Earthquake Engineering, Tenth World Conference © 1992 Balkema, Rotterdam. ISBN 90 5410 060 5

Full scale vibration test on pile-structure and analysis

Kaeko Yahata, Yukio Naito, Kenji Urao & Takashi Nakayama
Kajima Technical Research Institute, Kajima Corporation, Tokyo, Japan
Osamu Inada, Fukashi Mori & Mitsuo Tuzuki
Chubu Electric Power Company, Inc., Japan

ABSTRACT: There have been many analytical investigations on dynamic soil-pile interaction, but few attempts discussed the behavior of a large pile-supported structure subjected to vibration generation have been made. For this study, first, the dynamic behavior of an actual pile-supported structure which is obtained from carryed out vibration test is investigated. The results produced by two kinds of vibration, one being axial excitation and the other being lateral excitation are discussed. The properties of dynamic responses differ according to the type of excitation. Then an available analytical model which can reproduce the test results of the actual behavior of the structure is presented. The analytical model is mass-spring system consist of 31 nodal points. In order to find a simple and effective model, such impedances as piles, foundation and side of embedment should be taken into account for each node point of the model. The differences between the behaviors produced by both types of excitation are also considered when divising the model.

1 INTRODUCTION

This paper presents a simple method for analyzing large pile-supported structures subjected to vibration. It is important to understand the dynamic behavior of such structures which support vibrating machinery, and ensure that such machinery can be operated without trouble. Few experimental or analytical studies of this problem have been performed.

Vibration tests of a pile-supported thermal power plant were performed to understand its actual behavior, and then analytical efforts using the method presented here were carried out in order to reproduce the test results analytically.

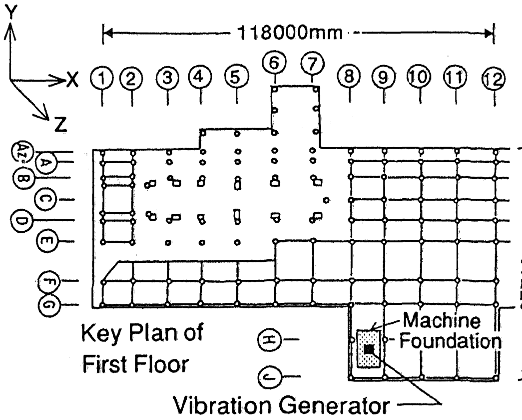

Figure 1. Outline of the first floor in objective building

It was confirmed that the analytical model could produce results similar to those obtained by the tests.

2 OUTLINE OF FORCED VIBRATION TEST

The first floor plan of the objective pile-supported building on a soft soil layer is shown in Fig.1 and the soil profile

Depth (m)	Layer Thickness (m)	ρ (g/cm³)	Poisson's Ratio	Vs (m/sec)
1.25	1.25	1.35	0.470	400
2.30	1.05	1.35	0.491	80
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 the underground for the building

is also shown in Fig.2. There were a large number of piles in the area of the building because of soft soil deposit.

In order to study its actual behavior during machinery operation, the forced vibration tests were performed using harmonic excitation (1~20Hz) produced by an exciter installed on the top of the machine foundation as indicated in Fig.1. Axial and lateral in X direction loads were

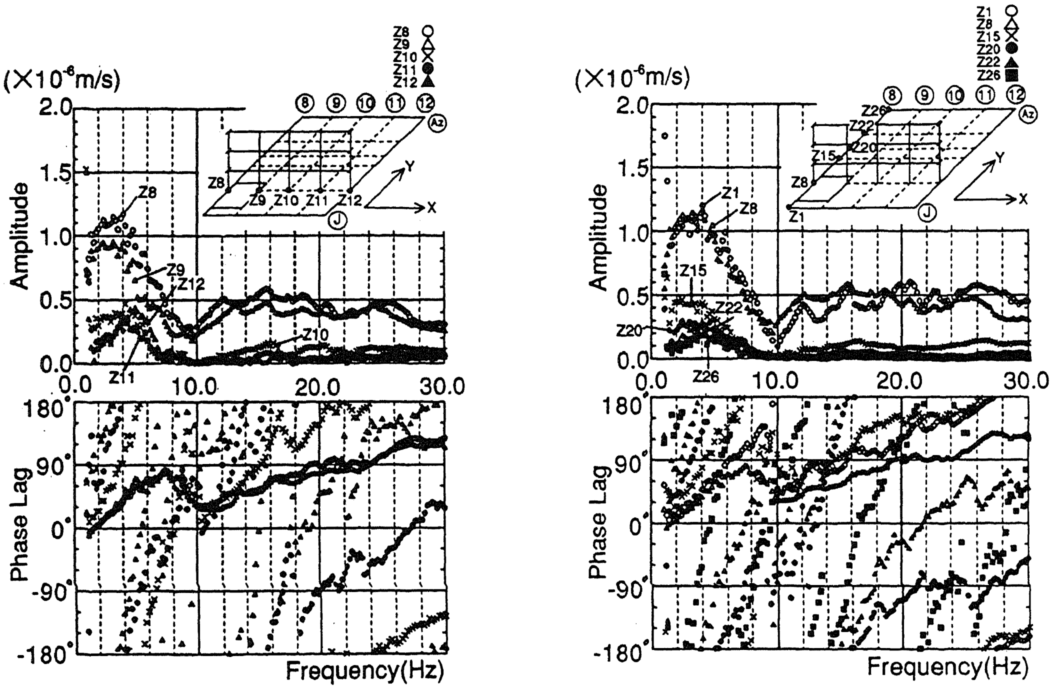

Figure 3. Response curves of the test for the axial excitation

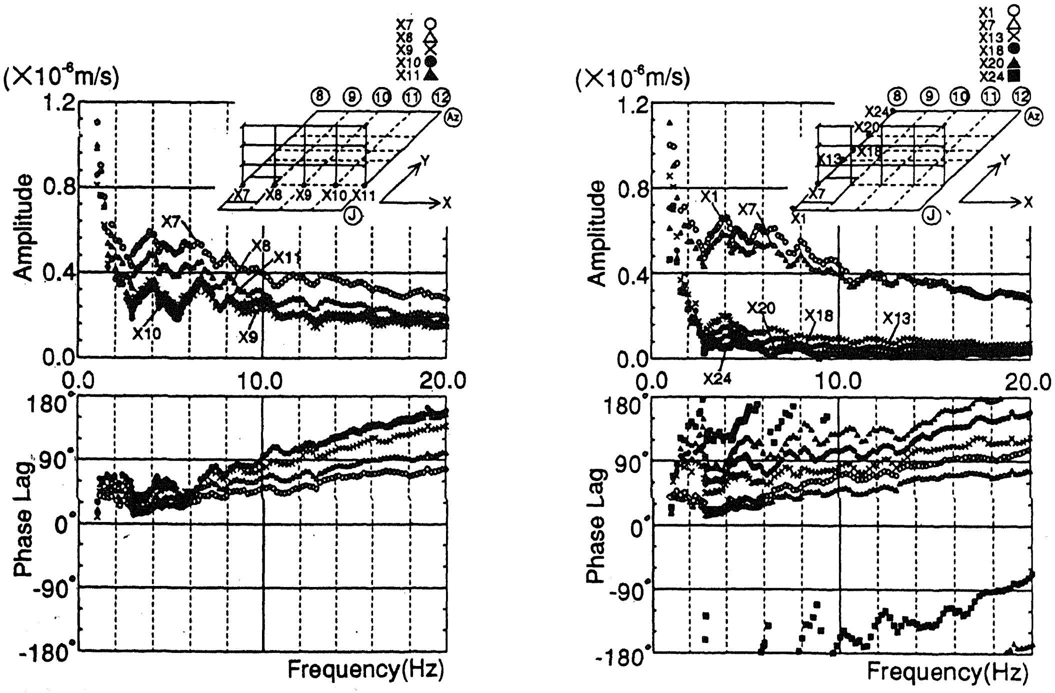

Figure 4. Response curves of the test for the lateral (X) excitation

applied separately to the foundation. As the building was a three-story steel structure, and the vibration tests were carried out so that the first resonance frequency of the structure for both excitations was measured.

After investigating the obtained test results, a simple analytical method of reproducing the results is devised in the paper.

3 RESONANCE CURVES OF THE TESTS

Resonance curves of the first floor for X and Y directions are shown in Fig.3 for axial excitations. Those for lateral excitation are shown in Fig.4.

1. The response for axial excitation decreases rapidly as the distance from the machine foundation increases.

Such tendency as decreasing response becomes pronounced at frequencies above 10Hz. Because the first response frequency of the building is 9.5Hz, the response of the foundation shows very small amplitude. However, the amplitude of the superstructure becomes maximal.

The results of measurements taken at the machine foundation which can be regarded as rigid body, are nearly identical.

2. Lateral excitation was applied to X direction.

While the vibration propagates widely in X direction , it does not propagate in Y orthogonal to the direction of excitation. The response of the foundation also decreases at the first resonance frequency of the building, 2.8Hz.

3. As sway motion couples rocking motion for lateral excitation, the vertical responses of the machine foundation are measured. The responses on both side of the foundation ,that is, lines 8 and 9 in Fig.1 show inverse phase angles, and thus rocking motion of the foundation is confirmed. The ratio of sway to rocking is 2:1. The lateral response at the center of the foundation base is obtained from that ratio and the obtained response is compared with that produced by the analytical model.

These properties of the resonance curves suggest that a small area model is possible to reproduce the test results.

An outline of the analysis for simulating the test results is provided below. An average response of several results on the machine foundation for the axial excitation and the lateral response of the machine foundation base for lateral excitation are used when comparing with the analytical results.

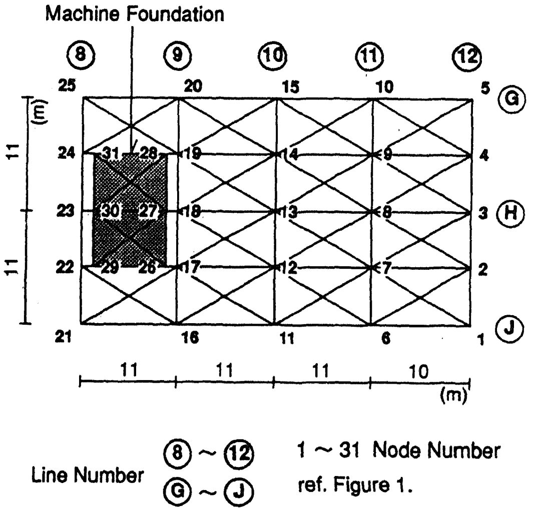

Figure 5. Outline of analytical model

4 OUTLINE OF ANALYSIS

There were over 1100 piles supported the structure. The piles were prestressed high-strength concrete with 60cm in diameter and 29m in length. The building was embedded 3.8m in the ground. The concrete machine foundation was considered to be rigid because its area was 8.5m × 10.3m and its height was 3.8m.

As in addition to the large structure, the piles, the foundation and the side of the embedment interactions are in the building, an available model is uncertain before investigating any analytical results. When devising an analytical model to reproduce the test results, the dynamic properties obtained from the tests, flexibility of the model to be able to suit the test results and the pile impedances are taken into account.

The approach to devising the analytical model is as follows.

1. Through the investigation for the responses of the tests, the responses at points distant from the machine foundation are, only with the exception of the responses in excitation direction (X) for the lateral excitation, slightly influenced by the foundation excitation. Taking this into account, a small area model is adopted for analyzing the test results. This model includes only the machine foundation and its circumferential area as shown in Fig.5. In order to enable the analytical model to be simple and effective for reproducing responses of an actual structure, spring-mass system which consists of 31 nodal points is considered and the model is estimated at the height of the pile heads equal to the foundation base. The contribution of the dynamic properties from the superstructure is not included in the model, but the mass of the superstructure is incorporated in the mass value at each nodal point.

Mass includes not only that of the superstructure but also that of the foundation and the beams in the ground.

2. As for spring, in order to express dynamic interactions, such dynamic spring as pile-soil, foundation-soil and side of embedment-soil interactions are introduced for each nodal point. Dynamic spring implies impedance, and there are many ways to obtain impedance for each case. Pile impedance here is estimated using method of (Nogami 1985), and side impedance is estimated also by (Novak 1978). Five kinds of pile head impedances for each nodal point, which are three displacements with X, Y and X axes, and two rotations with X and Y axes, are considered. In order to take into account coupling effect between piles, here pile impedances including the coupling term are obtained. Impedance of the foundation are as well known.

3. Since there are 127 piles in the area of the model, it is necessary to replace their impedances into virtual 31 piles for each nodal point, by estimating approximately the effects of pile groups. Compared with both results obtained from assuming the rigid foundation for the case of lateral excitation, impedance for 31 piles can represent that of 127 piles.

4. Once obtaining the impedance of the rigid foundation of the model and that of the side of the embedment, the foundation impedance can be distributed to each nodal point in proportion to occupying the area, but for the case of the side, it can be distributed to that in proportion to occupying the length.

Side impedances for axial and X direction excitations are calculated for nodal points along lines 8, 12, and J, and along lines 8 and 12, respectively shown in Fig.5.

5. If it is necessary to consider the influence of parts of the structure outside the small area of the model, the slab-stiffness of these area for shear deformation can be introduced into the node points 5, 10, 15, 20 and 25 along line G in Fig.5 which is a boundary of the small area model. When estimating the slab-stiffness for each nodal point, the effective length for shear deformation of this structure is uncertain. After trying several cases, maximum value $0.9x10^{-6}$ ton/m for which effective length is the shortest is adopted. The effective length is regarded as the span between lines G and F shown in Fig.1.

6. The soil profile shown in Fig.2 is used.

5 ANALYTICAL MODELS AND ANALYTICAL RESULTS

The following tables refer to analytical models for axial and lateral excitation described below.

Axial Excitation

Model	Impedance		
	Pile head	Foundation	Side
No.1	○	—	—
No.2	○	○	—
No.3	○	—	○
No.4	○	○	○

○ : Impedance is considered at each node point

Lateral Excitation

Model	Condition of node point along line G	Impedance		
		Pile head	Foundation	Side
No.1	Free	○	—	—
No.2	Fix	○	—	—
No.3	Shear Stiffness	○	—	—
No.3-1	Shear Stiffness	○	○	—
No.3-2	Shear Stiffness	○	—	○
No.3-3	Shear Stiffness	○	○	○

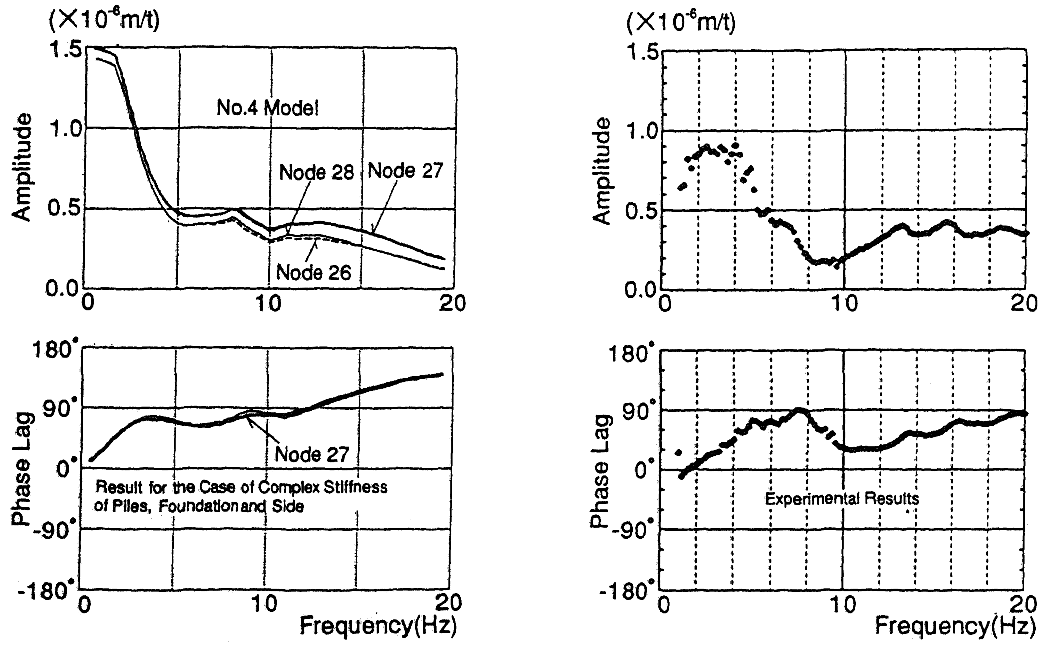

Figure 6-1. Analysis

Figure 6-2. Test

Figure 6. Comparison between analytical and test response curves for axial excitation

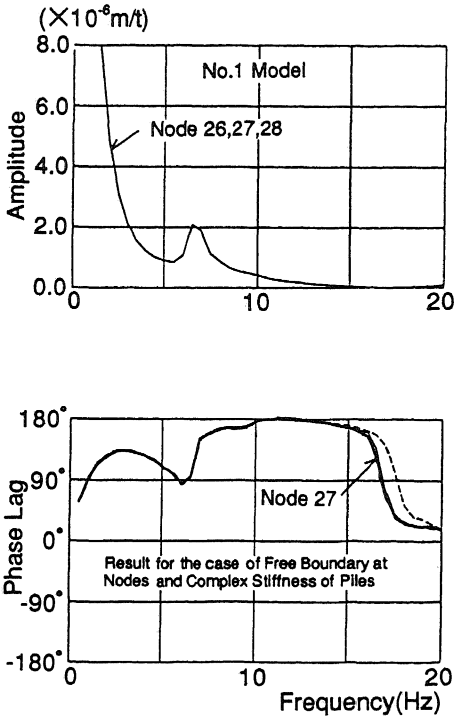

Figure 7-1. Analysis

It is not clear how to proceed to devise an analytical model able to simulate the test results, so a simple model incorporating only the impedance of the piles is considered as the initial model. For axial excitation, the condition of node point along line G is free.

The initial model is No.1 in above tables.

After investigating the results generated with this initial model, other impedances will be added incrementally until the test results can be reproduced. The analytical result for node point 27 is compared with the test result of the machine foundation, because that point is near the middle of the foundation as shown in Fig.5.

As for the case of lateral excitation, the results obtained from the model correspond to the response of the foundation base. For the case of axial excitation, the responses of the machine foundation measured at any position are almost identical. So the average response is used when comparing with that of the analysis.

However, only the results of No.4 for axial excitation and those of No.1 and No.3-3 for lateral excitation are plotted in the Figures presented here. The results of other models are discussed but not shown.

1. As for the case of axial excitation, the results of No.1 are similar tendency qualitatively to the test results, but the amplitudes are comparatively larger.

The agreement between results of No.2 and the test are better than the case for No.1. The results produced using No.3 are almost the same as those from No.1. Compared with the results obtained from No.1, No2, and No.3, those obtained from No.4 shown in Fig.6-1 are closest to the test results shown in Fig.6-2.

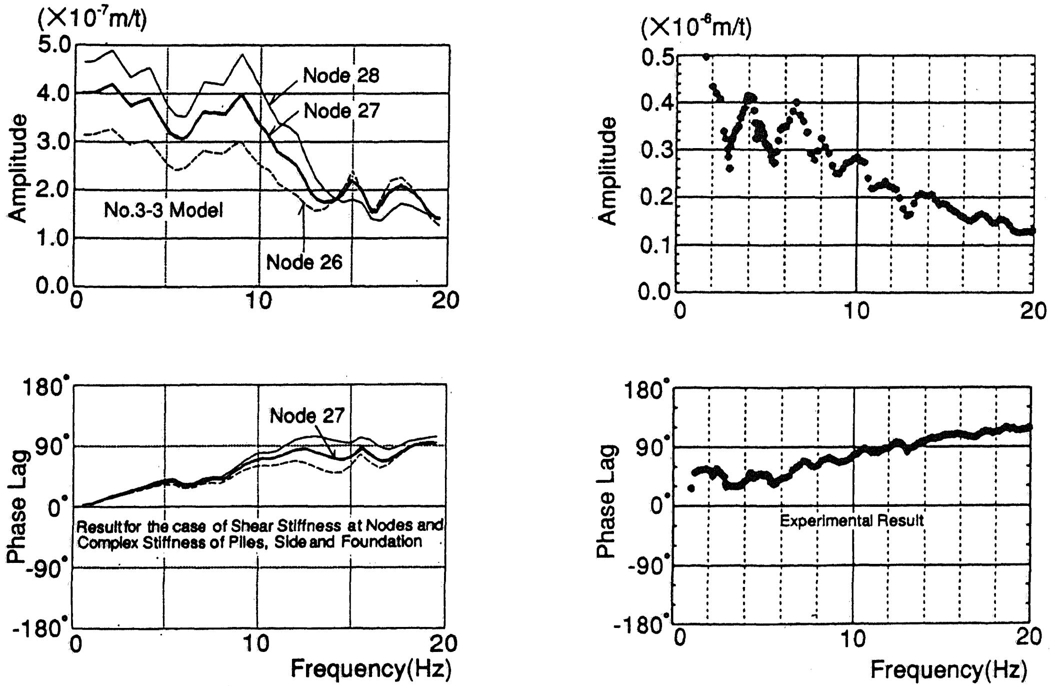

Figure 7-2. Analytsis

Figure 7-3. Test

Figure 7. Comparsion between analytical and test response curves for lateral excitation (X)

As described before, small amplitude at 9.5Hz caused by the first resonance frequency of the building can not be generated by the analytical models, since they do not express dynamic behavior arising from the influence of the superstructure.

The responses of the test results at points far from the machine foundation did not decrease rapidly frequencies below 10Hz, so the small analytical model separated from the structure and free condition at the nodes along the separated boundary can not adequately reproduce these test results.

2. It is more troublesome to find an appropriate analytical model for lateral excitation, because the response properties between the test results for X and Y directions are different. In addition to the three impedances, it may be expected that other factors which affect dynamic behavior produced by vibrating machinery must be introduced to the analytical model. Therefore, the number of models as shown in the above Tables is more greater than for the axial excitation.

3. For amplitude and phase angle, there is a large discrepancy between the results of the test and No.1 model shown in Figs.7-1 and 7-3. The amplitudes in No.2 model are similar to the test results except for frequencies near 12Hz, which is the resonance frequency of the model. The phase angle of the test results is between those of No.1 and No.2 models, so that, at this step it is meaningful to take into account the effect of slab-stiffness for node points along the boundary line G.

Compared with the results obtained from the previous two models, the amplitude and the phase angle of No.3 are closer to the test result. However a discrepancy is found near 8Hz which is its resonance frequency.

As no resonance frequency is apparent in the test results of the foundation, the influence of the resonance frequency on the curve produced by analysis can be reduced by considering other impedances in the models. This is the reason why No.3-1, No.3-2 and No.3-3 are schemed.

The results of No.3-1 are closer to the test results, and the resonance frequency is absent. However, amplitudes are somewhat greater than those measured. The agreement between the results of No.3-2 and the test is less than for the case of No.3-1.

The results of No.3-3 as shown in Fig.7-2, agree with the test results in amplitude and phase angle.

It is clarified that No.3-3 model can reproduce the test results.

As described above in the axial case, the small amplitude at 2.8Hz corresponding the first resonance frequency of the building in the test results can not be expressed using this analytical model.

6 CONCLUSION

1. The simple small model presented here is very effective for predicting the dynamic behavior of a large pile supported structure subjected to machine vibrating. However, the influences from the dynamic response of the superstructure can not be expressed using this model.

2. In order to obtain good agreement between the test results and those obtained by analysis, it is necessary for the model to take into account the impedances which occur in the structure. As for lateral excitation, moreover, slab-stiffness must also be considered.

3. It is clarified that the effects of impedances such as a foundation and a side of an embedment are different between axial and lateral excitation for the structure. The response to axial excitation of the first floor is influenced more by the impedance of the foundation than that of the side. However, the relationship between both impedances for lateral excitation is the reverse. The difference is caused by different responses of the first floor due to axial and lateral excitations.

4. If such structure are designed with consideration for dynamic behavior due to excitation using this method, it will enable machinery located upon the structures to be operated without trouble.

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