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Effect of Soil Dilatancy on Vibration and Earth Pressure

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SYNOPSIS A model ground of air dried sand compacted in a shear testing apparatus and two composite models each of which have the model pit of different rigidity buried in a same model ground as above one are excited horizontally with sinusoidal motions on a shaking table. From measured accelerations and dynamic earth pressure it is found that the vertical vibration is produced in the ground due to the dilatancy or volume change of soil and yet it produces the dynamic earth pressure acting horizontally on all outside walls of the model pit. In order to simulate the results of tests three dimensional finite element procedure with elasto-plastic dynamic response analysis is used. Good agreement between the tests results and predictions is obtained.

INTRODUCTION

The equivalent linear method has been often utilized for analyzing the soil-structure dynamic interaction problems, but, with the method, we can not take account of the dilatancy or volume change of soil which is one of the most important non-linear characteristics of soil. Therefore the authors carried out model vibration tests to study the effect of the volume change of sand on both the ground vibration and the dynamic earth pressure acting on underground structure. Furthermore, we performed a simulation of model vibration tests by use of the elasto-plastic dynamic response analysis based upon the flow theory.

EXPERIMENTAL METHOD

The vibration tests were carried out with a model scaled down to 1/100 of a prototype structure and ground. The structure model was made of acrylic resin plates of which young's modulus is almost satisfied with a law of similitude proposed by Kagawa and Kokusho (Kagawa,1978; Kokusho and Iwatate,1979), the surface of it was uniformly coated with same sand as the ground material to increase the coarseness of surface of the structure. The dimension of model structure and the arrangement of the sensors are shown in Fig.1. Air-dried Gifu sand was utilized as the material of the ground model. The sand was dropped into a shear testing soil container on a shaking table, and compacted under the sinusoidal excitation of 300gal in the amplitude and 35Hz in the frequency feeding with supplementary sand to make up for the settlement to prepare 50cm thick ground model. The shear testing soil container used for this experiment is composed of 16 rectangular frames of light weight shaped steel members which are piled up interposing ball bearings between each of them and rubbered on its inner and outer surfaces. The natural frequency of the container itself was 1.6Hz.

A free ground model and two composite models each of which had the model structure of different rigidity (the thickness of the wall is 1.5cm and 0.5cm) buried in same model ground as above one were excited horizontally with sinusoidal motions. The maximum acceleration of input excitation was set at 50 gal, 100 gal, 200 gal, and while it was kept constant, the frequency of input excitation was changed at every 1 or 2Hz interval from10Hz to 60Hz. Accelerometers were buried at 1, 3, 5, 15 cm depth from the model ground surface at the center of the container for the free ground model. For the soil-structure composite models, the arrangement of sensors is shown in Fig.2.

EXPERIMENTAL RESULTS

Fig.3 shows resonance curves of measured response accelerations of free ground model where the magnification of the response acceleration to the input one is plotted against the frequency of input excitation. Fig.3(a) indicates that when the amplitude of input excitation is increased, the magnification will decrease and the resonant frequency will shift to the lower frequency. This means the nonlinear phenomena appeared remarkably in the experiment. Fig.3(b) shows the same characteristics as the horizontal resonance curve, but as is evident from the figure, the vertical response acceleration does not occur under a frequency which is 32Hz,

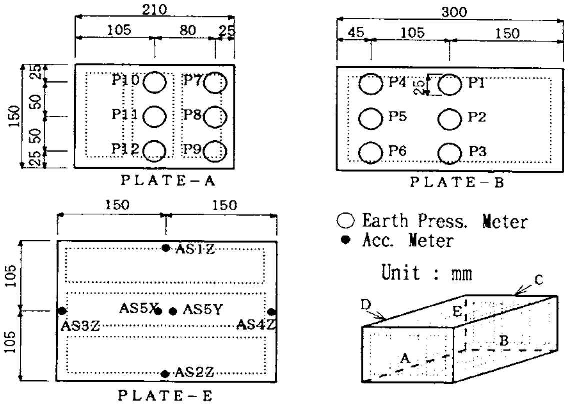


Fig.1 Dimension of Model Pit and Arrangement of Sensors

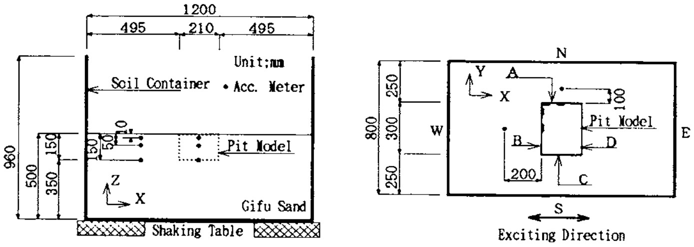
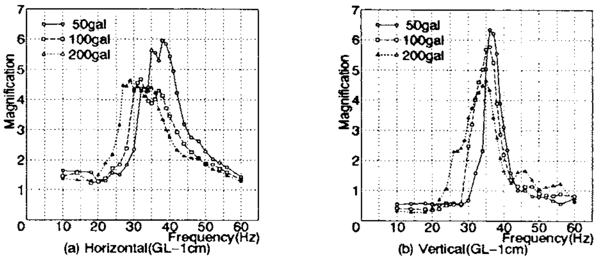


Fig.2 Soil-Structure Model and Arrangement of Sensors

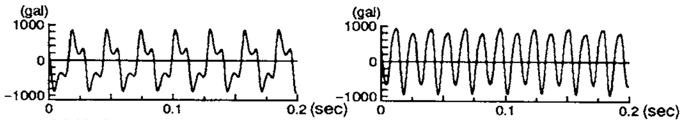
30Hz and 22Hz corresponding to the input excitation of 50 gal, 100gal and 200gal respectively. A slight magnification under those frequencies is due to the electrical noise measured in the experiment. Fig.4 shows an example of time history of response acceleration in the steady state of the test result against 200gal , 35Hz of input excitation. The frequency of the horizontal response acceleration is same one as the input motion, but the vertical one shows just 2 times as large as the horizontal one and this is the distinctive feature of the vertical response. These phenomena can be explained well by the dilatancy or volume change of soil. When the shear strain of soil is in the small region, only the simple shear deformation occurs, but when it becomes larger reaching yield, the shear deformation with the volume change occurs and it will produce the vertical vibration. This mechanism is illustrated in Fig.5 and it is clearly known from this that the frequency of the vertical vibration is just 2 times as large as the horizontal one.

Concerning the experimental results of the rigid structure model (thickness of the wall is 1.5cm), the test results obtained here are almost same independently of the difference of the rigidity of structure model. The resonance curves of measured accelerations at the points shown in Fig.1 and Fig.2 are given in Fig.6. The shape of the horizontal and vertical curves at the top of the structure model are similar to those at the ground point. It is clear from this that the behavior of the structure model is dominated by the ground vibration. Fig.7 is an example of



(a) Horizontal(GL-1cm)
(b) Vertical(GL-1cm)

Fig.3 Resonance Curves of Measured Response Accelerations of Free Ground Model



(a) Horizontal acceleration (GL-1cm)
(b) Vertical acceleration (GL-1cm)

Fig.4 Measured Response Accelerations of Free Ground Model (200 gal, 35Hz)

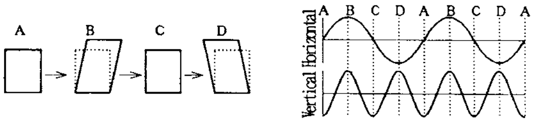
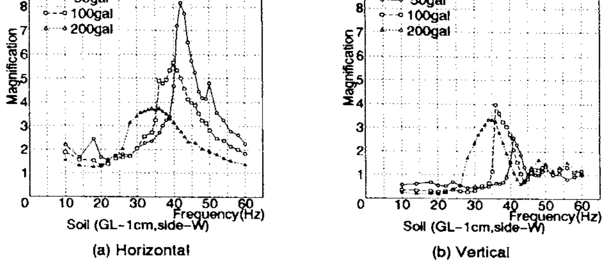


Fig.5 Schematic of Vertical Vibration Produced by Volume Change of Soil

the time history of measured dynamic earth pressure (Pd) normalized by the static earth pressure (Pst) which was measured just before applying the vibration for series of experiment. The response time histories at P10, P11 and P12 on the wall parallel to the exciting direction have the 2 times larger frequency than those on the perpendicular wall and this



(a) Horizontal
(b) Vertical

Fig.6 Resonance Curves of Response Accelerations of Soil-Structure Model

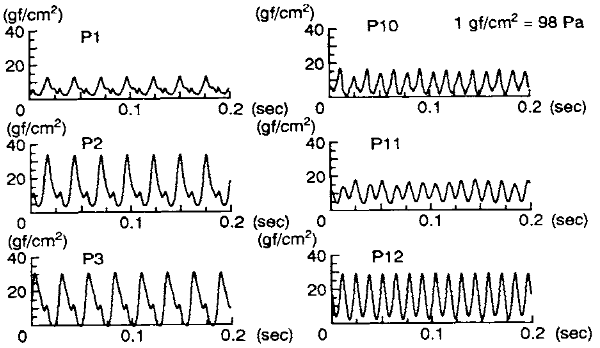


Fig.7 Measured Dynamic Earth Pressures (200 gal, 37Hz)

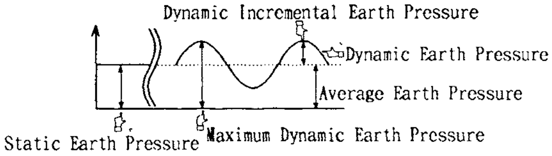
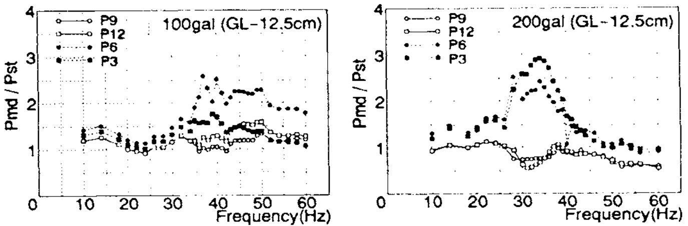
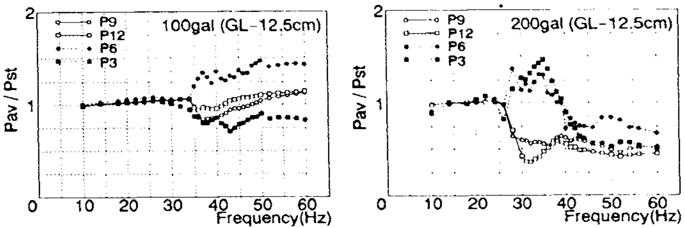


Fig.8 Definition of Various Kinds of Earth Pressures

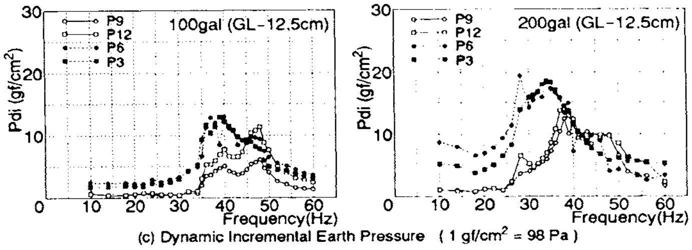
coincides with the character of the vertical response acceleration of the ground only. Fig.8 shows a definition for various states of earth pressure used in this paper. The earth pressure during the vibration is called dynamic earth pressure (Pd), maximum of it is called maximum dynamic earth pressure (Pmd), the average of maximum and minimum dynamic earth pressure is called average earth pressure (Pav), the difference between Pmd and Pav is called dynamic incremental earth pressure (Pdi), the earth pressure during the shaking table is at rest is called static earth pressure (Pst). Here, the maximum and minimum of Pd are defined as the average values of 10 number of waves in the steady state. Fig.9 shows an example of relationships of Pmd, Pav and Pdi versus the frequency of input excitation. Pmd and Pav are normalized by Pst just before the series of vibration tests. As for Pmd/Pst, the values at P6 and P3 on the wall perpendicular to the exciting direction increase in accordance with the increase of input acceleration, but we can hardly find whether the values at P9 and P12 on the wall parallel to the exciting direction change according to the variation of input acceleration or not, and yet the frequency-dependence of them is obscured too. Consequently, we discuss about Pav and Pdi instead of Pmd/Pst. At 35Hz and 25Hz corresponding to the input excitation of 100gal and 200gal respectively in Fig.9(b) and (c), Pav deviates from Pst and Pdi suddenly increases. In the lower frequency than these frequencies Pdi at P9 and P12 on the wall parallel to the exciting direction is considerably small. Comparing these with Fig.6, however, it is clearly seen that these frequencies coincide with those at which the vertical vibration begins to occur. In other word, when the vertical vibration is produced by yielding of soil, Pav deviates from Pst and Pdi increases, then dynamic earth pressure will act on the wall parallel to the exciting direction too. Pdi increases in accordance with the increase of the input acceleration, thus the frequency-dependence is distinctly.



(a) Ratio of Maximum Dynamic Earth Pressure against Static Earth Pressure



(b) Ratio of Average Earth Pressure against Static Earth Pressure



(c) Dynamic Incremental Earth Pressure ($1 gf/cm^2 = 98 Pa$)

Fig.9 Relations between Three Types of Earth Pressures and Frequency

ELASTO-PLASTIC DYNAMIC RESPONSE ANALYSIS WITH FINITE ELEMENT PROCEDURE

The ground is deemed as the Drucker-Prager material with the Cap (Chen and Baladi,1985) and in the elastic range the shear modulus is assumed to be such one that is possible to reappear the resonant state at 35Hz. The FEM model of the free ground is shown in Fig.10. The nodes on the sides of the FEM model which have the same Z coordinates are restricted in such way that they may undergo the same displacement in

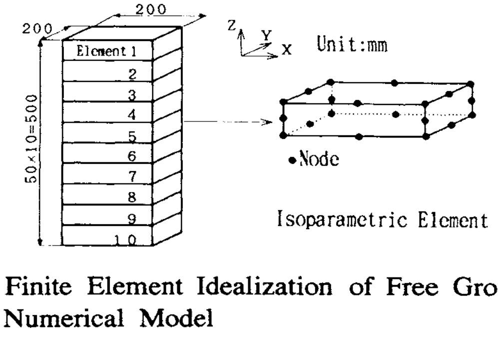
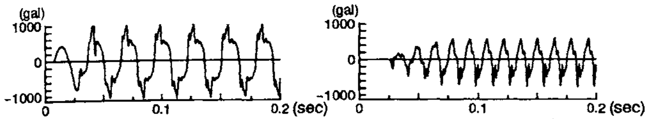


Fig.10 Finite Element Idealization of Free Ground in Numerical Model



(a) Horizontal acceleration (GL 0cm) (b) Vertical acceleration (GL 0cm)

Fig.11 Predicted Response Accelerations of Free Ground (200 gal, 35 Hz)

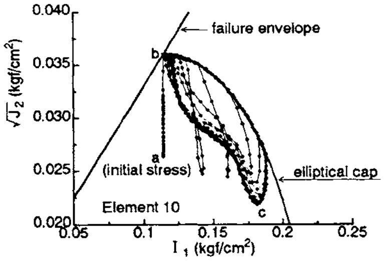


Fig.12 Predicted Stress Paths in Meridian Planes

X, Y, Z directions during the vibration. The bottom of the FEM model is assumed as a fixed boundary. We have performed the numerical simulation of the experiment with the sinusoidal excitation of 200gal, 35Hz. For the response analysis, the step by step integration method with β =1/4 of the Newmark's β scheme and the initial stress method (Zienkiewics, et al.,1969) are adopted for analyzing the non-linear behavior of material. Fig.11 shows the predicted response accelerations. They reproduce well the characteristics of the measured ones in Fig.4. Fig.12 shows the stress path in Element 10 on the meridian plane of 3-dimensional principal stress space. When the square root of second invariant of deviatoric stress tensor $\sqrt{J_2}$ changes in the path from **a** to **c**, only the horizontal vibration occurs because there is no change of first invariant of stress tensor I_1. But after stresses reach the yield surface, stress path in meridian plane will draw the loop connecting **b** and **c** in the steady state, and vertical vibration will be produced which will propagate to the ground surface.

The relationship between the dynamic earth pressure and vertical vibration mentioned before can be explained qualitatively with this figure. Point **a** corresponds to Pst, and while the horizontal response of the ground is small, the stress changes only in the path between the points of **a** and **c**, so that Pav is equal to Pst. When the horizontal response of the ground increases and the stresses reach the yield surface, not only $\sqrt{J_2}$ but also I_1 will change. It is clearly seen that in this state the center of I_1 leaves the initial position **a** so that Pav will differ from Pst.

CONCLUSIONS

Through the model vibration tests and the analytical study on them, following concluding remarks are summarized.

(1) It has been found from the tests results that the horizontal excitation produces a vertical response vibration. The frequency of it is 2 times as large as the horizontal one and the response magnification of it is greater than or equal to the horizontal one.

(2) Such phenomena mentioned above can be explained qualitatively by the dilatancy or volume change of soil.

(3) Furthermore, it has been confirmed that these phenomena can be simulated with the elasto-plastic dynamic response analysis by making use of finite element procedure.

(4) The dynamic earth pressure due to the horizontal response vibration acts on the outside wall perpendicular to the exciting direction, and once the vertical vibration is produced, the dynamic earth pressure due to it comes out to act on all the outside walls of the structure model.

(5) The correlation between the average pressure, dynamic incremental earth pressure and the vertical response vibration has been clearly found, provided that the dynamic earth pressure is decomposed into them. At the same time when the vertical response vibration is produced, average earth pressure shifts from the static earth pressure as well as dynamic incremental earth pressure increases.

We have also conducted three dimensional finite element procedure in order to simulate the test results of the soil-structure composite model. In this procedure separation and sliding between soil and structure have been taken into consideration and the behavior of the soil has been represented by the Drucker-Prager criterion with the elliptical Cap. Good agreement between the test results and predictions has been obtained. Details of this study are given in the paper (Ohshima and Watanabe,1994).

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