LIQUEFACTION SUSCEPTIBILITY OF SOILS IN HIMALAYAN REGION

B. K. Maheshwari[1], A. M. Kaynia[2] and D. K. Paul[3]

[1]Assistant Professor, Dept. of Earthquake Engineering, IIT Roorkee, India, e-mail: bkmahfeq@iitr.ernet.in
[2]Discipline Leader, Earthquake Engineering, Norwegian Geotechnical Institute Oslo, e-mail: amk@ngi.no
[3]Professor, Dept. of Earthquake Engineering, IIT Roorkee, India, e-mail: dpaulfeq@iitr.ernet.in

ABSTRACT :

Aim of this paper is to analyze the liquefaction susceptibility of some selected sites. The selected sites are near Dehradun, capital city of northern state of Uttarakhand, India. Site specific data related to Standard Penetration Tests and Shear Wave Velocity are collected for determination of liquefaction susceptibility of these sites using field-based procedures. In these procedures, shear stresses due to earthquake are evaluated using actual ground response analysis (where shear wave velocity is a key factor) and liquefaction resistance of soil is determined based on the N values.

Liquefaction susceptibility is also evaluated using laboratory tests. This includes tests on a small shake table where frequency and amplitude of harmonic excitation can be controlled. Number of cycles and pore water pressure at liquefaction is measured. The effect of non-plastic fines on liquefaction potential is evaluated. A comparison of results obtained from in situ tests and laboratory tests has been carried out. It has been found that few sites are very much susceptible to liquefaction.

KEYWORDS: Liquefaction susceptibility, Himalayan region, *In Situ* tests, Lab tests

1. INTRODUCTION

Himalayan region is one of the most seismic active zones in India. This region was home to many major earthquakes in the past including 1905 great Kangra earthquake, 1934 Nepal-Bihar earthquake, 1991 Uttarkashi earthquake, 1999 Chamoli earthquake and recent 2005 Kashmir earthquake. Many large cities in the region are located within a recent river alluvium valley with soft to very soft geological conditions, with shallow depths to bedrock and may be prone to liquefaction during a major earthquake.

Dehradun is a part of the Doon valley and located in the western part of the state of Uttarakhand in North India. Doon valley is bounded by Himalaya in the North, Siwalik in the South, river Ganga in the East and river Yamuna in the West. The city has a population more than a million. Geologically the whole Doon valley can be divided into three regions namely the Lesser Himalaya, the Siwalik group and the Doon Gravels. Selection of sites can be based on the local geology. Ranjan (2005) carried out geophysical survey at many locations in the city. Shear wave velocity of these sites were determined using SASW tests. However, most of sites in Dehradun are dry (water table is very deep) with gravels, and have a fairly high shear wave velocity; so, they may not be prone to liquefaction. Therefore, the focus was shifted to the nearby cities Haridwar and Roorkee.

A number of studies are reported in literature for liquefaction susceptibility e.g., Prakash (1981) and Kramer (1996). The effect of fines contents on liquefaction potential is presented by Patel (2006). In the present work, the liquefaction potentials of two sites in Haridwar, India have been investigated using field and laboratory tests. The field test involves SPT (Standard Penetration Test) while in laboratory testing, the sample collected from the field is submerged and imparted horizontal vibration in a shake table. The liquefaction potential of the sites is predicted based on these tests.

2. SOCIO-ECONOMIC ASPECT OF THE STUDY

Liquefaction has been a source of much damage in the past earthquakes (e.g. Niigata and Alaska earthquakes of 1964, Kobe earthquake of 1995, Kocaeli-Turkey and Chi-Chi earthquakes of 1999, Bhuj Earthquake 2001). New developments are planned in Haridwar. Since the soil condition at many places in Haridwar is loose saturated sands, they may be susceptible to liquefaction. The results of the study in terms of liquefaction assessment would be valuable for the future development and land use planning. Haridwar is a holy religious city and advancing towards both industrial and tourist development. Therefore, the present study has social and socio-economic values. The city has over a million population and is a district headquarter with administrative offices. The city is in a phase of industrialization for energy and for many consumable products. A number of private industries are setting up their businesses on the outskirts of the Haridwar. Therefore, the functionality of the city during an earthquake is very important for the whole district including other important nearby cities such as Roorkee.

3. LOCATION OF SITES AND THEIR CHARACTERISTICS

Both selected sites are situated in the Haridwar district as described below:

(i) Dhanuari Site: The site is about 10 km from Roorkee and situated between Roorkee and Haridwar. Play ground of an intercollege school is selected as a test site in this small village Dhanuari. The site lies between two canals and there is a river nearby. It was expected that water table may be at shallow depth. Location of the site is Latitude 29º 56′ 24.6″ and Longitude 77º 57′ 25.5″.

(ii) Roshnabad: The site is on the outskirts of Haridwar City (about 5 km south from the city centre). An open ground at a distance of about 500 m from the office of the District Magistrate has been selected as the test site which is on the backside of Vikas Bhawan campus. Location of the site is Latitude 29º 58′ 12.8″ and Longitude 78º 04′ 23.3″.

The SPT (Standard Penetration Tests) as per IS: 2131-1981 were conducted on both sites up to a depth till refusal was met. The samples collected were further tested in the laboratory for evaluation of grain size distribution, unit weight of soil and Atterberg's limits. It was observed that the soil at both sites is mainly sandy soil and can be classified as SM and SP. At Dhanuari, the water table was encountered at a depth of 4.75 m from the existing ground surface. In Roshnabad, the water table was not encountered up to the depth of exploration (7.5 m) and it may be very deep. Therefore, liquefaction was ruled out at Roshnabad, however further investigation was carried out assuming water table at the same level as observed in Dhanuari i.e. at a depth of 4.75 m from the ground surface.

4. LIQUEFACTION POTENTIAL BASED ON FIELD TESTS

The data obtained from the *in situ* tests and laboratory tests were analyzed for determination of liquefaction potential of both sites. The cyclic stress approach of Seed and Idriss (Seed and Lee 1966) was used for determination of liquefaction potential of the sites. Shear stresses τ_{av} due to earthquake loading is computed based on following two methods

(a) Simplified Method (Seed and Idriss, 1971): Average equivalent uniform shear stress at a particular depth, τ_{av} is given by

$$\tau_{av} = 0.65\sigma_{v0}\frac{a_{\max}}{g}r_d \quad (1)$$

Where σ_{v0} is total overburden pressure at that depth, a_{max} is peak ground acceleration and r_d is reduction factor. According to IS: 1893-2002 (Part 1), both sites are situated in seismic zone IV, therefore they have a PGA value $a_{max} = 0.24$ g.

(b) Ground Response Analysis: This has been performed using the program EERA (Bardet et al. 2000) which is based on one dimensional layered soil model. The shear wave velocity is an important parameter for the program EERA. It was determined from the *in situ* test, SASW (Spectral Analysis of Surface Waves).

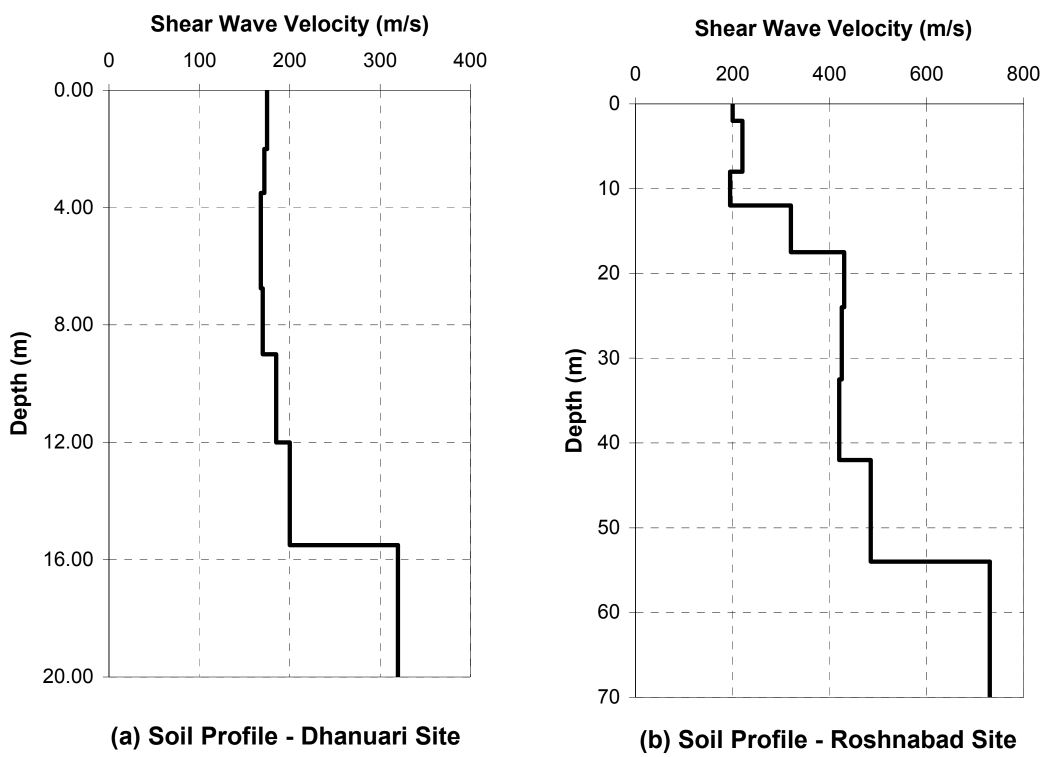

Fig. 1: Shear Wave Velocity Profiles of both Sites (Mahajan, 2008)

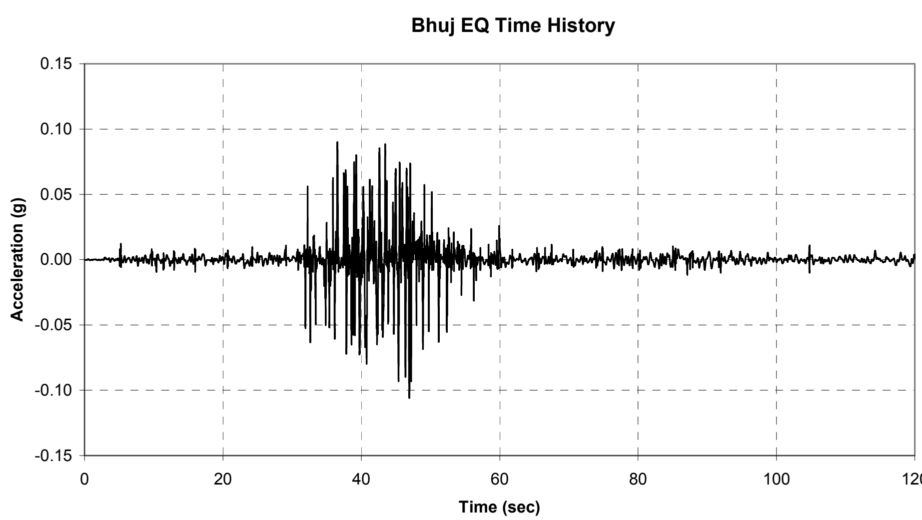

Fig. 2: N78ºE Component of Bhuj (2001) Earthquake Component Recorded at Ahemedabad

The shear wave velocity for both sites is shown in Fig. 1 (Mahajan 2008). It can be observed that Roshnabad site has higher shear wave velocities compared to Dhanuari site. Also in Roshnabad a bedrock with shear wave velocity 730 m/s is encountered below 54 m, however, in Dhanuari the maximum shear wave velocity recorded was 320 m/s below 16 m. The soil being in loose condition at Dhanuri, the SASW could indicate a shear wave velocity up to 16 m only. These observations are very much in consistent with N (SPT) values recorded on these sites. That is, for Dhanuri: for a depth 0~16 m, N = 2 ~18 and for Roshnabad: for a depth 0~7.5 m, N = 9 ~ 51. In Roshnabad SPT sampler indicated refusal as shallow as 7.5 m depth where N was recorded as 51.

The transient excitation (acceleration time history) was used as input loading to the program EERA. In the present study the N78ºE component of Bhuj (2001) Earthquake recorded at Ahmedabad (Chandra et al. 2002) was used. The acceleration time history has a PGA equal to 0.106 g as shown in Fig. 2. Duration of the actual time history is about 133 s, however the strong portion of it is only about 60s as shown in Fig. 2. For this loading, the maximum shear stresses at different depths were computed using the program EERA. The equivalent linear soil model (Seed and Idriss 1970) was used in the computation. The average shear stress was taken as 65% of the maximum value (Kramer 1996).

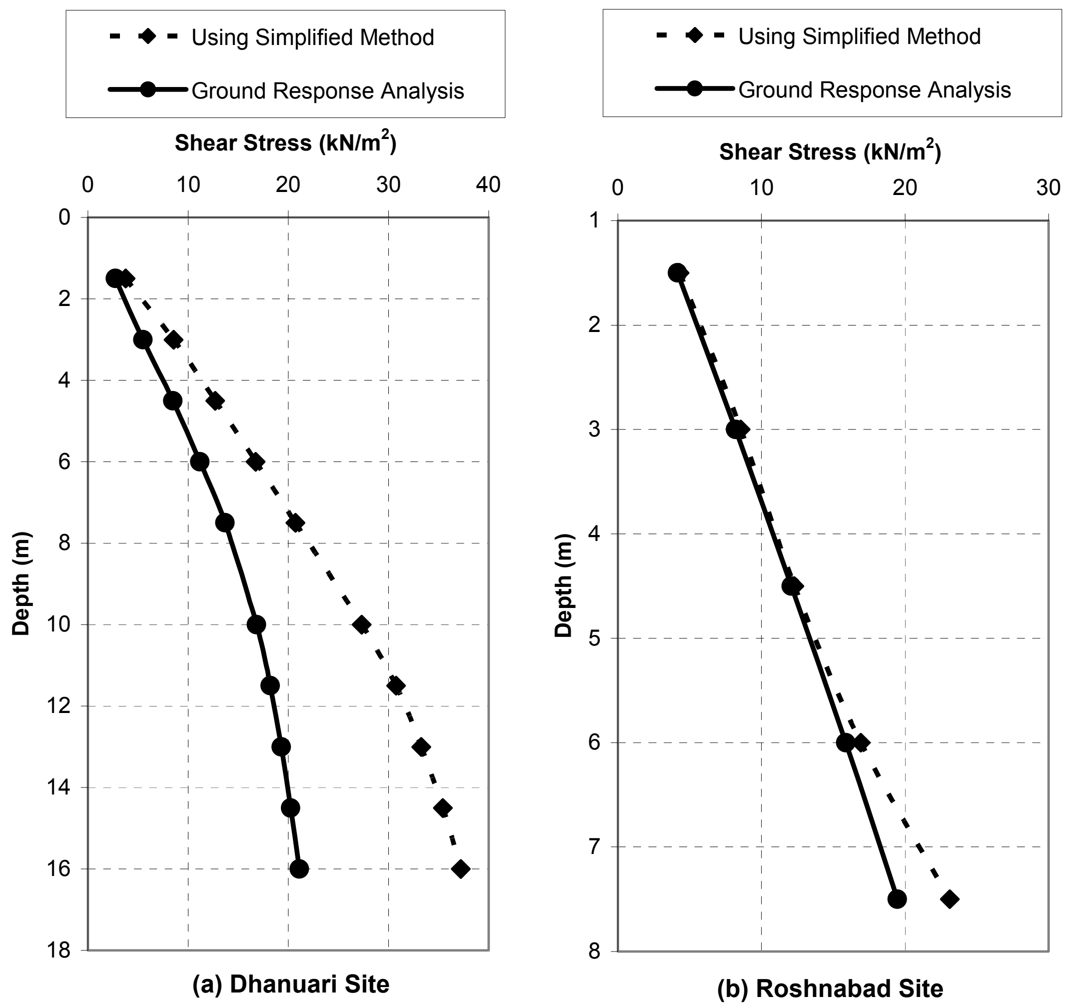

Fig. 3: Comparison of Shear Stresses induced due to Earthquake Loading Using Simplified Method and using Ground Response Analysis at both sites

The average shear stresses in soil at different depths computed using the Simplified Method (Eq. 1) and from Ground Response Analysis are compared for both sites in Fig. 3. It can be observed that at Dhanuri site, the shear stresses obtained from the simplified method is significantly higher than those obtained using the ground response analysis. However at Roshnabad site this difference is not significant. The larger of these stresses were used to evaluate the liquefaction potential of the site.

Shear stresses corresponding to liquefaction resistance of soil were computed using the Cyclic Stress Ratio (CSR) approach (Seed et al. 1985) where N values (penetration resistance) collected from the field is a key parameter. The measured value from field was normalized for an overburden pressure of 1 ton/ft^2 (100 kPa) and corrected to an energy ratio of 60%. Thus corrected SPT values $(N_1)_{60}$ was evaluated and used for determination of CSR. The magnitude of earthquake is assumed equal to 7.5 for evaluation of CSR. The selection of this magnitude was based on a site specific seismic study conducted for the region (INPIC report 2006). CSR is defined as:

$$CSR = \frac{\tau_{cyc}}{\sigma'_{v0}} \tag{2}$$

Where τ_{cyc} is cyclic shear stress and σ'_{v0} is initial effective overburden pressure. Thus τ_{cyc} is found from CSR evaluated. Wherever, τ_{av} is greater than τ_{cyc}, liquefaction is expected to occur. The ratio τ_{cyc}/τ_{av} provides a factor of safety against liquefaction.

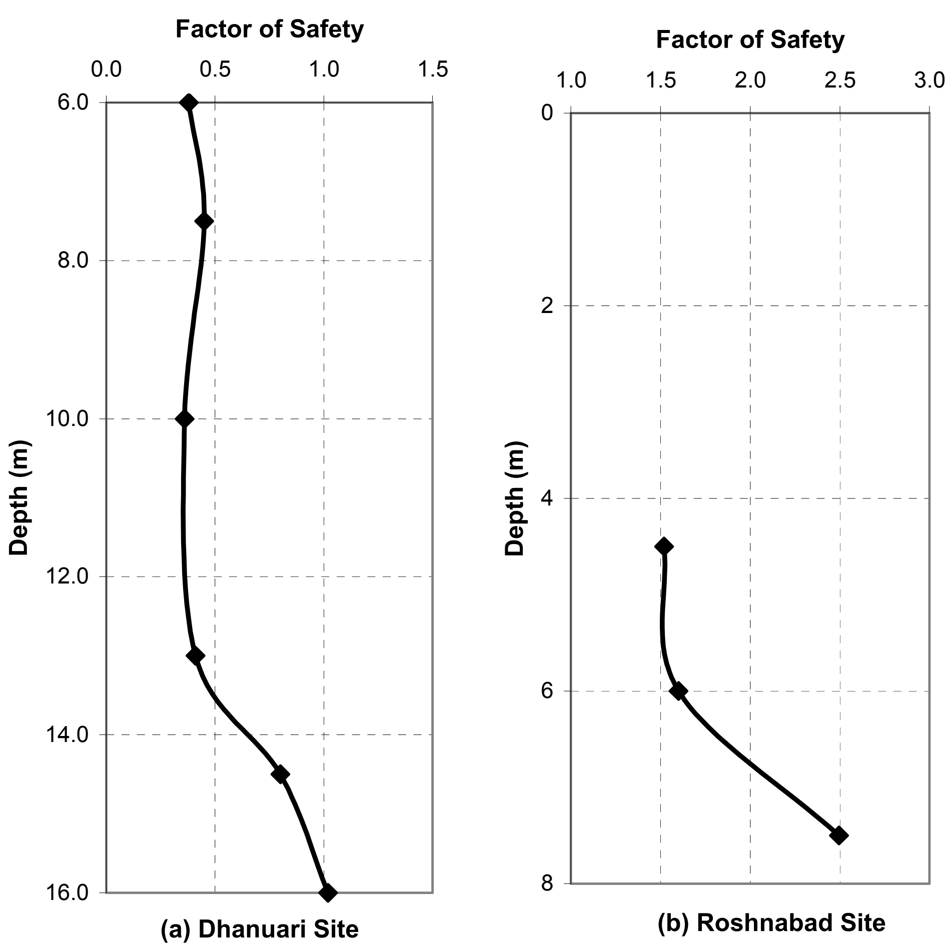

Fig. 4: Factor of Safety against Liquefaction with depth at both sites

The factor of safety against liquefaction is shown for both sites in Fig. 4. It can be observed that the factor of safety is less than unity at all depths (below water table) for Dhanuari site. Thus analysis indicates that site will liquefy in an earthquake of magnitude 7.5 with PGA=0.24g. The outcome is very much consistent with guideline given in IS: 1893-2002 which suggest that to avoid liquefaction in seismic zone IV the N value shall be in the range of 15~25 (increasing with depth). N obtained from SPT at the site are as low as 2. Contrary to this, no threat of liquefaction is indicated in Roshnabad site even assuming that water table exists at a depth of 4.75 m.

5. LIQUEFACTION SUSCEPTIBILITY BASED ON LABORATORY TESTS

The tests were performed on a simple but indigenously fabricated vibration table (Gupta 1977) in the Soil Dynamics Laboratory of the Dept. of Earthquake Engineering, IIT Roorkee, India. The test bin is a tank 1.05 m long, 0.60 m wide and 0.60 m high, in which soil sample is prepared. The test set up is shown in Fig. 5. The table can produce one-dimensional (horizontal) steady state vibrations.

Fig. 5: Liquefaction Table at Dept. of Earthquake Engineering, IIT Roorkee

The tests were conducted on the soil samples collected from both sites. Since a large sample (about 500 kg) of soil was required to conduct a test on this table it was not feasible to conduct the tests on the samples collected from different depths through SPT. However, a sample which is a good mix of the soil collected from different depths in a borelog was used in the shake table. Thus the test results will reflect the liquefaction susceptibility of the site in general but not depth-wise. The known quantity of soil sample was filled in the table and submerged for a couple of hours so that it is fully saturated. A harmonic motion with constant frequency of 5 Hz and amplitude 0.3 g was applied for 60 seconds. The equivalent number of cycles for an earthquake of magnitude 7.5 is 15 only. However, the number of cycles applied was intentionally high to observe the generation of pore water pressure. The pore water pressure with time was measured at different depths in the tank. Initially the pore water pressure rises and then reaches to a maximum value and then dissipation starts.

Fig. 6 shows the time history of excess pore water pressure developed for Dhanuari site (this is shown only for first 300 s, though dissipation continues and U_{excess} reaches zero after about 20 minutes). It can be observed that the pore water pressure rises for some more time even after the end of shaking (60 s) before dissipation starts. Also dissipation starts first in the top pick-up then proceed to middle and bottom pick-ups, as expected.

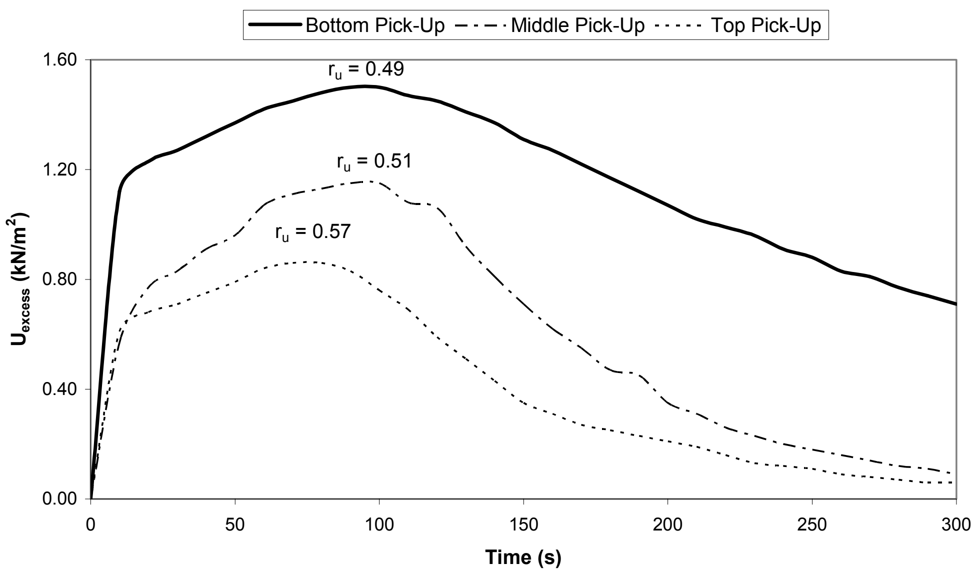

Fig. 6: Excess pore water pressure (U_{excess}) time-history for sample collected from Dhanuri site

Using Fig. 6, the maximum excess pressure (u_{max}) was evaluated at the three locations of pore water pressure pickups i.e. Bottom (B), Middle (M) and Top (T). This was normalized with respect to effective overburden pressure ($\sigma_{effective}$) to obtain the pore water pressure ratio (i.e. $r_u = u_{max}/\sigma_{vo}$). The results for Dhanuari site are summarized in Table 1. It can be observed that the average value of r_u is 0.52. A similar analysis (like shown in Fig. 6 and Table 1) was performed for Roshnabad site. The average value of r_u obtained was close to that for Dhanuari site.

Table 1: Pore water pressure ratio r_u of samples collected from Dhanuari Site

Location of Pick-up (m)		$\sigma_{effective}$ (kN/m^2)	U_{dyn} (kN/m^2)	r_u	Remarks
From Base of Tank	From top of Soil Sample				
0.040 (B)	0.320	3.04	1.50	0.49	Acceleration = 0.3 g Duration = 60 s Frequency = 5 Hz **Average r_u = 0.52**
0.125 (M)	0.235	2.24	1.15	0.51	
0.200 (T)	0.160	1.52	0.86	0.57	

Theoretically, the liquefaction occurs when r_u reaches unity; if it is less than unity, only partial loss of shear strength occurs. Although shake table result may suggest no liquefaction as $r_u < 1.0$, this outcome may not be necessarily representing the actual behavior in the field. Firstly, in the vibration table due to shaking, the densification of sample takes place and it may not allow pore water pressure to rise to unity. Secondly, the soil samples used in the tests are disturbed samples. Nonetheless, the tests in the vibration table indicate the extent of shear strength loss due to shaking.

6. CONCLUSIONS

Field tests indicated that there is a clear threat of liquefaction in Dhanuri but not in Roshnabad for the earthquake magnitude considered. This outcome has much practical significance as Dhanuri is very near to Roorkee, where a large industrial development is taking place. However, more field tests (at different locations) along with laboratory tests (such as cyclic triaxial tests) need to be conducted to come forward with a concrete conclusion.

ACKNOWLEDGEMENT

The work presented here is a part of a research project entitled "Earthquake Risk Reduction in Himalaya with institutional cooperation between India and Norway" sponsored by the Royal Norwegian Embassy in India conducted in cooperation with NORSAR, and NGI, Norway, WIHG, Dehradun, India. This support is gratefully acknowledged. The shear wave velocity measurement was performed by Dr. A.K. Mahajan and Dr. A.K. Mundepi of WIHG, Dehradun, this contribution is thankfully acknowledged. The authors would also like to thank Mr. H.P. Singh and staff of Soil Dynamics Lab at IIT Roorkee for the shake table tests, and Dr. Ashwani Kumar, Prof. and Head, Dept. of Earthquake Eng., IIT Roorkee for providing all the logistic support for the research.

REFERENCES

1. Bardet, J.P., Ichii, K. and Lin, C.H. (2000). EERA, A Computer Program for **E**quivalent Linear **E**arthquake Site **R**esponse **A**nalysis, Dept. of Civil Eng, University of Southern California, USA.
2. Chandra, B., Thakkar, S.K., Basu, S., Kumar, A., Shrikhande, M., Das, J., Agarwal, P., and Bansal, M.K. (2002). Strong motion records. Chapter 5 in Bhuj, India Earthquake of January 26, 2001 Reconnaissance Report, *Earthquake Spectra*, Supplement to Vol. **18**, 53-66.
3. Gupta, M.K. (1977). Liquefaction of Sands during Earthquakes, Ph.D. Thesis, University of Roorkee, Roorkee, India.
4. INPIC Report (2006). Final Report (2003-2006) of Indo-Norwegian Programme of Institutional Cooperation on Earthquake Engineering, by Dept. of Earthquake Engineering, IIT Roorkee, NORSAR, Norway and NGI, Norway.
5. IS: 1893-2002-Part 1: Criteria for Earthquake Resistant Design of Structures: General Provisions and Buildings. Bureau of Indian Standards, New Delhi.
6. IS 2131: 1981. Indian Standard Code of Practice, Method for Standard Penetration Test for Soils. Bureau of Indian Standards, New Delhi.
7. Kramer, S.L. (1996). Geotechnical Earthquake Engineering, Prentice Hall, Inc., Upper Saddle River, New Jersey.
8. Mahajan, A.K. (2008). Personal Communication, Wadia Institue of Himalayan Geology, Dehradun.
9. Patel, AK (2006). Effect of fines on liquefaction potential. M. Tech. Dissertation, Dept. of Earthquake Engineering, Indian Institute of Technology Roorkee, Roorkee, India.
10. Prakash, S. (1981). Soil Dynamics, McGraw-Hill Company, New York.
11. Ranjan, R. (2005). Seismic Response Analysis of Dehradun City, India, MSc thesis, Indian Institute of Remote Sensing, National Remote Sensing Agency, Dehradun Dep. of Space, Govt. of India.
12. Seed, H.B. and Lee, K.L. (1966). Liquefaction of saturated sands during cyclic loading. *Journal of the Soil Mechanics and Foundation Division, ASCE*, **92:SM6**, 105-134.
13. Seed, H.B. and Idriss, I.M. (1970). Soil moduli and damping factors for dynamic response analyses, Report EERC 70-10, Earthquake Engineering Research Center, University of California, Berkeley.
14. Seed, H.B. and Idriss, I.M. (1971). Simplified procedure for evaluating soil liquefaction potential. *Journal of the Soil Mechanics and Foundation Division, ASCE*, **107:SM9**, 1249-1274.
15. Seed, H.B., Tokimatsu, K., Harder, L.F., Chung, R.M. (1985). Influence of SPT procedures in soil liquefaction resistance evaluations. *J. of Geotech. Eng, ASCE*, **111:12**, 1425-1445.