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BEHAVIOR OF SATURATED SAND MODELS IN MULTI-DIRECTIONAL SHAKING TABLE TESTS

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ABSTRACT

Responses of saturated sand models during one and two-dimensional shaking table tests are presented. Both harmonic and irregular loading patterns are generated and applied to the identical models. Harmonic waves are sinusoidal type with out of phase components. It is shown that softening occurs easily in case of two-dimensional loading and the effective stress path response of identical soil elements are different to one or two-dimensional loading. This different behavior suggest that the dilatancy characteristics of saturated sand under two-dimensional loading might be different from those under one-dimensional one.

KEYWORDS

dilatancy; level saturated ground; liquefaction; multi-directional loading; physical model tests; shaking table.

INTRODUCTION

When a soil element in the level ground is subjected to the motions due to the upward propagation of shear waves during earthquakes, induced shear deformation time histories would be random sequences of simple shear stresses in the horizontal plane involving changes not only in amplitude but also in direction. In other words soil element is shaken by a two-dimensional force rather than one dimensional one.

Although some element tests considering the effect of multi-directional loading have been performed (Ishihara and Yamazaki 1980, Yamada and Ishihara 1983 and Ishihara and Nagase 1988 as examples), because of difficulty in duplicating of such irregular pattern of stress changes most of the laboratory cyclic tests performed so far have been concentrated on one- dimensional ones. Also, few number of *1g* model tests have been conducted in order to study the effect of multi-dimensional loading on the response of granular materials. The first attempt was made by Pyke *et al.*(1975) by performing several series of multi-directional shaking table tests in which behaviour of dry sand was studied. More recently Fujikawa *et al.*(1993) and Endo and Komanobe (1994) conducted some *1g* two-dimensional shaking table tests on saturated sand with using elliptical and circular cyclic loading patterns. They generally showed that the liquefaction resistance of models is reduced by application of two-dimensional shear stress cycles.

In this paper the results of conducted *1g* shaking table tests in order to study the effect of multi-directional loading on saturated *Toyoura* sand models, are presented. In this regard the effect of acceleration levels, randomness of stress components and phase difference of components are considered.

PREPARATION OF THE MODELS

General view of the models and deployment of the different type of sensors is shown in Fig.1. The container of the model is two-dimensional simple shear box type, combined from horizontal aluminum frames which are joined each other with ball bearings and can move almost separately in horizontal plane. The development of 12% shear strain at the top of the container in either of horizontal directions is possible. Sand pouring method was used for preparation of the models. After completion of sand pouring, dry models were saturated with water within few hours from two lower valves which are connected to the de-aired water tank. Standard Japanese sand called *Toyoura sand*, was used for preparation of the models.

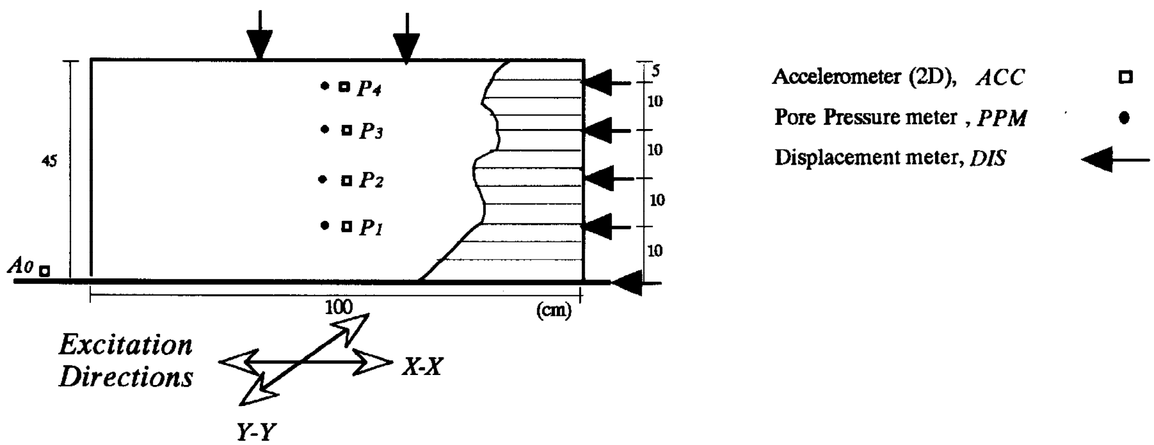

Fig.1: Schematic view of the models and their instrumentation.

INPUT MOTIONS

Saturated *Toyoura* sand models were excited with uniform sinusoidal or erratic patterns of real earthquakes. According to the recorded trajectories traced on a horizontal plane by combinations of two components of acceleration time histories, while strong motion records rarely show exactly equal maximum accelerations for two horizontal components, the direction of the absolute maximum acceleration usually appears to be arbitrary, and the direction of the resultant acceleration at any time varies randomly. In order to be able to reproduce similar situation to the reality during model tests subjected to two-dimensional sinusoidal waves, this fact should be observed. One method for considering this aspect might be producing of sinusoidal waves with out of phase components. A variety of shearing motions can be obtained by combining two out of phase horizontal components. In this study two types of harmonic two-dimensional patterns are considered which are shown schematically in Fig.(2). In the first pattern which is called "*Gyratory or Circular pattern*", two horizontal components are 90 degrees out of phase with each other; and phase difference, $\Delta\Phi$, in the second pattern called "*Variable phase pattern*", is not constant and varies from 45 to 135 degrees. In both cases each component of motion was cycled with a frequency of 5 *Hz* and number of cycles of 40.

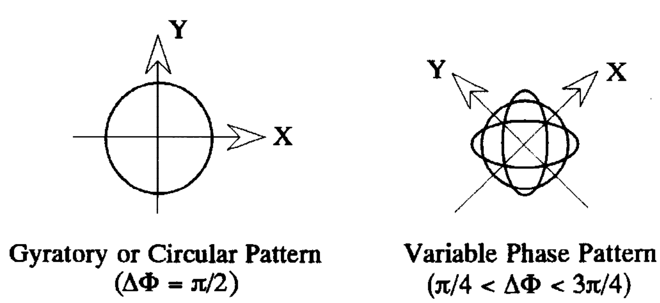

Fig. 2. Two-dimensional sinusoidal shaking patterns with out of phase components.

In case of irregular loading, combinations of *NS* and *EW* components of *Nihonkai-chubu* earthquake (1978) recorded on ground, was generated and applied to the models. The *NS* and *EW* acceleration time histories of this wave are shown in Fig.(3). Also the trajectory of the generated two-dimensional wave is shown in same figure. The acceleration amplitude of the input motions were scaled in order to have desired level of shear stresses and excess pore pressures at different points inside the models for both of harmonic and irregular loadings. Considering that the same materials of prototype have been used for construction of the models (natural sand and water) as well as depth of the model, in order to satisfy similitude laws in physical model tests, the time scale was shortened 10 times; (Jafarzadeh and Yanagisawa 1993).

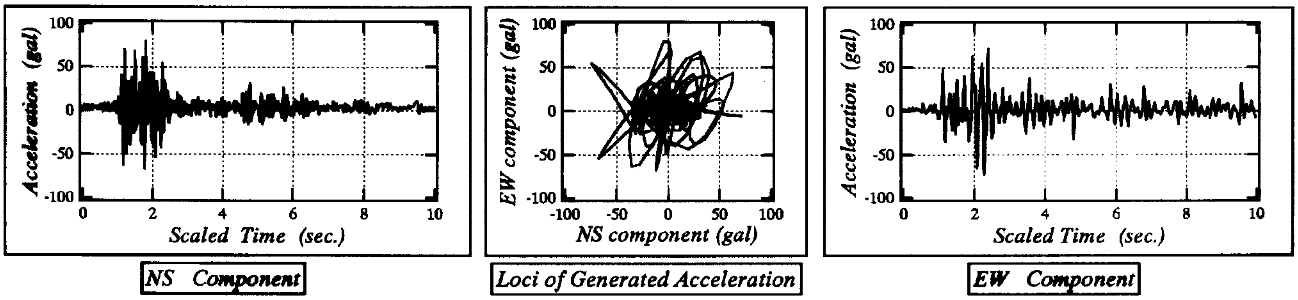

Fig. 3. General features of generated random acceleration loading pattern at base level.

EXPERIMENTAL RESULTS

In this part typical results of the measurements during two-dimensional sinusoidal or irregular tests are presented. Fig.(4) shows the acceleration time histories of a loose saturated model (*Dr*= 51.5%) subjected to *Circular* type loading, recorded at different points in *XX* and *YY* directions. According to these recorded acceleration time histories, in case of loose models, depending to the applied base acceleration amplitudes some points inside the model soften. As shown in Fig.(4), applied base acceleration amplitudes for this case in both directions are about 90 *gal*. It can be seen that points P_2, P_3 and P_4 are showing softening behavior after few cycles. Also by decreasing of the overburden pressure, softening takes place more easily with requiring of less number of cycles. Also, in same figure the excess pore water pressure time histories at different points are shown. In all of these pore pressure time histories the initial vertical effective stress at each specified point (σ'_{0v}) is indicated as the upper limit of the graph; therefore, the upper limit could be assumed as the zero effective stress or liquefaction line, ($u_r = U_{exc} / \sigma'_{0v} = 1$). As it is shown, in case of loose models, by application of stress cycles pore pressure rises rapidly and in this case initial liquefaction occurs at all points.

Fig.(5) shows the acceleration and excess pore pressure time histories of another loose model with relative densities of 43.6% subjected to random pattern loading of *Nihonkai-chubu* earthquake. It can be seen that by application of very first stress cycles pore pressure rises sharply at all points and it goes up with reduced rate until end of main shock. After that, the effect of dissipation becomes predominant, although at some points there are still stress cycles with considerable level. Also, according to the excess pore pressure time histories, larger excess pore pressure ratios are generated for the points with smaller initial effective stresses.

EFFECT OF TWO-DIMENSIONAL SHAKING

The response of different models subjected to one or two-dimensional (*1D* or *2D*) sinusoidal or random loadings are compared precisely in this part and it is aimed to focus on the soil behaviour form multi-dimensional loading point of view.

Fig.(6) shows the acceleration response of two saturated loose models subjected to sinusoidal *1D* or *2D* ***Variable phase*** pattern waves at P_2. The applied acceleration amplitude at base level for both cases are

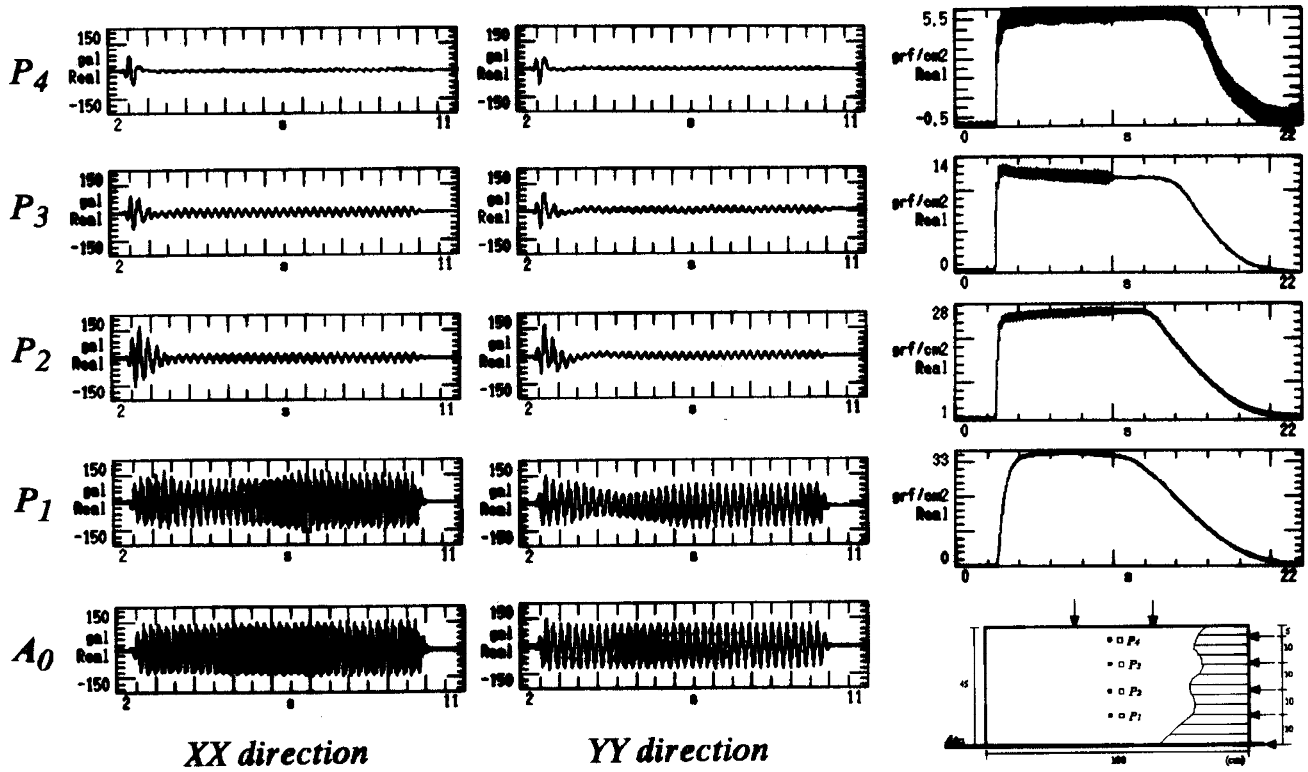

Fig. 4. Acceleration and excess pore pressure time histories of a loose model (*Dr* = 51.5%) subjected to *Circular* pattern loading at different points.

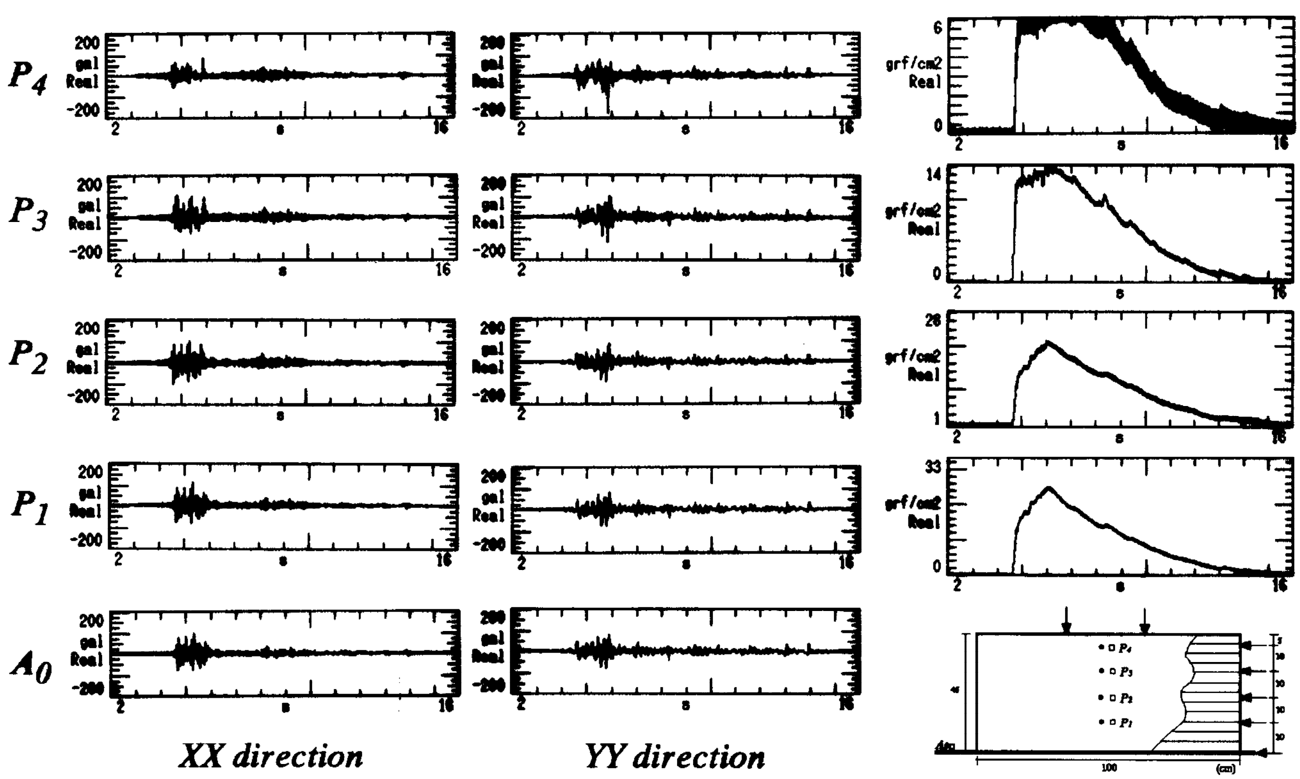

Fig. 5. Acceleration and excess pore pressure time histories of a loose model (*Dr* = 43.6%) subjected to *Nihonkai-chubu Earthquake* loading pattern at different points.

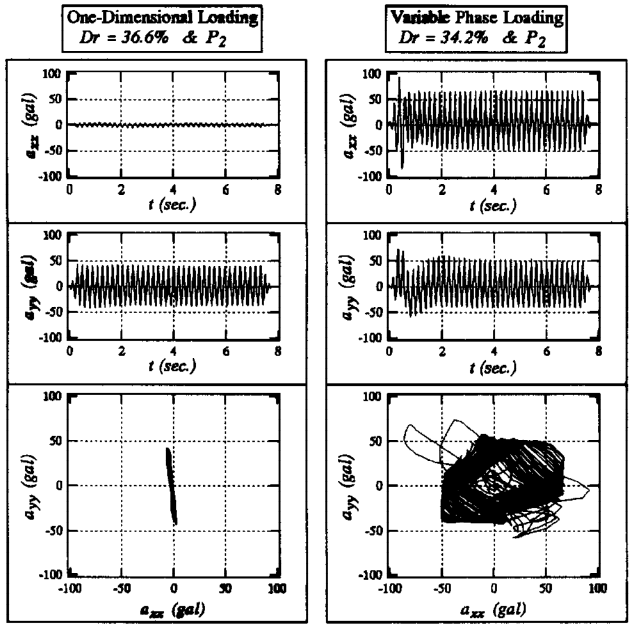

Fig. 6. Acceleration response of two loose models subjected to *1D* or *2D Variable phase* sinusoidal loadings at P_2.

almost same. Also, it is obvious from Fig.(6) that the amplitude of transmitted accelerations for both cases in *YY* direction are almost equal. Fig.(7) shows the stress-strain curves at P_2 in *YY* direction for both cases. Dynamic shear stress, τ_d, at each point inside the model could be estimated by integrating inertial forces from the surface to the depth of point, as given by Eq.(1):

$$(\tau_d)_n = \sum_{i=1}^{n} m_i.a_i \tag{1}$$

in which m_i is mass of the soil element, a_i is acceleration of the i-th element and n is the specified point number inside the model. Also, shear strain, γ ; is calculated from the measured displacements. It could be seen that for *1D* case soil element has an elastic behaviour until end of loading and the double amplitude of the generated dynamic shear strain is less than 0.2%. However, in *2D* loading soil element shows softening behaviour within few cycles and reduction of shear stresses and increasing of dynamic shear strain amplitudes are obvious. Also, the area of hysteresis loops for *2D* case is larger than for *1D* case. Time history of the excess pore pressure ratio for this case is shown in Fig.(8). The solid and dashed lines in this figure and other figures which are presented in this paper, represent the response of *1D* or *2D* cases, respectively. According to Fig.(8) the maximum generated excess pore pressure for *2D* loading is about 1.6 times of same parameter during *1D* one. Also, excess pore pressure in *2D* case rises more rapidly comparing to *1D* case and is stable until end of application of stress cycles, while in *1D* case effect of dissipation becomes dominant after few cycles. Effective stress paths of soil elements during loading are compared in Fig.(9). It is clear that in both cases the minimum mean effective stress, p', is far from zero, however, the reduction pattern of p' is different for two cases. In case of *1D* loading soil element loses some strength due to increase of pore pressure and starts to regain this strength after about 5 cycles, while for *2D* case the reduction of p' is larger and quicker and it does not regain the lost strength until ending of application of stress cycles.

Response of two other loose models subjected to *1D* or *2D Circular* type loadings at point P_3 is discussed hereafter. Figs.(10) and (11) show the excess pore pressure time history and stress path curves for *1D* and *2D* loadings, respectively. It could be seen that although the generated pore pressures are same for both cases, the amplitude of developed shear stresses according to Fig.(11) in *2D* loading is smaller than *1D* case. This means that the liquefaction potential of saturated sand elements increases by multi-directional shaking or low amplitudes of multi-dimensional shear stress cycles could generate considerable levels of excess pore

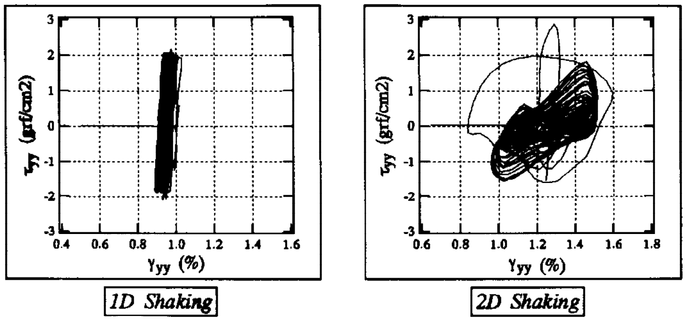

Fig. 7. Comparison of dynamic shear stress - strain curves in *YY* direction for *1D* or *2D* loadings at P_2.

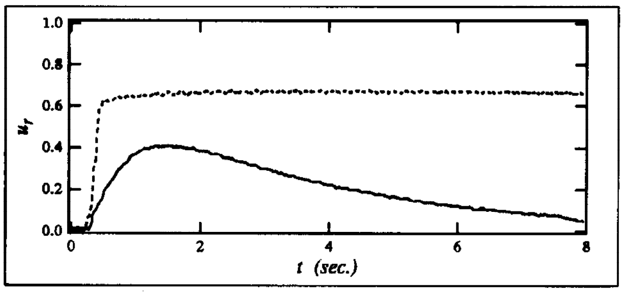

Fig. 8. Excess pore pressure ratio time histories for *1D* (solid line) and *2D* (dashed line) sinusoidal loadings at point P_2.

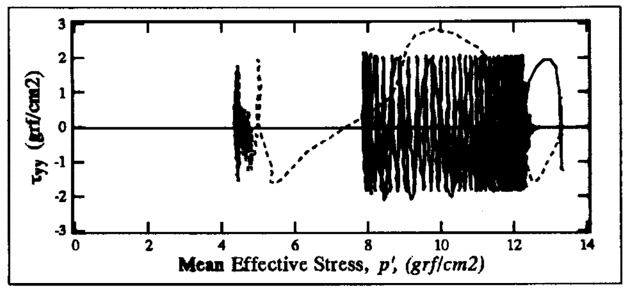

Fig. 9. Effective stress paths for *1D* (solid line) and *2D* (dashed line) sinusoidal loadings at point P_2.

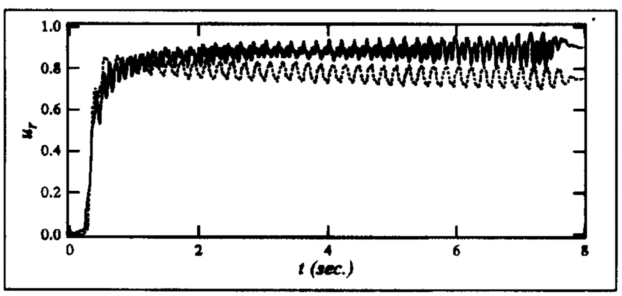

Fig. 10. Excess pore pressure ratio time histories for *1D* (solid line) and *2D* (dashed line) sinusoidal loadings at point P_3.

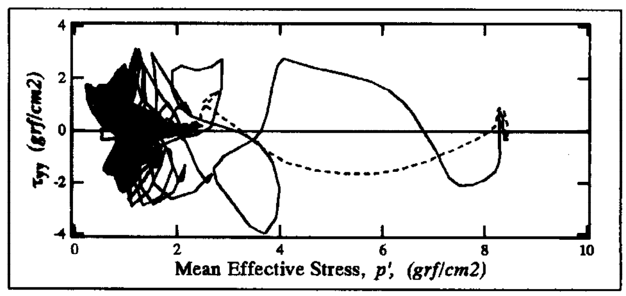

Fig. 11. Effective stress paths for *1D* (solid line) and *2D* (dashed line) sinusoidal loadings at point P_3.

pressures. Mean effective stress reduction pattern is also different for *1D* or *2D* loading, according to Fig.(11). Again, p' decreases more rapidly in *2D* loading. During *1D* loading stress path traces kind of *Butterfly* pattern and shows cyclic mobility behaviour, while this situation does not exist for *2D* loading.

Hereafter, the response of two other loose models subjected to *1D* or *2D* irregular pattern loadings similar to *Nihonkai-chubu* earthquake at P_2 is discussed. The general response of one of these models subjected to *2D* loading was presented in Fig.(5). Fig.(12) shows the time history of recorded accelerations at P_2 for either of *1D* or *2D* loadings. It could be seen that the excitations in *YY* direction in both cases are very similar. Also, Figs.(13) and (14) show the time history of excess pore pressure ratio and stress path, respectively. Fig.(13) indicates that the amount of generated pore pressure for *2D* loading within first two seconds of loading is considerably larger than *1D* case, however, dissipation patterns for both cases are similar. Again, Fig.(14) confirms that stress path for two type of loadings are different. This kind of dissimilar behaviors during *1D* or *2D* loading, could suggest that the dilatancy characteristics of saturated sand under two-dimensional loading might be different from those under one-dimensional one.

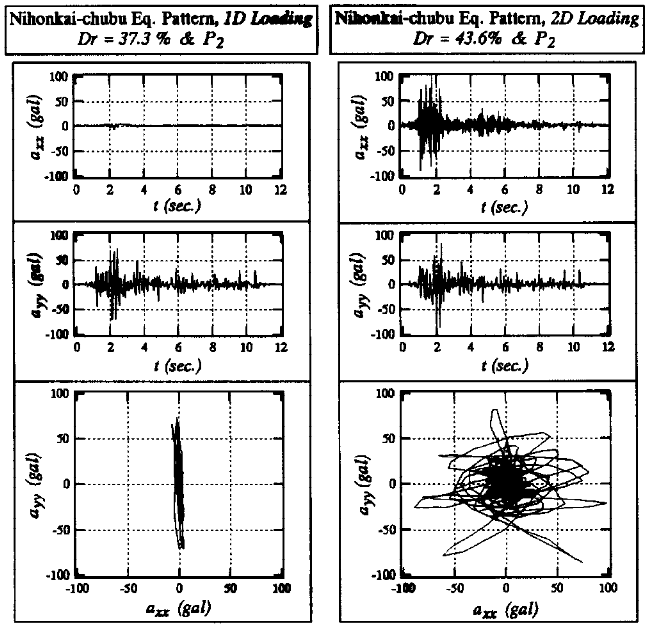

Fig. 12. Acceleration response of two loose models subjected to *1D* or *2D* irregular loadings at P_2.

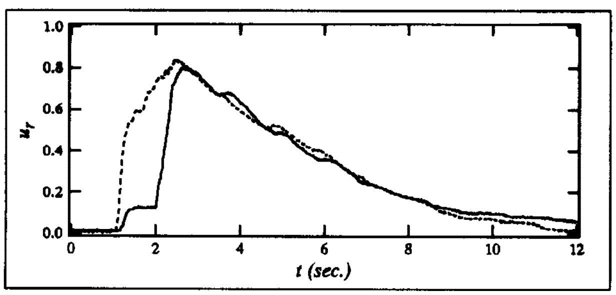

Fig. 13. Excess pore pressure ratio time histories for *1D* (solid line) and *2D* (dashed line) irregular loadings at point P_2.

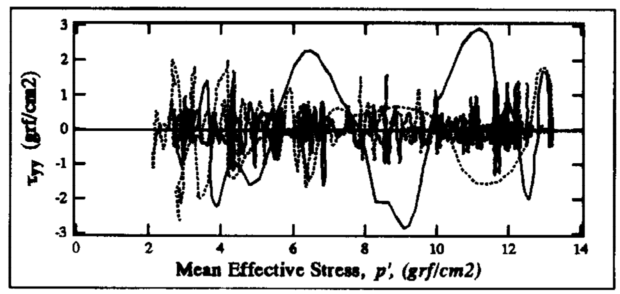

Fig. 14. Effective stress paths for *1D* (solid line) and *2D* (dashed line) irregular loadings at point P_2.

CONCLUSION

The results of multi-dimensional shaking table tests on physical models of saturated level grounds were presented. Excitations were sinusoidal and irregular types. It was shown that during two-dimensional loading liquefaction potential is increasing considerably. Also it seems that dilatancy characteristics of saturated granular material differs during two-dimensional loading comparing to one-dimensional one.

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