Behaviour of Saturated Sand Models under Principal Stress Axes Rotation in Shake Table Tests

Eiji Yanagisawa
Tohoku University, Japan

Fardin Jafarzadeh
Tohoku University, Japan

Proceedings: Third International Conference on Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics, April 2–7, 1995, Volume I, St. Louis, Missouri

Behaviour of Saturated Sand Models under Principal Stress Axes Rotation in Shake Table Tests

Paper No. 2.13

Eiji Yanagisawa and Fardin Jafarzadeh
Professor and Ph.D. Student, Civil Engineering Department, Tohoku University, Sendai, Japan

SYNOPSIS One dimensional shake table tests were performed on saturated loose or medium dense Toyoura sand models, in order to study the response of level grounds during earthquakes and the nature of generated excess pore water pressure. 12 virgin models which prepared under identical condition, were subjected to cyclic and three different irregular shear stress patterns. It is shown that there is correlation between excess pore pressure ratio and developed shear strain, independent from applied shear stress histories and density of the models. Also, the relations of accumulated shear work as well as normalized shear work, per unit volume, are considered with generated pore pressure. According to the results of this study, in the first part of the experiments that undrained condition can be assumed, mentioned parameters correlate with excess pore pressure. This relation is independent from stress path for shear work and from stress path and confining pressure for normalized shear work.

INTRODUCTION

During dynamic loadings like earthquakes, dynamic shear stresses induced at different points of saturated grounds rotate the principal stress directions and cause generation of excess pore water pressures. Pore pressure build up could cause two types of damages: complete flow failure due to reduction of soil strength or limited but often large amount of deformation due to softening behaviour which means significant reduction in soil stiffness. In this paper the second type of damage is considered, and is referred as cyclic mobility or liquefaction, which don't always represent same phenomena.

In the liquefaction analyses of saturated sand, a reliable constitutive model is needed for estimating the amount of deformation or probable pore pressure build up. Accumulated shear strain is sometimes considered as a parameter which describes pore pressure build up, Fukutake (1989). Also recently some researchers attempted to correlate undrained shear behaviour of sand in laboratory element tests, in terms of shear work, as examples Towhata (1985), Okada (1994) and Yanagisawa (1994). However, there are two important differences between responses of undrained dynamic element tests and real soil element inside saturated level ground during strong motions. The first one is that in element tests the effect of inertial forces, which is very important in dynamic phenomena, is not considered. The other one is that in real condition, pore pressure generation and dissipation exist, simultaneously; although most of the researches on element tests have been carried out in undrained condition.

In this paper for studying the behaviour of real sand layers during earthquakes, responses of loose models and medium dense models subjected to different type of irregular or uniform harmonic loadings are considered. It was shown that shear strain and normalized shear work are applicable parameters which correlate with pore pressure build up in the models of level ground.

CONSTRUCTION OF THE MODELS

Standard Toyoura sand (D_{50} = 0.22 mm) was pluviated in dry condition from a sand hopper to the inside of a container, with careful control of the height of pouring and discharge rate of sand from hopper, in order to ensure a uniform model with specified density. The container of the models is of a simple shear box type, consist of horizontal aluminum frames which are joined each other with ball-bearings, therefore the shear strain up to 12 % at the top of the model is possible.

As shown in Fig.1, the models with dimensions 100x100x45 (LxWxH; cm), were instrumented with three types of sensors at different points : strain gage type pore pressure meters, piezoelectric type accelerometers and displacement meters. After completion of sand pouring, dry models were saturated with water from two lower valves within few hours. For medium dense models, loose models in dry state were shaken until desired level of relative density.

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 (1993).

EXCITATION

The 1.5m by 1.5m shaking table with 6 hydraulic actuators was used in this study. One dimensional random waves and harmonic waves were generated and applied in X-X direction (Fig.1) to 6 loose (Dr=38±4%) and 6 medium dense (Dr=64±2%) models. General information about the input waves and the models is summarized in Table 1. The amplitude of maximum acceleration of random waves was scaled to have appropriate level of stresses in models. Fig.2 shows the shape of different input waves at the base level both in time and frequency domain.

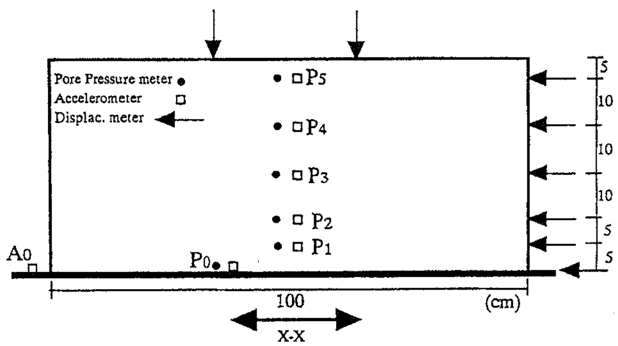


Fig.1. Schematic view of the models and instrumentation.

Specification of applied wave	Loose	Model	Medium	Dense Model
pattern	Dr	Amax	Dr	Amax
	(%)	(Gal)	(%)	(Gal)
Uniform Sinusoidal (5Hz)	37.6	80	65.7	69
Uniform Sinusoidal (5Hz)	37.6	300	64.8	239
Nihonkai Eq. (1978), NS comp.	34.1	1250	65.7	965
Nihonkai Eq. (1978), NS comp.	39.4	870	65.1	502
Niigata Eq. (1964), NS comp.	40.4	2180	65.4	1686
Kushiro Eq. (1993), NS comp.	36.9	2400	62.9	2355

Table 1. General information about models and applied input waves.

RESPONSE OF THE MODELS DURING STRONG SHAKING TESTS

In this part only a typical results of measurements obtained during irregular or harmonic excitations are presented.

Fig.3 shows the response at point P2 of loose sand models during uniform harmonic excitation and the irregular time history of Nihonkai earthquake at same point. Also responses of medium dense models to uniform sinusoidal wave at point

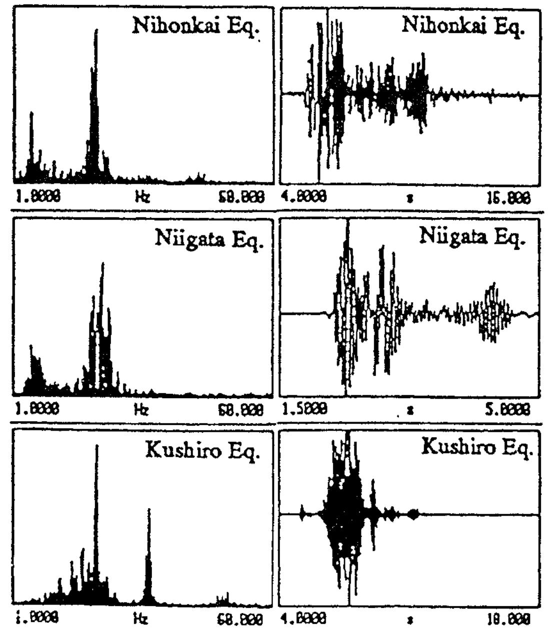


Fig.2. Generated input waves in time and frequency domain.

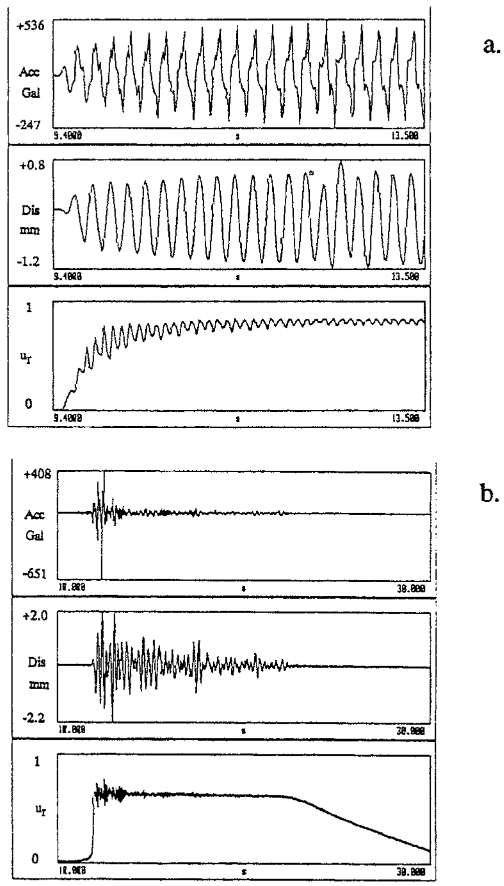
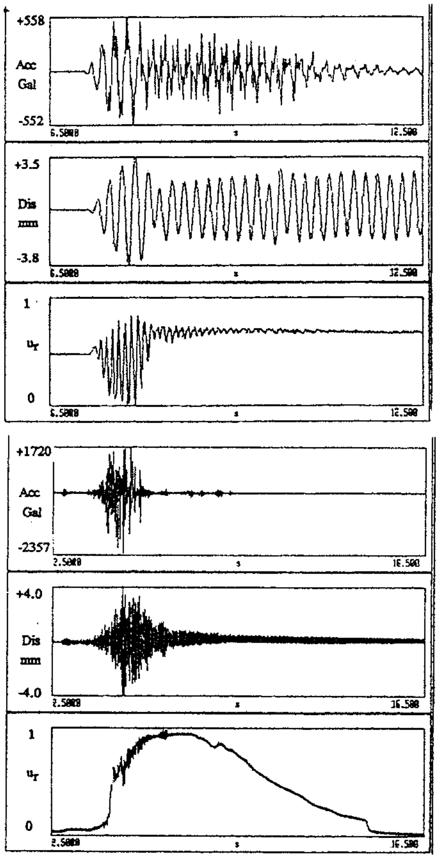


Fig.3. Acceleration, Displacement and Pore pressure ratio at P2 : a- Sinusoidal loading, b- Nihonkai Eq. pattern loading.



a.

b.

Fig.4. Acceleration, Displacement and Pore pressure ratio : a- Sinusoidal loading at P3, b- Kushiro Eq. pattern loading at P1.

P3 and to Kushiro earthquake stress history at point P1, are shown in Fig.4.

GENERATION OF EXCESS PORE PRESSURE

It has been shown that increase of deviator stress due to dynamic shear stress cycles, generates excess pore pressure ratios (u_r) and shear strains (γ), in saturated granular media, (Figs.3 and 4).

u_r - γ correlation

Fig.5 indicates the relation between generated excess pore pressures and maximum shear strains at different points of loose and medium dense models subjected to four random shear stress histories. From this figure it might be concluded that there is a kind of logarithmic relation between u_r and γ_{max}, independent of applied shear stress histories and density of the models. Also this figure shows that liquefaction in models of level ground takes place when single amplitude shear strain is attained to the strain of about 2%.

The same relation (u_r - γ_{max}), for medium dense models

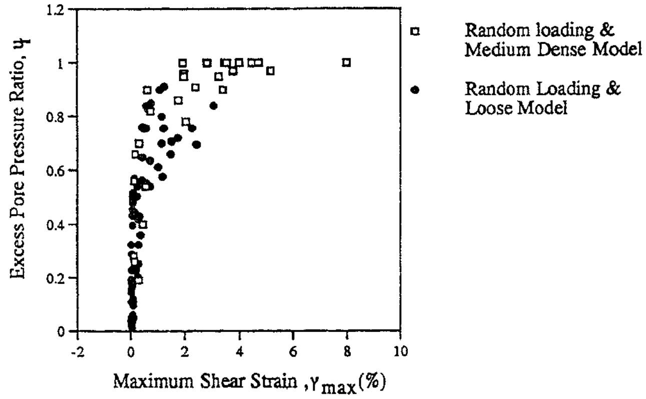


Fig.5. Excess pore pressure ratio and maximum shear strain relation for loose and medium dense models subjected to irregular loadings.

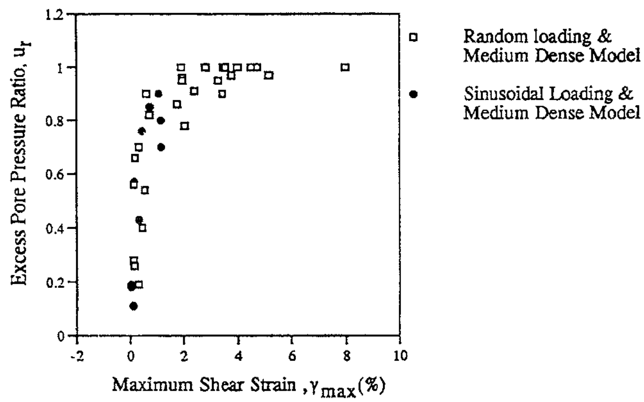


Fig.6. Excess pore pressure ratio and shear strain relation for medium dense models subjected to sinusoidal and irregular loadings.

subjected to four irregular loading and 5 Hz uniform sinusoidal one, is shown in Fig.6. In the case of harmonic excitations, shear strains around the 20th cycle and the corresponding pore pressure ratios have been considered. Again the u_r - γ relation is independent of shear stress time history.

In most of element tests for studying the equivalency of irregular and harmonic loadings, cyclic shear stress ratio needed to produce a given amount of shear strain in the course of 20 cycles of harmonic load application, is considered, like Nagase (1987). In this study also same number of cycles is considered for comparison of the irregular and uniform harmonic loadings.

u_r - a correlation

From Fig.7, it could be concluded that there is a logarithmic relation between maximum acceleration a_{max}, at each point

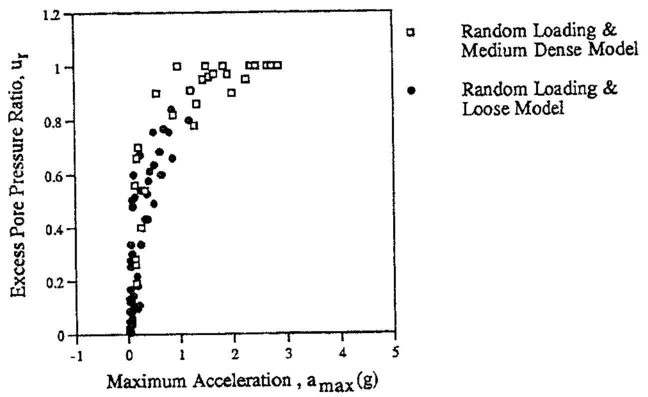


Fig.7. Excess pore pressure ratio and maximum acceleration relation for loose and medium dense models subjected to irregular loadings.

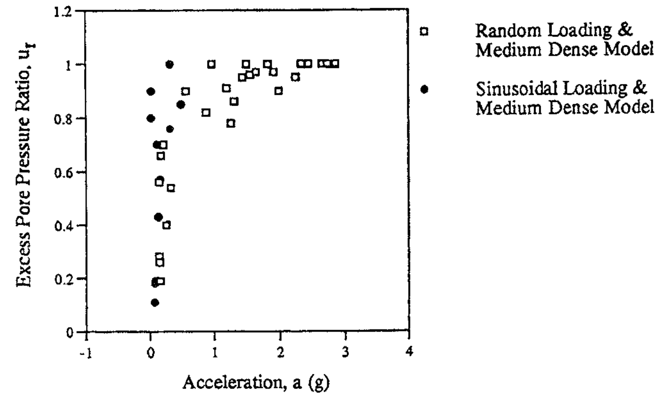


Fig.8. Excess pore pressure ratio and acceleration relation for medium dense models subjected to sinusoidal and irregular loadings.

and the corresponding u_r, caused by different kinds of irregular shear stress histories, which is independent of the density of the models.

Fig.8 shows same comparison between irregular and sinusoidal loading, both for medium dense models. In this figure for sinusoidal shaking, the accelerations of 20th cycle and their correspond u_r, have been considered. The difference of the results for two type of loading is obvious.

From comparison of the presented results, it might be concluded that in case of model experiments of level ground u_r - γ relation is not affected by wave type (irregular or 20 cycles of 5 Hz sinusoidal), but u_r-a relation is. Fig.4a which shows the response of P3 under uniform sinusoidal loading, might explain the reason. It could be seen that acceleration at this point is decreasing dramaticly, which shows the softening behaviour of model by generation of excess pore pressures. That is why around the 20th cycle the amplitude of acceleration (or shear stress) at mentioned point is very low, while the pore pressure and shear strain keep high levels.

SHEAR STRESS INDUCED BY IRREGULAR LOAD

In this study dynamic shear stress τ_d , at each point inside the model is estimated by integrating inertial force from the surface to the depth of point, as given by Eq.(1).

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

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, horizontal displacements were measured by using displacement gauges at the level of each point (Fig.1), and shear strain, γ was calculated from this displacement.

In Fig.9 maximum shear strains (γ_{max}) of loose or medium

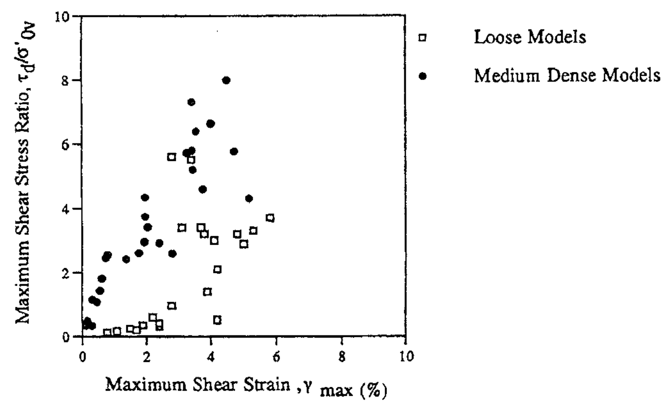


Fig.9. Maximum shear stress ratio versus maximum strain in irregular loadings for loose and medium dense models.

dense models at different points have been plotted in terms of the maximum shear stress ratios or τ_{max}/σ'_{0v} , in which σ'_{0v} is initial vertical effective stress at each point. It is noted from this figure that the larger the density is, the greater the cyclic stress ratio required to induce same amount of single amplitude shear strain becomes.

LIQUEFACTION POTENTIAL FROM STRAIN ENERGY POINT OF VIEW

The total strain energy or work which is dissipated during shearing of a soil element , can be assumed that consists of two parts, a term due to volumetric strain and the other one due to deviatoric strain, which both mentioned strains are the results of the same process of particle rearrangement. In incremental form this can be represented by following equations :

$$dW = dW_c + dW_s \quad \text{............................}(2)$$

$$dW_c = p' \,.\, dv \quad \text{.................................}(3)$$

$dW_s = \tau_d \cdot d\gamma$ ....(4)

in which: dW, dW_c and dW_s are the increments of strain energy, consolidation work (due to volumetric strain) and shear strain work (due to deviatoric strain), respectively. p' is effective mean stress, and dv and $d\gamma$ are the increments of volumetric strain and shear strain, respectively.

In Figs.3 and 4, it could be seen that in the first part of the model tests in this study (until peak excess pore pressure), system behaves as an undrained one. Also, the measured time histories of settlements make it clear that during the above mentioned period only a small amount of settlement occurs in the model, comparing to the total subsidence of the model at the end of test. Therefore, in the first part of the experiments due to undrained condition it could be assumed that the increment of volumetric strain (dv) as well as increment of consolidation work (dW_c) in Eq.2 comparing to dW_s are negligible, therefore :

$dW = dW_s = \tau_d \cdot d\gamma$ ....(5)

It should be noted that in response to changes in the stress state, the induced strains in a sand element can be divided into recoverable and irrecoverable strains. The recoverable (or elastic) one is generally the result of deformation of sand grains with very little or no particle rearrangement. Whereas, particle rearrangement is the major source of the irrecoverable (or plastic) strain. The emphasis in this paper is placed on the irrecoverable dW^p_s (plastic shear work increment), which is usually considered to be very large compared with dW^e_s (elastic shear work increment). Therefore, Eq.5 rewritten as:

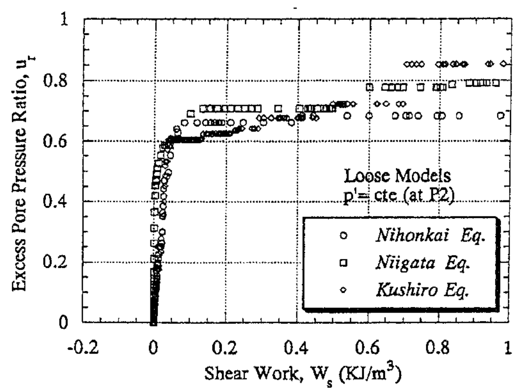
$dW = dW^p_s = \tau_d \cdot d\gamma$ ....(6)

Fig.10 shows W_s-u_r relationship for loose and medium dense models, at points P1 and P2, respectively. From this figure it might be concluded that shear stress histories don't affect the mentioned relationship.

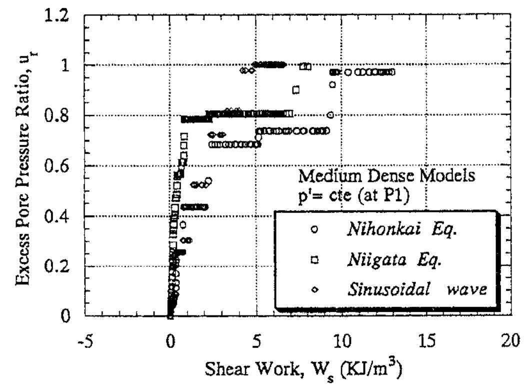
For eliminating the effect of confining pressure, a state parameter S'_s or normalized shear work has been introduced by Moroto (Moroto 1976):

$dS'_s = dW^p_s/p'$ ....(7)

The effect of variations of soil pressure ratio during pore pressure build up on p' is also considered in the calculations of S'_s, Jafarzadeh (1994). S'_s-u_r relationship for loose and medium dense models at different points with different confining pressures, is plotted in Fig.11. It is obvious from this figure that S'_s is independent from not only shear stress



a.



b.

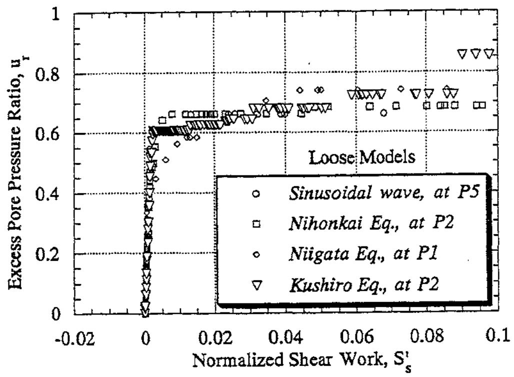
Fig.10. u_r - W_s relationship for: a- loose models at P2, and b- medium dense models at P1, subjected to different stress histories.

histories but also confining pressures.

CONCLUSION

Uni-directional shaking table tests under harmonic and irregular loading conditions were performed on 12 virgin loose and medium dense models of Toyoura sand by employing four irregular time histories. It was shown that dynamic shear strain is an applicable parameter for correlating the generated excess pore pressure ratio in loose or medium dense models.

In the precess of shaking table experiment in which undrained condition could be assumed, it was found that the normalized shear work has a unique relationship for each specific density, with excess pore pressure ratio, which is independent from confining pressure and stress path.



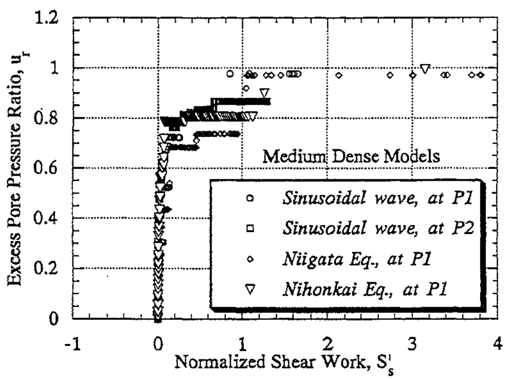


Fig.11. u_r - S'_s relationship for: a- loose models, and b-medium dense models, subjected to different stress histories.

ACKNOWLEDGEMENT

During this study, the second author received a scholarship from the Iranian Ministry of Culture and Higher Education, which is gratefully acknowledged.

REFERENCES

Fukutake, T. and Matuoka, H. (1989), "A unified law for dilatancy under multi-directional simple shearing", Proc. of JSCE, No.412/III-12, pp.143-151,

Jafarzadeh, F. and Yanagisawa, E. (1994),"Liquefaction potential of loose saturated sand models from energy point of view in shaking table experiments", Proc. of the 2nd International Conference on Earthquake Resistant Construction and Design (ERCAD, Berlin 94), pp.259-266,

Jafarzadeh, F. and Yanagisawa, E. (1993), "A preliminary study on multi dimensional shaking table tests on saturated sand models by random and equivalent seismic motions", Proc .of the 2nd International Seminar on Soil Mechanics and Foundation Engineering of Iran, pp.572-588,

Moroto, N. (1976), "A new parameter to measure degree of shear deformation of granular material in triaxial compression tests", Soils and Foundations, Vol.16, No.4, pp.1-9,

Nagase, H. and Ishihara, K.(1987), "Effects of load irregularity on the cyclic behaviour of sand", Soil Dynamics and Earthquake Engineering, Vol.6, No.4, pp.239-249,

Okada, N. and Nemat Nasser, S. (1994), "Energy dissipation in inelastic flow of saturated cohesionless granular media", Ge'otechnique 44, No.1, pp.1-19,

Towhata, I. and Ishihara, K. (1985), "Shear work and pore water pressure in undrained shears", Soils and Foundations, Vol.25, No.3, pp.73-84,

Yanagisawa, E. and Sugano, T.(1994), "Undrained shear behaviors of sand in view of shear work", Performance of ground and soil structures during earthquakes, 13th International Conference on Soil Mechanics and Foundation Engineering, New Delhi, pp.155-158.