SHAKING TABLE TESTING OF SEISMIC BUILDING-PILE-TWO-LAYERED-SOIL INTERACTION

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SUMMARY

This paper reports on shaking table tests of model building-pile-two-layered-soil system with a similitude law almost perfectly satisfied. The objectives of this study are to clarify the dynamic interaction among a building, piles and soil during earthquake and to evaluate seismic loads applied to piles. This study also examines some comparison of the results with those of previously conducted one-layered subsoil test. Effects of building inertia force and soil movement on seismic behavior of piles are discussed.

INTRODUCTION

Recently, damage of precast concrete piles in Off Miyagi Prefecture Earthquake (1978) has been examined from some viewpoints such as bearing capacity of the piles and construction details (Ref. 1). Seismic behavior of the building-pile-soil system and seismic loads applied to piles should be discussed based on soil structure interaction.

The current necessity to account accurately for building-pile-soil interaction has motivated the recent studies (Refs. 3 and 6) and the work reported herein. The objectives of this paper are to show the effectiveness of a newly developed approach of studying the dynamic soil structure interaction (Refs. 2 and 3), and to clarify by the presented method the dynamic interaction among a building, piles and soil which includes the effects of subsoil on a building and piles.

MODEL AND TEST SET UP

An eleven-storied apartment building supported on cast-in-place piles was selected as a prototype. In the building, earthquake observation was performed and its base-fixed fundamental natural period was evaluated to be 0.46 sec from the Fourier spectral ratios of observed earthquake waveforms (Refs. 4 and 5). The predominant period of the subsoil was 0.71 sec and about 1.5 times as long as the base-fixed natural period of the building. In modelling of the building in accordance with similitude ratios shown in Table 1, one of interior dwelling units was extracted through the height of the building and treated as a single-degree-of-freedom system with about 1 percent damping ratio adjusted. The height of the building was ignored in the modelling. A model building, an embedded base and piles were made of steel. The model piles were plates with round edges ; length 71.7 cm, width 5 cm, thickness 0.57 cm. Pile head was fixed and its tip was hinged. The ground was taken to

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be excited in the transverese direction. Model soil was composed of polyacrylamide and bentonite. This material had been confirmed to be elastic (Ref. 2). The prototype subsoil was approximated by two-layered model. shear wave velocities of upper and lower model layers were 17.3 m/s and 43.9 m/s, respectively. Table 2 summarizes the material and geometrical characteristics of the model as compared with those of the prototype. The effect of scaling in the modelling is also described in this table. This model defined as 'basic model' represents the case where the base-fixed natural frequency of the building, fb, is higher than the fundamental natural frequency of the subsoil, fg. Two other buildings were selected as the case where fb is nearly equal to fg and the case where fb is lower than fg. Table 3 describes the dynamic characteristics of these three model buildings.

Figure 1 illustrates the exerimental facilities and instrumentation used for the basic model. Blocks of water-saturated urethane foam were set around the cylinder-shaped soil model in order to simulate the infinite condition of the subsoil and the radiation condition of waves propagating from the foundation. Preliminary tests of this apparatus confirmed good simulation. Two trenches were excavated in both lateral sides of the embedment to remove friction between the embedment and model soil. This treatment was made to preserve the condition of the prototype in the model. The experimental program was carried out with type of building, embedment of the base, type of foundation, pile head condition as major parameters. The test program consisted of static pulling teat, free vibration tests of the building set up and shaking table tests. The shaking table tests had two kinds of shaking; steady state vibration and earthquake motion. Records of Off Miyagi Prefecture Earthquake (June 12th, 1978) and Central Chiba Prefecture Earthquake (Sept. 25th, 1980) observed at the pile tip of the prototype were adopted and condensed to 1/5 in the time scale. In order to verify the effectiveness of the modelling, experimental results were compared with the earthquake observation results of the prototype. Figure 2 presents the Fourier spectral ratios (building/pile tip) observed from the prototype and model tests. These results indicate that the modelling was appropriate.

DYNAMIC SOIL STRUCTURE INTERACTION OF PILE-SUPPORTED BUILDING

Steady State Vibration Tests

Figure 3 shows acceleration resonance curves of the three investigated buildings supported by the head-fixed piles. Frequencies fg* and fb* denote the frequency where the subsoil is mainly stimulated in the building-pile-soil system and the frequency where the building is mainly excited in the same system, respectively. The responses of buildings 1 and 3 have two peaks at the frequencies fg* and fb*. While, the response of building 2 where fb* is nearly equals fg* has one peak that is larger than the other cases. Figures 4 and 5 present earth pressure resonance curves acted on the base and bending moment resonance curves of the pile head of the three buildings and those curves obtained when no such building existed. The existence of building increases the responses of earth pressure and bending moments at the frequency fb*. Figure 6 summarizes natural displacement modes with phase and bending moments of the pile at the frequencies fg* and fb* in the case of two-layered model ground. Figure 7 shows the results of one-layered model ground for the sake of comparison (Ref. 6). In the cases of buildings 1 and 3, bending moments of the pile head have the maximum values at the frequency fg*. Those of building 2 has the maximum value at the frequency fb*. It is noticeable that the bending moment at the interface of two layers is larger than that at the same depth of the one-layered subsoil.

Earthquake Motion tests

Figure 8 shows time history responses of accelerations, earth pressure at the base and bending moment at the pile head in the case of building 1. The acceleration waveform of the building is similar to the earth pressure waveform, while the base acceleration similar to bending moment. Figures 9 and 10 illustrate time history modes of acceleration and pile bending moment when the building accelerations have peak values. These figures also include the natural modes in steady state vibration. In building 1. the natural mode at fg* is predominant in the time histiry modes. On the other hand, in buildings 2 and 3, the natural mode at fb* can be found significant.

EFFECTS OF BUILDING INERTIA FORCE AND SOIL MOVEMENT ON PILES

The responses of the base-pile-soil system without the building can be considered as those induced by soil movement, except the inertia force of the base and piles. The previous experiments confirmed that the pile behavior was affected predominantly by forced displacements of soil vibration. Consequently, responses by the inertia force of the building can be introduced by subtracting the that results of the base-pile-soil system from those of the building-pile-soil system.

Figure 11 summarizes resonance curves of bending moments at the pile head in three cases related to building 1 ; 1) building-pile-soil system, 2) base-pile-soil system and 3) component caused by the inertia force of the building. The component of bending moment generated by the building inertia force has two peaks at the frequencies fg* and fb*. The peak value at fg* is almost identical with the peak value of fb*. The bending moments in the base-pile-soil system have an unique peak at fg*. It is noticeable the effects of soil vibration on bending moments of the pile are significant. Figure 12 shows phase relations of bending moment between the response by soil movement and that by inertia force of the building in the three building cases. At the frequencies lower than the frequency fb*, both phases are the same, and at the frequencies higher than fb*, they are the reverse. In the former cases, the building and base vibrate in the same phase. While, in the latter cases, both vibrate in the reverse phase. Figure 13 shows waveforms of bending moment by ground vibration and by inertia force of building 1 in Off Miyagi Prefecture Earthquake excitation. In the figure, ratios of subsoil vibration effects to total bending moments are also plotted in the time history. The frequency histogram shows that the ratio of 70 - 80 percent is most probable. This ratio is nearly equal to that of steady state vibration test at the frequency fg*.

Lateral resistance of piles is calculated in design on the basis of an assumption that the ground keeps still and an inertia force of the excited superstructure exerts on piles. Sometimes lateral earth pressure acted on the base is included as part of the earthquake force resistance. This contribution in resistance is estimated as a participation factor. This factor is the ratio of the shear resisted by the earth pressure to the total inertia force of the building and base as defined in Table 4. Table 5 summarizes the participation factors in static pulling test of the base-pile-soil system and steady state vibration test of the building-pile-soil system as compared with those of mat foundations. The participation factors of the piles are about 30 percent in both tests. Figure 14 illustrates the seismic participation factors at the acceleration peaks of the building more than 60 percent of the maximum peak height in Off Miyagi Prefecture Earthquake shaking. The figure also includes the classification of time history modes and the participation factors in steady state vibration. In building 1, where the frequency fb* is higher than fg*, the building and base vibrate in the same phase, and the participation factors of the piles are located between the values at fb* and fg* obtained from the steady state vibration test. The participation factors of the base are smaller than those of buildings 2 and 3. In the cases of building 2 where fb* is nearly equal to fg* and building 3 where fb* is lower than fg*, the participation factors of the piles are more scattered, but the factors at each of classified three modes are confined in narrow range. The time-average participation factors of the piles at the mode when only the building is stimulated in buildings 2 and 3 are comparable to those at fb* in steady state vibration.

CONCLUDING REMARKS

This study reveals the dynamic interaction among a building, piles and soil with emphasis on the effects of the building inertia force and the soil movement on piles. The concluding remarks are summarized as follows; 1) The model experiment presented herein is proved a powerful new approach for the study of dynamic soil structure interaction. 2) The behavior of piles during earthquake are governed not only by the mode in which the building is predominantly stimulated, but also by the mode in which the subsoil is predominantly stimulated. Bending moments in the latter mode are larger than those in the former. 3) Quantitative comparison of pile bending moments by an inertia force and by soil movement leads to the following conclusions: Effects of soil movement on piles during earhquake should be taken account into design of lateral resistance of piles, especially in the case where the frequency fb* is higher than fg*. 4) The participation factor of piles in the sum of inertia forces of the building and base, that is usually used for pile design, is valid for only the mode in which the building is stimulated and the subsoil keeps still. 5) It is recommended that soil-structure interaction should be included in the design of piles, because the deformations of the soil may cause large bending moment in the pile.

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Table 2 Degree of Consideration in Modelling of Various Parameters (after Ref. 2)

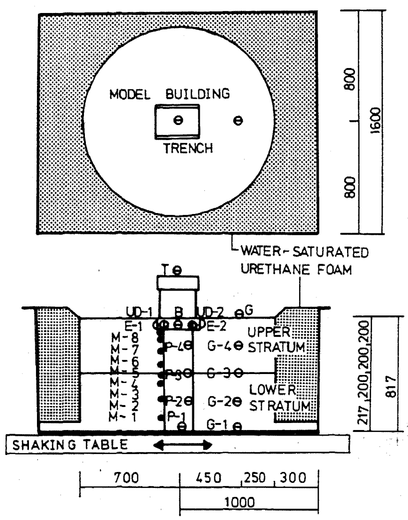
ITEMS	PARAMETER	DIMENSION	DEGREE OF CONSIDERATION IN MODELLING (suffix m and p denote model and prototype)
GROUND	Density	ML^{-3}	◎ Model Soil Density $\rho m=1.2t/m^3$. Clay Density $\rho p=1.6t/m^3$. Then $ML^{-3}=3/4$ is fixed.
	Shear Modulus	$ML^{-1}T^{-2}$	○ Satisfied
	Shear Wave Velocity	LT^{-1}	◎ Satisfied
	Depth of Layer	L	◎ Satisfied
	Predominant Period	T	○ Satisfied
	Damping Ratio of Soil	1	○ Material Damping, hm 6-9%. If strain level of clay is assumed $3\times10^{-4}\sim1\times10^{-3}$, hp 5~7%
	Poisson's Ratio	1	△ Model Poisson's Ratio $\nu m=0.22\sim0.39$. Clay $\nu p\fallingdotseq0.5$
	Coefficient of Horizontal Soil Reaction	$ML^{-2}T^{-2}$	○ This parameter is function of shear modulus and Poisson's ratio. Because G is based on the similitude ratio, this parameter varies according to the variation of Poisson's ratio.
EARTHQUAKE	Acceleration	MLT^{-2}	○ Depending on the ability of the table. Then relation between ML and T is fixed.
PILE	Bending Rigidity	ML^3T^{-2}	◎ Possible by substiting steel for reinforced concrete.
	Diameter	L	◎ Perfectly satisfied
	Length	L	◎ Perfectly satisfied
	Line Density	ML^{-1}	△ Ignored but the realized density was 62% of the required.
	Shape of Cross Section		✕ Ignored. Rectangle with round edges was substituted for circle.
EMBEDMENT	Length	L	◎ Perfectly satisfied
	Mass	M	◎ Embedment was considered as one mass. Then mass ratio of embedment to soil was the same as the prototype.
BUILDING	Mass	M	◎ Effective mass of fundamental mode (base-fixed) was considered.
	Fundamental Period	T	◎ Adjusted by column stiffness.
	Damping	1	○ Damping ratio of building was estimated as 1% and adjusted.
	Height	L	✕ Ignored
	Displacement		
	Deformation	L	○ Satisfied
	Sway Effect	L	○ Satisfied
	Rocking Effect	L	✕ Height is ignored. So this parameter is not exactly quantitative.
SYMBOL	◎: Perfectly Satisfied ○: Satisfied △: Not Exactly Quantitative ✕: Ignored		

Table 1 Similitude Ratios

Items	Dimension	Similitude ratio
Length	L	1/30
Weight	MLT^{-2}	1/36000
Time	T	$1/\sqrt{30}$
Bending Rigidity	ML^3T^{-2}	$1/324\times10^5$
Density of Ground	ML^{-3}	3/4
Velocity	LT^{-1}	$1/\sqrt{30}$
Acceleration	LT^{-2}	1

Table 3 Dynamic Characteristics of Buildings

KIND OF BLDGS	RELATION BETWEEN fb AND fg fb:BASE FIXED NAT. FREQ. OF BLDG fg:PREDOMINANT FREQ. OF GROUND	DIMENSIONS OF BUILDING		BASE-FIXED CHARACTERISTICS OF BUILDING	
		WEIGHT (kg)	HEIGHT (cm)	FREQ. (Hz)	DAMPING (%)
1	fb > fg	12.7	24.8	11.8	1.06
2	fb ≒ fg	12.1	31.5	6.80	0.99
3	fb < fg	20.2	40.8	3.59	0.98



ACCELEROMETER (Horiz., Verti.)

STRAIN GAUGE

EARTH PRESSURE TRANSDUCER

Fig. 1 Experimental Facilities and Instrumentation

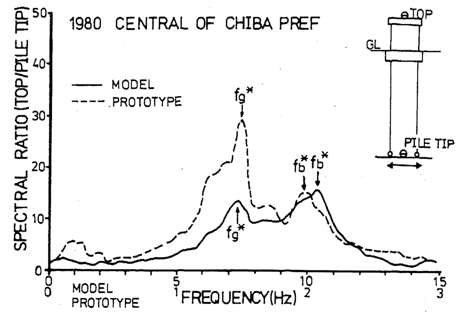


Fig. 2 Comparison of Fourier Spectral Ratios (Building/Pile Tip)

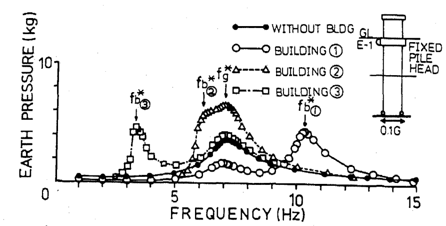


Fig. 4 Earth Pressure of Base in Three Building Cases (Head-Fixed Pile)

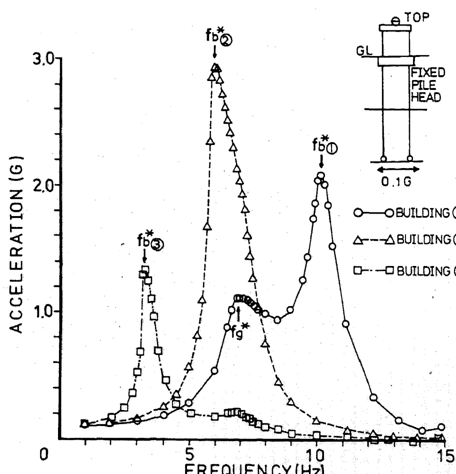


Fig. 3 Acceleration of Building in Three Building Cases (Head-Fixed Pile)

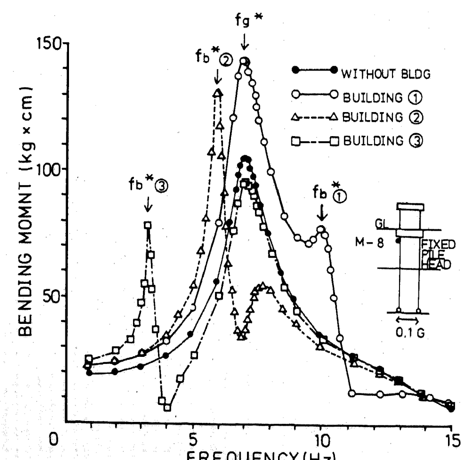


Fig. 5 Bending Moment of Pile Head in Three Building Cases (Head-Fixed Pile)

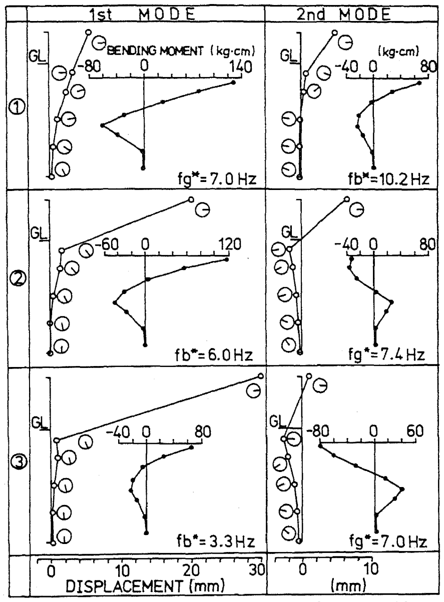


Fig. 6 Natural Modes and Pile Bending Moments at fg* and fb* (Two Layers)

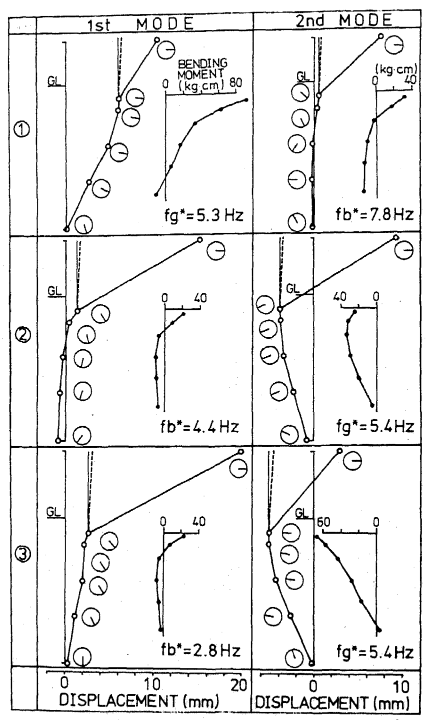


Fig. 7 Natural Modes and Pile Bending Moments at fg* and fb* (Single Layer)

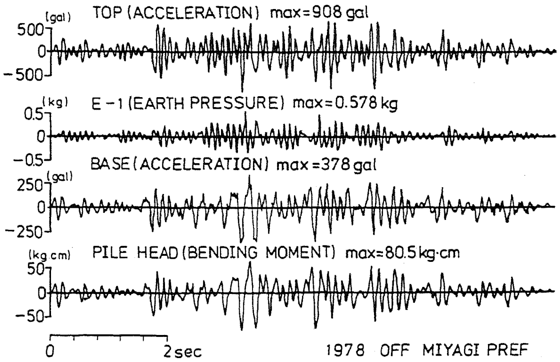


Fig. 8 Time Histories of Basic Model (Off Miyagi Prefecture Earthquake)

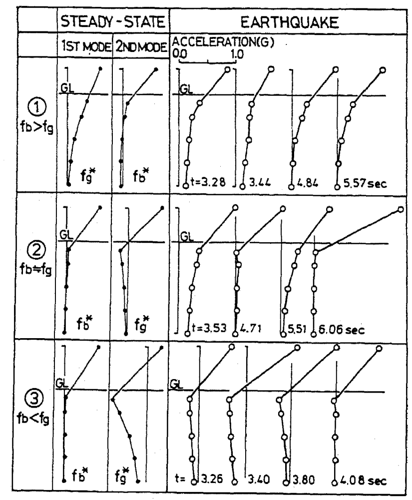


Fig. 9 Time History Modes of Acceleration (Head-Fixed Pile, Off Miyagi Prefecture)

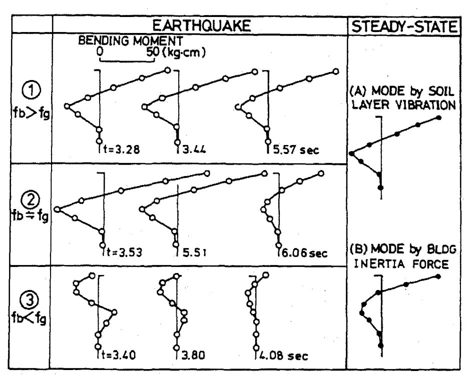


Fig. 10 Time History Modes of Pile Bending Moment (Head-Fixed Pile, Off Miyagi Prefecture Earthquake)

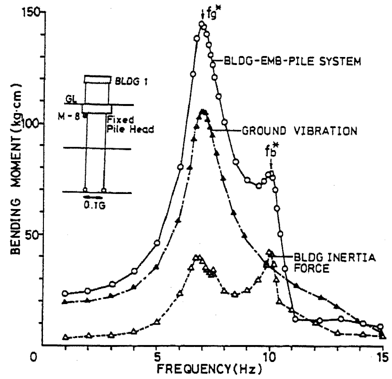


Fig. 11 Bending Moment of Pile Head by Building Inertia Force and Soil Movement (Basic Model)

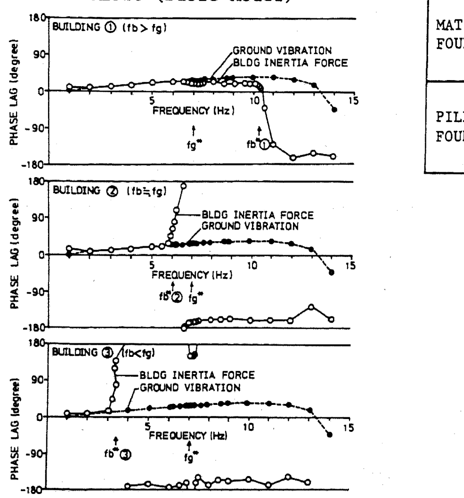


Fig. 12 Phase Relation of Pile Head Bending Moments by Building Inertia Force and by Soil Movement (Head-Fixed Pile)

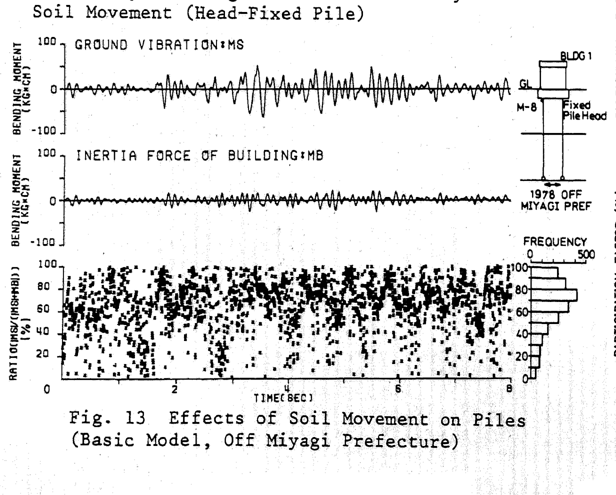
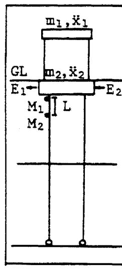


Fig. 13 Effects of Soil Movement on Piles (Basic Model, Off Miyagi Prefecture)

Table 4 Definition of Participation Factors



	EXTERNAL LATERAL FORCE; P
STATIC	P; Lateral Force on Basement
DYNAMIC	$P=m_1\ddot{x}_1+m_2\ddot{x}_2$ m_1, m_2; Mass of Building and Basement $\ddot{x}_1$, $\ddot{x}_2$; Acceleration of Building and Basement
	PARTICIPATION FACTORS
	(a) Sides of Basement ··· $\beta_E=(E_1+E_2)/P$
	(b) Piles ··· $\beta_P=(M_1-M_2)/(P\cdot L)\times 2$
	(c) Bottom of Basement ·· $\beta_F=1-(\beta_E+\beta_P)$
	E_1, E_2; Earth Pressure of Side of Basement M_1, M_2; Bending Moment of Pile L; Distance

Table 5 Participation Factors (Mat Foundation and Pile Foundation)

TYPE OF FOUNDATIONS	TYPE OF TESTS	TYPE OF BUILDINGS	PARTICIPATION FACTORS (%)		
			SIDES OF BASEMENT	PILE	BOTTOM OF BASEMENT
MAT FOUNDATION	STATIC		49.3		50.7
	STEADY STATE	1 (fb > fg)	55.6		44.4
		2 (fb ≒ fg)	62.4		37.6
		3 (fb < fg)	47.8		52.2
PILE FOUNDATION	STATIC		30.8	48.1	21.1
	STEADY STATE	1 (fb > fg)	24.8	44.8	30.4
		2 (fb ≒ fg)	26.1	53.4	20.5
		3 (fb < fg)	33.1	47.9	19.0

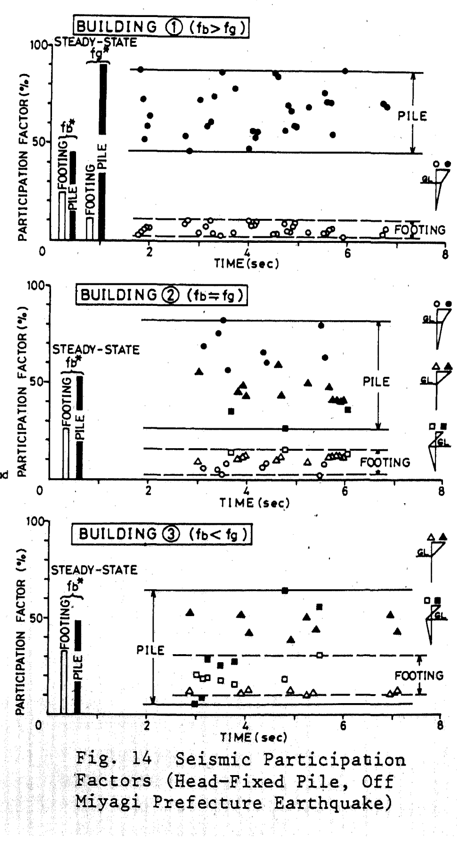


Fig. 14 Seismic Participation Factors (Head-Fixed Pile, Off Miyagi Prefecture Earthquake)