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Nonlinear seismic behavior of pile foundation structure systems

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ABSTRACT: The seismic response characteristics of pile foundation structure systems affected by the nonlinear behavior of the ground are investigated using data obtained from shaking table tests conducted on a group pile foundation structure model. A method is proposed for the analysis of the seismic response of pile foundation structure systems taking into account the nonlinear behavior of the ground in which nonlinearities in the effective seismic motion and pile head impedance are evaluated separately.

1 INTRODUCTION

A strong tendency has arisen in recent years to use pile foundations for many structures built on soft soil deposits. There are high expectations that this type of foundation can be widely applied due to its workability and economical efficiency. It is widely recognized that the establishment of a reliable earthquake-proof design method for pile foundations taking into consideration the nonlinear behavior of the ground is a matter of considerable importance today. However, very few proposals have been proven to be efficient enough for adoption to engineering practice.

In this paper, seismic response characteristics of pile foundation structure systems affected by the nonlinear behavior of the ground are investigated using data obtained from conducting shaking table tests on a model. A special soil container for shear mode vibration is utilized for the experiments. The variations of two main parameters, namely, natural frequency and the magnification ratio of the acceleration amplitude, are studied at the peaks corresponding to inertial and kinematic interactions. The frequency transfer function between the pile tip and the superstructure, obtained from the experimental data, is used for this study, and significant differences in the variations of the abovementioned parameters are identified. The results of the described studies are compiled and analyzed, and, by using them as a basis, a method is developed for the analysis of the seismic response of pile foundation structure systems taking into account the nonlinear behavior of the ground. Nonlinearities in the effective motion and pile head impedance are evaluated separately in this method. Validity of the proposed method is demonstrated by comparing the analytical and test results.

2 SEISMIC RESPONSE OF PILE FOUNDATION STRUCTURE SYSTEMS AFFECTED BY NONLINEAR BEHAVIOR OF GROUND

Soil behaves strongly nonlinearly when excited by high levels of seismic motion. It is obvious that the seismic response of pile foundation structure systems is considerably influenced by the nonlinear behavior of the ground. Since it is important to ascertain the real response characteristics of pile foundations affected by the nonlinear behavior of the ground, studies based on shaking table tests performed on a model using a special soil container for shear mode vibration were carried out.

Figure 1 is a schematic drawing of the test model. Piles are made of aluminum. The diameter of the piles, ϕ, is 30 mm; thickness, t, is 1 mm; and length, l, is 900 mm. The pile foundation has nine piles (distance between piles, d = 75 mm) arranged in three columns of three rows. The pile heads and pile tips are firmly connected to a rigid footing and to the base of the container, respectively. An iron plate of 33.8 kgf, simulating the superstructure, is supported by four steel plates arranged in such a way as to allow only shear deformation. The fundamental natural frequency, fso, of the superstructure is 24.5 Hz when the ends of the four supports are fixed to a rigid body.

Dried sand is used as the material for the ground model. Measurement is performed through the installation of accelerometers in the ground (A1-A2), on the superstructure (A4), and on the footing (A3); strain meters on the piles (S1-S10); and displacement meters on the side of the container (D1-D6).

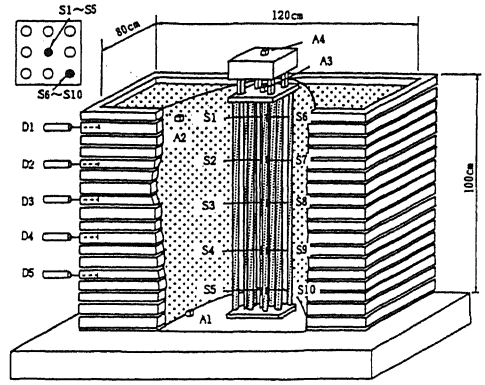
Figure 2 presents the transfer function between the base (A1) and the superstructure (A4) calculated by using the accelerations recorded during the tests. The model was excited by sinusoidal input motions, and values of maximum acceleration, A_{omax}, of 25, 100, and 250 cm/s^2 were adopted. The results in Fig. 2 indicate that two peaks appear clearly for each transfer function curve. The peak towards the left has a corresponding frequency, f_{g1}, that was found to have the same value as the fundamental natural frequency of the ground determined by using the transfer function between the base (A1) and the ground surface (A2). A frequency, f_{s1}, corresponds to the peak at the right-hand side of the transfer function curves. As expected, f_{s1} is smaller than f_{so} = 24.5 Hz. This reduction is the result of the soil-pile-superstructure interaction.

Dynamic interaction of soil-pile-structure systems can be treated by considering inertial and kinematic interactions separately. It can be seen that the frequencies, f_{g1} and f_{s1}, are governed by the inertial and kinematic interactions, respectively. Due to the increase in A_{omax}, f_{g1} and f_{s1} move toward the lower frequencies, that is, 10 Hz, 7 Hz, 5 Hz, and 17 Hz, 14 Hz, 13 Hz, respectively, and the magnification ratios, α_{g1} and β_{s1}, corresponding to f_{g1} and f_{s1}, also assume lower values, namely 12.0, 5.3, 3.3 and 17.3, 7.8, 6.7, respectively. These variations are a result of the nonlinear behavior of the ground. However, the variations of f_{g1}, f_{s1} and α_{g1}, α_{s1} demonstrate that the decreasing ratios of f_{g1} and α_{g1} are not the same as those of f_{s1} and α_{s1}. These differences seem to be a very important matter when dealing with seismic response analysis methods for pile foundation structure systems taking into account the nonlinear behavior of the ground.

The above-mentioned phenomenon is the result of the difference in the variation rates of the shear modulus and hysteretic damping corresponding to frequencies f_{g1} and f_{s1}. The variations of f_{g1} and α_{g1} are produced by the nonlinear behavior of the ground due to the ground shaking (kinematic interaction). The variations of f_{s1} and α_{s1} are the result of the nonlinear behavior of the ground surrounding the pile head due to the inertial force induced by the vibration of the superstructure (inertial interaction).

The differences observed in Fig. 2 can be confirmed analytically through comparison of the numerical results, calculated by using the seismic response analysis method (Tazoh 1987) for grouped piles including a multi-degree-of-freedom model for the superstructure which is based on the three-dimensional elastic wave propagation theory, and the test results.

Figure 3 shows the transfer function between the base (A1) and the superstructure (A4). The solid line and dotted marks represent the analytical and test results, respectively. The analysis was carried out using the values of the equivalent shear modulus, G^e_{g1}, and the equivalent damping constant, h^e_{g1}, of the ground obtained by making the analytical values of frequency f_{g1} and the corresponding magnification ratio α_{g1} coincide with the values of the test. Consequently, f_{g1} and α_{g1} agree with the test results, as shown in Fig. 3, but remarkable differences are found between the analytical and test results obtained for frequency f_{s1} and corresponding magnification ratio α_{s1}. From these findings, it is concluded that very significant differences occur between the nonlinear seismic behavior of the ground induced by the inertial interaction and that induced by the kinematic interaction.



A1~A4: Accelerometer, S1~S10: Strain Meter, D1~D5: Displacement Meter

Fig. 1 Test model and measurement equipment

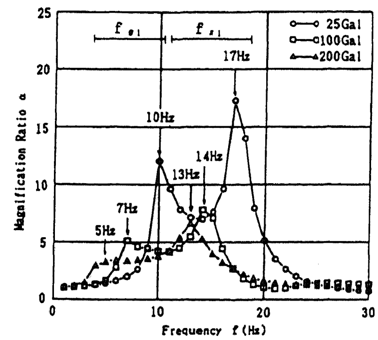


Fig. 2 Resonance curve of superstructure (A4)

3 VARIATIONS IN BENDING STRAIN OF PILE PRODUCED BY NONLINEAR RESPONSE OF GROUND

Figure 4 presents the frequency response functions of the bending strains to a unit acceleration at the base of the central and corner piles based on the sinusoidal excitation. The two peaks appearing for each curve obtained by the excitations of A_{omax} of 25, 100, and 200 cm/s^2 correspond to the peaks of fg1 and fs1 observed in the transfer function in Fig. 2.

In Fig. 4, the magnification ratio β_{g1} corresponding to f_{g1} takes larger values for increasing values of A_{omax} except for the results of S3 and S8. This indicates that the magnification ratio of the bending strain affected by the nonlinear response of the ground becomes larger than that affected by the linear response of the ground. Careful consideration of the variation in the bending strain of piles producing the nonlinear response of the ground should be taken into account in earthquake-proof design practice. On the other hand, the magnification ratio β_{s1} corresponding to f_{s1} becomes smaller for increasing values of A_{omax} in contrast to β_{g1}, indicating that the effect of the nonlinear response on the bending strain makes the variation of the value in the bending strain safe for the seismic design of the pile. From the variation in the bending strain in the depth direction of the piles, the bending strains are higher at both ends of the pile head and pile tip. Since the locations that have strain meters S3 and S8 installed are near the position where the sign of the bending strain changes, both points take on smaller values compared with the other points.

4 PROPOSED METHOD FOR RESPONSE ANALYSIS OF PILE FOUNDATION STRUCTURE SYSTEMS CONSIDERING NONLINEAR BEHAVIOR OF GROUND

According to the dynamic sub-structure method, the seismic response of pile foundation structure systems is obtained by inputting the effective seismic motion of the pile-soil system to the superstructure through the pile head impedance. The above-mentioned difference between the nonlinear seismic responses of the ground caused by the kinematic and inertial interactions suggest that the effective seismic motion and pile head impedance should be evaluated separately. Different values of equivalent shearing modulus and damping constant of the ground should be adopted for each case.

In this paper, evaluation of the effective seismic motion and the pile head impedance taking into account the nonlinear behavior of the ground is proposed as follows.

1. The effective seismic motion is evaluated by multiplying the nonlinear seismic motion of the free field by the coefficient of the effective seismic motion of a group pile foundation, $\eta(\omega)$. Here, the coefficient of the effective seismic motion is defined as the ratio of the effective seismic motion to the free field motion (Tazoh 1988). $\eta(\omega) = 1.0$ means that the effective seismic motion is the same as the free field motion.

2. Pile head impedance is determined considering the nonlinear behavior of the ground surrounding the pile head and may be evaluated using a nonlinear dynamic analysis method for pile foundations subjected to a load acting on the pile head, for example, the one proposed by Nogami et al.(1987), or using results from forced vibration tests of real pile foundations, or adopting a prediction equation based on experimental data.

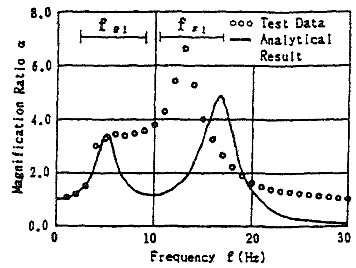


Fig. 3 Comparison between analytical and test results obtained for the resonance curve of superstructure (A4)

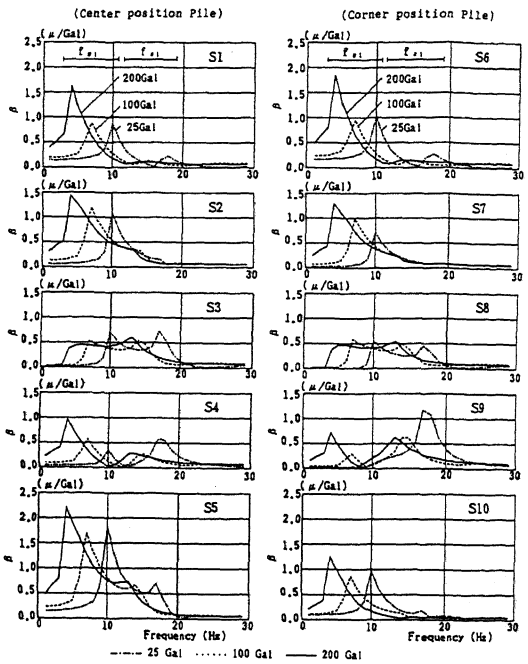


Fig. 4 Response functions of bending strains to unit acceleration of center and corner position piles

5 NUMERICAL ANALYSIS USING THE PROPOSED METHOD

The validity of the proposed method can be verified by comparing the response waves obtained analytically with those obtained from the shaking table tests of the model shown in Fig. 1. By assuming the coefficient of the effective seismic motion, $\eta(\omega)$, to be 1.0 for all frequencies, the acceleration data obtained at the ground surface (A2) were used to constitute the effective seismic motion in this numerical study. The pile head impedance was estimated from the method proposed by the authors (1987) based on the three dimensional elastic wave propagation theory, using the equivalent shear modulus, G^e_{s1}, and damping constant, h^e_{s1}, that were obtained from the tests.

Figure 5 illustrates the comparison between the analytical and test results of the acceleration response of the superstructure (A4) and the bending strain (S1) of the center pile head. Except for the maximum values, good agreement between both waves is observed, demonstrating the validity of the proposed method.

In this numerical analysis, the linear elastic analysis model was defined as using the shear modulus G^e_{g1} and hysteretic damping h^e_{g1} obtained by making the analytical values of f_{g1} and corresponding ratio α_{g1} coincide with the test values. Figure 6 presents the analytical results of the linear elastic model calculated by using the same input motion as shown in Fig. 5. This comparison between the analytical results and the test data confirms that the linear elastic analysis is insufficient for simulating the time history data for the amplification and phase characteristics.

6 CONCLUSION

When studying the effects of the nonlinearity of the ground on the seismic response of pile foundation structure systems, important differences in the variation rates of the shear modulus and the hysteretic damping constant corresponding to the kinematic and inertial interactions were clearly recognized from the shaking table tests. A seismic response analysis method was proposed for grouped pile foundation structure systems taking into account the nonlinear behavior of the ground. In this method, the effective seismic motion and the pile head impedance are evaluated separately. The validity of the proposed method was verified by comparing the analytical and test results.

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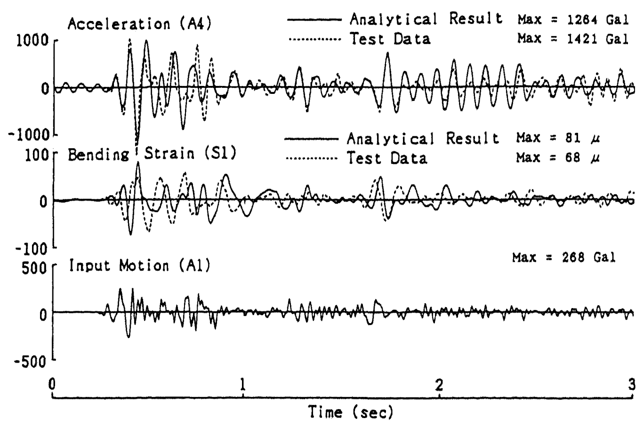

Fig. 5 Comparison between analytical and test results of the acceleration (A4) at the superstructure and bending strain (S1) at the pile head of the center position pile based on the nonlinear response analysis

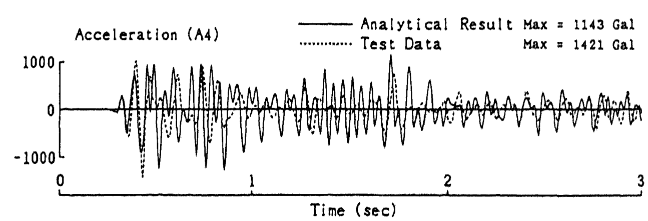

Fig. 6 comparison between analytical and test results of the acceleration at the superstructure (A4) based on the linear response analysis