SEISMIC ANALYSIS OF PILE FOUNDATIONS INCLUDING PILE-SOIL-PILE INTERACTION

G. Waas (I)
H.G. Hartmann (I)
Presenting Author: G. Waas

SUMMARY

The motion and the pile forces of a pile group subjected to earthquake excitation is analized. The soil is modelled as a layered medium of linear visco-elastic material employing the complex response method in the frequency domain. A semi-analytic solution for point and ring loads is used to establish a flexibility matrix of the soil, which can be joint to that of the piles. Thus pile-soil-pile interaction is included.

Inertial and kinematic interaction, assuming vertically propagating shear waves, are studied for a single pile, and for a small and a large pile group.

INTRODUCTION

The behavior of pile groups subjected to dynamic loads has received some attention in recent years. The interest in this topic has been raised by the use of pile foundations for nuclear power plants, LNG storage tanks and other important structures that have to be safe even during and after strong earthquakes.

Empirical knowledge on pile foundation behavior during earthquakes is sparse. Few cases of damage to pile foundations have been reported in the technical literature. Pile damage observed after the 1964 Niigata and Alaska quakes was mainly caused by failure of weak soils. In recent Japanese earthquakes, several pile foundations using prestressed concrete piles were damaged (Ref. 10). Very few experimental investigations on dynamic pile group behaviour have been performed to date.

However, computational methods have been developed for the analysis of dynamic pile group behavior (Ref. 1 to 9). The analized cases indicate that the pile displacements and forces under dynamic loads may be quite different from that under static loads and that single piles and piles in a group respond differently.

This paper presents computational results which are obtained using linear soil-pile models subjected to horizontal excitation.

METHOD OF ANALYSIS

Fig. 1 shows the type of model used. The soil is horizontally layered; it extends laterally to infinity and is underlain by a rigid base at a finite depth. The soil is treated as a linear elastic or visco-elastic medium using complex modulus representation. Non-linear soil behavior may be approximated

(I) HOCHTIEF AG, Department of Nuclear Power Plant Engineering, Frankfurt, F.R. of Germany

by an equivalent linear analysis. The piles are modelled by beam elements with linear bending and shear behavior. The location of the piles in plan is arbitrary. The piles may be pinned or fixed at the pile cap, which is assumed rigid for simplicity.

Each pile is connected to the soil at several, say 10 to 20, nodes as indicated in Fig. 1. Horizontal displacements and rotations of the soil and the piles are matched at these nodes and equilibrium is enforced. To this end, the soil and the piles are considered as substructures. First, the displacement field caused by time harmonic ring and point loads in a layered visco-elastic medium is computed as outlined in Ref. 7. Fig. 2 indicates the displacements due to a ring load in the radial direction. Corresponding figures for a tangential load and a vertical load would look similar. Second, the soil displacements caused by unit loads acting at each node, one at a time, are evaluated for all the nodes where the piles and the soil are to be connected. This leads to the frequency dependent flexibility matrix of the soil, F_s.

Next, the flexibility matrix of the piles, F_p, is computed, and finally, the soil and the piles are connected at the common nodes. This leads to

$$(F_s + F_p)\, P_i = F_p\, P_e - u_F \qquad (1)$$

with $$F_p\,(P_e - P_i) = u \qquad (2)$$

and $$F_s\, P_i = u - u_F \qquad (3)$$

where P_e = external loads, P_i = internal forces between soil and piles, u = total displacements of pile nodes, and u_F = free field displacement of the soil layers caused by vertically propagating shear waves. The matrices and vectors are complex valued, representing amplitudes and phases of harmonic motion at a given frequency. F_s includes radiation and material damping as well as inertia forces of the soil. F_p may include damping and inertia forces of the piles and a pile cap mass.

The earthquake response of the structure is computed here by splitting up the entire problem into kinematic and inertial interaction as indicated in Fig. 3.

DYNAMIC STIFFNESS OF PILE GROUPS

Two pile groups and a single pile, shown in Fig. 4, are studied. The pile diameter is D = 1.3m, the average pile spacing is d = 2.5D. Both the soft and the relatively stiff soil profiles are underlain by rigid rock at -50m. All piles are fixed at a rigid pile cap.

The dynamic horizontal stiffness (or impedance) function K_n^x is shown in Figs. 5 and 6 in normalized form:

$$\kappa = K_n^x \,/\, (n \cdot K_1) \qquad (4)$$

where n = number of piles in the group and K_1 = static horizontal stiffness of a single pile. K_1 is 53 and 175 MN/m for the soft and stiff profiles, respectively.

For a single pile κ is hardly affected by frequency, whereas for the pile groups, especially the larger group, κ varies with frequency. The variation is caused by the resonant frequencies of the soil layers (mainly the fundamental frequency at 0.7 and 1.3 Hz for the soft and stiff profiles, respectively), by the inertia forces of some soil around the piles, and by pile-soil-pile interaction. The latter may decrease or increase the group stiffness depending on the phase of the displacements caused by one pile at the other piles. The compliance functions (inverse of the impedance) presented in Figs. 7 and 8 show a pronounced peak for the larger pile group.

TRANSFER FUNCTION FOR EARTHQUAKE MOTION

An important question in the seismic design of a pile foundation is: Does the pile cap (without building mass) move as the soil surface in the free field, i.e., are kinematic interaction effects negligible? In Figs. 9 and 10 the transfer functions from rock to the pile cap, a_2/a_o, and to the free surface, a_1/a_o, are shown for soft and stiff soil conditions, respectively. For definitions of a_o, a_1, and a_2 see Fig. 11.

The displacement at the top of the single pile hardly differs at low frequencies from that at the surface of the free-field. This holds up to frequencies beyond the first and second resonant frequencies for the soft and stiff profiles, respectively. However, the motions of the pile groups deviate from that of the free field. The kinematic interaction effects are stronger for the larger pile group and the softer soil.

The effect of the inertial interaction due to the building mass, M, is shown in Fig. 12 for the stiff soil profile. An increase in the building mass reduces the natural frequency. The first resonant peak is largest at frequencies slightly below the first natural frequency of the soil profile, since below this frequency no radiation damping is possible and the soil profile and the structure are in resonance.

The peaks in Figs. 9, 10, and 12 are unusually high because in the present case the underlying rock base prevents radiation damping in the vertical direction and material damping is only about 4% of critical damping.

PILE FORCES

Fig. 13 shows the distribution of shear forces over the pile heads due to kinematic interaction for the case of zero building mass. The sum of all shear forces is zero because $M = o$. The shear forces in the outer ring of piles balance those of the internal piles. The forces which result from kinematic interaction are small compared to those shown in Fig. 14 which include inertial interaction effects as well. For practical purposes, the frequency response curves could be well approximated by a simple damped oscillator.

In Fig. 15 the amplitudes of the shear forces and bending moments are presented over depth. Near the pile head shear forces and bending moments of the outer piles are significantly larger than those of the inner piles. The pile forces due to kinematic interaction shown for pile 11 by the dotted lines are comparatively small.

CONCLUSIONS

1. Stiffness: The dynamic stiffness of a single pile is hardly affected by the frequency of motion. However the dynamic stiffness of a large group of piles may strongly depend on frequency with the layering of the soil

and the ratio of the shear wave length in the soil to the plan dimensions of the pile cap being important parameters.

2. Kinematic Interaction: A single pile will follow the earthquake motion of the soil with little deviation. However a large group of stiff piles in a soft soil layer will show a response significantly different from that of the soil in the free field.

3. Resonant effects: High response peaks must be expected when the fundamental natural frequencies of the pile-building system and that of the soil profile coincide.

4. Pile forces: Piles at the periphery of the group will experience higher shear forces and bending moments than internal piles. Pile forces due to kinematic interaction only are small compared to those produced by the inertia forces of a heavy building mass.

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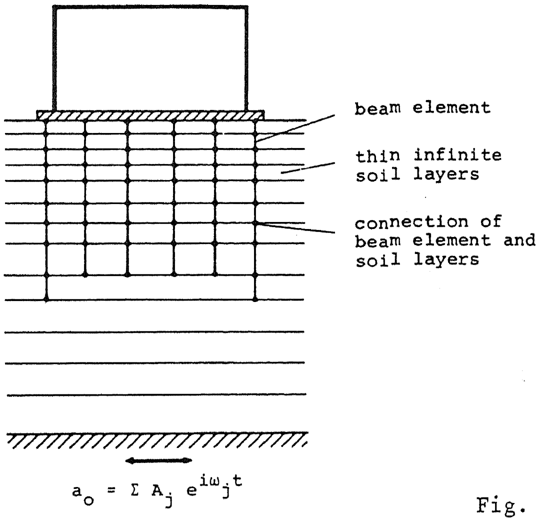

Fig. 1 : Pile foundation subjected to seismic excitation

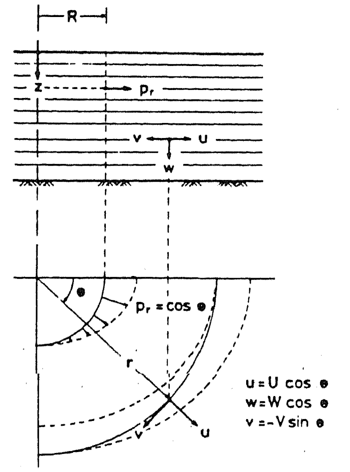

Fig. 2 : Displacements in a horizontally layered medium caused by a horizontal ring load p_r (Fourier term n=1)

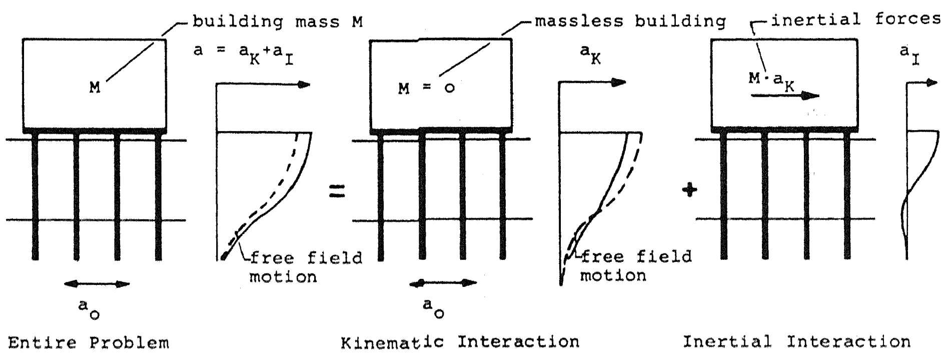

Fig. 3 : Separation into kinematic and intertial interaction

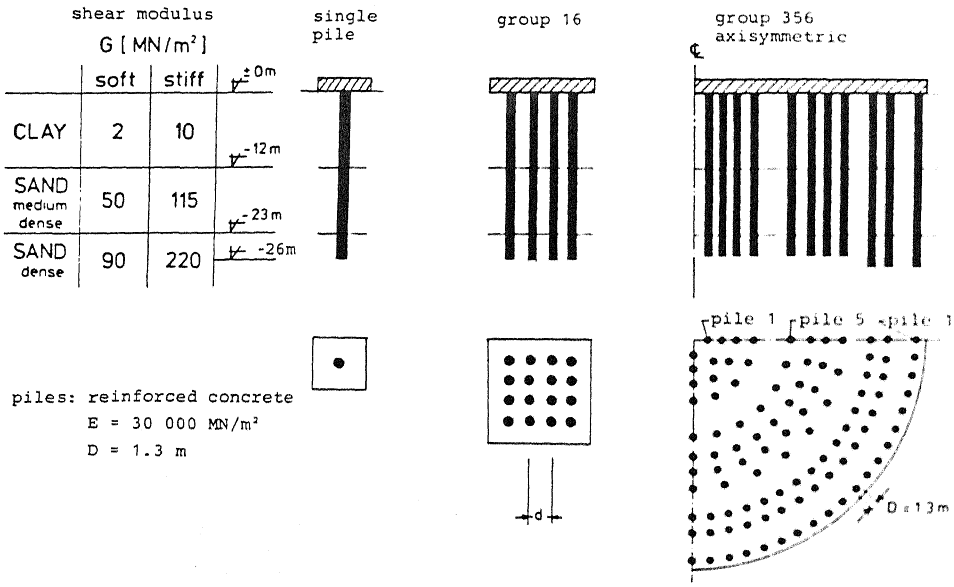

Fig. 4 : Pile groups and soil properties

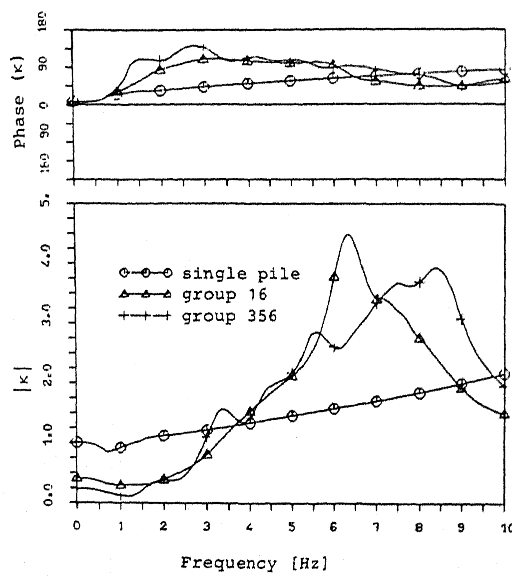

Fig. 5 : Related horizontal impedance for soft soil

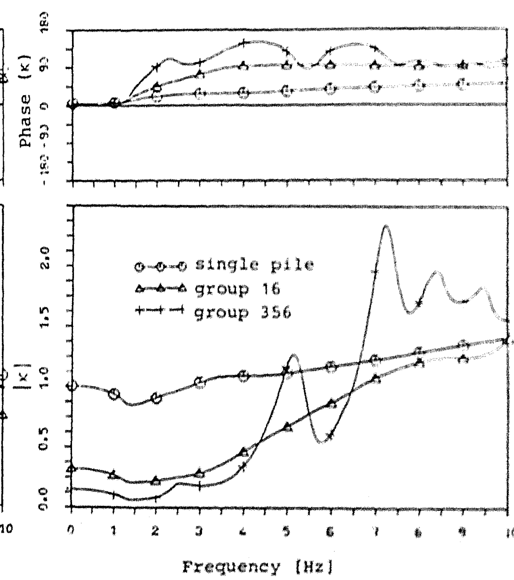

Fig. 6 : Related horizontal impedance for stiff soil

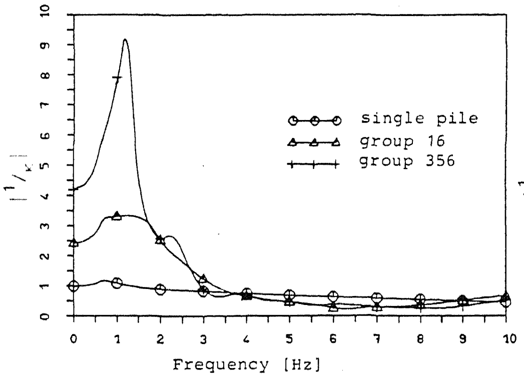

Fig. 7 : Related compliance function for soft soil

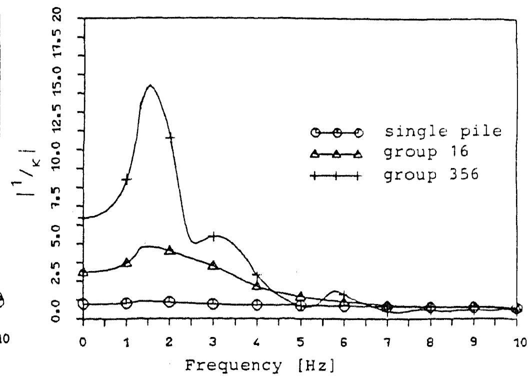

Fig. 8 : Related compliance function for stiff soil

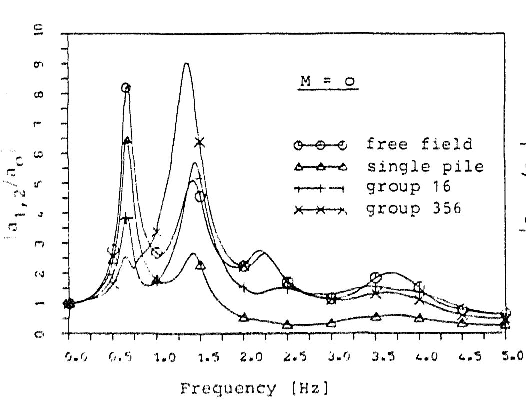

Fig. 9 : Transfer functions without building mass (soft soil)

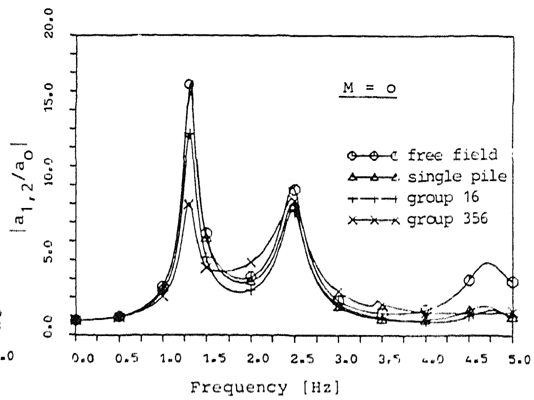

Fig. 10 : Transfer functions without building mass (stiff soil)

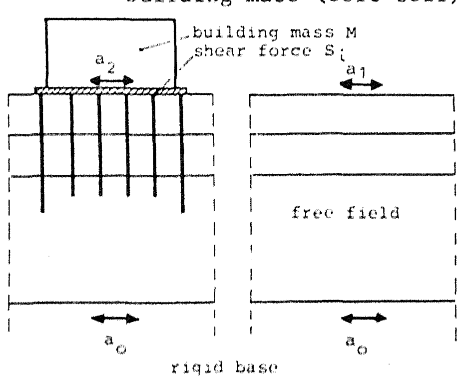

Fig. 11 : Definition of transfer function for horizontal motion

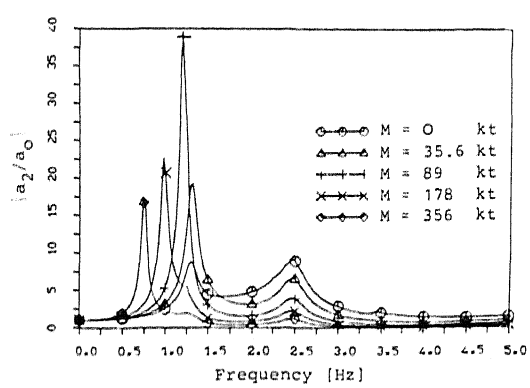

Fig. 12 : Transfer functions with different building mass for group 356 in stiff soil

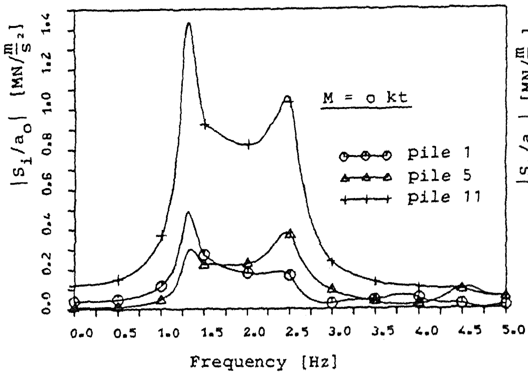

Fig. 13 : Shear forces at pile cap of group 356, M=0 kt (stiff soil)

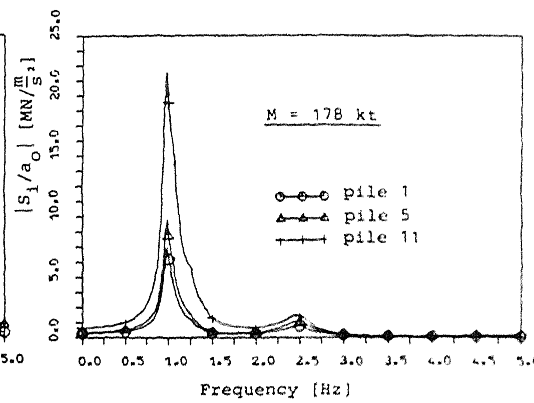

Fig. 14 : Shear forces at pile cap of group 356, M=178 kt (stiff soil)

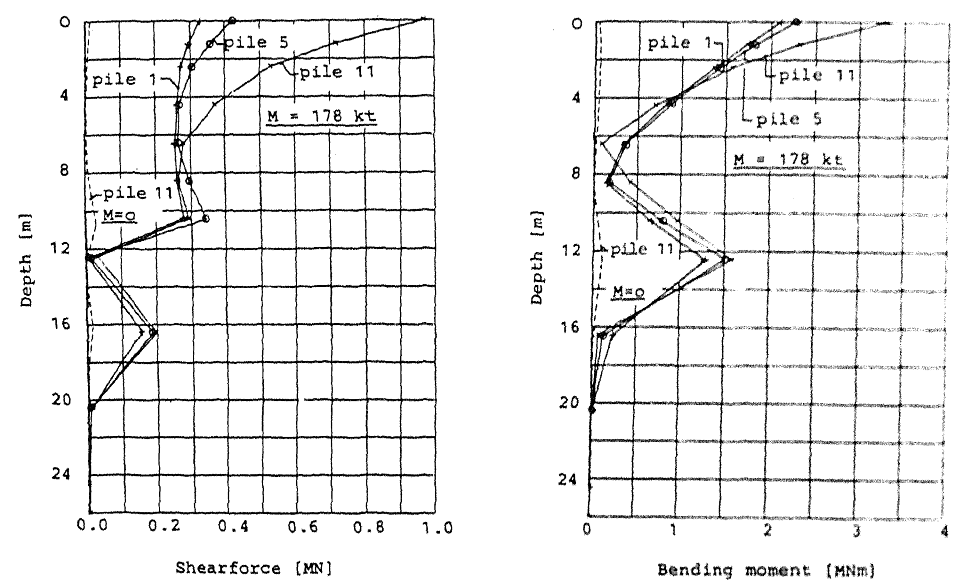

Fig. 15 : Amplitudes of pile forces of group 356 in stiff soil at resonance (f = 1.0 Hz) for a_2 = 1 m/s²