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Cement Column Treatment for Liquefaction Mitigation

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Introduction

Liquefaction of sandy ground during earthquakes often causes serious damage to civil engineering structures. The case histories are abundant in the seismically active areas of the world. The earthquakes that hit the regions of Valdez in Alaska, Niigata in Japan, in 1964, the 1989 Loma Prieta earthquake and the 1990 Philippine earthquake resulted in considerable damage to soil liquefaction. Since then, numerous research programmes had been organized in an attempt to understand and illustrate the conditions governing liquefaction (Seed et al. 1976; Seed 1987; Seed and Lee 1975).

If the sandy ground is potentially liquefiable, the liquefaction will likely to cause damage to the structures, and a countermeasure is usually taken to mitigate the potential damages. There are two methods to improve soil resistance to liquefaction. One is to reduce the buildup of excess pore water pressure, and the other is to facilitate the dissipation of the excess pore water pressure. Ground improvement techniques such as vibro compaction, sand compaction piles, blasting and dynamic compaction are commonly used to improve the liquefaction resistance of sand. But the above techniques cannot be applicable in many liquefaction susceptible urban areas, mainly due to difficulties in reaching the soil site to be treated and the unacceptable levels of noise and vibration associated with such procedures. In such situations treatment of soils with lime, cement, grout, etc. may be the options available to the engineer.

Dupas and Pecker (1979) studied the effect of artificial cementation on liquefaction resistance of foundation soil of a nuclear reactor in South Africa and recommended a cement content of 5% (by weight) for improvement of sand against liquefaction failure. Saxena et al. (1988) carried out cyclic triaxial tests on sand samples treated with cement and found that even a small amount of cement significantly increases the cyclic strength compared to uncemented sands. Clough et al. (1989) considered the effect of weak cementation on the liquefaction resistance of sand through cyclic triaxial tests and concluded that the behaviour of loose, cemented sand is similar to the behaviour of denser, uncemented sand.

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Ito et al. (1994) conducted shaking table tests to evaluate the earthquake resistance of soil treated with Quick lime Consolidated Briquettes (QCB); a soil stabilizer made of quick lime and cement. It was shown that, the response acceleration and pore water pressure in QCB-treated soils were scarcely affected and the settlement of treated soil was reduced by only one tenth of settlement of untreated soil. Maher et al. (1994) have performed monotonic and cyclic tests on Ottawa sand treated with sodium silicate, acrylate polymer and microfine cement grout. It is found that sand treatment with grout have increased initial liquefaction resistance and number of cycles to 5% double amplitude (DA) axial strain over untreated sand. Based on the case histories, Mitchell et al. (1995) have reported that a foundation system at a composite of eight projects in which soil-cement columns used as ground improvement performed very well during the Kobe earthquake.

Boominathan and Hari (2002) carried out a series of stress controlled cyclic triaxial tests on flyash samples reinforced with randomly distributed fiber and mesh elements. It was observed that the addition of fiber/mesh elements increases the liquefaction strength of flyash significantly and arrests the initiation of liquefaction even in samples at loose initial condition and consolidated with low confining pressure. Patricia and Mitchell (2002) studied the influence of colloidal silica grout on the deformation properties of saturated loose sand through cyclic triaxial tests and concluded that silica grout significantly improved the liquefaction resistance.

The above literature review reveals the effectiveness of the use of various type of admixtures particularly cement for the improvement of liquefaction resistance of saturated sand. However, in most of the above studies, the liquefaction resistance of treated sand is evaluated by carrying out element tests such as cyclic triaxial tests. In addition to that no study was reported on mitigation of liquefaction by using only cement columns. Hence, the present investigation aims to study the effectiveness of cement column treatment on the mitigation of liquefaction potential of soil. A series of shake table tests were performed on saturated sandy layer with and without cement column treatment. The influence of various material and test parameters such as initial relative density of sand, cement content, diameter of cement columns, curing period on pore pressure build up and settlement behaviour of the sandy layer treated with cement columns have been investigated.

Materials Used

Soil

The soil used in the present study is river sand and its grain size distribution is shown in Figure1. The index properties of the sand are given in Table 1. The soil is classified as poorly graded sand (SP).

Cement

The 53-grade Ordinary Portland cement is used to treat the sandy layer. The physical and chemical properties of the cement evaluated in accordance with IS 12269: 1987 are given in Tables 2 and 3 respectively.

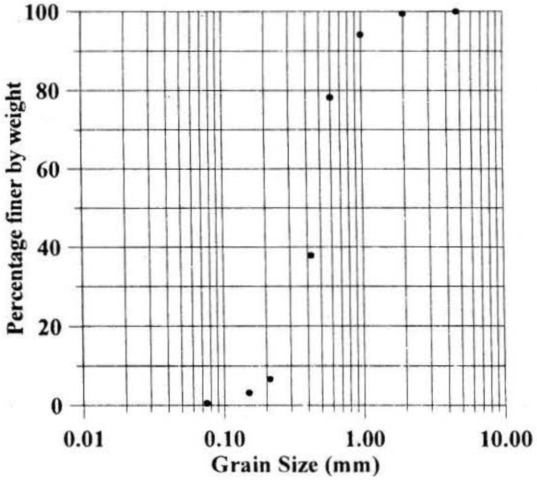

Fig. 1 Grain Size Distribution of Sand

TABLE 1: Index Properties of Sand

Index Property	Value
Uniformity Coefficient (C_u)	1.923
Coefficient of Uniform Curvature (C_c)	1.17
Specific Gravity	2.653
Maximum Unit Weight (kN/m^3)	18.36
Minimum Unit Weight (kN/m^3)	15.96
Maximum Void Ratio	0.66
Minimum Void Ratio	0.45

TABLE 2: Physical Properties of Cement

Sl.No	Physical Property	Value		IS 12269-1987			
1	Fineness (m^2/kg)	278.6		>225			
2	Specific gravity	3.15		-			
3	Standard Consistency (%)	29		-			
4	Initial Setting Time (min)	210		>30			
5	Final Setting Time (min)	325		<600			
6	Compressive Strength of Mortar cube (MPa)	3d	7d	28d	3d	7d	28d
		43.5	58.8	70.4	>27	>37	>53

TABLE 3: Chemical Properties of Cement

Sl. No.	Component	Value (%)	IS 12269-1987
1	SiO_2	19.3	-
2	Al_2O_3	5.687	-
3	Fe_2O_3	6.036	-
4	MgO	1.875	Not more than 6
5	SO_3	1.67	Not more than 2.5
6	CaO	61	
7	LOI	0.2963	Not more than 4
8	Insoluble residue	1.489	Not more than 2
9	Al_2O_3/ Fe_2O_3	0.94	Not less than 0.66

Experimental Setup and Instrumentation

Experiments were performed using a shaking table of 2730 mm × 1200 mm × 30 mm size made up of steel. This table is supported by 3 steel bearings in order to maintain low friction during operation and to restrict the movement to one direction. A container of size 1400 mm × 400 mm × 1000 mm made up of mild steel plate is mounted on the shake table using proper fixing arrangement. The mechanical oscillator mounted on the table connected to DC motor and speed control unit was used to generate sinusoidal horizontal excitations in one direction. An Hottinger-Baldwin measurement (HBM) acceleration transducer fixed on the shake table was used to measure the horizontal base acceleration. The pore pressure build up was measured with the help of three Kistler pore pressure transmitters mounted on the side wall of the container at different heights: one close to the bottom and other at a height of 150 mm and 250 mm from the surface of sandy layer The pore pressure transmitters used are diaphragm type with a measuring range of up to 0.5 bar. The acceleration and pore pressure transmitters are connected with a HBM digital carrier frequency amplifier system and Agilent digital storage oscilloscope to monitor and record the acceleration at the base and pore pressures at different height of the sandy layer. A 25 mm stroke HBM linear variable differential transformer (LVDT) connected to a digital indicator was used to measure the settlement of the surface of the sandy layer during shake table tests. A schematic of the set-up is shown in Figure 2.

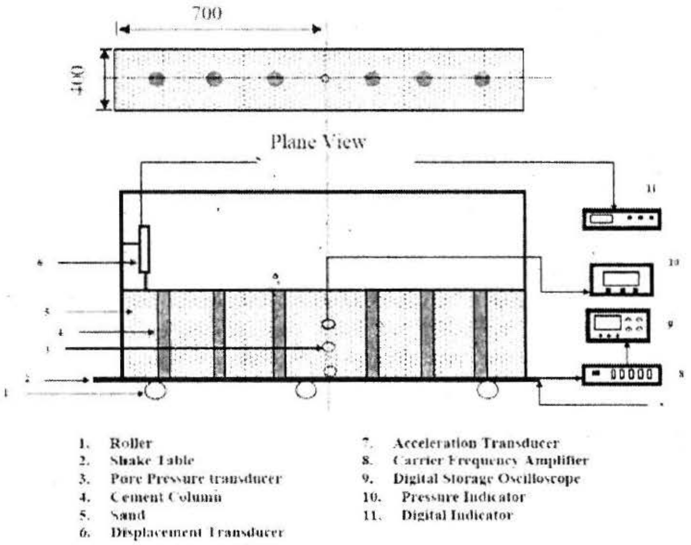

Fig. 2 Shake Table Test Set up

Experimental Procedure

Preparation of sandy layer and installation of cement columns

The cement columns are formed using PVC (Poly Vinyl Chloride) tubes of different diameters. Before filling the sand in the container, the PVC tubes of particular diameter are placed and held vertically at appropriate spacing. The test container is then filled with sand up to a height of 400 mm with a uniform relative density. Hence the size of the sand specimen tested in the shake table was 1400 mm × 400 mm × 400 mm. The required uniform relative density is achieved in the test tank by employing sand-raining technique. The cement in the slurry form with water to cement ratio of 1: 0.5 is poured into the PVC tube and later the tubes are slowly ejected out without disturbing the sandy layer. Then the sandy layer was saturated. Most of the tests were performed on cement column treated sandy layer after the curing period of 7 days.

Type of Tests

Shake table tests were performed on the untreated sandy layer with relative density of 40%, 50% and 60%. The sandy layers were subjected to horizontal sinusoidal excitation with frequency of 9 - 12 Hz and of force amplitude of 290 N to 880 N. The measured base horizontal acceleration varied from 0.1 g to 0.6 g.

Shake table tests are carried out on sandy layer treated with cement columns at an initial relative density of sand of 40%. The diameter of cement columns used in the present investigation was 25 mm, 50 mm, 75 mm and 100 mm. The percentage of cement content adopted was 0.5%, 1%, 2%, 3%, 4% and 5%. The cement column treated sandy layer were subjected to horizontal sinusoidal input motion with a frequency of 10 Hz and force magnitude of 490 N Although the tests are carried out at relatively higher frequency of input motion of 10 Hz that was higher than the predominant frequency of real seismic ground motion. However, it has been noted by Peacock et al. (1968) and Yoshimi et al. (1975) that the stress causing liquefaction for sand is practically independent of the frequency of cyclic loads.

Pore Pressure Response of Untreated Ground

The liquefaction failure of the soil in the laboratory cyclic tests is usually defined as the point at which initial liquefaction (when pore water pressure is equal to the initial vertical effective stress) has occurred (De Alba et al. 1979) or at which some limiting cyclic axial strain amplitude has reached (Wang and Tim Law 1994; Lee and Albaisa 1974). In the present investigation, the liquefaction failure was identified when the pore pressure, u became equal to the initial effective vertical pressure, σ_{vo}^{1}, i.e., pore pressure ratio (u/σ_{vo}^{1}) becomes unity.

A typical variation of pore pressure ratio versus number of cycles for untreated sandy layer subjected to the base acceleration of 0.14g is shown in Figure 3. It can be easily observed from Figure 3 that, the pore pressure builds up rapidly for untreated sandy layer at a low relative density of 40%. In this case, liquefaction failure occurred at 110 stress cycles. The number of stress cycles causing liquefaction, N_L was 190 and 260 for samples at relative density of 50% and 60% respectively. At higher relative densities, the pore pressure build up occurs gradually and number of cycles causing liquefaction, N_L is about 2 to 3 times higher than that at lower relative densities. It can be also found from Figure 3 that the number of cycles causing liquefaction even at low relative density of 40% is high even though the effective overburden pressure is low. It is due to the fact that the sandy layer is subjected to low intensity of horizontal shaking.

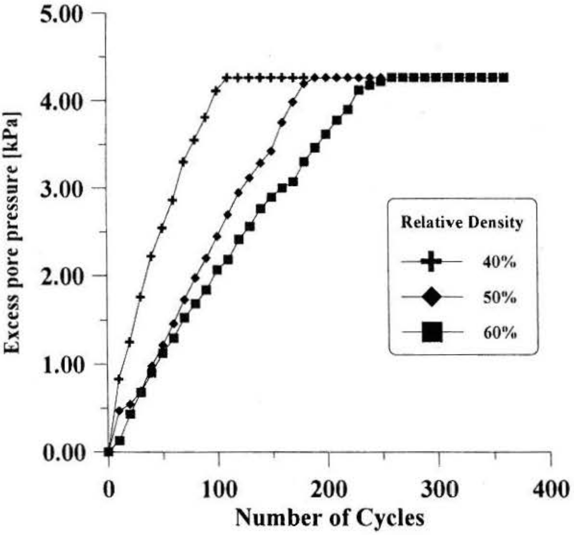

Fig. 3 Pore Pressure Response of Untreated Sandy Layer

Pore Pressure Response of Treated Sandy Layer

The variation of pore pressure ratio with number of cycles of shaking for cement column treated sandy layer with 1% cement content for different curing periods is shown in Figure 4. It is observed from Figure 4 that the nature of pore pressure build-up due to cement column treatment significantly differs from the untreated layer even at initial days of curing. Pore pressure build-up occurs gradually and number of cycles causing liquefaction, N_L increases with an increase of curing period. It can be easily found from Figure 4 that the pore pressure build-up after the curing period of 7 days is practically same due to the completion of process of hydration. Saxena et al. (1988) arrived similar conclusion based on the cyclic triaxial tests carried out on cement treated sands. Hence all other tests were performed after a curing period of 7 days.

A typical variation of pore water pressure measured at different depths of the treated sandy layer (1% cement content) during shaking is shown in Figure 5. It is clearly observed from Figure 5 that the excess pore pressure increases with depth at any instance of shaking and the maximum excess pore water pressure occurs at the bottom. The measured pore pressure is normalized with the effective overburden stress and the variation of the normalized pore water pressure i.e. the pore pressure ratio with number of cycles of excitation is shown in Figure 6. It can be easily noticed from Figure 6 that the pore pressure ratio curves match to a single curve, which indicates a unique relationship between pore pressure ratio and cycles of shaking. Hence, the further interpretation of test results was carried out using the pore pressure measured close to the bottom of the sandy layer.

Figure 7 shows the variation of pore pressure ratio with number of stress cycles for cement column treated layer (25 mm diameter columns) at different cement content. It can be easily observed from Figure 7 that a gradual build up of pore pressure for treated layer in contrast to rapid pore pressure build up for untreated layer and in addition that the number of cycles causing liquefaction, N_L substantially increases with an increase of cement content. It is due to the fact that the reaction of cement and water forms cementatious calcium silicate and aluminate hydrates, which bind sand particles together and makes a stronger and larger size columns, which resists shear forces induced by shaking. It results less volume change in the remaining part of the soil layer and hence the amount of pore pressure builds up is substantially lower than the untreated soil layer. Figure 7 indicates that even at low percentage of cement content of 1%, the liquefaction occurs only after larger number of cycles of about 400. For treated with greater than 2% cement content the liquefaction failure have not been observed even at very large number of cycles, which indicates the effectiveness of cement column treatment to the mitigation of liquefaction sandy layers. But the number of cycles causing liquefaction for treated sand even with 1% cement content is relatively high due to the fact that the induced horizontal acceleration is low (0.14 g). It also may be due to the fact that the soil under low confining pressure exhibited dilatancy. Hence the effect of cement column treatment on the liquefaction mitigation is evaluated in terms of pore pressure ratio at the number of cycles causing liquefaction of untreated layer, 110 cycles. At higher cement content of 4 to 5%, the strength of cement columns is strong enough to resist the developed shear force due to shaking.

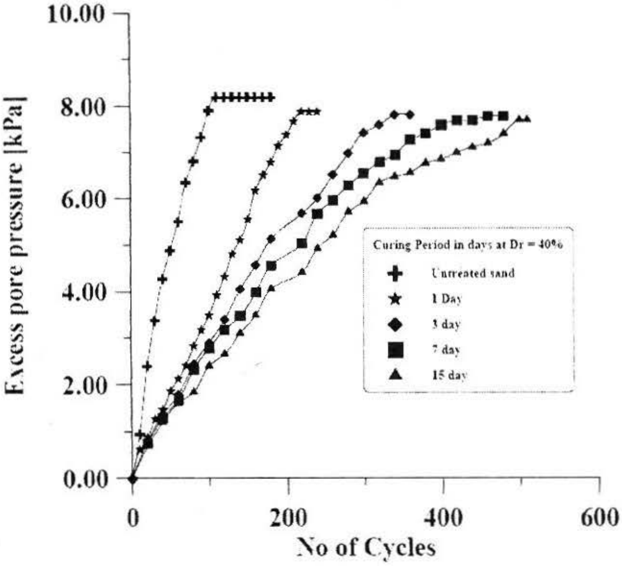

Fig. 4 Effect of Curing Period on Pore Pressure Response of Sandy Layer

(R_D = 40%; σ_{vo}^1 = 4.3 kPa; Cement content = 1%)

It can be easily noticed from Figure 8 that, at number of stress cycles causing liquefaction (N_L = 110 cycles), the pore pressure ratio for improved ground with 1% cement content reduces by about 60%. This indicates the significant improvement of liquefaction resistance even at low percentage of cement content. With further increase of cement content from 2 to 5%, the rate of increase of liquefaction resistance is not substantial only pore pressure ratio further reduces by 30% which indicates the completion of hydration and further addition of cement may not improve the liquefaction resistance. It is found that treating sandy layer with cement content of 1% gives pore pressure ratio of about 0.4, which insures factor of safety against liquefaction of about 1.2 to 1.5.

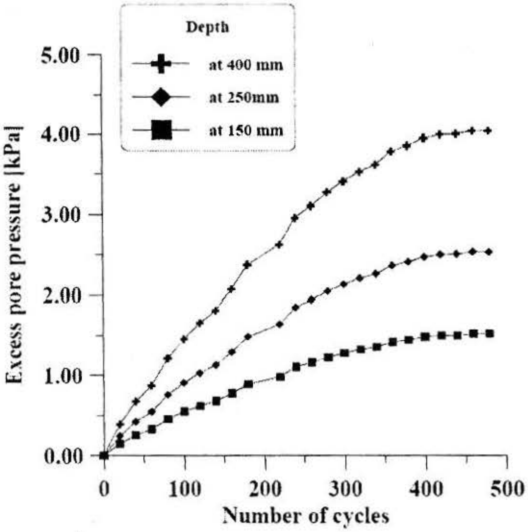

Fig. 5 Variation of Pore Pressure with Number of Cycles at Different Depths (R_D = 40%; Cement content = 1%)

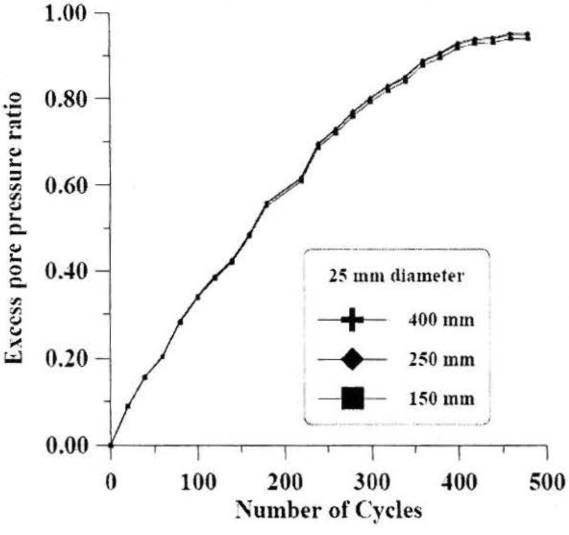

Fig. 6 Variation of Pore Pressure Ratio with Number of Cycles for Treated Sandy Layer (Cement content = 1%)

To determine strength of the cement columns unconfined compression tests (UCC) were performed on samples obtained from the selected cement columns excavated from the sandy layer after completion of the shake table tests. A typical stress-strain response curve obtained from the UCC tests on a cement column sample (cement content =1%; diameter = 25 mm) is shown in Figure 8. The Figure shows brittle failure, which is the typical failure mode for structural elements made from cement and the peak strength of about 100 MPa, which indicates cement columns formed are very strong. Test results showed that the values of unconfined compressive strength of cement columns (cement content =1%; diameter = 25 mm) varied from 7 to 10 MPa.

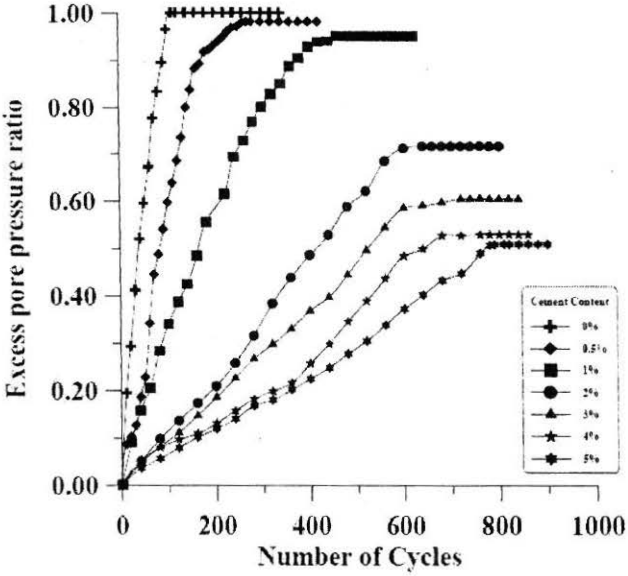

Fig. 7 Effect of Cement Content on Pore Pressure Response

(R_D = 40%; $\sigma_{vo}{}^1$ = 4.3 kPa; Diameter = 25 mm)

Fig. 8 Typical Stress-Strain Response curve obtained from Unconfined Compressive Test carried out on Cement Column Samples

The variation of pore pressure ratio with number of cycles for different diameter of cement columns at 1% and 4% cement content is shown in Figure 9. Figure 9(a) indicates that at low cement content of 1%, the pore pressure response is practically same for various diameters. However, it is noticed from Figure 9(b) that at higher cement content the effect of diameter on the pore pressure response is well seen and the pore pressure response increases with an increase of diameter of cement column. It is due to the fact the larger diameter cement columns have higher shearing resistance than small diameter columns as in the case of pile foundations.

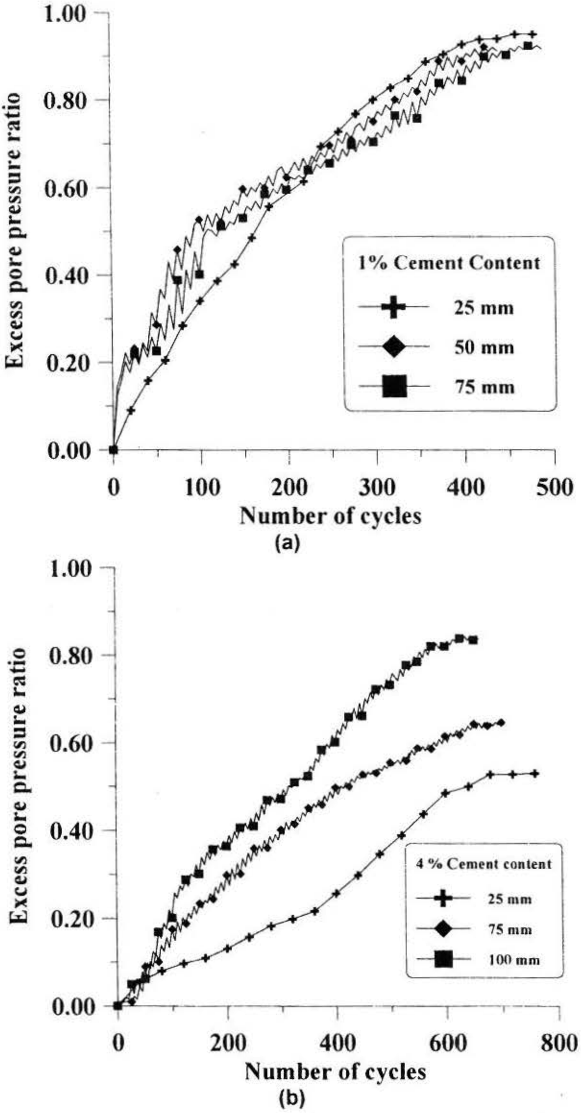

Fig. 9 Effect of diameter on Pore Pressure Response ($R_D = 40\%$; $\sigma_{vo}^1 = 4.3$ kPa)

(a) 1% Cement content (b) 4% Cement content

Even though the shake table tests were carried out with out fixing spacing between the columns, the spacing between the cement columns is arrived based on the cement content and diameter. Based on the shake table tests carried out on cement column treated sandy layer for different cement content at various diameters of cement column, the variation of pore pressure ratio with spacing to diameter (s/d) ratio is plotted and it is shown in Figure 10. It can be noticed from Figure 10 that the pore pressure ratio increases with an increase of spacing between the columns. It can be concluded from Figure 10 that in order to restrict the pore pressure development to be greater than 50% to 60% that is normally considered to be detrimental to the structures (Seed and Lee 1975), the spacing between the columns may be less than seven times the diameter of the cement columns.

Settlement of Treated Sandy Layer

Figure 11 shows the variation of settlement with number of cycles for untreated and treated sandy layer with different percentage of cement content. It is observed from Figure 11 that the settlement of untreated sandy layer increases rapidly with an increase of number of cycles and the maximum settlement recorded is about 17.3 mm at the moment of liquefaction, i.e. at N_L of 110 cycles, which is approximately 4.4% of the height of unimproved sandy layer. The similar amount of liquefaction-induced settlement occurred in the field during Fukui Earthquake, Japan, 1948 as reported by Lee and Albaisa (1974). At 110 cycles of loading i.e. the number of stress cycles causing liquefaction of unimproved soil layer N_L, settlement of the treated soil layer with 25 mm diameter cement column (1% cement content) is only about 2.5 mm. With addition of cement content from 2 to 5%, the settlement reduces from 1.9 mm to 0.7 mm. It clearly shows that even with addition of small percentage of cement the settlement of saturated sandy layer significantly reduces.

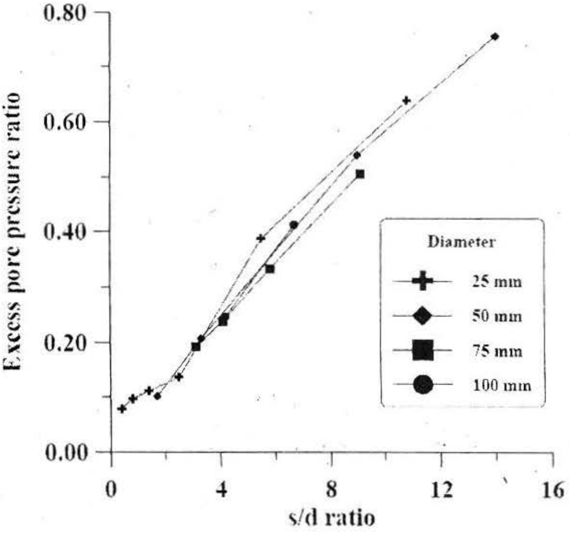

Fig. 10 Effect of s/d Ratio on Pore Pressure Response

(R_D = 40%; $\sigma_{vo}{}^1$ = 4.3 kPa; Cement Content = 1 to 5%)

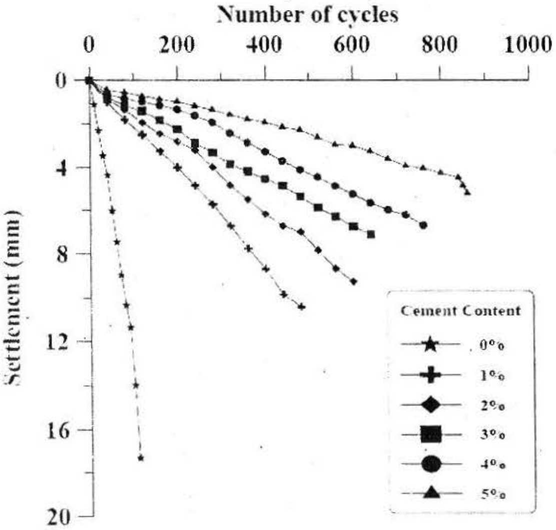

Fig. 11 Effect of Cement Content on Settlement of Sandy Layer

(R_D = 40%; $\sigma_{vo}{}^1$ = 4.3 kPa; Diameter = 25 mm)

Conclusions

Based on the shake table tests carried out on cement column treated sandy layer of 400 mm thick at a base horizontal acceleration of 0.14 g, the following conclusions are drawn:

1. It is found a gradual build up of pore pressure for sandy layer treated with cement columns in contrast to rapid pore pressure build up for untreated ground and in addition that the number of cycles causing liquefaction (N_L) substantially increases with an increase of cement content. It is due to the fact that the reaction of cement and water forms cementatious calcium silicate and aluminate hydrates, which bind sand particles together and makes a stronger and larger size columns, which resists shear forces induced by shaking. It results less volume change in the remaining part of the soil layer and hence the amount of pore pressure build up is substantially lower than the untreated soil layer. The pressure generation of cement column treated sandy layer due to shaking is practically stabilized after a curing period of 7 days due to the completion of hydration process.
2. The liquefaction resistance of sandy layer increases with an increase of cement content but the rate of increase of liquefaction resistance of sandy layer is not significant at relatively high cement content due to the of saturation of cement. It is found that the treating of sandy layer with low cement content of 1% gives pore pressure ratio of about 0.4 which insures factor of safety against liquefaction of about 1.2 to 1.5.
3. In order to restrict the pore pressure development to be greater than 50% to 60% which is normally considered to be detrimental to the

structures, the spacing between the cement columns should be less than seven times the diameter of the cement columns to reduce the liquefaction potential.

4. The settlement of the improved sand layer with 1% cement content is only 40% of the untreated sandy layer, proving the effectiveness of application of cement columns to mitigate the liquefaction potential saturated sandy layer.

References

Boominathan, A. and Hari, S. (2002): "Liquefaction Strength of Fly Ash Reinforced with Randomly Distributed Fibers", *Soil Dynamics and Earthquake Engineering,* 22, pp. 1027–1033.

Clough, G. W., Iwabuchi, J., Rad, N. S. and Kuppusamy T. (1989): "Influence of Cementation of Liquefaction of Sands", *Journal of Geotechnical Engineering,* ASCE, 115, pp. 1102–1117.

De alba, P., Seed, H. B. and Chan, K. (1979): "Sand Liquefaction in Large Scale simple Shear Tests", *Journal of Geotechnical Engineering,* ASCE, 102, pp. 909–927.

Dupas, J. M. and Pecker, A. (1979): "Static and Dynamic Properties of Sand-Cement", *Journal of Geotechnical Engineering,* ASCE, 105, pp. 419–436.

IS 12269: 1987. *Indian Standard on Specification for 53 Grade Ordinary Portland Cement*, Bureau of Indian Standards, New Delhi.

IS 1498: 1979. *Indian Standard on Classification and Identification of Soils for General Engineering Purposes*, Bureau of Indian Standards, New Delhi.

Ito, T., Mori, Y. and Asada, A. (1994): "Evaluation of Resistance to Liquefaction caused by Earthquakes in Sandy Soil Stabilized with Quicklime Consolidated Briquette Piles", *Soils and Foundations*, 34, pp. 33–40.

Kramer, S. L. (1996): *Geotechnical Earthquake Engineering*, Prentice Hall, New Jersey.

Lee, K. L. and Albaisa, A. (1974): "Earthquake Induced Settlements in Saturated Sands", *Journal of Geotechnical Engineering*, ASCE, 100, pp. 387–406.

Maher, M. H., Ro, K. S. and Welsh, J. P. (1994): "Cyclic Undrained Behavior and Liquefaction Potential of Sand Treated with Chemical Grouts and Microfine Cement (MC-500)", *Geotechnical Testing Journal*, 17, pp. 159–170.

Mitchell, J. K., Baxter, C. D. P. and Munson, F. C. (1995): "Performance of Improved Ground during Earthquakes", *Soil Improvement for Earthquake Hazard Mitigation, Geotechnical Special Publication*, 49, pp. 1-36.

Patricia, M. G. and Mitchell, J. K. (2002): "Influence of Colloidal Silica Grout on Liquefaction Potential and Cyclic Undrained Behavior of Loose Sand", *Soil Dynamics and Earthquake Engineering,* 22, pp. 1017–1026.

Peacock, W. H. and Seed, H. B. (1968): "Sand Liquefaction under Cyclic Loading Simple Shear Conditions", *Journal of the Soil Mechanics and Foundation Engineering Division*, ASCE, 94, pp. 689–708.

Saxena, K. S., Krishna Reddy, R. and Anestis, A. S. (1988): "Liquefaction Resistance of Artificially Cemented Sand", *Journal of Geotechnical Engineering*, ASCE, 114, pp. 1395–1413.

Seed, H. B. (1987): "Design Problem in Soil Liquefaction", *Journal of Geotechnical Engineering*, ASCE, 113, pp. 827–845.

Seed, H. B. and Lee, K. L. (1975): "Liquefaction of Saturated Sands during Cycling Loading", *Journal of the Soil Mechanics and Foundation Engineering Division*, ASCE, 92, pp. 105–134.

Seed, H. B., Martin, P. and Lysmer, J. (1976): "Pore Water Pressure changes during Soil Liquefaction", *Journal of Geotechnical Engineering*, ASCE, 103, pp. 323–345.

Wang, J. G. Z. Q. and Tim Law, K. (1994): *Siting in Earthquake Zones*, A. A Balkema, Rotterdam.

Yoshimi, Y. and Oha-Oka, H. (1975): "Influence of Degree of Shear Stress Reversal on the Liquefaction Potential of Saturated Sand", *Soils and Foundations*, 15, pp. 27–40.