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EFFECTIVE MOTION OF GROUP PILE FOUNDATIONS

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SUMMARY

This paper deals with the effective motion of grouped pile foundations. In order to clarify differences in frequency characteristics between effective motion and free field motion, investigations are made based on numerical studies, model vibration test data, seismic observation records and microtremor data. For all the cases under consideration, the same general behavior and a good agreement between experimental and analytical results are observed. It is found from the results *that the effective motion of grouped pile foundations coincides with* the free field motion for vibration periods which are longer than the predominant period of the soil layer. In addition, it is found that the effective motion is smaller than the free field motion for shorter periods.

INTRODUCTION

The study of the effective motion of foundations is one of the important problems concerning aseismic design of structures with foundations. Effective motion is defined as the response of the massless foundation, taking into account the kinematic interaction of the soil-foundation system. In the design of earthquake-resistant structures, the acceleration response spectrum based on free field motion is used even though there is a foundation constructed beneath the superstructure. This is common practice despite the fact that the motion transferred through the foundation is not the same as that of the free field surface, due to the dynamic soil-foundation interaction. Therefore, it is necessary to use the effective motion as the input motion to the superstructure.

This paper presents the effective motion of grouped pile foundations which has been studied analytically and experimentally. First of all, analytical studies using three-dimensional elastic wave propagation theory were carried out for grouped pile foundations with various pile configurations. The analytical method originally proposed by Tajimi (Ref. 1) is expanded to apply to grouped piles. Vibration tests conducted on the shaking table were carried out for two types of grouped pile foundation models. Seismic observation records were obtained from a foundation supported by 64 piles of a pier of a road bridge. Microtremor data were obtained from a foundation supported by 92 piles of an abutment of a highway bridge. Finally, by comparison between the results of observed data and analytical studies, the characteristics of the effective motion are examined.

THEORETICAL ANALYSIS

Method The effective motion $u^{G}_{p}{}^{eff}$ of the grouped pile foundation shown in Figure 1 is represented by Equation (1), which is solved using three-dimensional elastic wave propagation theory. This equation is expanded to apply to the grouped pile foundations originally proposed by Tajimi (Ref. 1).

$$u^{G\,eff}_{p}(H,\omega) = u_{g}\, e^{g}{}_{N}(\omega)\, G^{*}(H,\omega) \tag{1}$$

where ω is the angular frequency of the excitation, H is the pile length, and $G^{*}(H, \omega)$ is the ratio of the horizontal displacement of the pile-head to the input motion u_g at the base that is shaking the surrounding ground. $e^{g}{}_{N}(\omega)$ is the pile group effect due to ground shaking. The details of $G^{*}(H, \omega)$ and $e^{g}{}_{N}(\omega)$ are described in Refs. 2 and 3. In this study, the effective motion factor $\eta(\omega)$ in Equation (2) is defined as the ratio of effective motion to free field motion in the frequency domain.

$$\eta(\omega) = \left| \{u^{G\,eff}_{p}(H,\omega) + 1\} / \left[(\omega/\omega_{g})^{2} \sum_{n=1,3,\cdots}^{\infty} \{4/(n\pi)\} \xi_{n}^{-2} (-1)^{\frac{n-1}{2}} + 1 \right] \right| \tag{2}$$

where $\xi_n = \sqrt{n^2 - (\omega/\omega_g)^2 + i2h_g(\omega/\omega_g)}$, $i^2 = -1$, ω_g is the predominant angular frequency, and h_g is the critical damping ratio of the soil. When the effective motion factor $\eta(\omega)$ equals 1.0, the effective motion coincides with the free field motion. If the factor $\eta(\omega)$ is greater than 1.0, the effective motion is greater than the free field motion.

Analytical Results Figure 2 shows the analytical results for a 16-pile and a 64-pile foundation for different values of the predominant period Tg of the soil layer. The arrangement of these foundation piles are 4 rows x 4 columns (number of

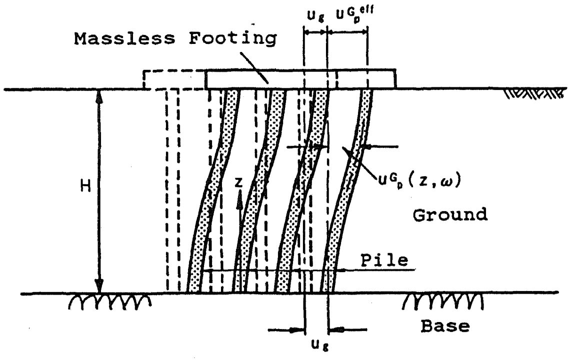


Fig. 1 Effective Motion of Grouped Pile Foundation

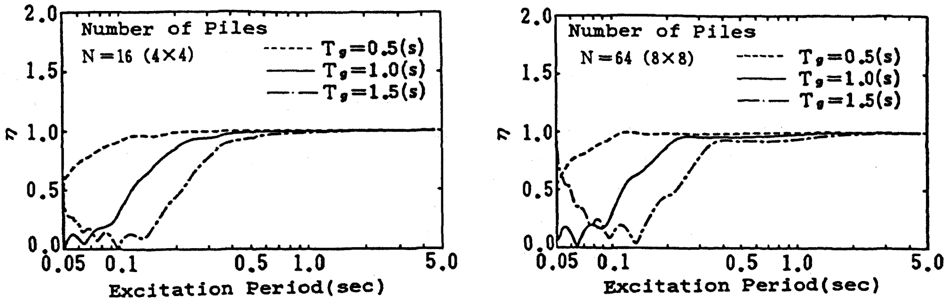


Fig. 2 Effective Motion Factor Based on Analyses

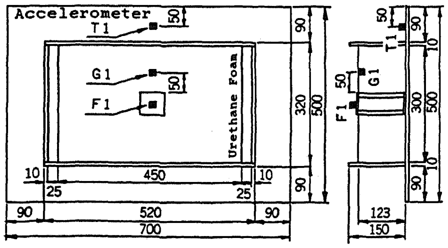
piles N=16) and 8 rows x 8 columns (N=64). All foundation piles consist of steel pipe piles with a diameter D=0.6 m, thickness t=9 mm, length H=20 m, and the distance between each pile is 1.5 m. When making a model of the ground, three types of ground with predominant periods Tg of 0.5, 1.0, 1.5 seconds are used. Poisson's ratio ν of the soil is estimated to be 0.45, and the critical damping ratio hg of the soil is taken to be 0.10. The pile group effect $e^{g}{}_{N}(\omega)$ is taken to be the static value $e^{g}{}_{N}(\omega=0)$ for all frequencies because of difficulty of evaluating the dynamic effect exactly. $e^{g}{}_{N}(\omega=0)$ is estimated from the theory proposed by Wakahara et al. (Ref. 4).

Since the effective motion factor $\eta(\omega)$ is 1.0 for vibration periods which are longer than the predominant period of the soil layer, it is found that the effective motion coincides with the free field motion in this period range. Furthermore, it can be seen that the effective motion is smaller than the free field motion for shorter periods.

MODEL VIBRATION TEST

Model of Grouped Pile Foundations Figure 3 shows the models for the vibration tests for a 4-pile foundation which were carried out using a shaking table (Ref. 5). The piles are made from an acrylic tube (D=13 mm, t=1 mm, H=120 mm). The arrangement of the foundation piles are 2 row x 2 columns (N=4), and two types of pile foundations were made with distances between each pile of 50 mm (Model-1) and 20 mm (model-2). Because each pile-head must be fixed to the massless footing for examination of the effective motion, all pile-heads are fixed to an acrylic plate 3 mm thick. The ground is made up of gelatin with predominant periods of 0.11 seconds (Ground-A) and 0.08 seconds (Ground-B). The static pile group effect $e^{g}{}_{N}(\omega=0)$of the Model-1 and the Model-2 for the Ground-A are 0.60 and 0.42, and those for the Ground-B are 0.63 and 0.45.

Experimental Results Figure 4 shows the transfer functions between the ground surface (G1) and the table (T1), and between the footing (F1) and the table (T1) for Ground-A. The function of the footing can be regarded as the effective motion of grouped pile foundation. It can be seen from this figure that the peak appears at 0.11 seconds corresponding to the predominant period of Ground-A. In the case of making a comparison between the peak value of the effective motion, it can be seen that Model-2 is smaller than that of Model-1, and the ratio of both peaks corresponds to the ratio of both pile group effect $e^{g}{}_{N}(\omega=0)$ due to ground shaking. The distance between each pile of Model-2 is narrower than that of Model-1, thus it is found that the effective motion becomes smaller when the pile distance is narrower. This means that the stiffness of the pile-soil system due to ground shaking becomes greater when the pile distance is narrower. This phenomenon can be understood from the deformation patterns since the deformation of the ground deforms the piles. The analytical results on transfer functions are also shown in Figure 4, and they are in good agreement with the experimental data.



(Unit:mm)

Item	Contents
Pile (Acrylic Tube)	EI = 5.04×10^{3} kgf/cm^{2} ϕ = 13 mm t = 1 mm l = 120 mm
Distance Between Each Pile	Model-1 : 50 mm Model-2 : 20 mm
Ground (Gelatin)	Vs = 4.60 m/s Tg = 0.11 s

Fig. 3 Vibration Test Model for 4-Pile Foundation

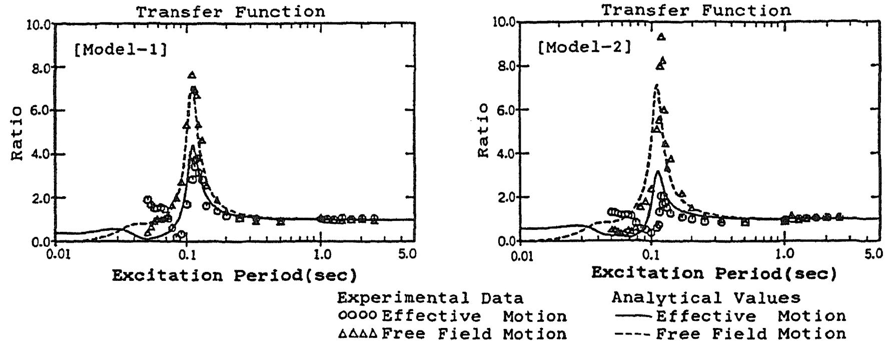


Fig. 4 Transfer Functions between Ground Surface and Table, and between Footing and Table

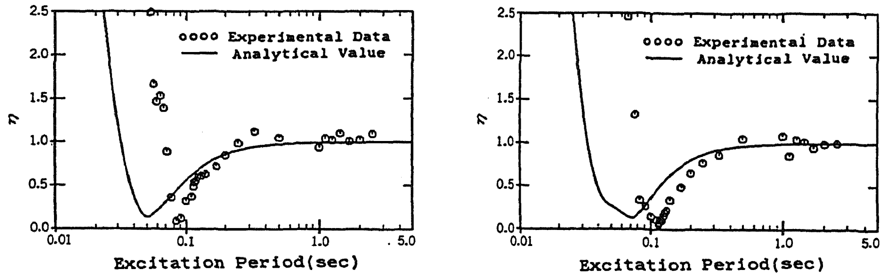


Fig. 5 Effective Motion Factor for 4-Pile Foundation Based on Vibration Test Data

Figure 5 shows the effective motion factor $\eta(\omega)$ for Ground-A and Ground-B. Although the effective motion factor $\eta(\omega)$ is about 1.0 for longer vibration periods, the factor increases greatly for shorter periods. This tendency is also recognized from the experimental results by Mizuno et al. (Ref. 6). It is found from these figures that the experimental results on effective motion agree with the analytical results.

SEISMIC OBSERVATIONS

The authors carried out seismic observations for a pier of a road bridge (Ref. 2). The arrangement of the foundation piles is 8 rows x 8 columns (N=64). Figure 6 shows the positions of the accelerometers at the ground surface (GS1), the base layer (GB1) and the footing (BS1). The piles are made from steel pipe (D=0.6 m, thickness of vertical piles t=9 mm, thickness of batter piles t=12 mm, H=22 m). The predominant period Tg of the ground is 1.4 seconds. The details of the seismic observations are described in Ref. 2.

Figure 7 shows the mean transfer functions between the ground surface (GS1) and the base (GB1), and between the footing (BS1) and the base in the direction of the bridge axis. The functions are calculated by taking an average over all the observed data. The solid line shown in Figure 8 is the ratio of both transfer functions, and the dashed line represents the effective motion factor $\eta(\omega)$ obtained from the analysis. The solid line, based on the seismic data, does not completely agree with the real definition for the effective motion factor, because it includes the influence of the inertial force of the superstructure with predominant period of 0.5 seconds. However, by concluding from the comparison between both lines, it can be seen that the effective motion of the actual case is smaller than the free field motion for periods shorter than the predominant period.

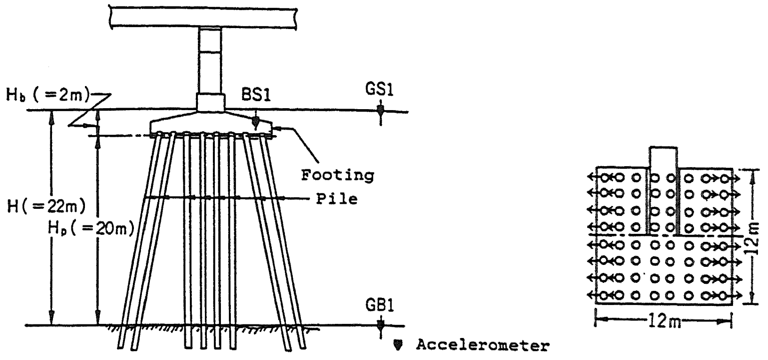


Fig. 6 Location of Accelerometers for Road Bridge

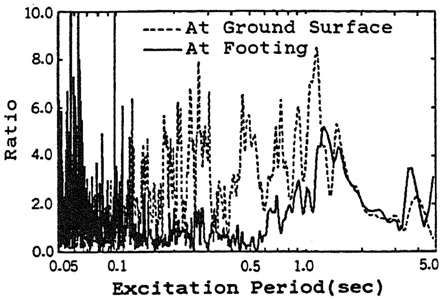


Fig. 7 Transfer Functions (GS1/GB1, BS1/GB1)

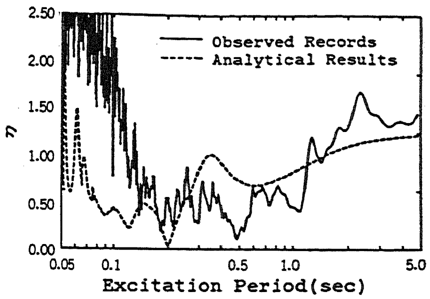
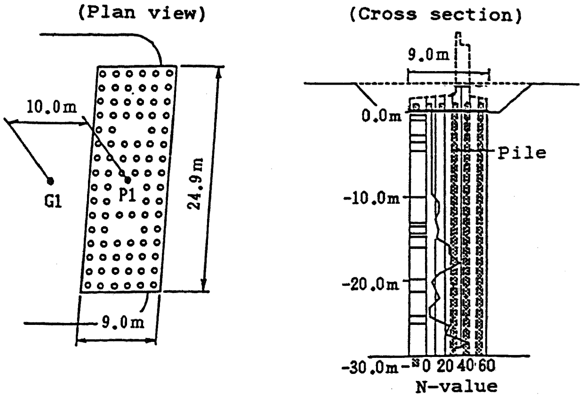


Fig. 8 Effective Motion Factor Based on Seismic Resords

MICROTREMOR OBSERVATION

Figure 9 shows the microtremor observation points for an abutment of a highway bridge which is supported by a 92-pile foundation (Ref. 7). While the observation was being carried out, only a thin concrete slab was constructed on each pile-head, and the pier and the footing were under construction. The piles are made of steel pipe (D=0.6 m, t=9 mm, H=30 m), and the distance between each pile is 1.5 m. The microtremor meters were set on the pile-head and at ground surface. The predominant period of the ground is 0.33 seconds.

Figure 10 shows the effective motion factors $\eta(\omega)$ based on the microtremor data and analyses. It is found from the results of microtremor observations that


(Plan view)

(Cross section)

Fig. 9 Microtremor Observation Points for Highway Bridge the effective motion factors equal 1.0 for periods which are longer than the predominant period of the soil layer. The effective motion factors are smaller than 1.0 for periods shorter than the predominant period. It is also found that the effective motion factors based on microtremor data are in good agreement with the analytical results.

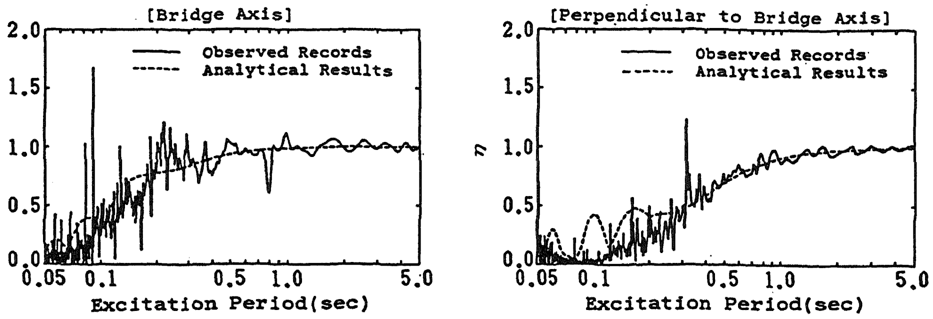


Fig. 10 Effective Motion Factors Based on Microtremor Data

CONCLUSIONS

The effective motion of grouped pile foundations has been studied analytically and experimentally. In obtaining the experimental results, three different cases have been considered: a model vibration test by using the shaking table; seismic observation for a pier road bridge; and microtremor observation for an abutment of a highway bridge. As a result of this study, the following conclusions are drawn.

(1) For all the cases under consideration, a good agreement between experimental and analytical results was obtained. In addition, the same general behavior was observed for all the considered cases.

(2) The effective motion of grouped pile foundations agrees with the free field motion for vibration periods which are longer than the predominant period of the soil layer.

(3) The effective motion is smaller than the free-field motion for shorter periods.

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