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ACCELERATION RESPONSE SPECTRUM CONSIDERING DYNAMIC SOIL-PILE INTERACTION

Takashi TAZOH,[1] Toshihiro WAKAHARA,[1] and Katsumi SHIMIZU[1]

[1]Institute of Technology, SHIMIZU Corporation,
Koto-ku, Tokyo, Japan

SUMMARY

This paper deals with the seismic response features of superstructures, considering the dynamic interaction between the soil and the pile foundations. The objectives of this study are to evaluate the acceleration response spectrum taking into account the dynamic interaction, and to discuss the effects of this interaction. The acceleration response spectrum features are different when the dynamic soil-pile interaction is taken into account. These differences can be summarized as a shift of the peak response toward shorter periods than the predominant period of the ground, and generally larger acceleration values in the period shorter than the predominant period of the ground.

INTRODUCTION

In designing earthquake-resistant structures with foundations in soft soil deposits, it is becoming more obvious that the structural response to seismic excitations has much to do with the dynamic soil-foundation interaction. The deeper the foundation is, the stronger is its influence on the dynamic behavior of superstructures set in a seismic environment. This is evidenced by the historic record of damages mainly to pile foundations.

However, the acceleration response spectra usually used in aseismic design are based on superstructures with a fixed foundation movement, and are used in free-field surface motion as an input earthquake motion. In the case of actual superstructures with pile foundations constructed in soft soil deposits, the foundations are moved by an inertial force of the superstructure due to inertial-interaction, and because of a kinematic-interaction, the input motion transferred through the pile foundation is not the same as that of a free-field surface. Therefore, the acceleration response spectra for aseismic design should take into account these two dynamic interactions.

The authors have developed a simplified analytical method for pile foundation structures in order to estimate the effects of dynamic interaction on structure response (Refs. 1, 2). In this paper, the simplified method is applied to the analysis of an acceleration response spectrum considering the dynamic soil-pile interaction. By using this method, the effects of the dynamic interaction on the acceleration response spectrum are clarified for the design of superstructures with pile foundations in soft soil deposits.

MODELING AND METHOD OF ANALYSIS

Figure 1 shows the analytical model adopted in this study. The superstructure is represented by a lumped-mass system where the natural angular frequency is ω_1, and the damping constant is h_1. The pile-soil system is modeled on a continuum model based on three dimensional elastic wave propagation theory (Ref. 3). The whole system consists of these two models which are coupled using substructure theory.

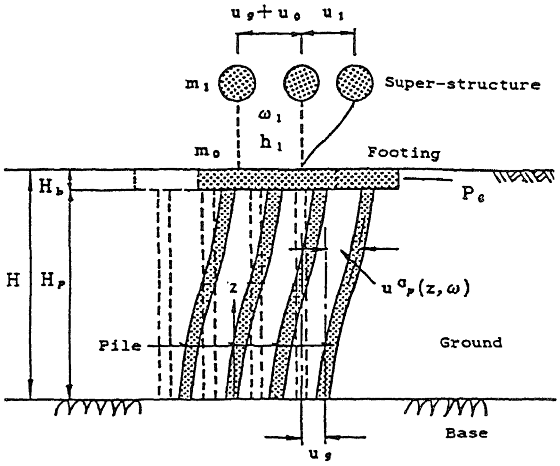

Fig.1 Analytical Model

The maximum response of the superstructure considering the dynamic interaction, $|u_1+u_0+u_g|_{max}$, is derived by using this system as follows (Refs. 4, 5):

$$|u_1+u_0+u_g|_{max}=\left|\frac{H_1^*(\omega/\omega_1,h_1)\{1+u^G{}_p{}^{eff}\}u_g}{1-\omega^2(M/K^G{}_p{}^{imp})\{\mu_1 H_1^*(\omega/\omega_1,h_1)+\mu_0\}}\right|_{max} \tag{1}$$

where

$$H_1^*(\omega/\omega_1,h_1)=\frac{1+i2h_1(\omega/\omega_1)}{1-(\omega/\omega_1)^2+i2h_1(\omega/\omega_1)} \tag{2}$$

and $i^2=-1$, $M(=m_1+m_0)$ is the total mass of structure, $\mu_1(=m_1/M)$ is the mass ratio of superstructure, $\mu_0(=m_0/M)$ is the mass ratio of the footing, and $H_1^*(\omega/\omega_1,h_1)$ is the transfer function between the superstructure and the fixed footing movement. Furthermore, $K^G{}_p{}^{imp}$ is the pile-head impedance of pile-soil system which is relative to inertial-interaction, and $u^G{}_p{}^{eff}$ is the effective motion of the system which is concerned with kinematic-interaction. $K^G{}_p{}^{imp}$ and $u^G{}_p{}^{eff}$ are given as a function of soil properties, pile material, the number of piles and the group effects of pile foundation (Refs. 1, 2, 3) as follows:

$$K^G{}_p{}^{imp}=K^G{}_p{}^{imp}(N,e^f{}_N,H/d,V_p,V_s,\nu,EI,H_p/H_b,h_g,\rho_p/\rho,\omega/\omega_g) \tag{3}$$

$$u^G{}_p{}^{eff}=u^G{}_p{}^{eff}(N,e^g{}_N,H/d,V_p,V_s,\nu,EI,H_p/H_b,h_g,\rho_p/\rho,\omega/\omega_g) \tag{4}$$

where N is the number of piles, e^f_N is the group effect due to the lateral load at pile-head for inertial-interaction, e^g_N is the group effect due to ground motion for kinematic-interaction. H is the thickness of the ground, ν is Poisson's ratio of the soil, ω_g is the predominant angular frequency of the ground, h_g is the damping constant of the soil, ρ is the density of the soil, and V_p, V_s are the velocities of compression and shear waves of the ground, respectively. EI is the flexural rigidity of the pile, H_p is the length of the pile, d is the diameter of the pile, ρ_p is the equivalent density of a solid beam which has the same sectional properties as the original hollow pile, and H_b is the embedded depth of the footing.

Thus, the acceleration response spectrum taking into account the dynamic interaction is calculated by Equation (1) by varying values of the natural angular frequency ω_1 and the damping constant h_1 of the superstructure (Refs. 4, 5).

ANALYTICAL MODEL AND GROUP EFFECT

Figure 2 shows the arrangement of the pile foundation used for numerical calculation. Three types of foundation are considered: the 4 rows x 4 columns model (N=16), the 6 rows x 6 columns model (N=36), and the 8 rows x 8 columns model (N=64). All these types consist of steel pipe piles, whose diameters are all 0.6 m, and the distance L between piles is 1.5 m.

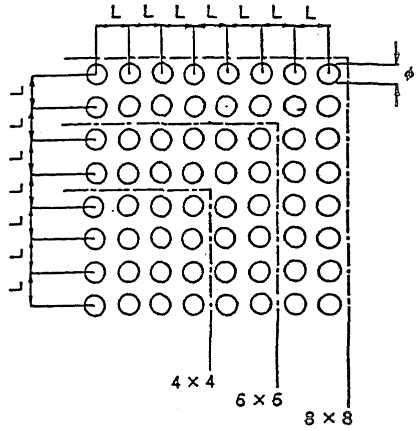

Fig.2 Arrangement of Pile Foundation

When making a model of the ground a typical soft soil deposit is assumed. The depth, H, of that ground is taken to be 20.0 m, which is generally the same as the pile length. Poisson's ratio, ν, of the soil is estimated to be 0.45. The damping constant, h_g, of the soil is taken to be 0.10 by including consideration for the wave propagation downward from the base. The predominant period, $T_g(=2\pi/\omega_g)$, of the ground is 1.0 second.

The superstructure is modeled by a single-degree-of-freedom lumped-mass system whose mass ratio μ_1 is 0.7 where the total weight of the structure including the footing is 3000 ton force, and the damping constant, h_1, is taken to be 0.05.

Since it is difficult to evaluate the dynamic effects of the grouped piles on e^f_N and e^g_N exactly, the values of the static($\omega=0$) grouped effects are used. Figure 3 shows the values of $e^f_N(\omega=0)$ and $e^g_N(\omega=0)$ for this numerical calculation. The values of $e^{f}_{N}(\omega=0)$ in Figure 3 are calculated using the theory proposed by Kotsubo et al. (Ref. 6), and that of $e^{g}_{N}(\omega=0)$ are estimated from the theory proposed by Wakahara et al. (Ref. 7).

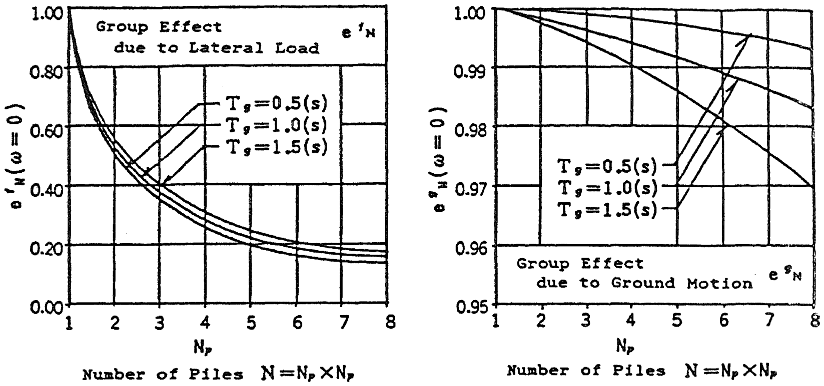

Fig.4 Group Effect of Pile Foundation

ANALYTICAL RESULTS

Figures 4 and 5 show the analytical results of the acceleration response spectra taking into account the dynamic soil-pile interaction. The response spectra in Figure 4 are computed using an input motion at the base. The input motion is the El-Centro NS component with a peak acceleration of 100.0cm/s^2. The response spectra in Figure 5 are based on the Tokachi-oki Hachinohe EW component also with a maximum acceleration of 100.0cm/s^2. In Figures 4 and 5, the solid lines indicate the acceleration response spectra considering dynamic interaction, the broken lines represent the response spectra based on a free-field surface motion, that is, without considering dynamic interaction.

From the analytical results, it can be concluded that the dynamic soil-pile interaction introduces some differences in the acceleration response spectra.

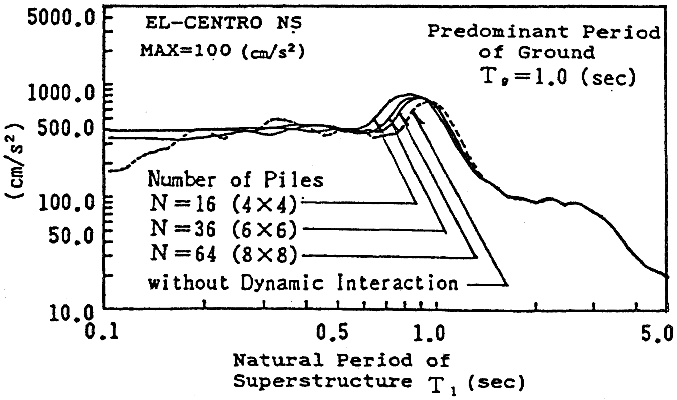

Fig.4 Acceleration Response Spectrum Considering Dynamic Interaction (EL-CENTRO NS,MAX=100 cm/s^2)

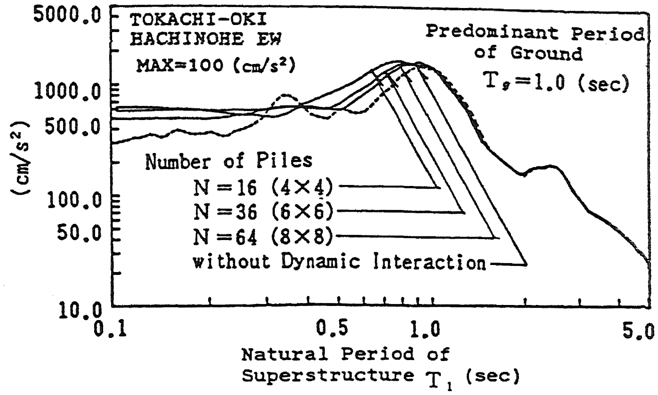

Fig.5 Acceleration Response Spectrum Considering Dynamic Interaction (TOKACHI-OKI HACHINOHE EW MAX=100 cm/s².)

These differences can be summarized as a shift of the peak response toward shorter periods than the predominant period of the ground, and with larger acceleration values in the shorter natural period range and nearer the predominant period of the ground.

The shift of the peak response is caused by an increase in the natural periods of the coupling of the superstructure's system and the pile-soil system. In order to investigate this shift on the response spectra, the increase in the natural period, ΔT_N, of the coupling system is calculated using eigen-value analysis. Figure 6 shows the relationship between the natural period, T_1, of the superstructure with a fixed foundation movement, and the increase in the natural period ΔT_N. It can be seen that the shorter the natural period T_1 is, the larger the increase in the natural period, ΔT_N. Therefore, the shorter the natural period T_1 of the superstructures is, the stronger the influence of the dynamic interaction. And because of pile foundation movements due to inertial forces of

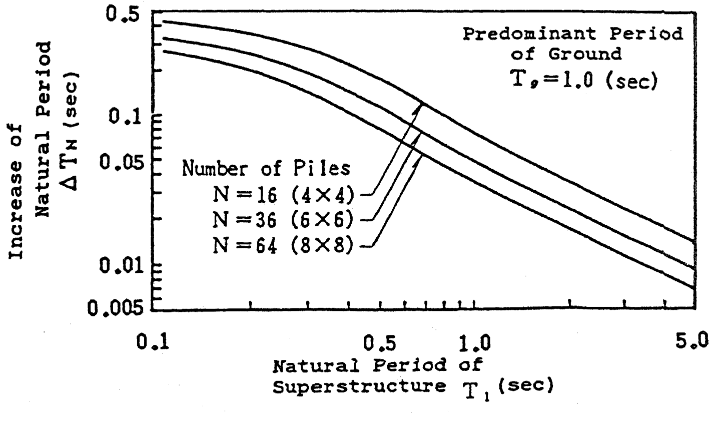

Fig.6 Increase of Natural Period by Dynamic Interaction

the superstructure, the acceleration response values in the shorter natural period range become larger than those values which do not take into account the dynamic interaction. It is evident that the pile foundation movements become larger when the natural period $(T_1+\Delta T_N)$, of the coupling system of the superstructure and soil-pile system is close to the predominant period of the ground.

CONCLUSIONS

Through discussion on the effects of the dynamic soil-pile interaction on the acceleration response spectrum, it has been demonstrated that this interaction is an important parameter to be considered when designing earthquake-resistant structures. The dynamic soil-pile interaction cannot be neglected when investigating the dynamic behavior of the structure, especially in the case of soft soil deposits.

As a result of this research, the following conclusions can be drawn.

(1) The acceleration response spectrum profile is different when the dynamic soil-pile interaction is taken into account. This is particularly true for the values of the period of the superstructure shorter than the predominant period of the ground.

(2) Peak response values appear at unexpected periods which are generally shorter than the predominant period of the ground.

(3) The peak response acceleration is larger when the dynamic soil-pile interaction is taken into account.

All these considerations indicate that more attention should be paid to the natural period range under the predominant period of the ground when designing for pile foundations in soft soil deposit. The influence of the soil-pile interaction is especially important for the periods near to the predominant period of the ground.

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