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ABSTRACT

In this paper, a study on liquefaction resistance of Solani sand reinforced with geogrid sheets is reported. Tests were carried out on shake table (vibration Table) with sand samples prepared at relative density of 25% without and with geogrid sheets. In this investigation biaxial synthetic geogrid sheets having the dimension equal to plan dimension of the shake table tank were used in three different combinations of 3 layers, 4 layers and 5 layers at different depths within the sand sample. The liquefaction parameters such as maximum pore water pressure (U_{max}), maximum pore water pressure built up time (t_1) and pore water pressure dissipation time (t_3) were measured with the help of transparent piezometer tubes and stop watch for each combination of geogrid sheet corresponding to various levels of accelerations varying from 0.1g to 0.4g. In each test, the frequency of dynamic load was kept constant (5Hz). The liquefaction resistance of sand was evaluated in- terms of pore pressure ratio. Tests results indicate that on inclusion of geogrid sheets into the sand samples, the U_{max} decreases and t_1 and t_3 increases. It was also observed that on increasing the number of geogrid sheets, U_{max} decreases further and this decrease is significant at small amplitude of excitation. The average increase in liquefaction resistance of sand was found to be about 31 % in case of 5 layers of Geogrid sheets at 0.1g acceleration.

INTRODUCTION

The liquefaction of saturated loose sands during earthquakes has been the cause of severe damage to various buildings, embankments and retaining structures. The devastating nature of this type of failure attracted the attention of researchers in this area and considerable work has been reported to evaluate the liquefaction susceptibility (e.g. Seed and Lee 1966, Seed and Idriss 1971, Seed et al. 1976, Gupta 1977, Prakash 1981, Seed et al. 1985, Kramer 1996, Saran 2006).

Many studies have been conducted relating to the behaviour of soil reinforced with randomly distributed fibers and mesh elements under static loading conditions. Various types of randomly distributed elements such as polymeric mesh elements (Andrews et al. 1986), synthetic fibers (Gray and Ohashi 1983; and Ranjan et al. 1994), Coir fibers (Sivakumar -Babu and Vasudevan 2008), and discontinuous multioriented polypropylene elements (Lawton et al. 1993) had been used to reinforce soils. It was shown that the addition of randomly distributed elements or mesh elements to soils contributes to increase in strength and stiffness. However, the studies on behaviour of soils reinforced with randomly distributed elements and mesh elements under cyclic loading are very limited in the literature. Vercueil et al. (1997) studied the liquefaction resistance of saturated sand reinforced with geosynthetics circular sheets, and concluded that the reinforcement increases the liquefaction resistance significantly due to reduction in the interstitial pressure distribution. Improving site conditions to eliminate liquefaction is one of the areas that received considerable attention from practicing engineers.

Krishnaswami and Isaac (1995) explored the feasibility of the reinforced earth technique as a counter measure to liquefaction. They have conducted a laboratory studies on small size (38mm dia.) samples reinforced with woven and non woven geo-textiles and coir fibers using cyclic triaxial shear tests and concluded that the liquefaction potential of sand deposit significantly reduced. Boominathan and Hari (2002) also conducted the similar studies with fly ash reinforced with geosynthetic fibers and mesh elements and found that the liquefaction resistance of fly ash significantly increased. However, all these studies were on small size (38 mm-76 mm and 50 mm-100 mm) samples using the cyclic triaxial apparatus and so far no study has been reported with large size sample test on the assessment of liquefaction using the shake table (vibration table) apparatus. Shake tables were used for experimental research in earthquake engineering. These instruments are capable of reproducing the motion of the ground during an earthquake allowing for controlled testing of structures subjected to earthquakes (Finn 1972, DeAlba et al. 1976). In this paper, the results of experiments conducted on shake table for sand with geogrid are reported, and liquefaction resistance of reinforced sand has been evaluated.

MATERIALS USED FOR TESTING

Sand

The sand collected from the bed of Solani River, Roorkee, India was used in testing. Laboratory experiments were carried out on the sand to find out its index properties. It was observed that this is poorly graded sand with little fines. The specific gravity G is 2.68; e_{max} and e_{min} are found to be 0.87 and 0.55, respectively.

Geogrid sheet

The biaxial geogrid sheet of Netlon 121 CE type having wall thickness 4 mm and area of aperture 400 mm^2 were used in this study.

EXPERIMENTAL SET UP

The tests were performed on a simple but indigenously fabricated vibration (shake) table (Gupta, 1977) in the Soil Dynamics Laboratory of the Dept. of Earthquake Engineering, IIT Roorkee, India. The test bin is a watertight tank 1.05 m long, 0.60 m wide and 0.60 m high, in which soil sample is prepared. The tank is mounted on a horizontal shake table. The sides of the tank consist of a rigid mild steel frame with 5 mm thick steel panels.

The pore pressure measurement was done with the help of glass tubes piezometer attached to the tank through rubber tubes. At the mouth of tubes porous stones were fixed. Complete test set up is shown in Figure 1. The table can produce one-dimensional harmonic excitation of varying amplitude (0.05 to 1g) and frequency (0-10 Hz). The measurements of the pore water pressure were taken at three locations on the shake table. Their locations from top of the tank were as follows

Bottom Pick-Up (B):	560 mm
Middle Pick-up (M):	400 mm
Top Pick-up (T):	240 mm

The total effective depth of the tank is 600 mm. The soil samples were filled such that the top layer of soil sample was 30 mm down (approximately) from the top of the tank

EXPERIMENTAL PROCEDURE

Preparation of samples

The following sequential procedure has been evolved for preparing the submerged sample of sand to achieve the relative density to 25 %:

a) The amount of water (240 liter), which is sufficient to submerge the points where piezometer tubes are connected was filled in the tank, it ensures removal of air bubbles from G.I. pipes, rubber and piezometer tubes.

b) Using Equation (1) the void ratio (e) corresponding to the desired relative density i.e. 25 % was obtained using the values of maximum void ratio (e_{max}), minimum void ratio (e_{min}) and specific gravity (G), was determined by the following equation:

$$R.D. = \frac{e_{\max} - e}{e_{\max} - e_{\min}} \times 100 \qquad (1)$$

Where *R.D.* is the relative density

c) Knowing the value of void ratio (e) from equation (1), dry density of sand (γ_d) was determined by the following equation:

$$\gamma_d = \frac{G}{1+e}\gamma_w \qquad (2)$$

Where γ_w is the unit weight of water

d) Assuming the constant height of the sand sample in the tank i.e. 570 mm, the volume (V) occupied by the sample in the tank was determined using the plan dimension of the tank (i.e. V=1050x600x570)

e) Knowing the values of γ_d and V, the dry weight of sand (W_d) was determined by the equation:

$$W_d = \gamma_d \times V \qquad (3)$$

f) The dry sand was dropped into the tank through funnel, keeping the tip of the funnel at a constant height from the water surface. This height is that which makes the thickness of the saturated sample equal to 570 mm (approx.) in the tank and determined by trial and error method.

g) For the preparation of geogrid reinforced sand sample, the geogrid sheets were placed at specified depths depending upon the number of sheets to be placed. The locations of geogrid sheets in the tank corresponding to different combinations (i.e. 3 layers, 4 layers, and 5 layers) are shown in Figs. 2 (a-c). In all the cases, the thickness of sand sample in the tank was kept the same i.e. 570 mm (approximately).

Fig. 1*: Liquefaction Table at Dept. of Earthquake Eng. at IIT Roorkee*

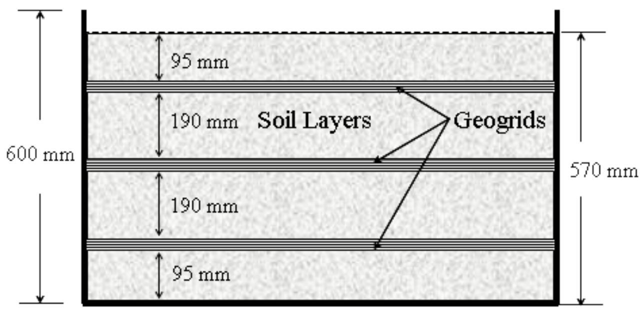

Fig. 2 (a): *3 layers of geogrid*

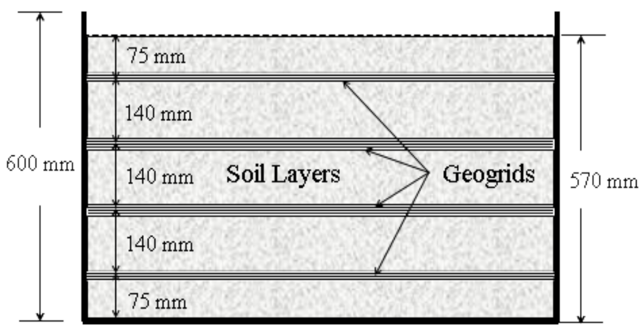

Fig. 2 (b): *4 layers of Geogrid*

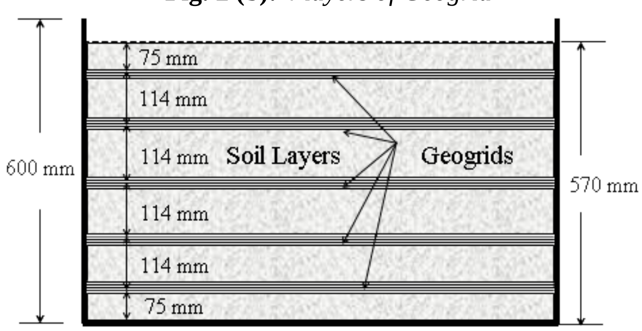

Fig. 2 (c): *5 layers of geogrid*

Test Procedure

At outset of the experiment, the desired level of frequency (5Hz) and excitation (from 0.1g to 0.4g) was fixed The value of static pore water pressures in all the three piezometer tubes attached at three different depths within the soil sample were first recorded. The motor was then switched on and the rise of pore water pressures was recorded continuously with time until the excess pore water pressure is completely dissipated after reaching a maximum value. The duration of shaking in each test was kept as 40 sec. At the end of the test, the water overlying the sample was removed and top surface was leveled to find out the amount of settlement of the sample due to shaking.

TEST RESULTS

In each test, variation in excess pore water pressure with time has been recorded using three piezometer tubes and stopwatch. In all the results presented, the following legends are used to show the variation of excess pore water pressure (U_{excess}) with time

Bottom Point
Middle Point
Top Point

Further the value of maximum pore water pressure ratio, r_u is marked on each curve where r_u is defined as

$$r_u = \frac{U_{excess}}{\sigma'_{vo}} \qquad (4)$$

Where σ_{vo}' is the effective overburden pressure at the location of pore pressure measuring point.

Pure sand

Figures 3 (a-d) show the variations in excess pore water pressure with time for sand at accelerations level varying from 0.1 g to 0.4 g. Time (s) has been shown along the abscissa and U_{excess} (kN/m^2) is shown along the ordinate. From Figs. 3 (a-d), it is observed that the general trend of the results is almost similar in all the cases. The pore water pressure rises immediately after motion is imparted to the shake table; after some time, it reaches the maximum value and then starts dissipating at all the three points i.e. bottom, middle and top. Time duration for three events are noted and defined as follows

- t_1 – Time to build up maximum pore water pressure
- t_2 – Duration for which U_{max} stays (duration for liquefaction)
- t_3 – Time for dissipation of excess pore water pressure

It is also observed that the magnitude of excess pore water pressure (U_{excess}) is maximum at bottom point and minimum at top point. At middle point this is in between the two values. This is expected as the value of effective overburden pressure is maximum at bottom point and minimum at top point.

However, the pore water pressure ratio (r_u) is more important as this indicates liquefaction potential. It can be observed that at all the four level of acceleration; r_u reaches near unity for bottom and middle points. Thus liquefaction may occur at these points. But, at the top point the value of r_u remains less than unity indicating that there may be reduction in strength of soil but liquefaction may not occur. This behavior may be explained with the fact that for pure sand condition, drainage path is shorter for the top point and the dissipation of pore water pressure may occur even before the maximum pore water pressure is reached. Also, it was observed that the maximum pore water pressure stay time i.e. t_2 is negligible in all the tests. This may be due to the coarser nature of the soil sample (D_{50} > 0.25 mm).

It can also be observed from Figs. 3 (a-d) that on increasing the level of excitations from 0.1 g to 0.4 g, there is no appreciable increase in the value of r_u , but the built up time t_1 decreases. This trend is observed in all the tests. This is attributed to the fact that the Solani sand liquefies at 0.1 g acceleration (as the value of r_u is greater than unity) and increasing the level of excitation does not further increase the r_u but decreases the built up time (t_1).

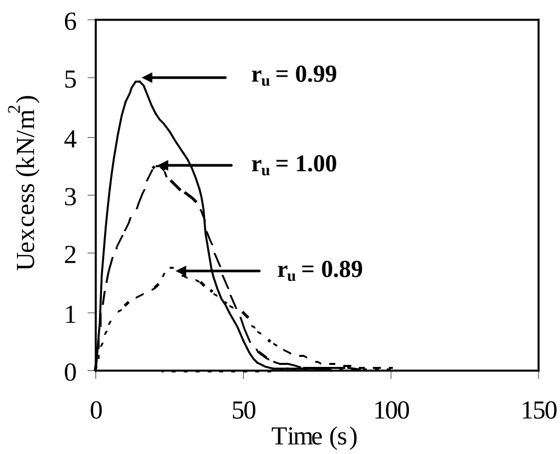

Fig. 3 (a): *Sand at 0.1g acceleration*

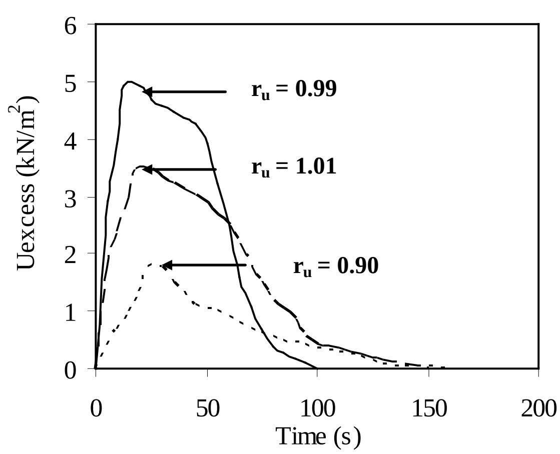

Fig. 3 (b): *Sand at 0.2g acceleration*

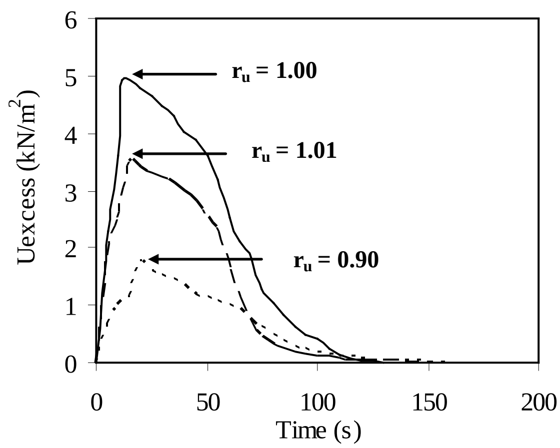

Fig. 3 (c): *Sand at 0.3g acceleration*

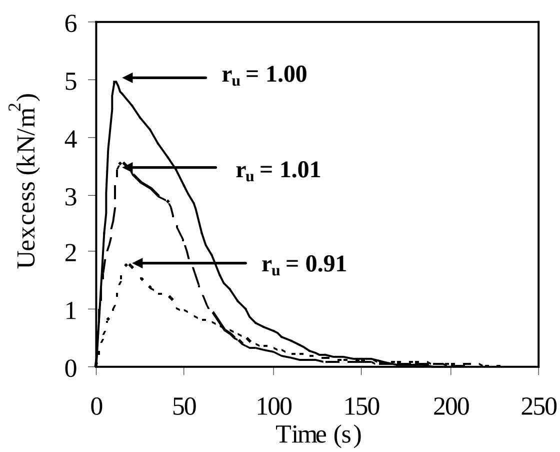

Fig. 3 (d): *Sand at 0.4 g acceleration*

<u>Sand with 3 Layers of Geogrid</u>

Figures 4 (a-d) shows the variations in excess pore water pressure with time for sand reinforced with three layers of geogrid sheets at accelerations varying from 0.1 g to 0.4 g. It can be observed from Figs. 4 (a-d) that the trend of rise of pore water pressures for all the pick ups is similar to that observed in case of pure sand. The magnitude of pore water pressures developed at all the three points i. e. bottom, middle and top are less than that of pure sand and this resulted into decrease in the value of maximum pore water pressure ratio r_u, marked on each curve. However, unlike the pure sand, the value of r_u increases from bottom to top pick up and the maximum value is in the top pick up.

Since the value of r_u decreases significantly (on average about 20%), this indicate that liquefaction resistance of sand increased due to geogrid. Further, the observed value of t_1 is increased from the corresponding value of pure sand and this also indicates the improvement in liquefaction resistance of sand. Although the value of t_3 is also increased marginally but it has negligible effect on strength and stiffness of soil corresponding to the value of pore pressure ratio less than unity (i.e. $r_u < 1$). The similar trend is observed in the case of sand reinforced with 4 layers and 5 layers of geogrid as presented in following sections.

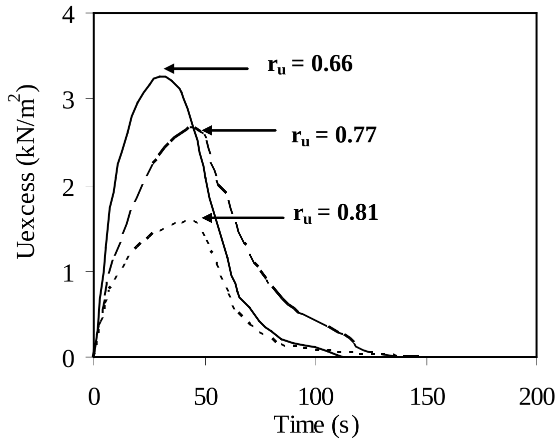

Fig. 4 (a): Sand with 3 layers geogrid at 0.1 g

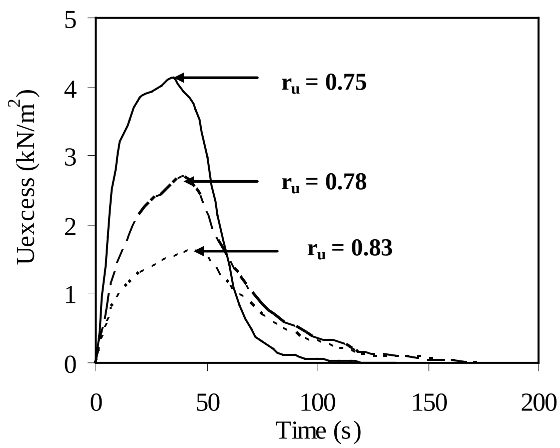

Fig. 4 (b): Sand with 3 layers geogrid at 0.2 g

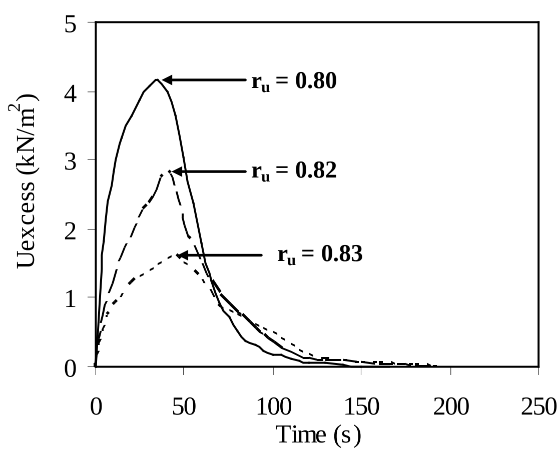

Fig. 4 (c): Sand with 3 layers of geogrid at 0.3 g

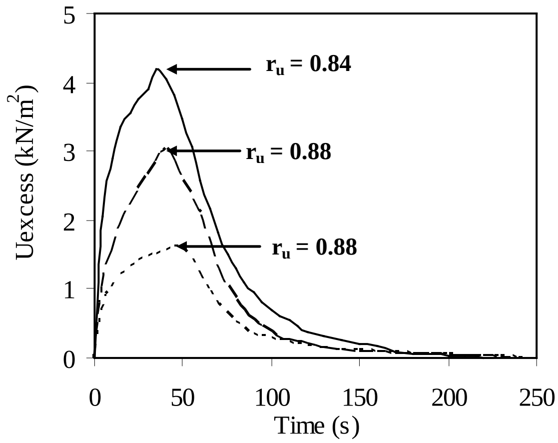

Fig. 4 (d): Sand with 3 layers of geogrid at 0.4 g acc^n.

Sand with 4 Layers of Geogrid

Figures 5 (a-d) show the variations in excess pore water pressure with time for sand reinforced with four layers of geogrid sheets at accelerations varying from 0.1 g to 0.4 g. The trend of result is similar to that observed in case of pure sand and sand reinforced with 3 layers of geogrid. Here the magnitude of maximum pore water pressures developed at all the three points i.e. bottom, middle and top is further decreased with respect to 3 layers of geogrid sheets which leads to decrease in r_u value and further improvement in liquefaction resistance of sand although there is no significant change in time parameters i.e. t_1 and t_3.

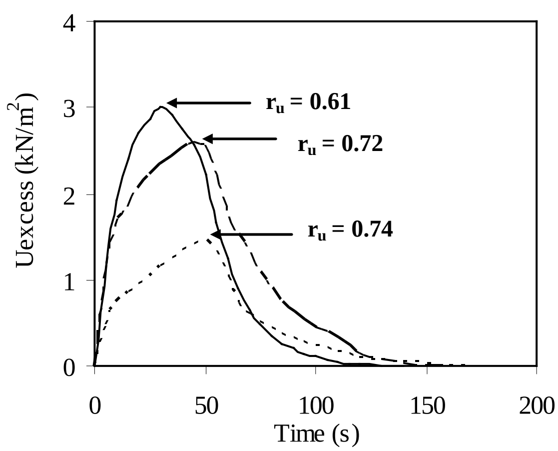

Fig. 5 (a): Sand with 4 layers geogrid at 0.1 g

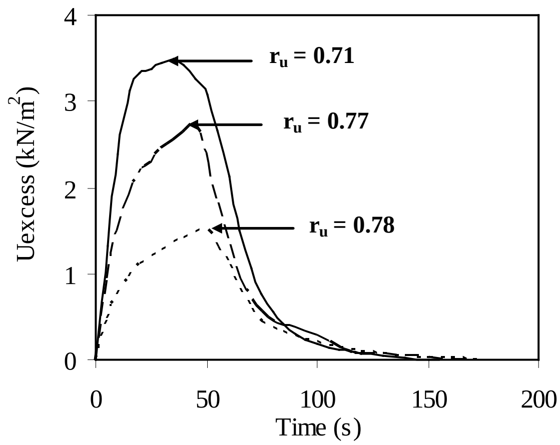

Fig. 5 (b): Sand with 4 layers geogrid at 0.2 g

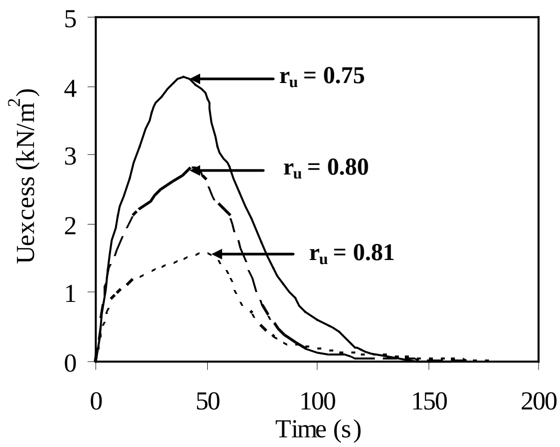

Fig. 5 (c): Sand with 4 layers geogrid at 0.3 g

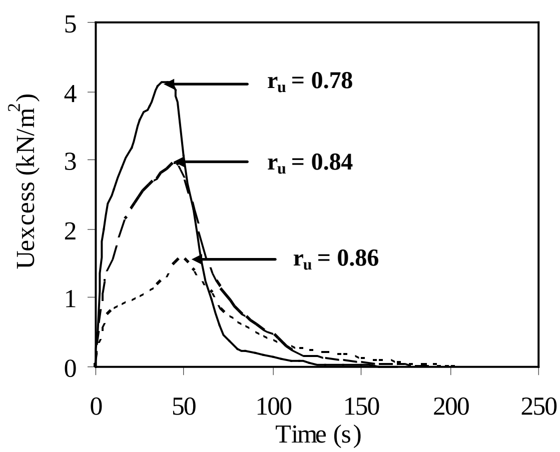

Fig. 5 (d): Sand with 4 layers geogrid at 0.4 g

<u>Sand with 5 Layers of Geogrid</u>

The figures 6 (a-d) show the variations in excess pore water pressure with time for sand reinforced with five layers of geogrid sheets at an accelerations varying from 0.1 g to 0.4 g. Here also the trend is similar to that observed for two other cases of sand with geogrid. Only difference is that the value of r_u marked on all the plots for bottom, middle and top points for this case is the lowest one for all the three cases considered. This indicates that the liquefaction resistance of sand is further improved due to increasing number of geogrid sheets.

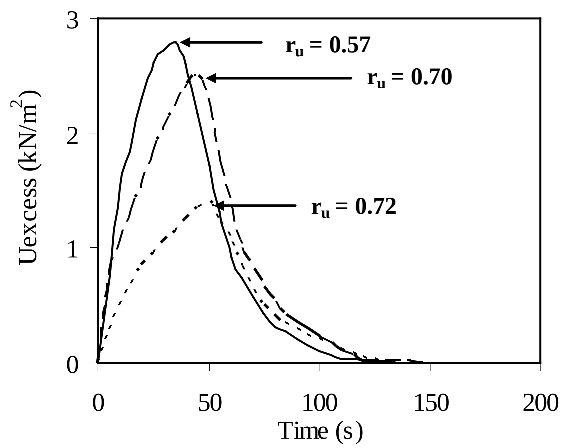

Fig. 6 (a): Sand with 5 layers geogrid at 0.1 g

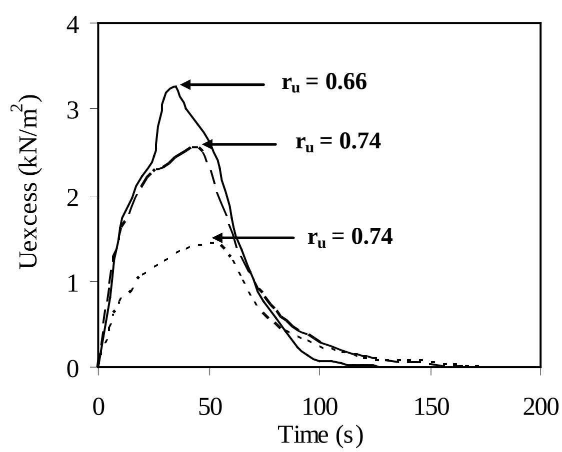

Fig. 6 (b): Sand with 5 layers geogrid at 0.2 g

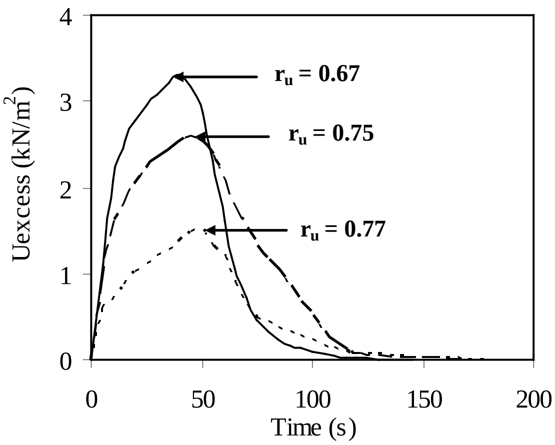

Fig. 6 (c): Sand with 5 layers geogrid at 0.3 g

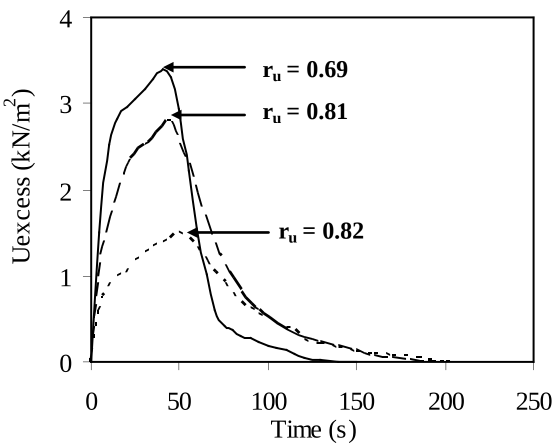

Fig. 6 (d): Sand with 5 layers geogrid at 0.4 g

<u>Liquefaction and shear parameters of geogrid reinforced sand</u>

The value of various liquefaction parameters i.e. the maximum pore water pressure ratio (r_{umax}), maximum pore water pressure built up time (t_1) and excess pore water pressure dissipation time (t_3) for bottom point are presented in Tables 1, 2 and 3, respectively. The shear parameters (c & Ø) of sand reinforced with different layers of geogrid are shown in Table 4 for further interpretation of the test results.

Table 1: Pore pressure ratio (r_{umax}) of geogrid reinforced sand

No. of Geo-grid Sheets	Acc^n. (g)	Maxm. Pore water pressure ratio (r_{umax}.)				% decr-ease in r_{umax}. due to geogrid sheet
		B	M	T	Average of r_{umax}	
0	0.1	0.995	1.005	0.89	0.96	
	0.2	0.995	1.008	0.90	0.97	
	0.3	0.997	1.011	0.90	0.97	
	0.4	0.997	1.011	0.91	0.97	
3	0.1	0.66	0.72	0.77	0.72	25
	0.2	0.75	0.78	0.80	0.78	20
	0.3	0.80	0.82	0.83	0.82	15
	0.4	0.84	0.88	0.88	0.87	10
04	0.1	0.61	0.75	0.75	0.70	27
	0.2	0.71	0.77	0.78	0.75	23
	0.3	0.75	0.80	0.81	0.79	19
	0.4	0.78	0.84	0.86	0.83	14
05	0.1	0.57	0.72	0.72	0.67	30
	0.2	0.66	0.74	0.74	0.71	27
	0.3	0.67	0.75	0.77	0.73	25
	0.4	0.69	0.81	0.82	0.77	21

Table 2: Built up time t_1 (s) of Geogrid reinforced sand measured at bottom point.

Acc^n (g)	Sand without geogrid	Sand with 3 layers of geogrid	Sand with 4 layers of geogrid	Sand with 5 layers of geogrid
0.10	15	30	30	35
0.20	13	35	35	35
0.30	12	35	40	40
0.40	10	35	40	40

Table 3: Dissipation time t_3 (s) of geogrid reinforced sand Measured at bottom point

Level of exci-tation (g)	Unreinforced Sand	Sand reinforced with 3 layers of geogrid sheets	Sand reinforced with 4 layers of geogrid sheets	Sand reinforced with 5 layers of geogrid sheets
0.10	70	95	110	100
0.20	87	100	120	100
0.30	120	130	120	105
0.40	190	195	130	110

Table 4: Shear parameters (c & Ø) of geogrid reinforced sand

Number of geogrid sheets	Values of shear parameters	
	c	Ø
0	0	28
3	0	32
4	0	36
5	25	38

EFFECT OF GEOGRID SHEET

It can be observed from the test results shown in Tables 1-3 for bottom point that the magnitude of maximum pore water pressures ratio (r_{umax}) decreases and built up time (t_1) and dissipation time (t_3) increases when the sand is reinforced with geogrid sheets. It is also observed from the last column of Table 1 that the average decrease in (r_{umax}) for 3 layers of geogrid reinforced sand is 25 % at 0.1g acceleration and this is further decreased to 27 % and 30 % respectively for 4 layers and 5 layers of geogrid sheet at the same level of excitation i.e. 0.1 g. It is further observed from the Table 2 that the value of t_1 increases from 15 sec for unreinforced sand to 30 sec for sand reinforced with 3 layers of geogrid sheet at 0.1 g acceleration. This is further increased to 35 sec in case of 5 layers geogrid reinforced sand at the same level of excitation (0.1 g). This shows that the liquefaction resistance of Solani sand increases if it is reinforced with geogrid sheets. This is attributed to the fact that due to addition of geogrid sheet the magnitude of pore water pressure developed decreases due to reduction in interstitial pressure distribution. Also geogrid sheet makes the soil a composite material whose strength and stiffness is higher than that of soil alone. The variations in strength parameters of sand due to reinforcement by geogrid sheets are shown in Table 4. It can be observed from Table 4 that there is significant increase in the value of Ø due to reinforcement and thus increases strength. Therefore, the Solani sand which is vulnerable to liquefaction will not liquefy as well as will not loose strength much during earthquake, if it is reinforced with geogrid sheets.

CONCLUSION

From the experimental studies carried out on Solani sand without and with geogrid sheet, the following conclusions are drawn.

1. The liquefaction resistance of sand is improved by addition of geogrid sheet. In case of 3 layers of geogrid sheets the average increase in liquefaction resistance is more than 24 % at 0.1g acceleration. If the number of geogrid sheets is increased from 3 layers to 4 layers, liquefaction resistance of sand increases from 25 % to 27 % and in case of 5 layers of geogrid sheets this increase goes up to 30 % at the same level of excitation (i.e. 0.1 g).

2. There is a significant increase in built up time (t_1). It increases from 15 second to 35 second at 0.1g acceleration in case of 5 layers of geogrid sheets. It is also found that by increasing the level of excitation i.e. from 0.1g to 0.2g, 0.3g and 0.4g, the percentage increase in liquefaction resistance is reduced.

3. The use of geogrid sheet to increase the liquefaction resistance of soil is effective at lower value of acceleration i. e. 0.1 g, in comparison to higher values of acceleration.

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