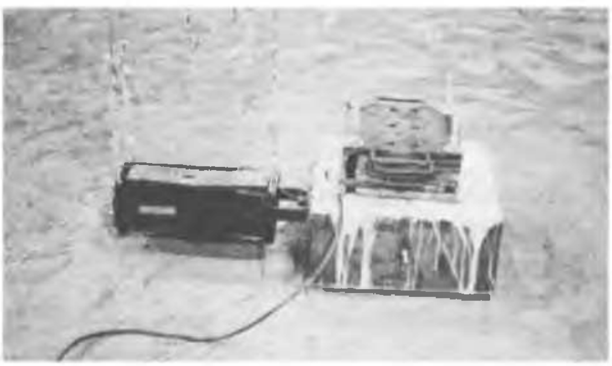

Fig. 4 Test Set-up for group of four.

and in order to test for larger vibration amplitudes, a rotating-mass type of shaker capable of generating large forces with frequency-dependent (i.e., proportional to w^2) amplitudes was used. The maximum displacement for the same group of 2 was 1/40 the pile diameter for a force amplitude at resonance of 401 N.

RESULTS AND DISCUSSION (Low Strain Tests)

Typical frequency response curves are shown in Fig. 5 for horizontal vibration. It can be seen from the shape of curves that foundation response to dynamic forces is similar to that of a damped, single degree of freedom system (SDOF). This supports the fact that a SDOF model can be used to interpret results of these dynamic experiments. In particular the dynamic stiffness coefficients can be taken as parabolic and linear functions of frequency respectively (i.e., stiffness and damping). Weak softening can also be seen for horizontal response as response curves bent slightly to the left and resonance frequency decreases with increase in force. This may be explained by material behavior under different displacement amplitudes. Damping increase with vibration amplitude

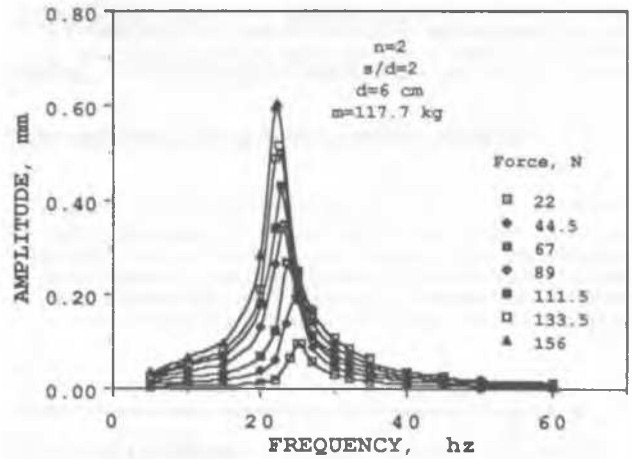

Fig. 5 Dynamic Response Curves from Small Amplitude Harmonic Horizontal Tests

causes non-proportionality between displacement at resonance and force. Damping was measured by free vibration decay and demonstrated viscous behaviour.

Damping ratios and coefficients from decay curves are shown in Table I for groups of 2 and 4, and forces of 44.5 and 89 N respectively. From previous works on damping of steel structural elements the damping ratio of the steel piles should not exceed 1.0 %. The contribution of soil to system damping can then be appreciated. Damping coefficients increase significantly with spacing for spacing ratios less than 8. This may be due to increase in size of soil block between piles moving in phase with them and then causing more energy radiation. Dynamic signals of strain gages installed along piles down to a depth of about 1.0 m showed that piles do move in phase, when excited at cap level. For large spacings it seems that wave reflection due to piles has little effect on system damping. This may not be true for large groups. So interaction effects on damping is expected to increase with group size for the same spacing.

TABLE I
Damping Ratios and Coefficients

n	s/d	Mass (Kg)	D (%)	c (N.sec/m)	Change (%)
2	2	117.6	6.8	2495.5	-
	4	210.9	6.25	4111.8	65
	6	262.4	6.6	6190.6	50
	8	317.8	6.44	7291.6	18
	10	380.0	6.1	7989.1	10
4	2	245.0	5.67	5262.1	-
	4	410.5	5.36	8879.4	68
	6	620.0	5.88	13215.7	48
	8	676.5	6.21	16426.2	24
	10	810.0	5.72	18509.3	13

Fig.6 shows relative change of group stiffness RC for groups of 2 and 4. Results from both horizontal and vertical vibration tests are shown. Relative change is defined as

$$RC(i) = \frac{k_i - k_{i-2}}{k_{i-2}}, \; i = 4,6,8,10 \quad \ldots\ldots\ldots\ldots\ldots(1)$$

in which k_i is stiffness of group with spacing ratio i. This is a good index to evaluate the importance of interaction as low values indicate small interaction, upward concavity means that rate of decrease of interaction decreases with spacing ratio, and vice-versa. Interaction

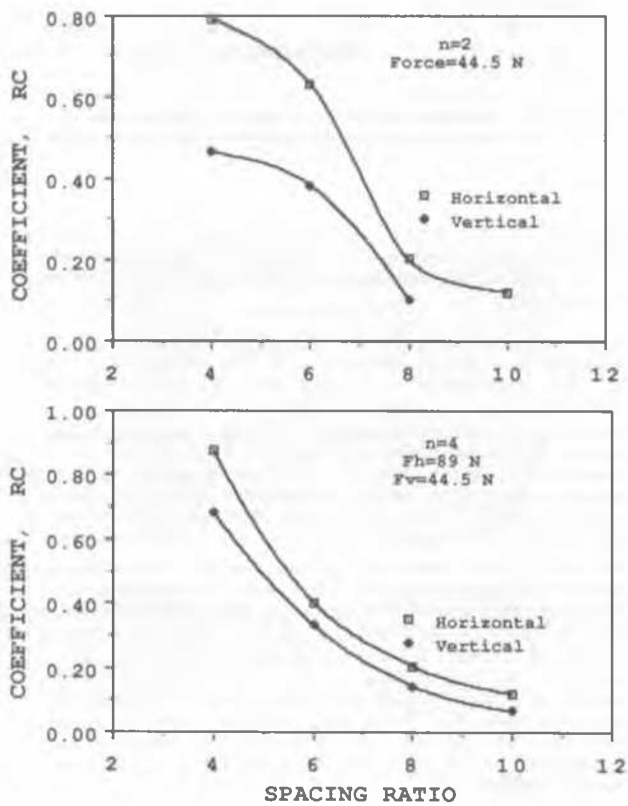

Fig. 6 Relative Change of Group Stiffness

effects are evident for both modes of vibration and although by extrapolating curves these effects would to some extent exist for spacing ratios up to 20, a practical limit beyond which piles in small groups do not interact could be set at 14 (i.e., RC < 5 %). The importance of horizontal vis-a-vis vertical interaction is generally clearly seen especially for small spacing ratios. This may be due to the difference in mode of soil resistance mobilized by piles motion, i.e., essentially compression and friction 'springs' respectively. In horizontal vibration, the upper portion of piles displace significantly. This affects an area of soil around piles relatively large enough to cause an almost rigid deformation of material between piles for small spacings and particularly for large groups. However in the vertical mode, the ring of directly displaced material around pile-soil interface is smaller and rigid motion hardly occurs especially for groups of two. From curves in Fig. 6 it also seems that interaction increases with number of piles for small spacings and for both modes, and that the rate of decrease of coefficient RC and then of interaction as a function of spacing ratio changes from increasing for groups of 2 to decreasing for groups of 4. The second deduction means that group effects decrease faster for groups of two and range of spacing considered here. The group geometric configuration as it changes from one to two dimensions could be at the origin of such behavior. It is then expected that larger groups would have an interaction pattern similar to that of the group of four.

CONCLUSIONS

The present experimental study has led to the following conclusions with regard to the dynamic behavior of small pile groups.

i) Dynamic interaction effects on the horizontal direction are of paramount importance and are more significant than in the vertical direction. These effects could practically occur for spacing ratios up to 14.

ii) As strain amplitude increases but still in the range of relatively small amplitudes weak non-linearities occur in group response. These are attributed to softening of embedment material.

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