Liquefaction Triggering Criterion Using Shake Table Test

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***Abstract*- Earthquake induced liquefaction in saturated granular soils is an important phenomenon causing severe damages. In order to minimize the ill-effects due to liquefaction, various lab tests, field tests are being used which assess the liquefaction potential. In the present study the shake table test has been used for assessing soil liquefaction of loose saturated cohesionless sand by simulating earthquake conditions in the laboratory. The tests are conducted on shake table apparatus, with the varying range of relative density and maximum acceleration. This paper deals with the experimental investigations carried out to establish an unique criterion for initiation of liquefaction for shake table test, which best delineate with the initialization of liquefaction in clean uniform sand. It is observed that for the clean sand tested in shake table test liquefaction is observed to trigger at pore pressure ratios even less than or equal to one for loose and medium state of soil up to maximum shaking of 0.32g.For higher magnitude of shaking and for denser soils initiation of liquefaction is observed to take place for pore pressure ratios greater than one. Few tests are based on the field data where actual field parameters are used to prepare laboratory soil model and is observed that the criterion of the occurrence of liquefaction in the laboratory shake table model is in close agreement with actual field data.**

Keywords: Liquefaction, shake table test, Pore pressure ratio, cyclic stress ratio, Maximum acceleration.

I. INTRODUCTION

Earthquakes are among the most devastating natural phenomena, resulting in loss of life and damage worth billions of dollars worldwide. Seed H.B. [1] defined that “liquefaction” denotes a condition in which a soil undergoes continued deformation at constant low residual stress or with low residual resistance, due to the build up and maintenance of high pore water pressures that reduces the effective confining pressure to a very low value.

The liquefaction phenomenon of soil deposits can be described as [1] the reduction of shear strength due to pore pressure buildup in the soil skeleton .When saturated loose sands are subjected to earthquake loading, an upward propagation of shear waves takes place. However the duration of cyclic stress application is so short as compared to time required to drain, that soil volume contraction cannot occur immediately and excess pore water pressure builds up progressively. When this excess pore water pressure equals total stress, it reduces effective stress to zero and sands completely lose their stiffness & shear strength temporarily; such a state is called as initiation of liquefaction. Previously, liquefaction initiation criteria were commonly based on either pore-pressure or strain amplitude within a sample. Some of the criteria are very broad and general, some of them lack practical application, and some of them are interdependent on various factors. There are various methods to assess soil liquefaction. They are mainly divided into laboratory methods and field methods. The field study mainly deals with CPT and SPT data. The laboratory methods include direct shear test, triaxial shear test, centrifuge tests, ring shear test, torsion shear test, shake table test.

In these types of tests, the stress conditions and deformations in the soil elements are significantly affected by the boundary conditions, and the loading conditions are generally not the true field conditions. Therefore, it is believed that large soil specimens can reproduce the actual seismic ground shaking [1]. Thus, the soil behaviors, including liquefaction, under the true seismic conditions could be observed and analyzed in laboratory model test. Hence from various laboratory methods used to asses’ soil liquefaction, in the present study the focus is given on the shake table test.

II. LITERATURE REVIEW

In the present study the emphasis is given on the literature based on various parameters of liquefaction phenomenon using shake table apparatus. To study liquefaction behaviour of silty sand, investigations were carried out by Behra K.C et al. [2] & a non dimensional parameter pore pressure ratio (r_u) has been introduced with $r_u > 1$, indicating complete liquefaction. A large bi-axial shear Box [3] is used to compare one dimensional and two dimensional effects of shaking on liquefaction & the criterion adopted for liquefaction, is pore pressure ratio $r_u = 1$. Shake table was also used [4] for assessment of soil Liquefaction & was observed when excessive pore water pressure exceeds the overburden pressure during liquefaction. Yegian M.K., et.al [5] used Shake Table to study the effect of Induced-Partial Saturation for Liquefaction mitigation. The maximum excess pore pressure ratios in the fully and partially saturated specimens using electrolysis and drainage-recharge method are compared & the results indicate that a reduction in the degree of saturation prevented the onset of liquefaction. For the large scale simple shear box [1] the initiation of liquefaction is defined as the condition at which dynamically induced pore pressure reaches the value of initial effective vertical stress followed by quickly developed large shear strains.

The results of experiment on the liquefaction of saturated sands with a Shaking Box are compared with other methods which are dynamic triaxial and dynamic simple shear by Sukeo O–Hara [6]. It was observed that for the same number of cycles causing liquefaction the stress ratio required is largest for shake table followed by triaxial and simple shear test in order. The primary cause of discrepancies between triaxial and simple shear test is due to difference in direction of principal stress, maximum principal stress and average principal stress and for sand box particularly because of angle of internal friction used and limitation of box itself. Behaviour of saturated sand models in shake table test was studied by Yanagisawa et.al [7], with the objective to study the response of level grounds during earthquakes and nature of generated pore water pressure. Prasad et al [8] have developed a manual shake table using laminar box. However, it does not take into account pay load and the criterion for initiation of liquefaction in terms of CSR.

As discussed there is enormous use of shake table test in literature taking care of diverse parameters allied to liquefaction but a unique criterion for initiation of liquefaction for shake table test has not been reported so far. It is also observed that there are varying ranges of criteria for initiation of liquefaction in the literature with use of different parameters for various methods and conditions. Therefore in the present study an attempt has been made to assess the proper criterion which best delineates with the initialization of liquefaction in clean uniform sand using shake table test.

III. EXPERIMENTAL INVESTIGATIONS

The Test program consisted of total 19 tests conducted on shake table apparatus, out of which 16 tests are conducted on typical soil samples in laboratory with the relative density range of 30% to 60% and maximum acceleration range of 0.21g to 0.54g the variation is based on the field variables available from literature reviewed for the field data[9] and 3 tests are based on the actual field data, where soil model was prepared using field variables from Stark T.D. and Olson M.S.[9], with the relative density range of 67% to 70% and maximum acceleration range of 0.16g to 0.29g.

A. Material and Apparatus Specifications

A fine uniformly graded sandy soil; more prone to liquefaction, has been selected for present work. The properties of such clean sand and gradation are as shown in Fig. 1 & Table I respectively.

Experimental set up consists of Shake Table test apparatus which is specifically designed by Pathak et.al [10] to conduct the tests for studying the criterion for initiation of liquefaction by simulating ground shaking during Earthquake. It comprises mainly of three main components, a vibrating platform which vibrates with the soil model attached to it. The size of the platform is 1000 mm X 1000 mm and is made up of cast iron coated with silver paste. A control panel is the most important component of the shake table as it controls the frequency of the shaking. The control panel has been given standard combinations of amplitude to produce the required acceleration. A motor of capacity 3 H. P. with a three phase connection is used. Two types of soil models made of Perspex sheet have been manufactured. One is a square model with size 400 x 400 x 400 mm used by Pathak et al. [10] and other one is a rectangular model with size 800 x 600 x 400 mm. The present work necessarily deals with rectangular soil model as shown in Fig. 2. The model is sufficiently strong & rigid, 12mm thick. Larger size model has been found to lower the degree of extrapolation and the undesirable effects associated with small model [1]. Three pore pressure transducers are attached to the shake table model, connected at 0.1m, 0.2m & 0.3m height from bottom of the model as shown in Fig.2; each with capacity of 100 kPa and the least count of 0.1 kPa. Measurement of displacement of shake table is carried out with Linear Variable Displacement Transducer [LVDT] of Capacity 50 mm and the least count of 0.1mm. Three pore pressure transducers and LVDT are connected to Data Acquisition System (DAQS) for recording the observations accurately. The necessary Calibration involves conversions of analog signals from display units of instrument to the exact output of instruments and records for given time interval.

TABLE I
Properties of clean Sand

Properties	**Details**	**IS codes Details**
γmax	17.441 kN/m3	IS :2720 [Part 14]-1983
γmin	15.068 kN/m3	IS :2720 [Part 14]-1983
G	2.6582	IS :2720 [part 3 /sec1-1980]
emax	0.7641	IS :2720 [Part 14]-1983
emin	0.524	IS :2720 [Part 14]-1983
D50 [mm]	0.30	IS :2720 [Part 4]-1985
D10[mm]	0.175	IS :2720 [Part 4]-1985
D60[mm]	0.32	IS :2720 [Part 4]-1985
D30[mm]	0.24	IS :2720 [Part 4]-1985
Cc	1.028	IS :2720 [Part 4]-1985
Cu	1.82	IS :2720 [Part 4]-1985

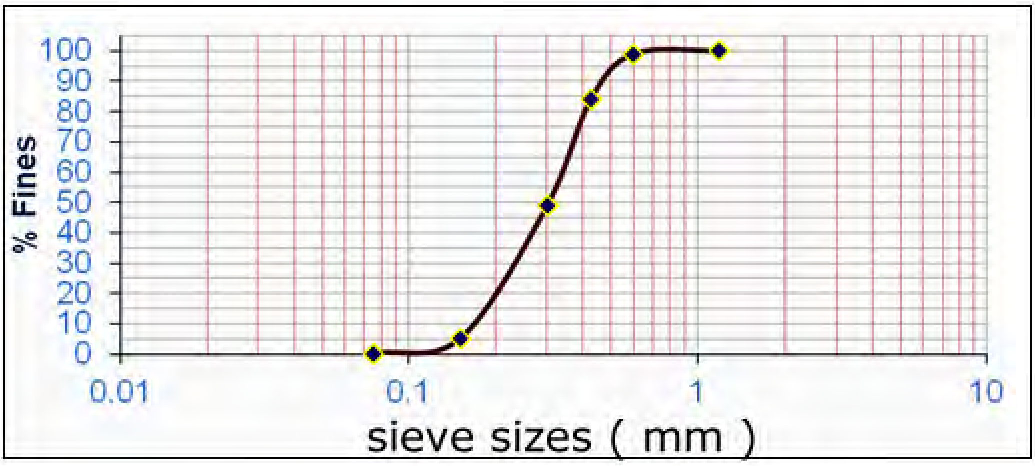

Fig.1. Grain Size Analysis

B. Test Procedure

One of the important aspects of test procedures is the method of sample preparation. The basic requirement is to obtain homogeneous sample with specific uniform density for which the wet sedimentation method is adopted ensuring complete saturation. The soil model is divided into seven equal parts, for the convenience of specimen preparation. The soil model is filled in seven layers by pouring sand from specific height using raining technique to achieve the required density. Readings on the LVDT are set according to the current position of shake table and amplitude is set on the shake table according to the acceleration and frequency required in testing program. The knobs of the pore pressure transducers are opened and at the instant of start of shaking, pore water pressure values are recorded. When instrumentation work is complete, display connections and DAQS are checked. The shake table is then switched on. It starts shaking at the required acceleration and the data is recorded through data acquisition system at one second interval. It is observed that the pore water pressure first increases, shows a peak value then decreases or remains constant with respect to initial value. Fig.3 shows the fluidization at the end of the test. Observations of Pore pressure variation at each of the three transducers are recorded for all the tests.

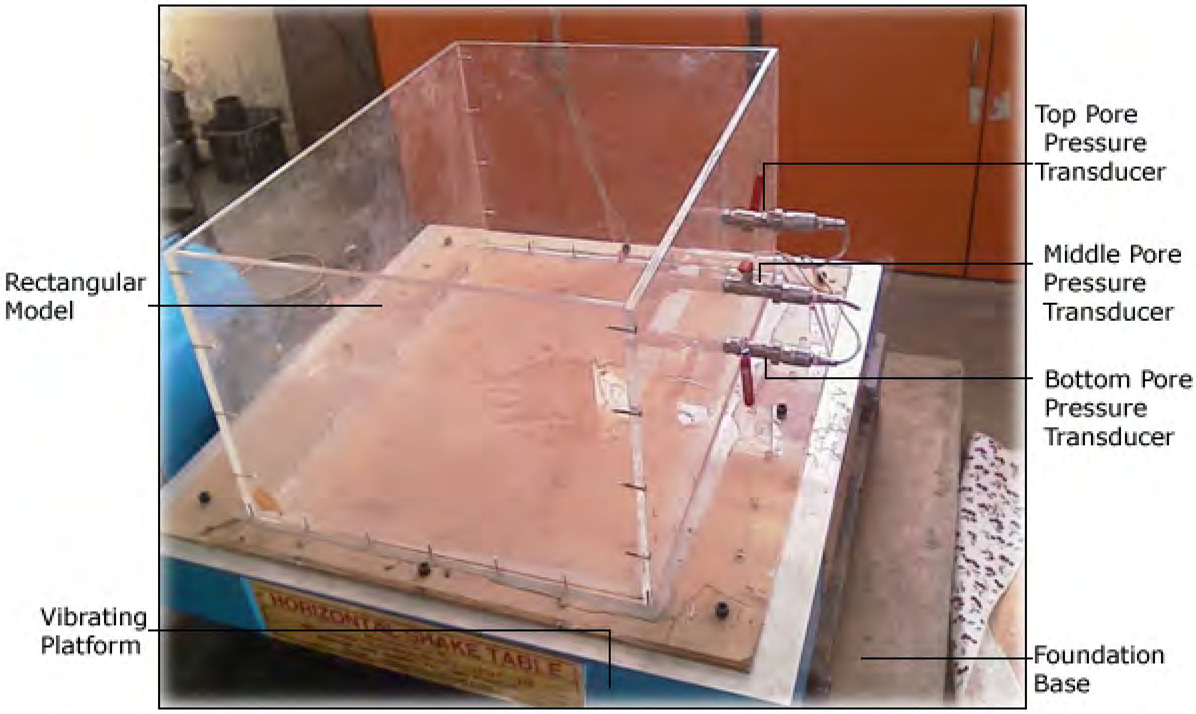

Fig.2. Shake Table Apparatus (Rectangular Model) showing pore pressure transducers

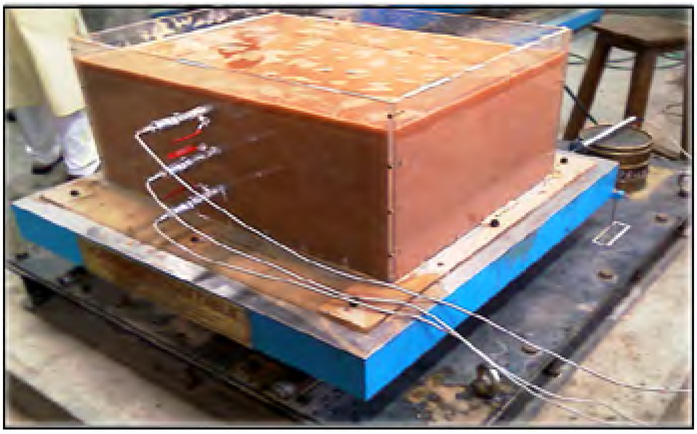

Fig.3. Specimen after the Test

IV DISCUSSION OF TEST RESULTS

Based on the test program the tests are conducted on shake table apparatus, a parametric study was carried out and is discussed in the following sections.

A. Pore Pressure and Acceleration versus Time

The variation of excess pore water pressure with time is as shown in Fig. 4, for all the three transducers as a typical test result of 30% relative density at maximum acceleration 0.45g. It is seen that pore water pressure increases with the time initially and then decreases after attaining a peak. This stage could be considered as initiation of liquefaction which is also reported by Singh H.P. [4]. The peak value of pore water pressure for bottom transducer is 2.447 kPa after 7 seconds and that for middle transducer is 1.56 kPa after 5seconds. The top layer remains liquefied during the entire test as the top transducer is connected at 0.05m from the top surface of soil model where immediately after few seconds pore water comes out at the top and turbulence is seen in the top layer. Hence the results of the top transducer are not reported. From variation of pore pressure with the time at all the three transducers; it is observed that for all the test results, that liquefaction proceeds in the downward direction for the laboratory shake table apparatus in tune with Singh H.P.[4]. In the present study the input motion is one directional, sinusoidal, and simple harmonic. With LVDT the displacement of the base of the shake table is recorded in data acquisition system. From this data, the graph of acceleration versus time is plotted for confirmation as shown in the Fig.5.

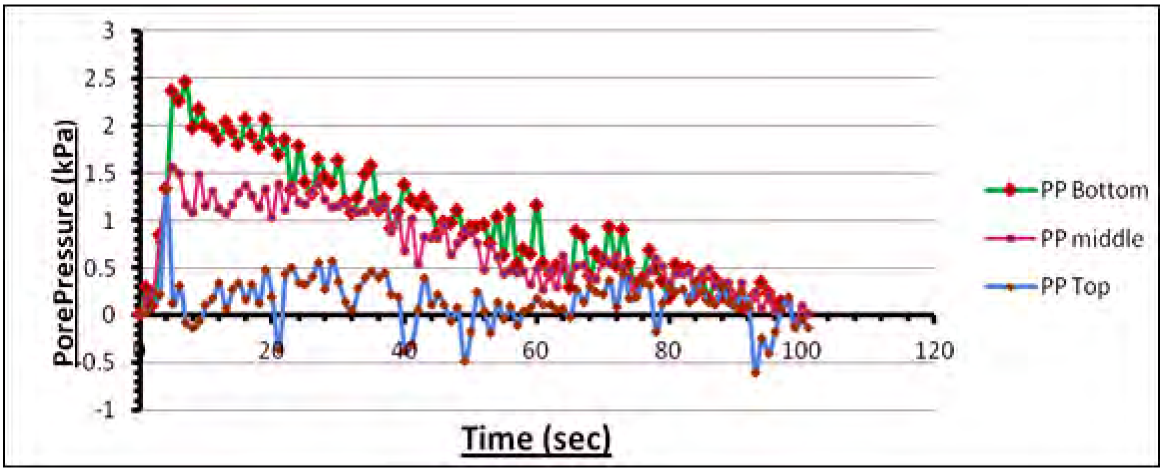

Fig.4. Pore pressure Vs Time for all transducers

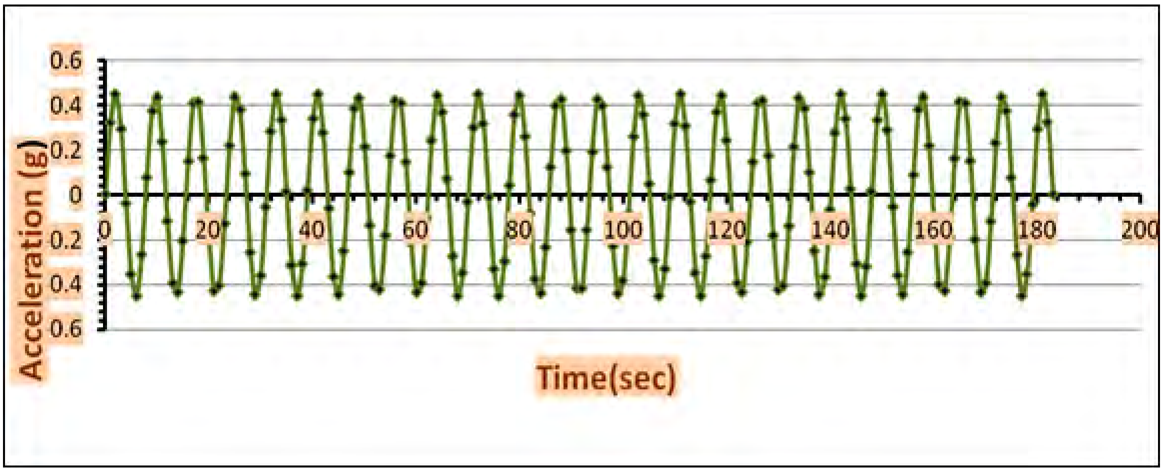

Fig.5. Acceleration –time Diagram

B. Variation of Pore Pressure

Fig. 6 shows a typical variation of pore pressure at middle transducer. As the acceleration of shaking increases, number of cycles required to liquefy the soil decreases. It is also observed that the value of maximum excess pore pressure is slightly higher for 0.21g as compared to 0.32g for both the transducers. However it is in the range of 2 to 3 kPa for bottom transducer whereas for middle transducer the range is 1 to 2 kPa. In Fig.7 it is seen that as the density increases, the number of cycles required for initiation also increases. The same trend is observed for both the transducers. At 0.21g density increases from 30% to 60% the number of cycles required increases from 33 to 66. Similarly at the shaking of 0.54g, as density increases from 30% to 60% the number of cycles required increases from 18 to 57. Again it is observed that with the increase in shaking from 0.21g to 0.54g at a particular density, the number of cycles required decreases as discussed previously. Thus, it is observed that as the density increases the number of cycles for initiation of liquefaction increases which is in tune with Yanagisawa E. et.al [7].

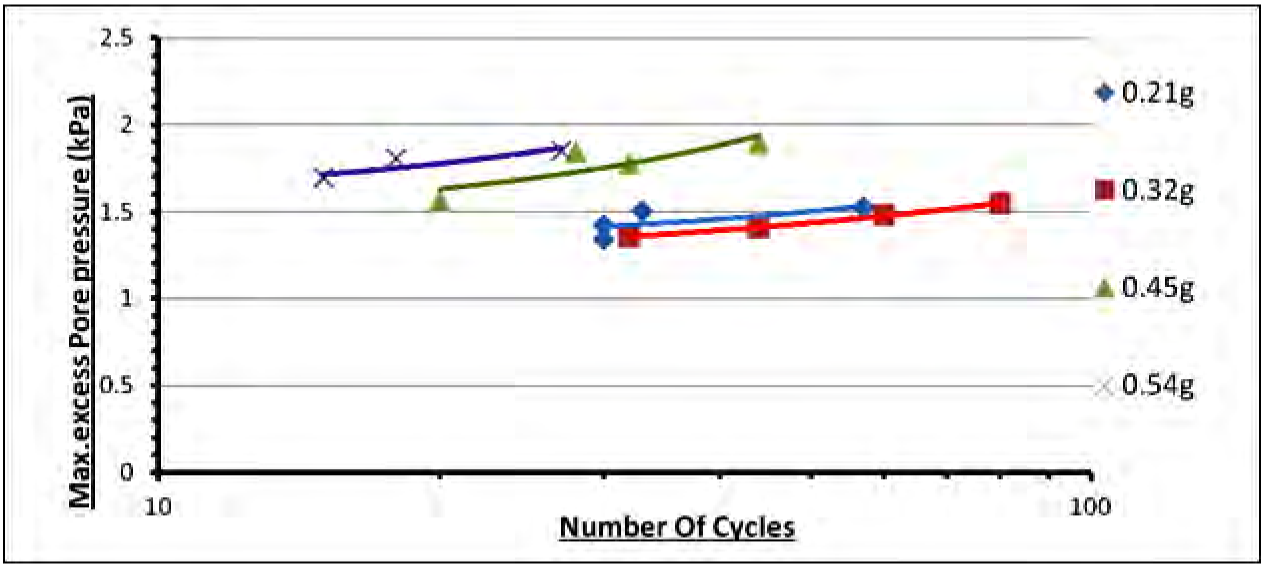

Fig.6. Maximum Pore Pressure Vs Number of cycles at different maximum acceleration Middle Transducer

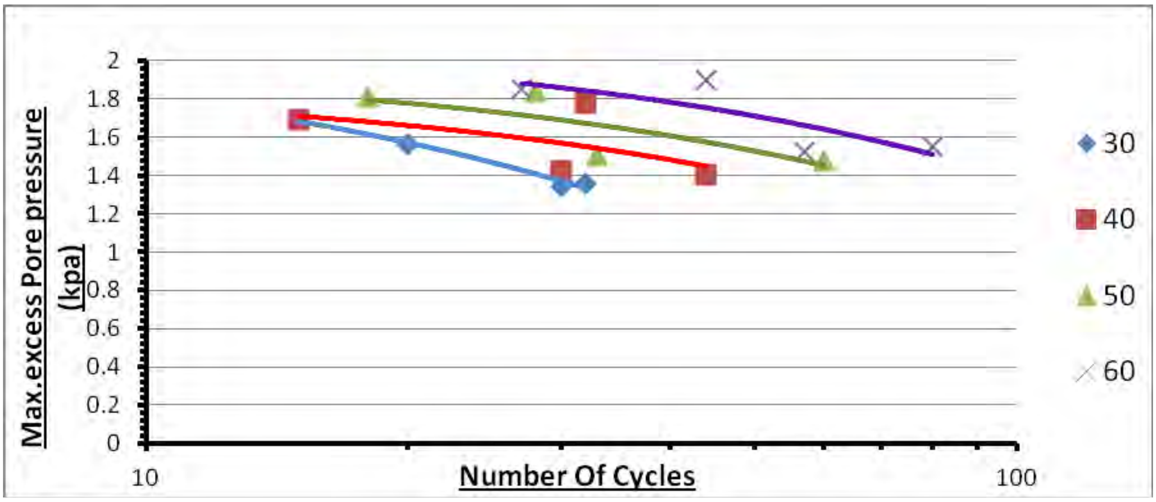

Fig.7. Maximum Pore Pressure Vs Number of cycles at different densities for middle transducer

C. Variation of Cyclic Stress Ratio

Cyclic stress ratio [CSR] is considered as an indication of number of cycles required for liquefaction. In the present study for assessing soil liquefaction, CSR is calculated using the Eq. (1) Kramer [11],

$$CSR = \frac{\tau_{avg}}{\sigma'_v} = 0.65 \cdot \frac{a_{max}}{g} \cdot \frac{\sigma_v}{\sigma'_v} \cdot r_d \quad \text{Eq. (1)}$$

Where,

a_{max} = maximum ground acceleration

σ_v = total stress

σ'_v = effective stress

g = acceleration due to gravity [9.81 N/m2]

r_d = reduction factor

CSR values for all tests conducted in the present study are evaluated using Eq.(1). The variation of cyclic Stress ratio (CSR) with relative density for middle transducer is shown in Fig. 8, the same trend is observed in bottom transducer.

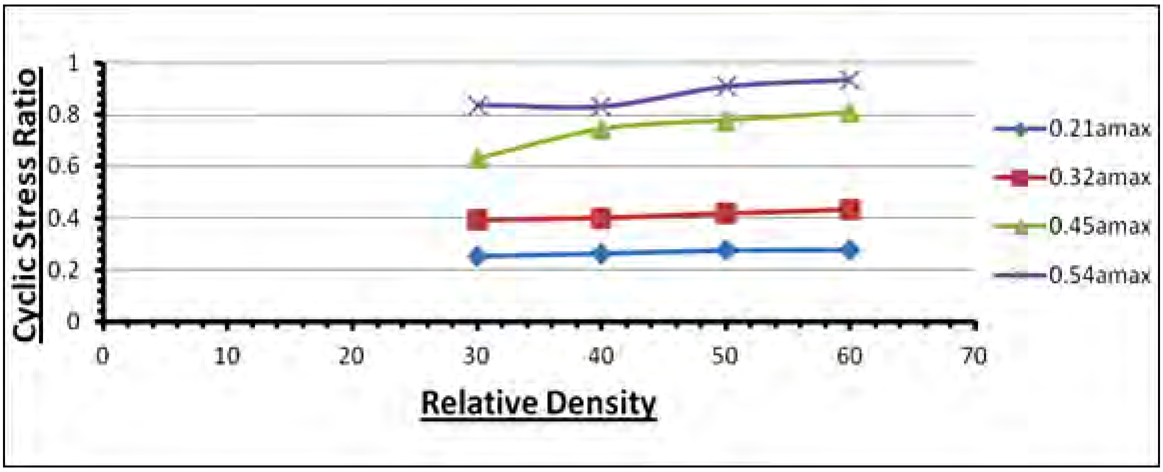

Fig.8. CSR Vs Relative Density Middle Transducer

For both the cases, it is observed that with the increase in the relative density, CSR increases. It is seen that for the maximum acceleration of 0.21g & 0.32g with the increase in relative density there is slight increase in CSR values whereas for the maximum acceleration of 0.45g & 0.54g, considerable increase can be seen in CSR values. For 30% relative density at maximum acceleration 0.21g & 0.54g the CSR value increases from 0.253 to 0.76 for bottom transducer and 0.25 to 0.83 for middle transducer. Thus, as the maximum acceleration increases from 0.21g to 0.54g the CSR values increase nearly in the range of 0.25 to 0.9. The plot of CSR versus Number of cycles to initiate liquefaction as shown in Fig. 9 drawn for the middle transducer shows that with the increase in density, CSR increases and number of cycles to initiate liquefaction also increases. Similar trend is observed for bottom transducer. One more observation in the present study is that with the increase in shaking from 0.21g to 0.54g, for a particular relative density, CSR increases.

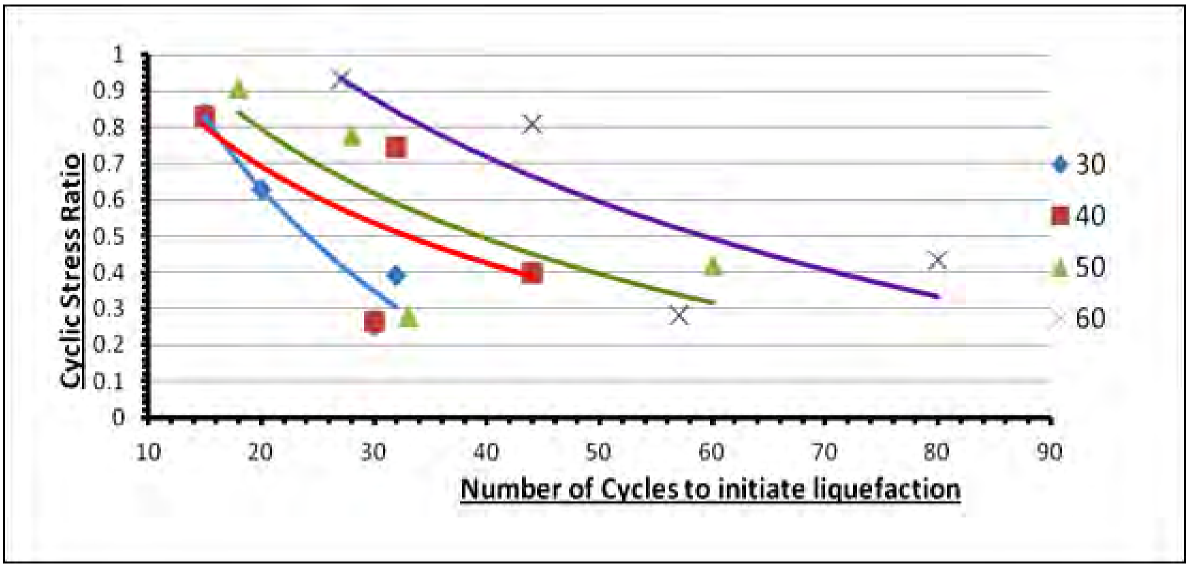

Fig.9. CSR Vs Number of cycles at different densities for Middle Transducer

Based on pore pressure-related criteria [12], soil liquefaction has often been defined as the state at which the excess pore water pressure ratio (r_u) equals 1.0. This occurs when the pore water pressure increase (Δu) becomes equal to the initial vertical effective overburden stress [$r_u = \Delta u / \sigma'_o = 1.0$] in simple shear tests and in field studies, or when Δu equals the initial effective minor principal stress [$r_u = \Delta u/\sigma'_{3c} = 1.0$] in triaxial compression tests. In the present study for assessing soil liquefaction, Pore Pressure Ratio [r_u] and cyclic stress ratio are computed for all four acceleration levels for a particular relative density. Thus the Fig.10 shows a plot of such CSR and Pore Pressure Ratio values obtained for all the four relative densities.

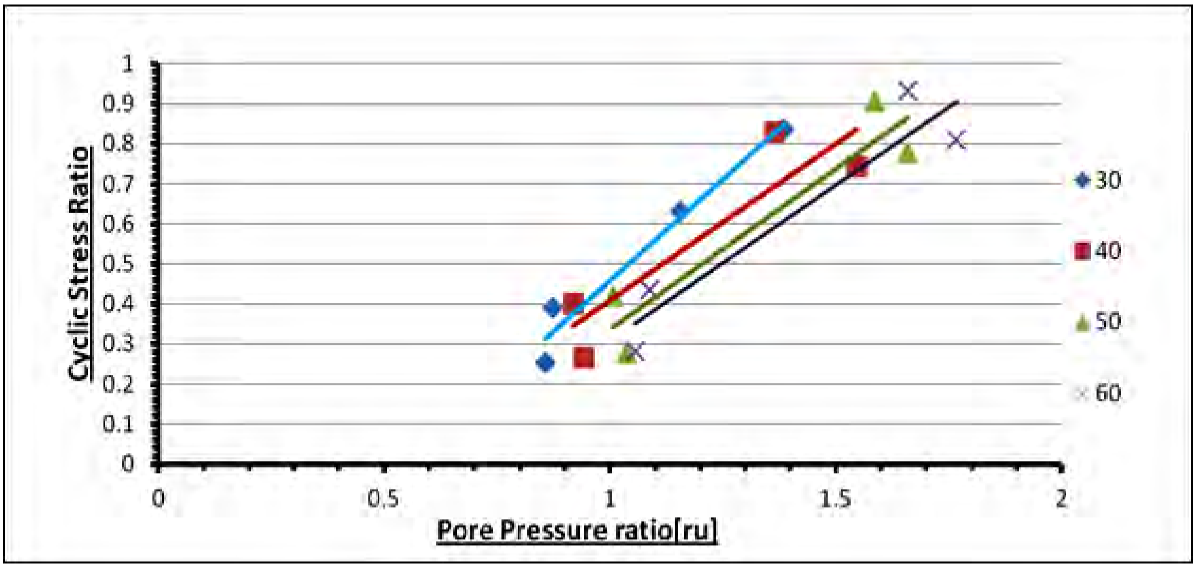

Fig.10. CSR Vs Pore Pressure Ratio at different densities for Middle Transducer

It can be observed that with the increase in pore pressure ratio CSR increases for all relative densities. Further it is noticed that for the relative densities less than or equal to 50 with 0.21g & 0.32g the values of pore pressure ratio are less than one [r_u < 1] ; for higher relative densities even for lower acceleration the values of pore pressure ratio are more than one [r_u > 1]. However typically for relative density 50%, specimen with 0.32 shaking showed the value of pore pressure ratio are equal to one [r_u=1] for middle transducer. Similar trend is observed for bottom transducer, for relative densities less than or equal to 50 with lower values of acceleration pore pressure ratio are less than or equal one; for all the relative densities at for higher acceleration the values of pore pressure ratio are more than one [r_u > 1].

From this analysis it could be stated that initiation of liquefaction takes place even if r_u < 1, [0.85 to 1] for shaking upto 0.32g for loose and medium soil. Jiaer W.U. et.al. [12] have also reported pore pressure ratio values less than one for the specimen tested in cyclic simple shear tests. Thus Pore pressure ratio could be considered as the criterion for assessing the initiation of soil liquefaction along with corresponding relative density, for a particular maximum acceleration for laboratory Shake Table Test.

D. Comparison of the Results with Shake Table Test & other Laboratory Tests

The results available in present study are compared with Shake Table Test and other laboratory tests available in literature [10]. In Fig. 11 results from present study for 3 Hz frequency and lower values of maximum acceleration are plotted as cyclic stress ratio versus number of cycles required to initiate liquefaction are compared with various Shake Table Tests. The Fig. 12 shows a similar graph compared with various other laboratory Tests. In both the cases, the values obtained in the present study are slightly on the higher side as compared to those from the previous study by various researchers but the trend observed is the same. One of the reasons attributed to this is length to depth (L/d) ratio of the sample which might have affected the value of CSR considerably. It is observed that with the increase in L/d ratio (L/d ratio for the present study is 2.28, for O-Hara is 3.4, Finn et al is 10.3, and Seed and De Alba is 22) the CSR decreases. Thus smaller L/d ratio in the present study could be one of the reasons for higher values of CSR.

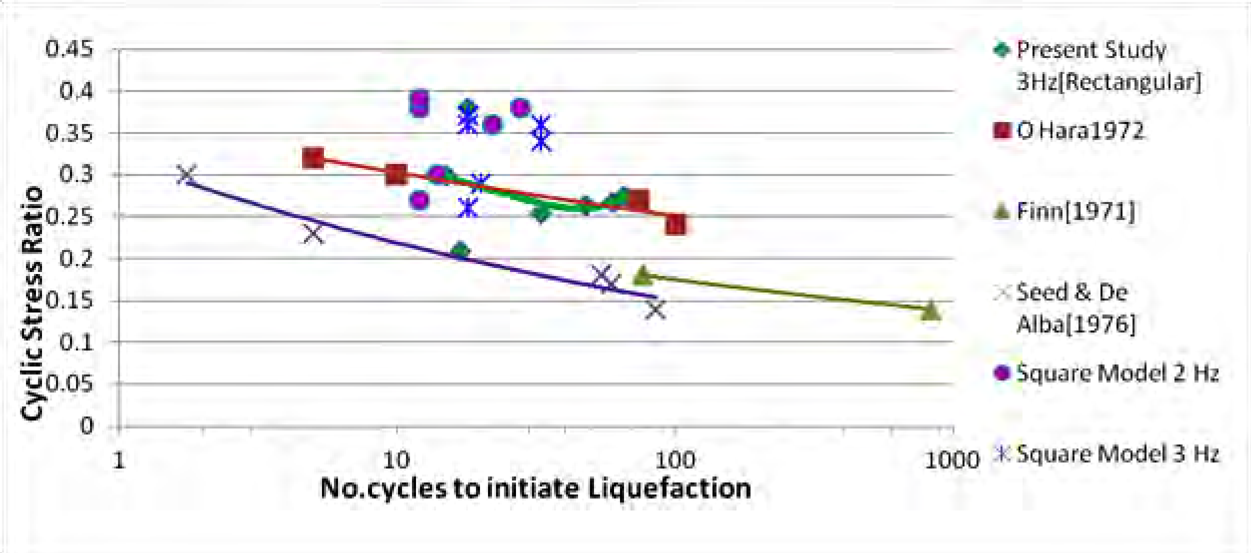

Fig.11. Cyclic Stress Ratio vs. Number of cycles for Shake Table Tests [10]

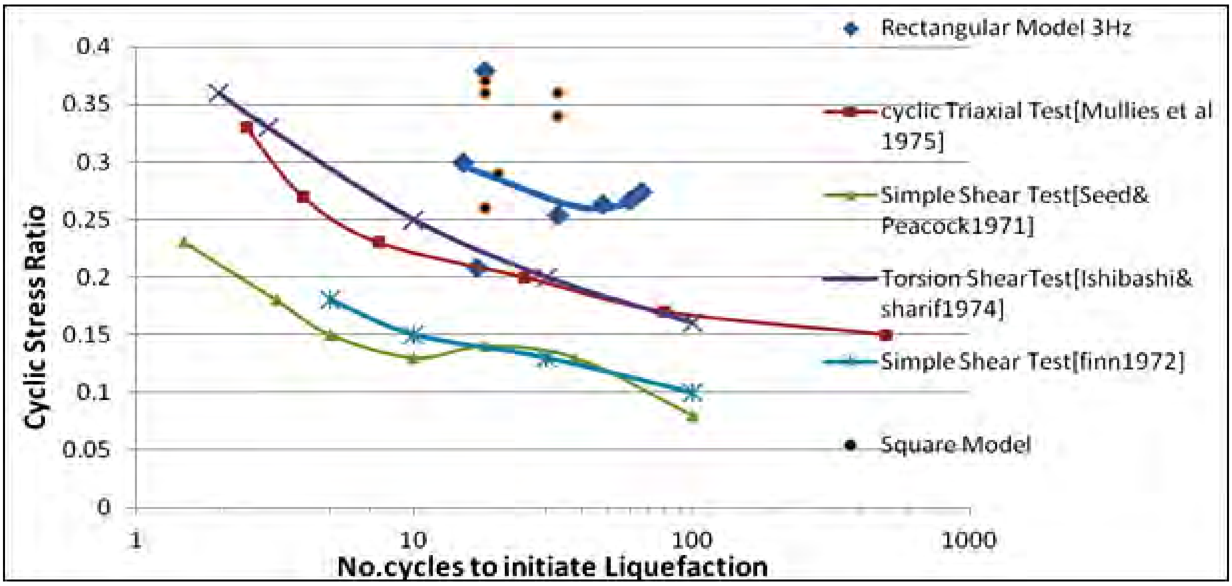

Fig.12. Cyclic Stress Ratio vs. Number of cycles for Various Laboratory tests

Fig.12 also shows the values obtained by cyclic shear test conducted by Mullis in 1975, Simple shear test by Seed and Peacock 1971, Simple shear test by Finn 1972, Torsion shear test by Ishibashi and Sharif in 1974,and shake table test (square modle) Pathak et al[10]. With the increase in CSR the number of cycles to initiate liquefaction also increases. It is observed that the values obtained in the present study are on the higher side as compared to those from the previous study by various researchers the reason being same as discussed earlier. Moreover, it is also observed that irrespective of the variations in properties of the clean sands, size of specimen, methods of sample preparation for different tests used by the researchers the trend observed is the same.

In Fig. 13 the values obtained in the present study at lower values of maximum acceleration (0.21g, 0.32g) are superimposed on the graph given by Seed [1] and further by Pathak et.al [10]. It could be seen that similar trend is observed for both the acceleration levels in the present study are same as the other lab tests with higher values.

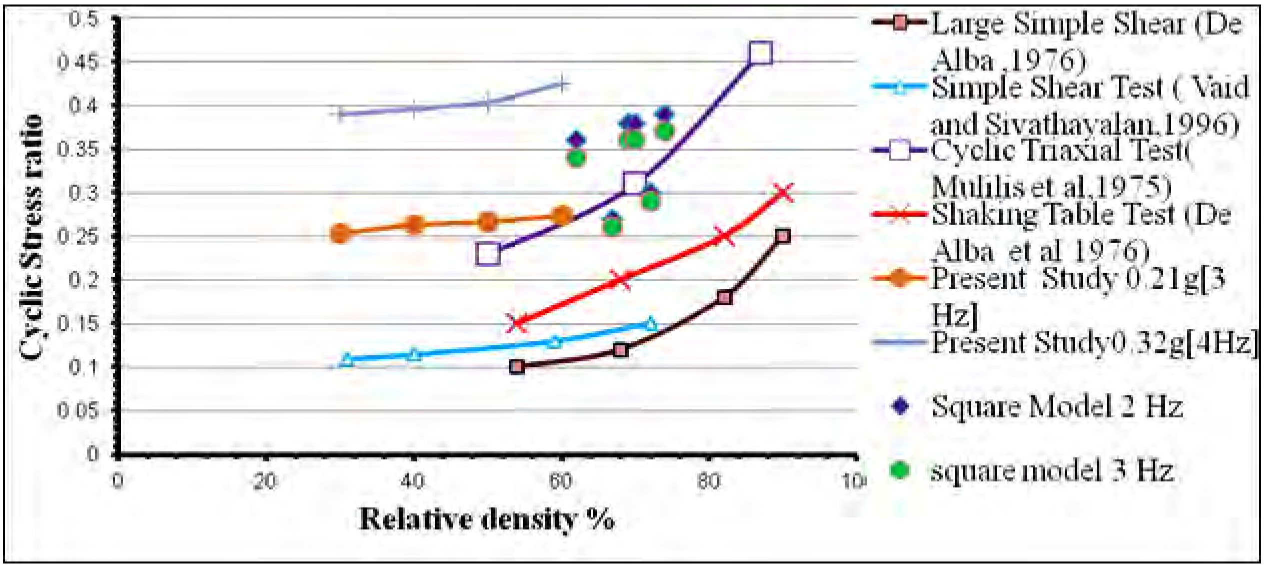

Fig. 13. Cyclic Stress Ratio vs. Relative Density for Various Laboratory tests

E. Comparison of Results with Field Data

Table II Selected Data from the field [9]

Earthquake Site	**D50 Size [mm]**	**C. P. T. qc[Mpa]**	**Site amax**	**Vertical effective Stress [kPa]**	**Dr %**
Nigatta [M = 7.5] Kwagishi-Cho Building	0.33	7.80	0.16g	78.5	67
Nihonkai-Cho EQ [M =7.7] Noshiro Cho	0.32	7.80	0.23g	65.7	67
Lomo-Prieta EQ [M = 7.1] Port of Oak land	0.25	8.57	0.29g	82.4	70

The shake table test is conducted in the lab on soil specimen prepared in the laboratory based on the field parameters. The test data is collected based on field parameters from Stark & Olson [9] as shown in table II. The data for “Yes” liquefaction selected from field are based on D50 size and acceleration values. All the laboratory shake table tests show the liquefaction. The CSR has been computed from these laboratory test results and $[N_1]_{60}$ are obtained from the CPT values given in the field data. These values are then plotted on the curve given by Kramer [11], which demarcates “Yes” & “No” zones of liquefaction as shown in Fig. 14. Simulating the same soil conditions in laboratory when the shake table test was conducted on these soil samples, it is observed that all the points lie in “Yes” zone of liquefaction, thus confirming the present laboratory work with corresponding field results.

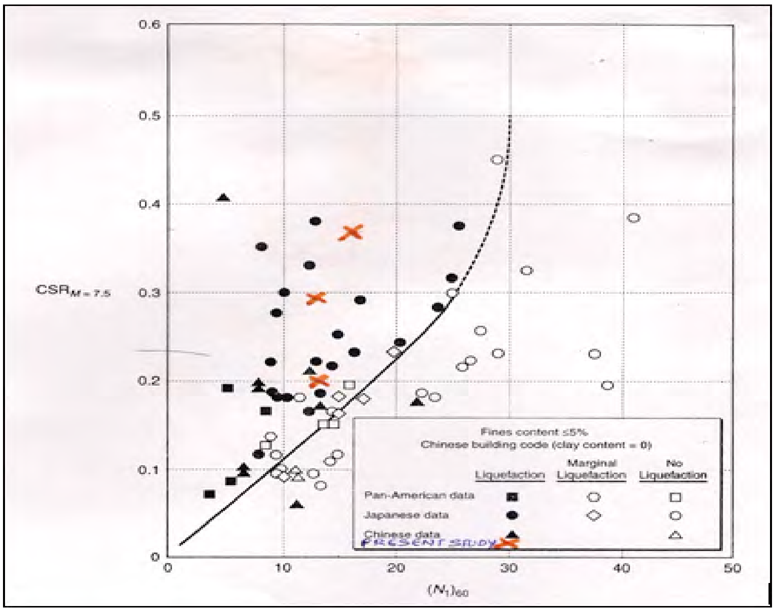

Fig.14. Cyclic Stress Ratio vs. [N1]60 (Ref:-Kramer [11])

V. CONCLUSION

It is observed that for the clean sand tested in shake table test soil liquefaction is observed to trigger at pore pressure ratios even less than or equal to one for loose and medium state of soil up to maximum shaking of 0.32g. For higher magnitude of shaking and for denser soils initiation of liquefaction is observed to take place for pore pressure ratios greater than one. Thus from the present experimental investigation, the Pore pressure ratio could be considered as the criterion for assessing the initiation of soil liquefaction along with corresponding relative density, and for a particular maximum acceleration for laboratory Shake Table Test.

In general, it is seen that for all the tests pore water pressure increases with the time initially and then decreases after attaining a peak. This stage could be considered as initiation of liquefaction. From variation of pore pressure with the time at all the three transducers; it is observed that for all the test results, that liquefaction proceeds in the downward direction for the laboratory shake table apparatus.

With the increase in maximum acceleration the number of cycles required for initiation of liquefaction decreases. As the density increases, number of cycles required for initiation also increases.

The points where liquefaction has occurred in the field when checked in present study also lie within "Yes" zone of liquefaction. Thus shake table test could be effectively used to simulate the liquefaction in the field.

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