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DYNAMIC BEHAVIOR OF A MODEL PILE FOUNDATION-GROUND SYSTEMS IN THE LIQUEFACTION PROCESS

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SUMMARY

This paper describes model vibration tests to find out the dynamic behavior of ground-pile foundation systems just before complete liquefaction. For this study, loose saturated sand and a model pile foundation are used in a flexible shear vessel attached to a shaking table. The nonlinear dynamic interaction of ground-model pile foundation systems in the liquefaction process were investigated by comparing the results obtained for the ground system with those of the ground-pile foundation combined system. The authors conclude that the pile foundations have effective liquefaction resistance and that selecting a suitable pile foundation stiffness will provide a more adequate stabilization technique against the failure phenomena due to liquefaction.

INTRODUCTION

Liquefaction of sandy ground surrounding a foundation-structure is characterized by geometrical nonlinearity caused by floating up, separation, sliding, and the material nonlinearity due to plastic deformation of the ground. Since it is difficult for an element test of sand, such as the dynamic triaxial test, to reproduce the same stress condition as the complicated three dimensional phenomena caused by the interaction between the ground and a pile foundation, model vibration tests of a ground-pile foundation are made using a shaking table. But, in model vibration tests of ground there is a problem with the similarity of ground properties. Functions such as time and effective overburden pressure must be smaller than those of the prototype, since the small scaled model is tested in the same gravitational force field. When loose saturated sand is used as the model ground, the results of the model test emphasize the progressive rise of pore pressures, and on the contrary hasten the dissipation of pore pressures because of the shallow depth compared with the real ground depth. In our past studies (Refs. 1, 2), a new model material was developed which has superior reproductiveness of softening characteristics of ground, but the behaviors of the pore pressure were not obtained because of the condition of total stress.

In this study, loose saturated sand is used to find out the effects of liquefaction on a pile foundation. The dynamic characteristics of the liquefaction phenomena were studied by comparing the response properties obtained by horizontal excitation of the ground (without foundation and adjacent ground) to the pile foundation. Next simultaneously excitation was applied to the model and the values obtained were compared with the horizontally excited response values. The failure phenomena due to liquefaction were observed from the time that the pore pressures reached maximum value and started to dissipate, and from the response values such as acceleration and vibratory earth pressure.

EXPERIMENTAL PROCEDURE

The real piles assumed in this study support 30m wide and 3m deep square footing and are embedded into rigid ground. In the modelling a superstructure is treated as a virtual mass approximately. The properties of the superstructures, ground and pile foundation are tabulated in Table 1. Three dimensional scaled model used in this study is shown in Fig. 1.

Model Ground and Similarity The ground model material is a loose saturated sand with Vs (velocity of secondary wave) 70 m/s in Dr (relative density) 30%. The ground model is surrounded by the flexible shear vessel with the dimension of 200cm x 200cm x 80cm to minimize the influences of finite boundaries. The pile foundation models are made of aluminum. The model law and the ratio of similarity used are tabulated in Table 2. The models calculated from these scale factors are listed in Table 1.

Experiments and Experimental Facility The measuring points where the micropickup were used were located at the ground surface and the ground (displacement gauge $D_1 \sim D_2$, accelerometer $A_1 \sim A_7$, pore pressure gauge $P_1 \sim P_6$, shear strain meter $S_1 \sim S_3$), and the side of the pile (earth pressure gauge $E_1 \sim E_3$) as shown in Fig. 1. Horizontal excitation in sinusoidal wave form of acceleration amplitude 100 cm/s², constant wave number of 50 and frequencies 10Hz, 15Hz and 25Hz were applied first to the model.

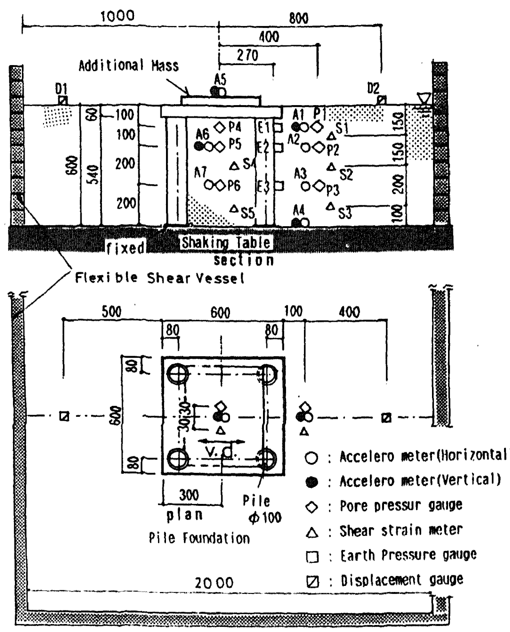


Fig. 1 Ground-Pile Foundation Model

Table1 Design Details of Prototype and Model

Prototype	Model Aim	
PILE FOUNDATION		
Length 27(m)	54(cm)	
Diameter 5	6 (conversion wide)	
Footing 30,30,3	60,60,6	
Viaduct 28,28,10	Additional mass	
Young's Modulus (GPa) 20.6	70.6	
Poisson's Ratio 0.17	0.34	
SOIL SYSTEM	SAND	
Reclaimed Sand	Aim	Execution
Vs(m/s) 200	28	70
fg(Hz) 1.7	12	10
Depth(m) 30		60(cm)
$\rho d_{min.max}$ (g/cm³)	1.5 , 1.7	
D_{50} (mm)	0.46	
Uc	2.5	
Poisson's Ratio	0.45	

Table2 Similarity and Scale Factor

Function	Similitude	Scale Factor
Length	lm/lp	1/50
Stress	$(\rho m/\rho p)(lm/lp)$	1/50
Cohesion	$(\rho m/\rho p)(lm/lp)$	1/50
Time(Period)	$(lm/lp)^{1/2}$	1/7.1
Frequency	$(lm/lp)^{-1/2}$	7.1
Displacement	lm/lp	1/50
Velocity	$(lm/lp)^{1/2}$	1/7.1
Modulus	$(\rho m/\rho p)(lm/lp)(\nu m/\nu p)$	1/50
Mass Density	$\rho m/\rho p$	1
Acceleration	$\alpha m/\alpha p$	1
Internal Friction Angle	$\phi m/\phi p$	1
Damping Constant	hm/hp	1
Strain	$\varepsilon m/\varepsilon p$	1
Poisson's Ratio	$\nu m/\nu p$	1

suffix m: model, p: prototype

Horizontal and vertical simultaneous excitations were applied next to the *model*. The rate of the vertical acceleration 50 cm/s² was kept constant to the horizontal 100 cm/s² with the same phase. With horizontal excitation at input frequency 25 Hz, complete liquefaction phenomena can not be observed since the excessive pore pressure did not reach an effective overburden pressure (Ref. 3, 4). In this study, mainly at the frequency 10 Hz and 15 Hz, the results of the horizontal excitation are compared with those of the simultaneous excitation. The shaking table (rated carrying weight 20 tf, max. accel. 3G) is shown in Fig. 2. It can simulate a three-dimensional motion as well as the triaxial rotations by developing the hydrostatic joint which enables to communicate smoothly to activating force by oil films. The experiments were carried out for three cases, namely, two mono system (the simple ground system and the pile foundation system fixed to the base) and the combined system (ground-pile foundation system).

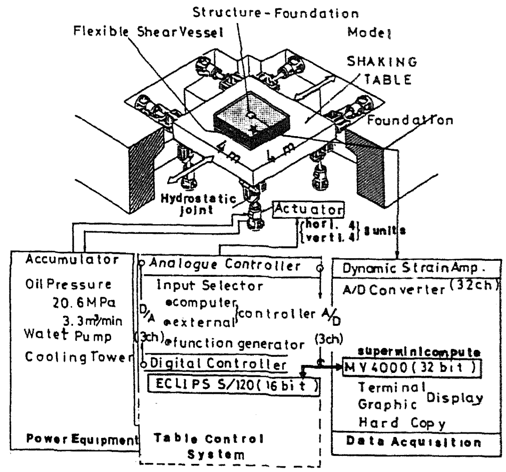


Fig. 2 3Dimensional 6Freedom Shaking Table

RESULTS OF EXPERIMENTS

<u>Ground System</u> The time-response curves of the acceleration, the shear strain and the excessive pore pressure at the each depth of the ground are shown in Fig. 3. The time that the exces. pore pressure curve is paralleled to the time axis is shown as TPih (i=1, 3) and the arrows. The time that the exces. pore pressure curves begin to decrease is put in parentheses. The liquefaction phenomena reaches from the surface ground to the inground, corresponding to the order of magnitude of the exces. pore pressure times, TP1h <TP2h <TP3h. The ground in all layers becomes muddy after TP3h passed. After keeping the muddy condition, the liquefaction stops from the inground to the surface ground.

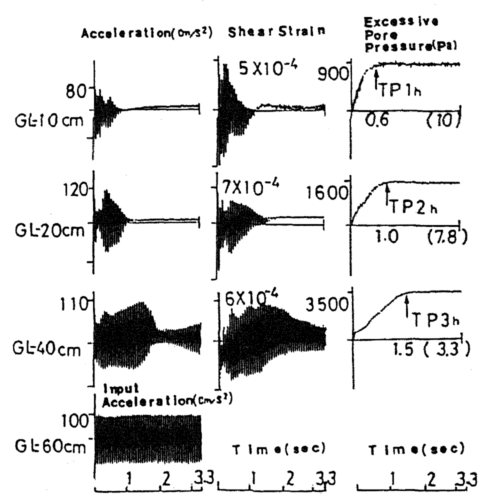
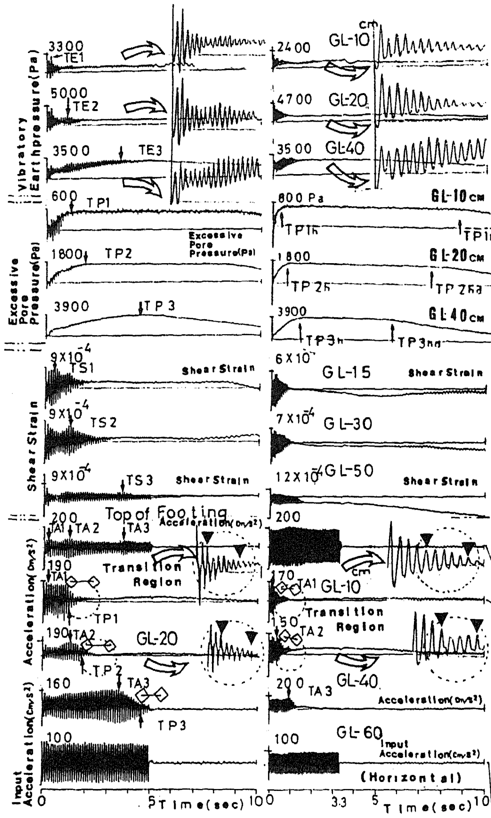


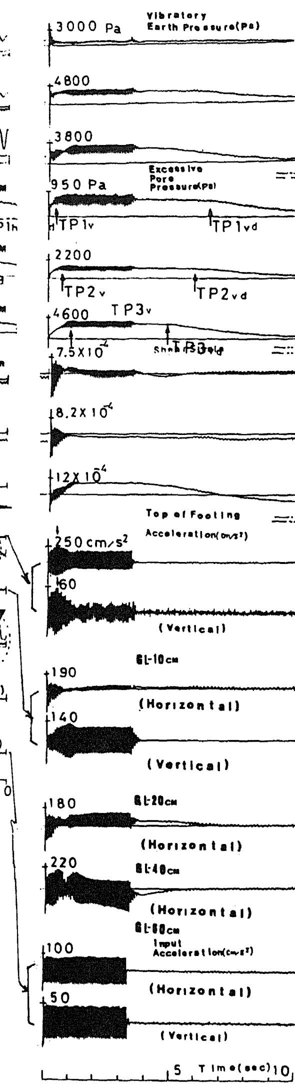
Fig. 3 Time-Response Curve of Ground (Horizontal, 15Hz)

<u>Pile Foundation System without Ground</u> The resonant frequency, the damping constant, and the response acceleration magnification factor at the top of footing are 25Hz, about 4%, and 19 respectively.

<u>Combined System</u> The time-response curves of the acceleration measured in the top of the footing and adjacent ground, the vibratory earth pressure, shear strain and exces. pore pressure at the each depth of the ground are shown in Fig. 4 (a, b, c). The large difference between the response values of 10Hz and

15 Hz are not observed in the process to the complete liquefaction where the physical quantities such as the response acceleration and exces. pore pressure etc. reach to the maximum values, except for the absolute values of the response time and quantity.





(a) 10 Hz (b) 15 Hz
(Horizontal Excitation)
Fig.4 Time-Response Curve of Ground-Pile Foundation (compare horizontal with simultaneous excitation)

(c) 15 Hz (simultaneous)

DISCUSSIONS

The displacement modes of the ground system at the input acceleration amplitude 100 cm/s² and the frequency 10 Hz are shown in Fig. 5 to obtain the failure form. The characteristics of modes changing with time can be obtained by T1 (time that exces. pore pressure reaches to the max. value), T2 (time that the response accel. reaches to the max. value) and T3 (time that the response accel. reduces to zero). In progress of the liquefaction, the vibrating part changes from the surface to the inground. At the complete liquefaction more than 40 wave numbers, the ground stops vibrating in all layers. From Fig. 3 and 4, the difference between ground without foundation and the adjacent ground concerning the exces. pore pressure, the accel. and the shear strain can be derived; In the ground without foundation, the response accel. and the shear strain reduce to zero as soon as the exces. pore pressures reach to the effective overburden pressures. On the other hand, in the combined system, the response accel. and the shear strains at the each layer are close to zero about one second late from time TP1h, TP2h, TP3h that the exces. pore pressure of the adjacent ground reaches to the max. value. The surrounding ground has the transition region where the ground does not lose the resistant strength due to the pile rigidity as shown in Fig. 6. In the transition region, the first half wave forms of the response accel. amplitude have the peak by the nonlinear coupled vibration due to the softening of the ground. The latter half wave forms are gradually distorted and at last reduce to zero. The ground and the pile foundation vibrate gradually with the different phase since the resonant period of ground gets longer due to the softening of ground. The pile foundation is apt to be subjected to the bending moment. From Fig. 7, the difference between the horizontal excitation, and the horizontal and vertical simultaneous excitation can be derived; The time series wave form of the exces. pore pressure at the surface part by the hori. excitation has two peaks to one wave form of input acceleration. On the other hand, with simultaneous excitation, the peaks of the exces. pore pressure have one to one correspondence to the repetition of input accel., and after completing liquefaction, the excess. pore pressure repeats to increase and decrease. With simultaneous excitation a drainage effect to the ground surface and a compaction effect are observed. The vibratory earth pressures at the side of the pile increase again after they are close to zero in the simultaneous excitation. The restoring force characteristics that can be obtained by the hysteretic relationship between shear stress and strain of the ground (without the foundation and the adjacent ground) are shown in Fig. 8 (a, b). Shear modulus G and the hysteresis damping constant h change in accordance with the increase of the input wave numbers (Ref. 5). The arrow shows the time that the complete liquefaction started. In the ground without pile foundation, G (simultaneous) is larger than G (horizontal) excluding the surface layer. On the contrary h (simultaneous) is smaller than h (horizontal) in all ground layers. With horizontal excitation G decreases and h increases in accordance with the increase of the input wave number. On the contrary with simultaneous excitation G increases excluding the surface layer and h decreases after 7 or 8 wave numbers. With simultaneous excitation, comparing G (or h) of the adjacent ground to the pile foundation with G (or h) obtained in the ordinary ground without pile installation, G of the adjacent ground is larger than G of the ordinary ground and h of the adjacent ground is smaller than h of the ordinary ground. Thus the adjacent ground hastens to compact itself due to the vertical motion as soon as the complete liquefaction occurs.

CONCLUSION

The important results obtained in this study on liquefaction characteristics of ground-model pile foundation interaction are summarized as follows; (1) The failure phenomena due to liquefaction occurs from the surface to the inground. At complete liquefaction the ground stops vibrating in all layers. (2) The measured acceleration and shear strain in the ordinary ground reduces to zero as soon as the excessive pore pressure reaches maximum value. In the ground surrounding a pile foundation, however, a transition region is observed where the liquefaction resistance is retained owing to the rigidity of the piles. (3) With simultaneous excitation a drainage effect to the ground surface and a compaction effect are observed. With simultaneous excitation the time that the excessive pore pressures reach maximum value and start to dissipate is shorter than that with horizontal excitation alone.

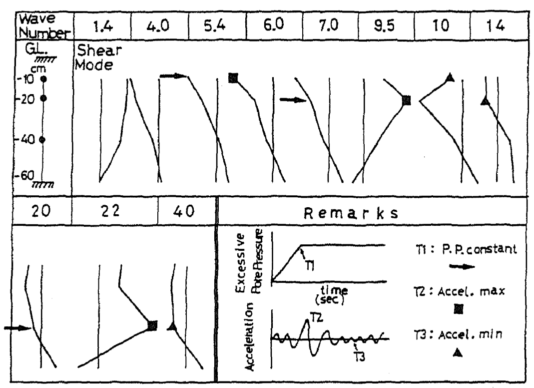


Fig. 5
Displacement Mode (Ground, $100cm/s^2$, 10Hz)

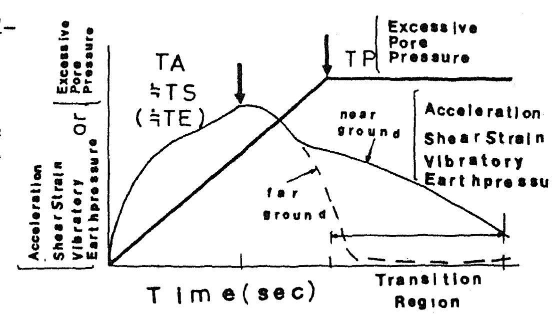


Fig. 6 Liquefaction Resistant Region (Schematic Illustration)

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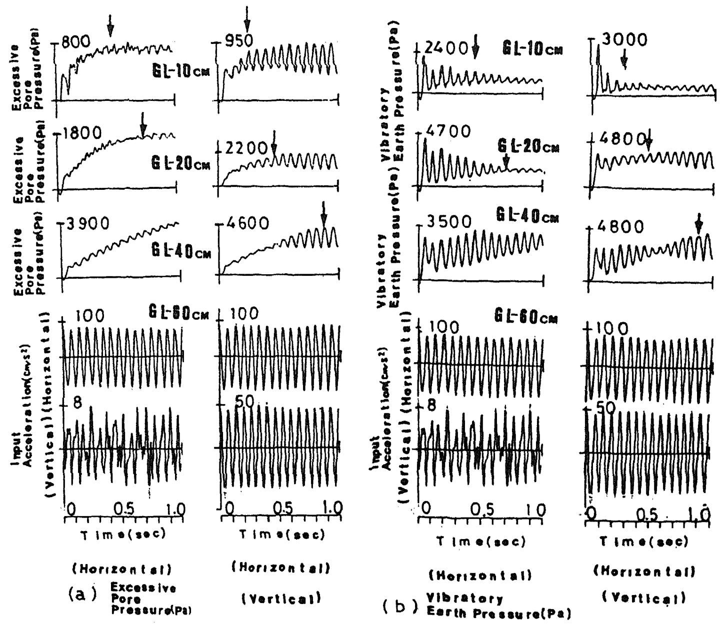
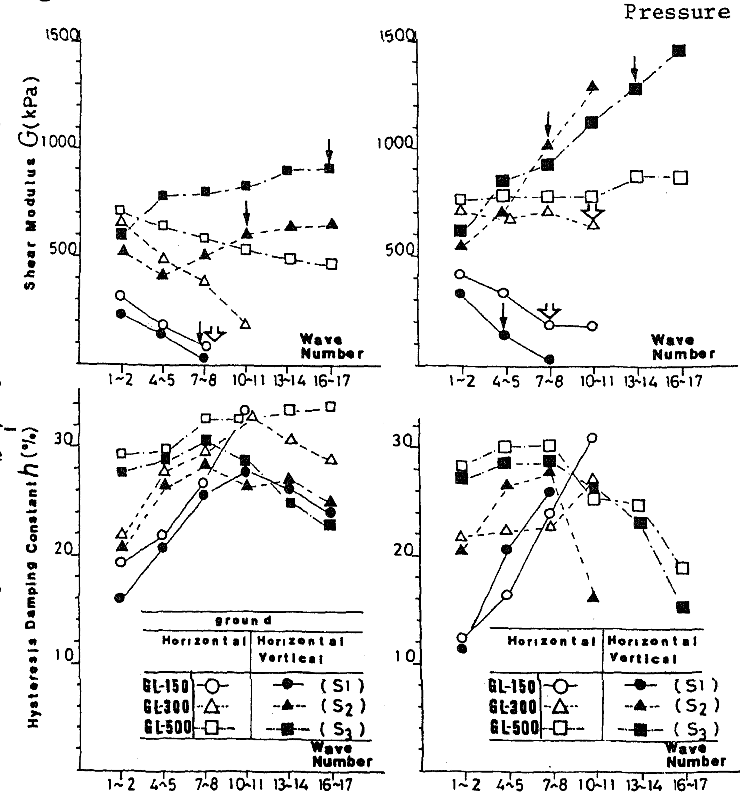


Fig. 7 Excessive Pore Pressure and Vibratory Earth Pressure



(a) Ground without Pile Foundation (b) Combined System

Fig. 8 Restoring Force Characteristics