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ABSTRACT

Loose saturated cohesionless soils may undergo liquefaction due to strong ground motions. Such liquefaction causes significant damage to the structure resting on such soil. The extent of damage primarily depends upon soil properties, intensity of earthquake and type of structure. Various analytical models have been developed to estimate the likelihood of liquefaction of particular site based on field performance. However, if it is possible to identify the sites which are likely to liquefy due to specific intensity of earthquake it will help implementing the reduction in the damage which it would otherwise cause. One such analytical model has been developed by one of the authors of this paper and has been found to satisfactorily demarcate ‘Yes’ and ‘No’ zones of liquefaction for number of earthquakes. However, earlier research shows that laboratory tests could also be conducted to study the liquefaction behavior of soil under specific condition.

The present study mainly deals with an attempt made in conducting Shake Table Test in laboratory by simulating earthquake conditions on site. The results obtained from the trial tests have been compared with the actual field cases and also with laboratory tests conducted for such soil by other researchers. It is observed that the criterion of the occurrence of liquefaction in the laboratory model is in close agreement with actual field data. Shake table test is found to be more effective in simulating the strong ground motion during earthquake.

INTRODUCTION

One of the major causes of destruction during an earthquake is the failure of the ground structure. The ground may fail due to fissures, abnormal or unequal movement or loss of strength. The loss of strength may take place in sandy soils due to increase in pore pressure. This phenomenon is termed as liquefaction. The increase in pore pressure is due to shaking of ground. Naturally occurring earthquake is a major source of vibration of ground soil. The waves produced during an earthquake are random in nature which are responsible for liquefaction. Thus earthquake induced liquefaction leads to detrimental effects to a larger extent and thus is to be assessed. The hazards caused due to liquefaction could be of various types such as flow failure, lateral spreads, development of fissure and cracks, loss of strength, increased lateral pressure on retaining walls etc.

Since earthquake induced liquefaction is very commonly observed phenomena, leading to detrimental effects, there is a need to assess the same. There are various methods to assess soil liquefaction. They are mainly divided into laboratory methods and field methods. The field study deals with SPT data. Field performance model developed by Phatak & Pathak (1999) has been found to demarcate "Yes' & "No" zones of liquefaction reasonably well. The model has also been verified with Arias Intensity approach for assessing the susceptibility of a particular site to liquefy (2004). The laboratory methods include mainly direct shear test, triaxial shear test, shake table test. The present paper deals with the one of the laboratory Model tests namely Shake Table test.

LITERATURE REVIEW

Prasad et al (2004) 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
Behra K. C. et al (2005) studied liquefaction behavior of silty sand by conducting shake table tests on samples with different silt contents. The work focused mainly on resistance offered by silty sand to liquefaction for steady state of vibrations.

Singh et al (2008) presented the liquefaction behavior of the Solani sand by performing shake table tests at varying acceleration with constant frequency. The results were interpreted in terms of the pore water pressure and the time elapsed during various stages. It was observed that there was little effect of level of acceleration on the magnitude of maximum pore water pressure; however time required in reaching the peak value decreased at higher acceleration.

However, no work has so far been reported for use of shake table test to initiation of liquefaction.

EXPERIMENTAL INVESTIGATION

Test progaramme

Total 12 no. of tests are conducted on sand, the properties of which are as shown in Table1.with relative density 62%,67%,69%,70%,72% and 74%.and frequency 2Hz and 3Hz.

Experimental set up

Shake Table test apparatus is specifically designed 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:
This is the platform which vibrates with the soil model attached to it. The size of the platform is 1000 mm X 1000 mm. It is made up of cast iron which is coated with silver paste.
Control panel:
This is 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.

Table 1. Properties of Sand

Property	Value	IS Code
γ_{max}	17.99 kN/m^3	IS :2720 (Part14)-1983
γ_{min}	14.33 kN/m^3	IS :2720 (Part 14)-1983
G	2.55	IS :2720 (Part 3 /sec1-1980)
e_{max}	0.828	IS :2720 (Part 14)-1983
e_{min}	0.455	IS :2720 (Part 14)-1983
(D_{50})	0.30 mm	IS :2720 (Part 4)-1985

Motor:
It actually vibrates the vibrating platform. The capacity of the motor is 3 H. P. with a three phase connection.

In addition to this, a piston arrangement is provided which translates rotary motion of the piston into vibratory motion. The shake table is mounted on foundation plate of size 1900 mm x 1600 mm. It is made up of cast iron. The total pay load of the shake table is 300 kgs. with a frequency range of 1-10 Hz. All the components of the Shake Table Apparatus are shown in the Photograph 1.The soil model used in the present study is a square model of size 400 x 400 x 400 Height x 12 mm thick (Photograph 2).

Pore water Pressure is measured in terms of height of water in a stand pipe. The potentiometer is connected to the vibrating base of the shake table to measure the displacement of the base with respect to time. This potentiometer is connected to the data acquisition system, which records the data. From the recorded values of displacement the velocity and acceleration are computed.

Test Procedure

The specific values of frequency and amplitude are set on the shake table apparatus. Then the square model 400mm x 400mm x 400mm is fixed to the base plate of the equipment. The soil model is divided into five equal parts, for

Photograph 1. Shake Table Apparatus

Photograph 2. Soil Model (Square)

the convenience of specimen preparation. The calculated amount of sand and water are weighted accurately. They are also divided into five equal parts, and the soil model filled in layers. The care is taken to achieve required density, corresponding to a particular relative density.

The porous stone is fixed at the inlet of the pore pressure to avoid any chocking due to infiltration of sand and the pore water pressure measuring stand pipe. Excess water if any found in the model, is removed and weighed. Similarly quantity of sand left out is weighed. Accordingly the saturated density of sand is calculated and the relative density is also checked. The potentiometer is connected to the vibrating base of the shake table which is further connected to the data acquisition system to record the data with time. The standpipe is then connected to the outlet to measure the pore water pressure.

Amplitude is then set on the instrument and frequency is adjusted digitally on the display. Photograph. 3 shows a specimen ready for the test. Thereafter, the equipment is switched on which starts shaking the soil in the model at the required acceleration. The data of acceleration versus time is recorded through data acquisition system and pore water pressure is measured manually.

Photograph 3. Specimen ready for the test

At the instant of start of shaking pore water pressure is recorded. During shaking, pore water pressure and displacements are recorded with time. The displacement and pore water pressure are recorded at an interval of 10 second. The shake table is accelerated till pore water pressure decreased or showed a constant value with respect to initial value. This stage is considered to indicate the initiation of liquefaction. Once the fluidization occurs, the liquefaction is inevitable, and thus at this stage the test is stopped.

DISCUSSION OF TEST RESULTS

Each of the 12 soil samples with relative densities 62%, 67% , 69% ,70% ,72% and 74% are tested for both frequencies 2Hz and 3Hz.During testing, the values of acceleration and frequency were predefined based on earthquake data. Each of these tests is conducted till initiation of liquefaction is observed. During each test, pore water pressure and acceleration with time are measured. Graph of acceleration with time is recorded through Data acquisition system while variation of pore water pressure with time is recorded manually.

From the tests results of variation of pore pressure with time it is observed that the pore pressure increases with time initially. As the time passes it either decreases after attaining a peak value or remains constant at the peak value irrespective of the relative density of sample tested. Further it is also observed that the time required to attain peak value decreases with increase in frequency. From the acceleration values recorded during shaking of the sample a-t diagrams for each

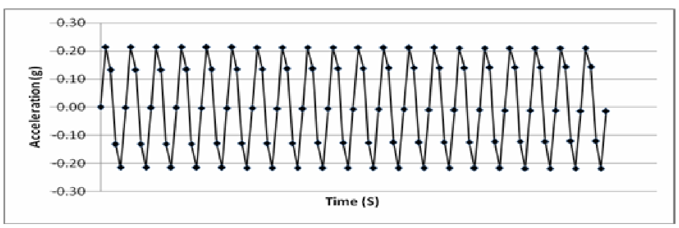

Fig.1(a). a-t diagram for 62% relative density at 2Hz frequency

sample are drawn. The Fig. 1 (a) and (b) show the a-t diagrams for 62% and 74%relative density at 2Hz frequency. These diagrams indicates the simple harmonic motion as is assumed for this experimental work.

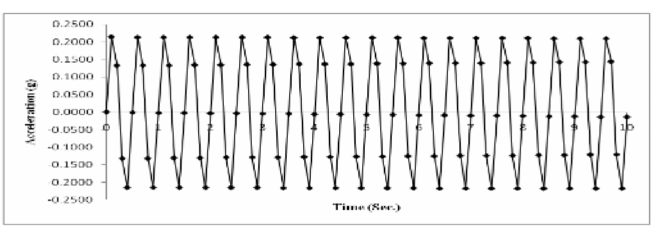

Fig.1(b).a-t diagram for 74%relative density at 2Hz frequency.

Effect of relative density on pore pressure

Fig 2(a) and (b) show pore pressure variation for samples tested with relative density less than 70% and relative density more than 70% respectively typically for 3Hz frequency.

It is clear from the figure that as the relative density increases, peak value of pore pressure also increases. However, the peak value increases marginally from 1.99 kPa for 62% relative density to 2.25 for 74% relative density.

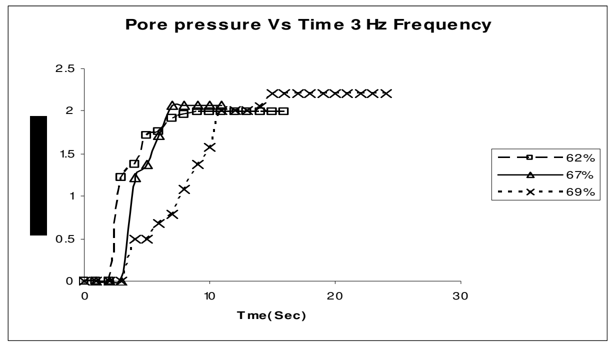

Fig.2(a)Pore pressure diagram for R.D.<70% at 3Hz frequency.

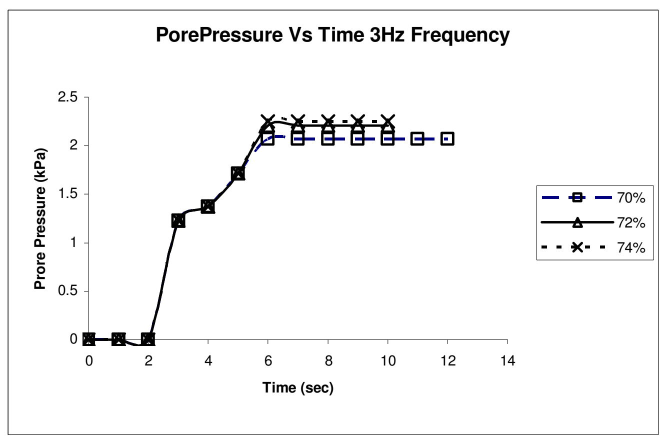

Fig.2(b)Pore pressure diagram for R.D.>70% at 3Hz frequency

Comparison of the results with laboratory tests other than shake table test

The test results obtained in the present study are compared with those obtained by other researchers (De Alba et al 1976). As available literature by other researchers is in the form of plot of number of cycles required for liquefaction versus cyclic stress ratio both these values are obtained for the present study and are then superimposed on the plot as given by other researchers shown in Fig 3.

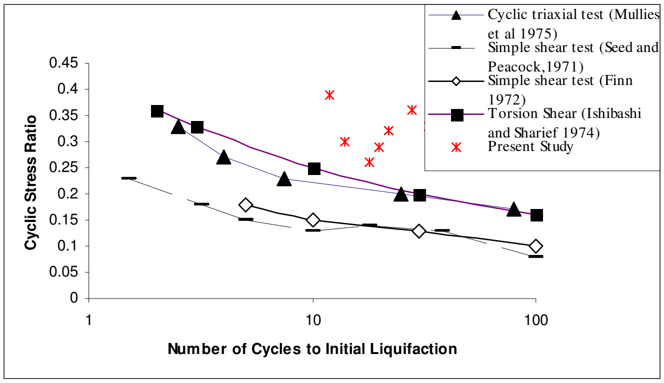

Fig. 3 Comparison of present study values with available literature

It is observed that the values obtained in the present study are on higher side as compared to those from the previous study by various researchers (De Alba et al 1976). One of the reasons attributed to this is the confined boundary of the soil model used in the present experiments. Because of the confinement the soil is hard to liquefy which ultimately means that more number of cycles are required to liquefy the soil under otherwise identical conditions. The other reason could be length to height ratio of the sample which affects the value of cyclic stress ratio considerably. For study of O-hara L/height ratio of 3.4:1 is considered, while Finn et al have considered L/height ratio of 10.3:1. The highest ratio is 22.5:1 by De Alba et al (1976) whereas for present study length to height ratio is 1, giving highest cyclic stress ratio value. It is observed that cyclic stress ratio increases with decrease in length to height ratio. So a smaller L/d ratio also attributes to higher value of CSR. However, some more tests with higher frequencies are required to be conducted to get a specific trend in the variation of CSR with number of cycles to initiate liquefaction.

Comparison of the results with Shake table tests by other researchers

The data from present study is compared with data from shake table test conducted by O-Hara in 1972 and De Alba et al in 1976. As shown in the Fig.4 the values obtained in the present study are again on higher side as compared to those from the previous study by other researchers. The reason could again be the same as discussed earlier.

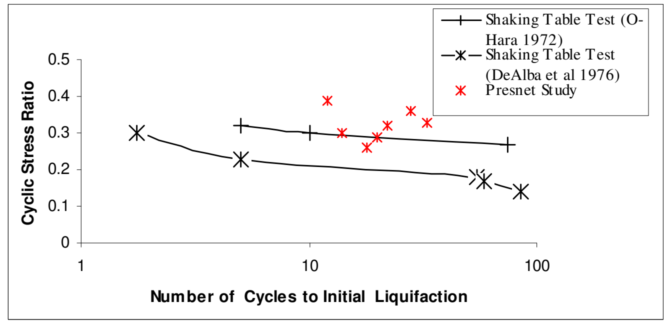

Fig. 4. Number of cycles to liquefaction versus Stress Ratio for Shake Table Tests

Fig.5. depicts a plot of cyclic stress ratio versus relative density as obtained from large shear test conducted by De Alba et al in 1976, Simple shear tests conducted by Vaid and Sivathayalan in 1996, also Cyclic Triaxial Test performed by Mullies et al. in 1975.Values obtained in the present study are superimposed on the plot for the comparison which shows similar trend with higher values.

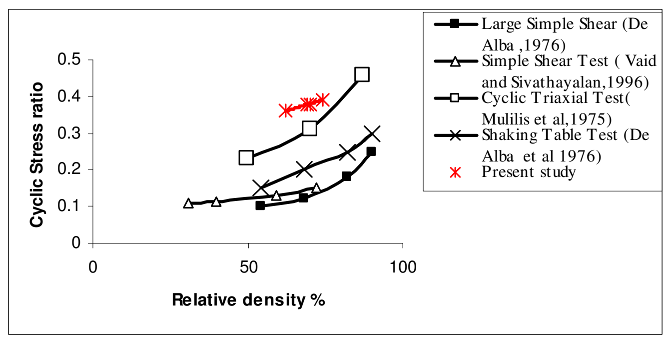

Fig. 5. Cyclic Stress Ratio Vs relative density

Comparison with field data

The results obtained in the present study are compared with the data from the field for earthquakes, selected based on D_{50} size and acceleration values for the cases where liquefaction has occurred and is as shown in Table 2. Values from the present laboratory work are converted to field data using relationship between effective stress and blow count (Nayak 1998). From the curve the values of relative density are obtained by using effective overburden pressure value. The value of SPT Blow count is then calculated by interpolating the relative density value. The $(N_1)_{60}$ & CSR data thus computed for present study is then plotted on the curve given by Seed et al (1985) which demarcates “Yes” & “No” zones of liquefaction (Fig.6).

Table 2 Selected Field Data

Earth quake Site	**D_{50} Size (mm)**	**C. P. T. q_c (Mpa)**	**Site a_{max}**	**D_r %**	Reference
Nigatta (1964) (M = 7.5) Kwagishi-Cho Building	0.33	5.64	0.16	67	Stark & Olson 1994
	0.33	7.80	0.16	67	Stark & Olson 1994
	0.33	9.51	0.16	71	Stark & Olson 1994
Tangshan Area (1976) (M = 7.8)	0.0	7.45	0.40	62	Stark & Olson 1994
	0.2	7.08	0.20	65	Stark & Olson 1994
	0.2	10.54	0.20	74	Stark & Olson 1994
Nihonkai-Cho EQ(1983) (M =7.7)	0.3	1.76	0.23	29	Stark & Olson 1994
	0.2	4.02	0.23	51	Stark & Olson 1994
	032	7.80	0.23	67	Stark & Olson 1994
	0.32	8.80	0.23	69	Stark & Olson 1994
Lomo-Prieta EQ(1989) (M = 7.1)	0.25	9.00	0.29	70	Stark & Olson 1994
	0.25	9.40	0.29	71	Stark & Olson 1994
	0.30	8.70	0.29	72	Stark & Olson 1994
	0.25	-	0.29	73	Stark & Olson 1994
	0.25	-	0.29	72	Stark & Olson 1994

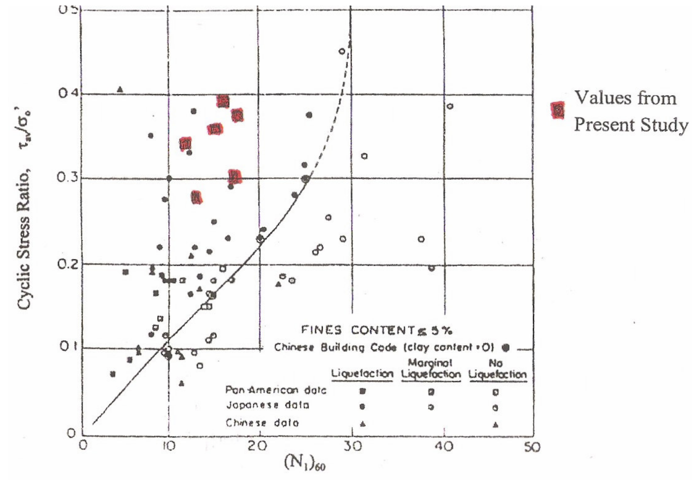

Fig. 6. $(N_1)_{60}$ Vs CSR
(Ref. Seed et al, 1985)

It is observed that all the points lie in "Yes" zone of liquefaction, thus confirming the present laboratory work with corresponding field results. Therefore the test results in the present study in terms of initiation of liquefaction, number of cycles required for liquefaction and pore pressure values are in close agreement with laboratory results reported in literature Further the possibility of liquefaction is verified with the field results.

CONCLUSION

From the present experimental investigation following conclusions are drawn.

Increase in pore water pressure is faster at higher frequencies. However, the maximum value of pore pressure is almost same for the frequencies studied in present work. This applies for soil sample with all relative density values.

a-t diagram indicates simple harmonic motion as assumed during shake table experiments.

CSR values obtained in the present study are on the higher side as compared with those obtained by other researchers.

As relative density increases the cyclic stress ratio also increases which is in well agreement with laboratory test results reported earlier.

Soil Sample conditions in terms of D_{50} and earthquake condition in terms of a_{max},when simulated to laboratory model it is found that points with "Yes" liquefaction in field are also observed in the yes zone for laboratory results. Hence, Shake table tests are found to be more effective in simulating the strong ground motion during earthquake and thus can be effectively used to assess soil liquefaction in laboratory.

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