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Field testing and analysis of dynamic loaded pile group

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ABSTRACT: This paper presents experimentally parametric study on soil-pile interactions. The parameters considered are the number of piles, pile spacing that is ratio of spacing to diameter, and pile arrangement. In order to investigate actual dynamic properties, four pile-soil-foundation models were made on a soft soil layer and vibration tests were carried out. The models were a single pile, two piles, a couple of two piles and four piles. As the models were effective for parametric study and linear test results were obtained, significant findings could be pointed out from the tests. It is worth noting that the test results agree with analysis based on three-dimensional wave propagation theory.

1 INTRODUCTION

The purpose of this paper is to experimentally clarify the effects of various parameters on dynamic soil-pile interaction. Dynamic analytical studies have been presented in recent years, but few experimental studies, especially parametric studies based on actual ground, have been done.

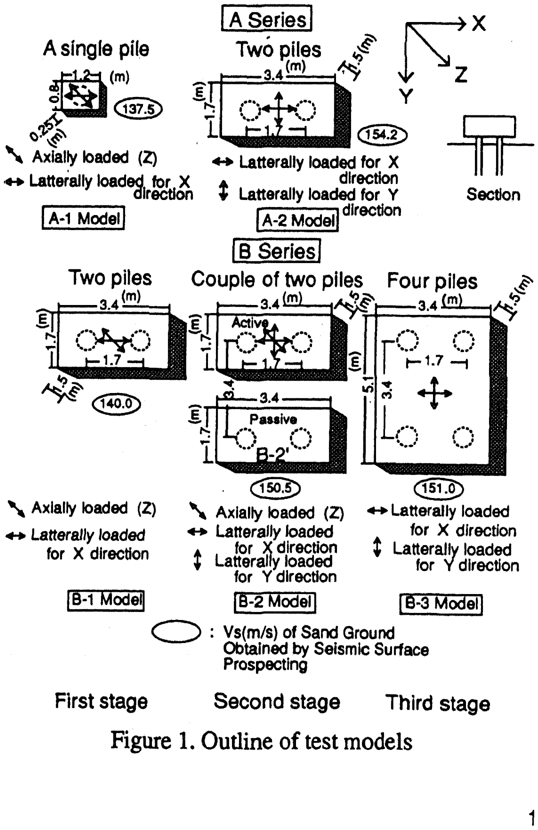

Figure 1. Outline of test models

In order to enable parametric studies, four pile-soil-foundation system models were made on a soft soil layer as shown in Fig.1 and vibration tests were performed. The couple model which paired two two-piles was very effective for exploring the characteristics of pile-groups.

Correlative analytical results obtained from a thin layer formulation based on three dimensional wave propagation theory presented by (Waas 1981) are also shown for comparison with the test results.

2 OUTLINE OF THE TEST AND THE ANALYSIS

The four kinds of test models as shown in Fig.1 which were a single pile, two piles, a couple of two piles, and four piles. They were built on a soft soil layer. The reasons for choosing these models are as follows.

1. The single pile is a basic model for comparison with other models.
2. The effect of the number of piles is revealed by

Depth (m)	Layer Thickness (m)	ρ (g/cm^3)	Poisson's Ratio ν	Vs (m/sec)	
1.25	1.25	1.35	0.470	Sand *	
2.30	1.05	1.35	0.491	80	100 **
4.80	2.50	1.45	0.491	110	
6.80	2.00	1.45	0.496		
8.80	2.00	1.51	0.498	90	
10.80	2.00	1.65	0.498		
13.80	3.00	1.82	0.498		
19.80	6.00	1.82	0.497	120	
23.20	3.40	2.12	0.492		
24.80	1.60	2.12	0.486	230	
29.00	4.20	2.12	0.486	300	
		1.80	0.462	450	

Figure 2. Soil profile of test ground
*The value is noted in Fig.1 **100m/s is adopted in the analysis

comparing the result of the single pile with those of two piles and four piles.

3. The model of the four piles permits the estimation of influences due to different pile spacings, because the pile spacings of the model along the X and Y axes are different. The ratios of spacing to diameter along X and Y axes are about 3 and 6, respectively.

4. The couple of two piles is significant for understanding the dynamic properties of pile-foundation response. As the four pile model was joined the couple models, the investigation on the couple model reveals much about the dynamic behavior of the four pile model.

In order to estimate the impedances due to only piles, all foundation bases were about 15cm above the ground. The piles were made of prestressed high strength concrete 0.6m in diameter and 29m in length. A portion of the piles of 7m from the top was covered with steel of 9mm thickness. The foundations were concrete. The dimensions of the models are also shown in Fig.1.

Forced vibration tests were carried out in three stages as shown in Fig.1 using sinusoidal excitation (1~20Hz) produced by an exciter installed on the top of the foundations. Two lateral loads, in the X and Y directions, and axial load were applied independently to the models. The directions of the forces applied to the models are described in detail in Fig.1. For the couple model, only one foundation was excited, that is, the exciting foundation was active and the other was passive (B-2').

Two series of models, A and B, were built on the same ground to avoid the influence of soil nonlinearity. If soil nonlinearity occurs in the results of the models of A series, especially for the case of the lateral excitation of the single pile, it can obtain linear results from the models of B series. Moreover, the amplitude of the exciting force was applied as small as possible to obtain linear test results of dynamic pile-soil interaction. The linearity of the test results was confirmed after increasing the amplitude of the force. If the normalized test results agree with those obtained from the smallest amplitude, the test results are considered to be linear. The test results discussed below are the case being linear.

The soil profile shown in Fig.2 was obtained by PS logging, but S-wave velocities of the surface layer as shown in Fig.1 were measured by seismic surface prospecting at every test stage for each model.

In order to compare the test results with those for analysis, the results obtained from thin layer method are presented below.

3 RESPONSE CURVES OF THE TESTS AND DISCUSSION

For the lateral excitation, lateral responses at the center of the foundation base, obtained from measuring displacements on the foundation top is shown in Fig.3-1 for X direction excitations of models A-2, B-1 and B-2, and in Fig.3-2 for Y direction excitations of A-2 and B-2. For model B-2, the results of B-2' are shown. Though rotational displacement associated with a lateral displacement for a lateral excitation is obtained in similar manner, only the lateral displacement is presented here.

As for model A-1, it was found that the responses for lateral excitation were affected by soil nonlinearity. So the obtained result is not discussed here.

The response curves of the two piles, A-2 and B-1, and the couple of two pile, B-2, models for lateral excitation are discussed next.

1. A-2 is the same model as B-1 but B-1's amplitude is slightly smaller and its resonance frequency is higher than those of A-2 shown in Fig.3-1. Compared with both cases quantitatively, the difference resulting from the soil conditions should be taken into account.

2. As for the relationship between B-1 and B-2, the passive pile foundation makes stiffness of B-2 greater than that of B-1, because resonance frequencies of B-2 are 13.0Hz and 10.5Hz in X and Y direction excitations, respectively, while those of B-1 are 12.5Hz and 8.5Hz shown in Figs.3-1 and 3-2.

3. As the pile head conditions were different between X and Y excitation cases, the ratios of rocking to sway for pile-foundation displacement are roughly 0.3 and 1.0, respectively.

4. The response ratios of the passive pile-foundation to the active pile-foundation for X and Y direction excitations are about 0.2 at low frequencies. At the resonance frequency for Y direction excitation, the ratio is about 0.7 while that for X direction is unchanged from that of low frequencies. Therefore, these ratios are very strongly affected by the type of subjected incident waves of the passive pile-foundation due to the active pile-foundation and the pile head condition.

Compared with the passive pile-foundation's tendency toward increasing phase angles for X direction excitation as frequencies increase above 14Hz, that for Y direction excitation changes little. The passive pile-foundation in X direction excitation was subjected to horizontally incident SH waves and that for Y direction excitation was subjected to horizontally incident P-SV waves. As the length of incident waves becomes smaller with increasing frequencies, the relative relationship between wave length and pile spacings affects the dynamic response in high frequency range. Therefore, phase angle depends on the type of incident waves and their frequency.

Lateral responses for X and Y direction excitation of model B-3 are shown in Fig.3-3 and discussed next.

1. The ratios of rocking to sway in X and Y direction excitations are 0.3 and 0.15 respectively and the former is similar to the value obtained from two pile models. Moreover the amplitude at low frequencies is about half that of two pile models. This may be explained that the dynamic properties of four piles jointed the two models of two-piles keep those for two piles in low frequency range in X direction excitation.

2. The amplitudes and phase angles in X and Y excitation are similar in low frequencies but the differences in amplitudes appears at frequencies above 8Hz. Phase angles diverge slightly at frequencies above 14Hz.

3. It may be pointed out that the results described above are dependent on the relationship between pile spacings and correlative frequency, and pile arrangement. Significant properties could be found experimentally because the model adopted here is very revealing of the influence due to different pile spacings.

Axial responses for the three excitations of models A-1, B-1 and B-2 are plotted in Fig.3-4 and comparison of the responses for the three models ,the single pile, the two pile and the couple of two piles, are discussed next.

1. The amplitude of B-1 is half that of A-1. If the different soil conditions between the A and B series investigated before is not considered, the effect of the number of piles is not apparent.

2. The phase angle of the passive pile-foundation (B-2') in model B-2 is increasing with increasing frequency and a similar tendency is also found for X direction excitation. Since both are the cases for subjected SH incident waves, such phenomena are appreciated.

As for the analytical investigation, though good agreement between the results of the tests and corresponding analyses were obtained, the analytical results are not shown here. The significant observations as described above were confirmed by comparing the test results with those produced by analyses.

4 DYNAMIC IMPEDANCE

Dynamic impedances of pile-soil interaction for each test model are calculated based on the motion equation for the lateral and rotational responses of mass-spring systems. The condition of pile-foundations and the height of the applied forces are necessary in order to obtain the impedances. The soil conditions adopted for the analysis are shown in Fig.2. Though lateral and rotational impedances are obtained simultaneously for a lateral excitation, only lateral impedances for X and Y direction excitation of model B-3 are shown here in Fig.4-1.

As the ratio of sway to rocking displacements for Y direction excitation of model B-3 is 6:1, the lateral impedance is close to pure lateral impedance commonly termed as K_{HH}, which does not couple rotational displacement. The lateral impedance for X direction excitation of B-3 is roughly 20% smaller than K_{HH} because of the influence of rotation by investigating the analytical result.

First, comparisons between the results of X and Y

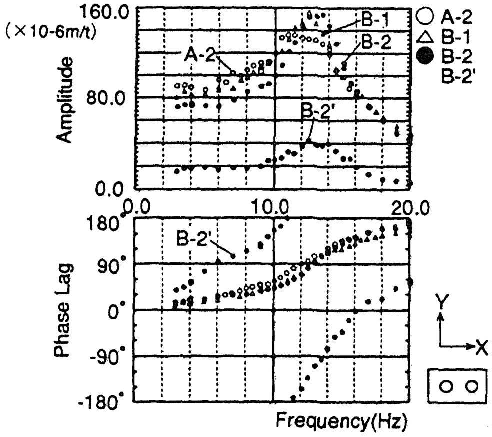

Figure 3-1. Results for X direction excitation

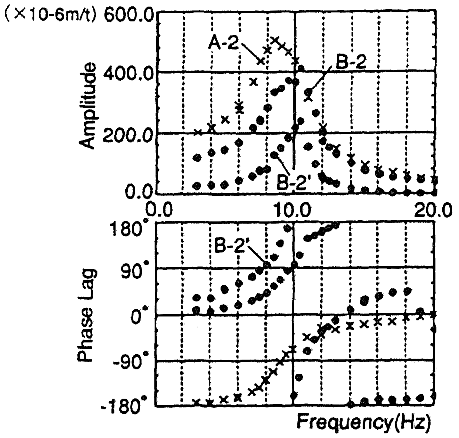

Figure 3-2. Results of for Y direction excitation

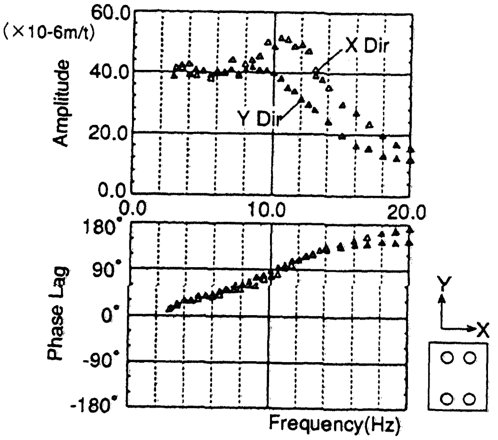

Figure 3-3. Results of B-3 for X and Y direction excitations

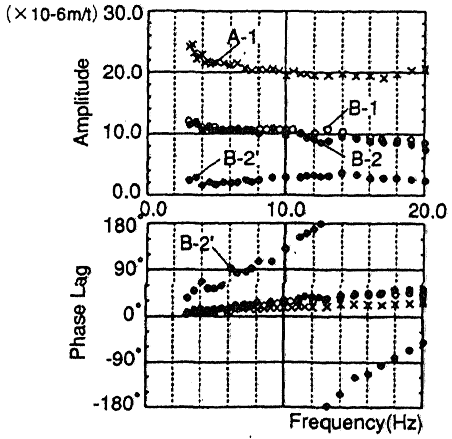

Figure 3-4. Results for axial excitation

Figure 3. Response curves of the test for each model

direction excitations for model B-3 are shown.

1. Both the real parts for X and Y direction cases are close in low frequency range, however the discrepancy between both for real and imaginary parts expands in high frequencies above 14Hz. This is because the real part is increasing and the imaginary part is decreasing for X direction case for frequencies above 10Hz, but both for Y direction excitation grow gradually with increasing frequency.

2. Impedances depend very much on pile spacings and pile arrangement at high frequencies. The relative relationship between pile spacing and incident wave length becomes more significant as frequency rises. As already mentioned for B-2, X and Y direction excitation may be regarded as the cases of SH and P incident waves, respectively. If the shear wave velocity for the layer near the free surface is assumed to be approximately 120m/s because those for the first and the second layer are about 140m/s and about 100m/s, as shown in Figs.1 and 2, the wave lengths of incident SH waves are 12m at 10Hz and 8m at 15Hz. The pile spacings is 3.4m in Y direction as shown in Fig.1. The length of incident P waves is 4 times more that of incident SH waves at identical frequencies if Poisson's ratio is 0.47 shown in Fig.2. Therefore a similar relationship as mentioned above occurs in higher frequencies for Y direction excitation.

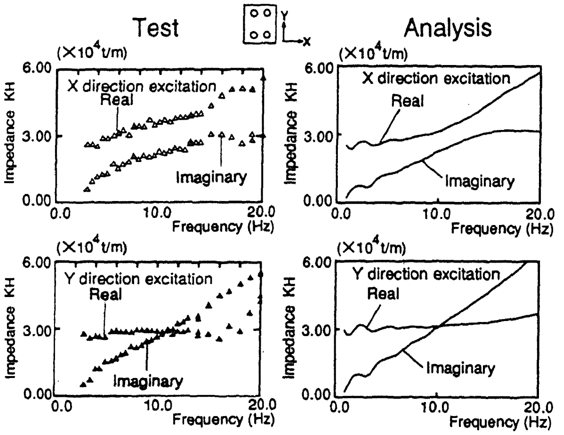

Figure 4-1. Impedance of B-3 for X and Y direction excitation

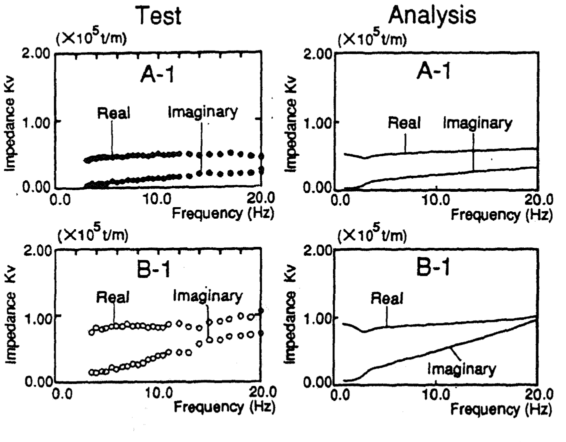

Figure 4-2. Impedance of A-1 and B-1 for axial excitation

Figure 4. Comparison between test and analytical impedances

3. It may be noted that for X direction excitation, the real part of B-3 is almost double that of B-1 not shown here in the frequencies below 10Hz. This phenomenon points to a tendency similar to that found in the amplitude of the response curves of B-1 and B-3. Recall that the amplitude of B-3 is roughly one-half to that of B-1 in the low frequency range below 10Hz.

4. The dynamic impedances of the test results agree with the analytical results which were obtained in the same manner based on the analytical response curves.

Next, comparisons between A-1 and B-1 for axial excitation are described.

1. Impedances obtained from axial response curves are shown in Fig.4-2, where the impedance of B-1 was plotted after taking into account the quantitative difference of the real part of impedance between A-2 and B-1 for the lateral excitation tests, which was discussed above. The stiffness of B-1,that is the real part, was 15% greater than that of A-1.

2. While the real part of B-1 is about 1.8 times to the test of A-1 at frequencies below 15Hz, it is difficult to evaluate effectively the relationship for the imaginary part between both cases because the frequency dependencies are very different. Compared with the results for A-1, the imaginary part for B-1 depends strongly on frequency. The dynamic effect of the number of piles is complex. On the other hand, the evaluation of the effect as a static problem discussed by (Poulos 1980) is easier than as a dynamic problem.

3. When the test results are compared with analytical results, good agreement is obtained.

CONCLUSIONS

1. Significant properties of dynamic pile-soil interaction were experimentally clarified by making of effective models on the ground and obtaining the linear test results.

2. The effects of number of piles and pile arrangement on dynamic behavior are very different from those for static case because the dynamic characteristics of the effects are closely related to the frequency and type of incident waves.

3. As good agreement was found between the results in the test and the analysis of pile-soil interaction, the findings in this study are available.

REFERENCES

Waas, G. & H.-G.Hartmann 1981. Analysis of pile foundation under dynamic loads. 6th International Conference on Structural Mechanics in Reactor Technology. K5/20: 1-8

Poulos, H.G. & E.H.Davis 1980. Pile foundation analysis and design. New York: John Wiley and Sons.