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EFFECT OF LOADING FREQUENCY ON CYCLIC BEHAVIOUR OF SOILS

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ABSTRACT

Very few studies have addressed the effect of frequency on liquefaction of soils [Wong et al. (1975) and Wang and Kavazanjian (1989) using stress-controlled technique]. Both these studies have shown that the liquefaction potential of soil is not dependent on the loading frequency. However, the effect of frequency on liquefaction potential of soils using strain-controlled technique remains unexplored. Also not many studies have been carried out to evaluate the effect of frequency on pore water pressure build up, dynamic properties of sandy soils beyond shear strains of 0.01%. This paper presents the results of the detailed studies on strain – controlled cyclic triaxial tests on sandy soils subjected to loading frequencies in the range of 0.2 Hz to 3 Hz (i.e. 0.2, 0.5, 1.0, 2.0 and 3 Hz). Undrained strain-controlled cyclic triaxial tests were carried out on cylindrical samples. The effect of frequency on pore water pressure build up, liquefaction potential and dynamic properties of sandy soils have been explored. The investigations reveal that the pore water pressure build up in sands, liquefaction potential and shear modulus of soils is independent of frequency of cyclic loading in the range of frequencies considered. However there has been some effect of frequency on damping ratios.

Keywords: dynamic properties, frequency, liquefaction, pore water pressure, shear modulus

INTRODUCTION

Cyclic stress-controlled tests indicate that the factors such as fabric and its associated anisotropy, stress-strain history, applied stress path and aging, etc., affect the cyclic strength as well as shear modulus of sands (Drnevich and Richart, 1970; Seed and Idriss, 1971; Hardin and Drnevich, 1972; Pyke et al., 1974; Anderson and Stokoe, 1977; Dobry and Ladd, 1980). As demonstrated by Dobry et al., (1982), if both cyclic shear strength (τ) and shear modulus (G) are influenced by the above factors, then the ratio $\gamma = (\tau / G)$ may be affected less by the same factors (in which γ shear strain). Further, the pore pressure buildup in soils using strain-controlled tests will be less sensitive to the above factors than in stress-controlled tests. The effect of frequency on liquefaction of soils were also studied by Wong et al. (1975) and Wang and Kavazanjian (1989) using stress-controlled technique. However, the effect of frequency on pore water pressure build up and liquefaction potential of soils using strain-controlled technique remains unexplored. Also, studies were carried out by Lin and Huang (1996) employing cyclic torsional shear tests on dry Ottawa sands under constant volume conditions to study the effect of frequency on shear moduli and damping ratios in the range of shear strains 0.004 % to 0.01%. However, the effect of frequency on dynamic properties of soils at large shear strains remain questionable and hence need further studies beyond shear strains of 0.01%.

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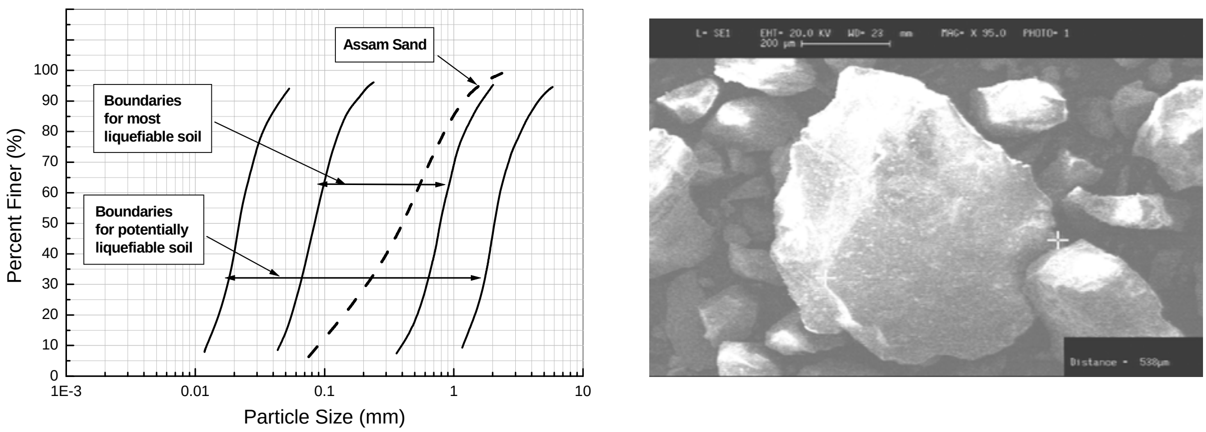
EXPERIMENTAL INVESTIGATION

In the present study, a computerized indigenously developed triaxial testing facility with the options of both static and dynamic testing was used. The equipment essentially comprised a submersible type load cell, an LVDT and four transducers to detect the chamber pressure, pore water pressure, volume change, and lateral deformations. The triaxial cell is built with a very low friction piston rod seal to which a servo-controlled submersible load cell is fitted. The loading system consists of a load frame and hydraulic actuator capable of performing strain-controlled as well as stress-controlled tests with a frequency range of 0.01 Hz to 10 Hz employing built-in sine, triangular, and square waveforms. Also, the wave pattern could either be generated on the computer or could be generated from the wave pattern obtained on the seismograph by means of an external input. The conditioned output from the sensors is received by process interface, which forms the communication link between the computer and the loading system.

Selection of Material and Characterization

Liquefied soil samples were collected from a location close from river bed profiles in Shillong Plateau, Assam, India where large scale sand dykes were noticed due to liquefaction. Figure 1(a) shows the ranges of grain size distribution for liquefaction susceptible soils proposed by Tsuchida (Iwasaki, 1986). Also shown in this figure is the grain size distribution of the soils from Assam for comparison purpose. This clearly highlights that the sands collected from the region fall well with in the range of most liquefiable soils. Minimum and maximum void ratios were determined as per the guidelines from ASTM: D 4254-2000 and ASTM: D 4253-2000 respectively. Scanning electron microscope studies reveal that the sand grains are angular to sub angular (Fig. 2 b). Table 1 gives the summary of the index properties of the soil samples collected.



(a) (b)

Figure 1: (a) Grain size distribution of soil liquefaction proposed by Tsuchida (Iwasaki, 1986) (b) Microscopic view of soil particles from Assam area

Sample Preparation

It has been shown that dry pluviation would create a grain structure similar to that of naturally deposited river sands. Further, many of the water sedimentation depositional methods tend to produce inhomogeneous specimens with the coarser fraction on the bottom and the finer fraction on the top of the specimen (Lade and Yamamuro, 1997). In view of these observations, dry pluviation method was employed in the present study to prepare the soil samples. Cylindrical soil specimens of size 50 mm diameter and 100 mm height at a relative density (RD) of 50% were created by placing the dry sand in to a funnel having a nozzle of about 12 mm in diameter with a tube attached to the spout. The tube was placed at the bottom of the membrane lined split mould. The tube was slowly raised along the axis of symmetry of the specimen, such that the soil was not allowed to have any drop height. Next, the surface of the specimen was trimmed flush with the top of the mould and the triaxial cell was installed. After the preparation of specimens, a small vacuum of about 10 kPa was applied to the specimens to reduce disturbance during the removal of split mould and triaxial cell installation. Next the split mould was removed and the triaxial cell was assembled and positioned on the loading device. While preparing the soil specimens at relatively higher densities, the mould was gently tapped in a symmetrical pattern until the desired density was achieved.

Table 1: Index properties of liquefied sand

Specific Gravity	2.66
Gravel (%)	NIL
Coarse Sand (%)	NIL
Medium sand (%)	48.8
Fine Sand (%)	45.0
Silt Size (%)	6.2
Clay size (%)	NIL
Liquid Limit (%)	NP
Plasticity Index (%)	NP
Maximum void ratio (e_{max})	0.91
Minimum void ratio (e_{min})	0.53

Saturation, Consolidation and Shearing

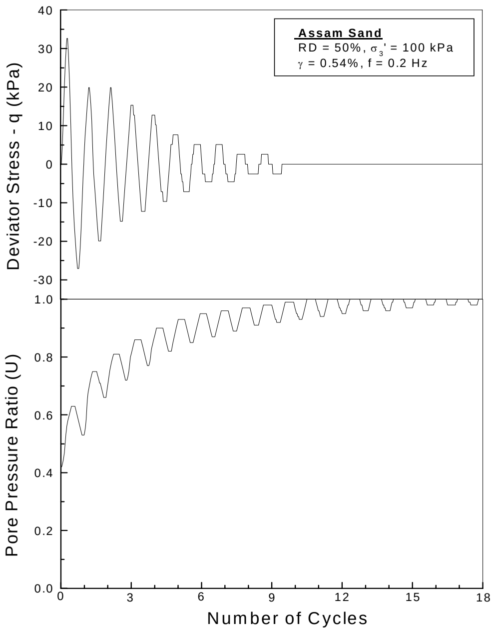
The specimens were saturated with deaired water using backpressure saturation. The back pressure was increased gradually while maintaining the effective confining pressure at 15 to 20 kPa. This process was continued until the Skempton's pore pressure parameter (B) exceeded 0.95. Following saturation, the specimens were then isotropically consolidated to the required confining pressure. The consolidation process was considered to be complete when the drainage valves closed, the pore pressure did not change for a sufficient length of time. The volume change of the specimens after consolidation was recorded by the sensitive volume change measuring device. Once the consolidation process was complete, the specimens were subjected to undrained shearing with constant confining pressures.

RESULTS AND DISCUSSION

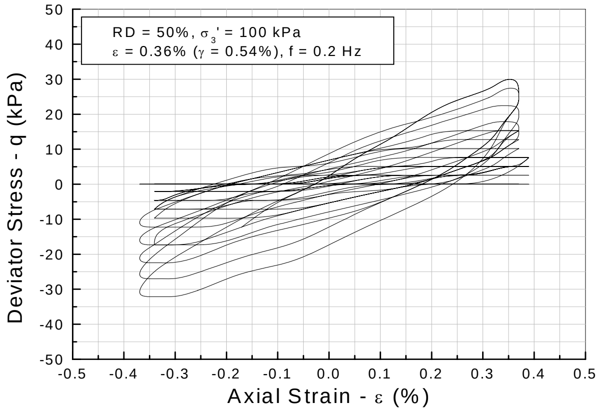
Undrained cyclic shear tests were carried out on sand samples at a constant relative density of 50% and confining pressure of 100 kPa. Samples were subjected to cyclic loading frequencies of 0.2 Hz, 0.5 Hz, 1.0 Hz, 2.0 Hz and 3.0 Hz. employing sine wave.

Effect of Frequency on Pore Water Pressure Build up in sands

Figure 2 (a) shows the variation of deviator stress and pore pressure ratio with number of loading cycles for the sample at a frequency of 0.2 Hz and figure 2 (b) shows the corresponding stress strain diagram. In this case the soil attains 100% pore pressure ratio in about 12 cycles when subjected to shear strain amplitude of 0.54 %.



(a)



(b)

Figure 2: (a) Grain size distribution of soil liquefaction proposed by Tsuchida (Iwasaki, 1986) (b) Microscopic view of soil particles from Assam area

Figure 3 (a) shows a typical relationship between pore pressure ratio and number of cycles at a frequency of 0.2 Hz. It has been observed that the increase of the pore pressure ratio up to the level of effective confining pressure is a function of both cyclic shear strain amplitude and number of cycles. For a given relative density and loading cycle, the rate of pore water pressure build up in sand increases with increase in the amplitude of cyclic shear strain. Similar observations have been made for loading frequencies of 0.5, 1.0, 2.0 and 3.0 Hz also as shown in figures 3(b) to 3 (e) respectively.

Figure 4 shows the relationship between pore water pressure build up and number of loading cycles at cyclic shear strain amplitude of 0.4% in the range of frequencies 0.2 Hz to 3.0 Hz. It is interesting to note that the difference between the amounts of pore water pressures at any given cycle is not significant.

While analysing the relationship given in say figure 3(c), it has been found out in case number of cycles (N) is normalized by dividing it with N_L which is the accumulative number of cycles required to build up excess pore water pressure to the level of effective confining pressure, there appears a tendency of establishment of a single relationship range independent of amplitude of cyclic shear strain (γ). Such typical relationship is shown in figure 5. Similar observations of establishment of a single relationship range independent of amplitude of cyclic shear strain were made at frequencies 0.2 Hz, 0.5 Hz, 2.0 Hz and 3.0 Hz also.

In a similar way, if the results shown in figure 4 are presented in the form of relationship between normalized pore water pressures and cycle ratios, then a single relationship is obtained as in figure 6. Even with a slight scatter in the results, it can be demonstrated that the pore water pressure build up in sands is independent of frequency of cyclic loading in the range of frequencies tested.

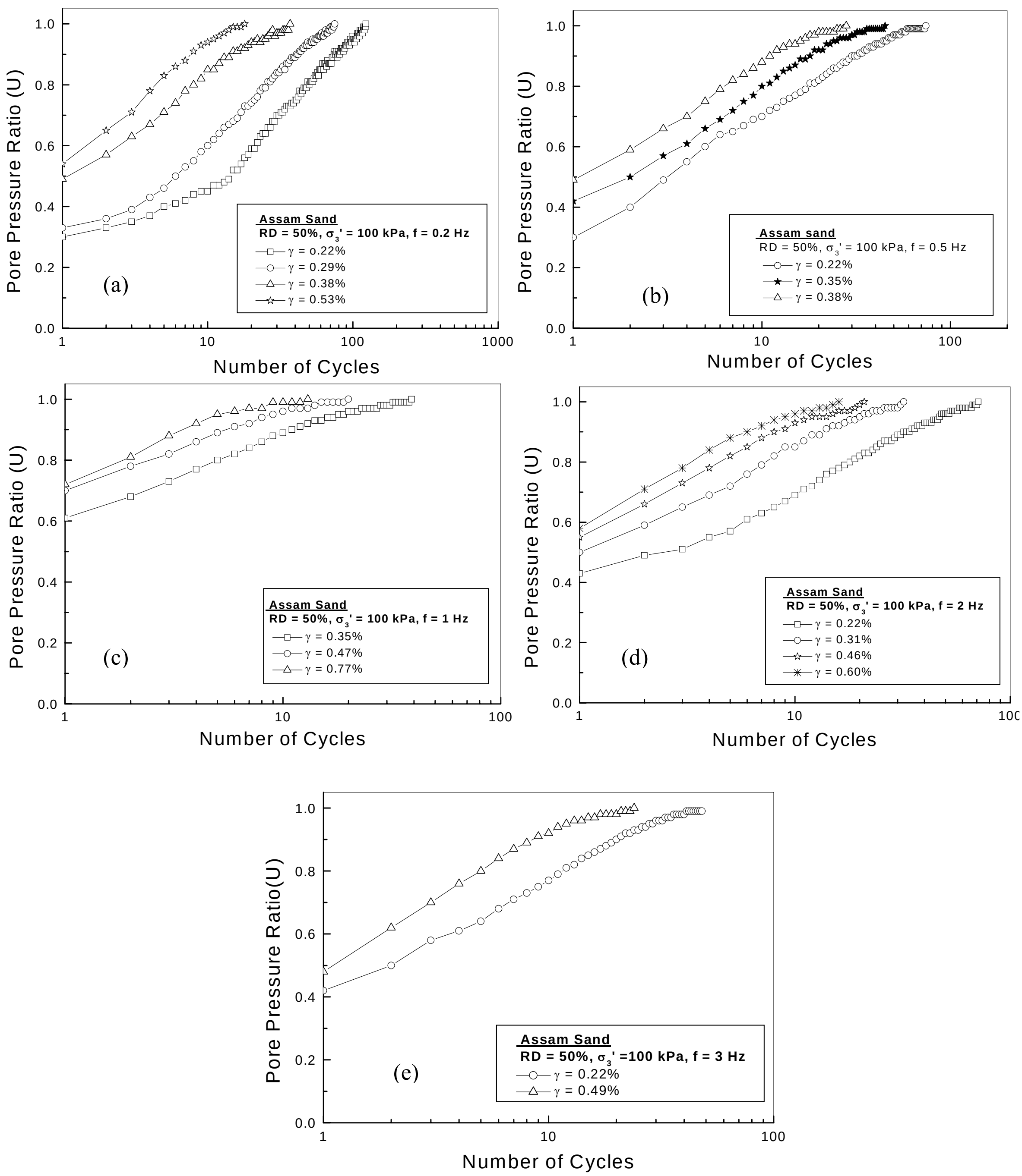


Figure 3: Pore water pressure build up as a function of number of cycles at frequency (a) 0.2 Hz (b) 0.5 Hz (c) 1.0 Hz (d) 2.0 Hz (e) 3.0 Hz

Dobry (1985) summarized the results of 50 cyclic triaxial tests on saturated sands in the form of pore pressure ratio versus cyclic shear strain after 10 loading cycles (N = 10) as shown in the figure 7 (lower and upper bound curves). The test data included seven different sands, and the tests were performed on undisturbed, remolded, loose and dense sands at relative densities ranging from 20-80% and at confining pressures from 530 to 4000 psf (19.8 kPa to 196.8 kPa). It has been demonstrated that despite wide range of materials, confining pressures and testing conditions, there is a consistent relationship between pore pressures build up in sands and shear strains and the results fall in a narrow band (Fig. 7). But, these studies by Dobry (1985) do not consider the effects of frequencies on pore pressure build up in sands. However, from the results of the present study, the effect of frequency on pore water pressure build up is explored by plotting the data at ten cycles in the same in figure 7. As observed from this figure, it is clear that the data obtained at ten cycles for sand fall well with in the band which indicates very little effect of frequency on pore water pressure build up.

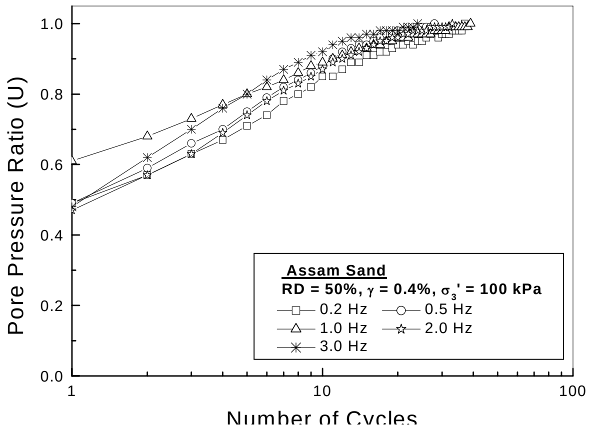


Figure 4: Relationship between normalized pore pressure ratio and cycle ratio at 1.0 Hz frequency

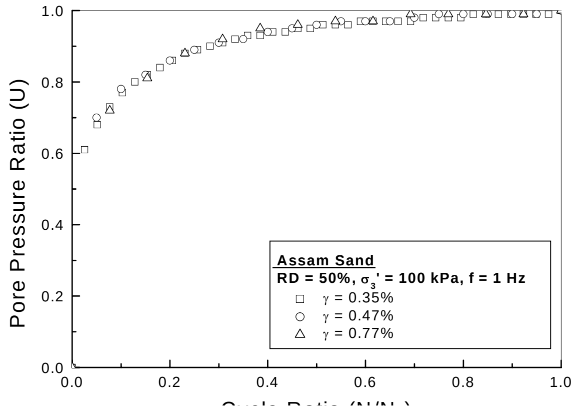


Figure 5: Relationship between normalized pore pressure ratio and cycle ratio for different frequencies at shear strain of 0.4%

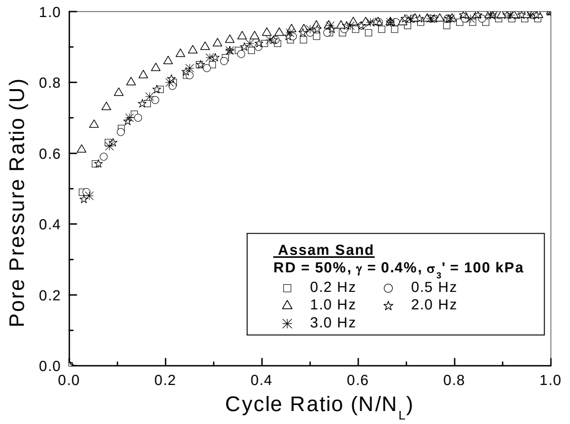


Figure 6: Relationship between normalized pore pressure ratio and cycle ratio for different frequencies at shear strain of 0.4%

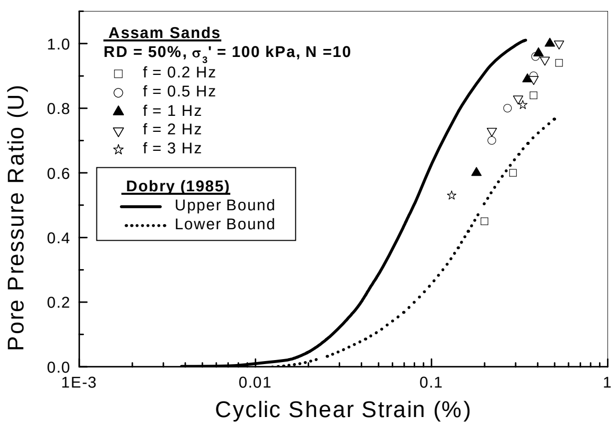


Figure 7: Relationship between pore pressure ratio and cyclic shear strain at different frequencies

Talaganov (1996) conducted cyclic triaxial strain-controlled tests on dry and saturated sands reconstituted at relative densities ranging from 44% to 85% under constant volume conditions. Tests were conducted on these samples at confining pressures of 100, 200 and 300 kPa. In case of dry sands, as a result of cyclic shearing in constant volume conditions a decrease in initial effective confining pressure of the sample takes place. The effect of pore pressure increase in saturated samples was simulated through the decrease in initial pressure. Based on the analysis of the results, Talaganov (1996) indicate that the relationship between normalized pore water pressures and normalized cycles is different from the standard relationships obtained by the application of the stress-controlled tests. Instead of having a tendency of separating the different relationships between the amplitude of shear strain and the number of cycles for pore water pressure build up based on separate relative density and confining pressure, there exists a single relationship range between normalized pore pressures and normalized cycles for prediction of pore water pressure build up for all relative densities and confining pressures. The relationship is shown in figure 8. But, these studies by

Talaganov (1996) do not account for the effect of frequencies on pore pressure build up. In this case also, from the results of the present study, the effect of frequency on pore water pressure build up is explored by plotting the data along with the bounds reported by Talaganov (1996) (Fig. 8). As observed from the this figure, it is clear that the data obtained at ten cycles fall with in the band suggested by Talaganov (1996) which indicates that the pore water pressure build up in sands is independent of frequency of cyclic loading.

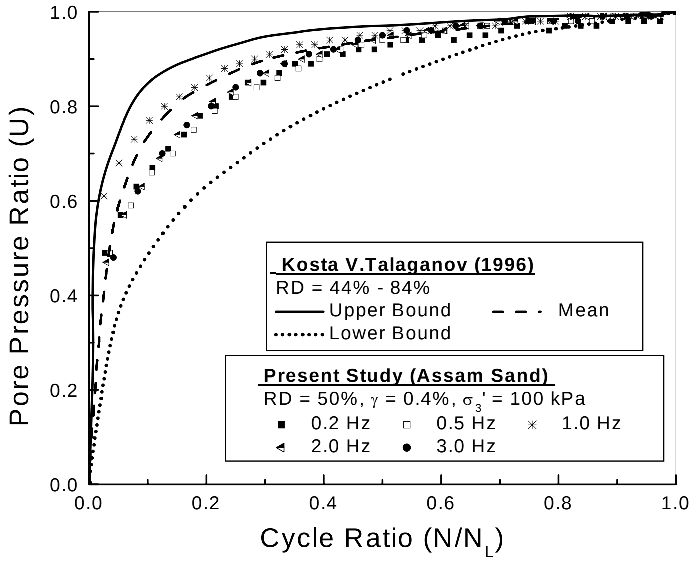


Figure 8: Relationship between normalized pore pressure ratio and cycle ratio for different frequencies at shear strain of 0.4 %

Effect of Frequency on Liquefaction Potential of Sands

The effect of frequency on the relationship between cyclic shear strain and the number of cycles required to cause initial liquefaction of sand is shown in figure 9. As seen from this figure, for the range of frequencies used in the present study, the data fall in a narrow band indicating that the effect of frequency on the liquefaction potential of a soil is not significant in strain-controlled tests also.

Talaganov (1996) also investigated the effects of relative density and confining pressure on the liquefaction potential of sands employing strain-controlled cyclic triaxial tests. The tests were conducted on dry and saturated sand samples prepared at relative densities from 40-80% and confining pressures of 100, 200 and 300 kPa. Figure 9 illustrates the typical results of the tests. The analysis of the results indicate that the effects of both relative density and confining pressure on liquefaction potential of sand are not significant. It is to be noted that studies by Talaganov (1996) does not reflect the effect of frequencies on liquefaction potential of sands. However, the results from the present investigations were also explored for the effect of frequency on liquefaction potential of sands by plotting the data with the results reported by Talaganov (1996) (Fig. 9). It is clear that the results fall in a narrow band with out much deviation from the best fit of the data. This demonstrates that the effect of frequency on the liquefaction potential of sandy soil is not significant even in strain-controlled approach.

Effect of Frequency on Dynamic Properties

Figure 10 illustrates the variation of shear modulus with shear strain at various loading frequencies of 0.2, 0.5, 1.0, 2.0 and 3.0 Hz. For the data shown in the figure 10, it is found that the range of frequencies used in the testing does not significantly affect the shear modulus values. These findings are in close agreement with the results reported by Drnevich and Richart (1970), Hardin (1965), Iwasaki et al. (1978) and Lin and Huang (1996) leading to the conclusion that the frequency of loading does not affect the response of sands to cyclic loading. Figure 11 illustrates the effect of frequency of cyclic loading on the damping ratios of sand. It is observed that the damping ratios are affected to some extent by the frequency of loading. Higher damping ratios are noticed at higher frequencies for a given shear strain in the range of frequencies considered. Therefore from the results of the present study it can be even possible to have frequency effect on damping ratios in the shear strains beyond 10^{-4} (0.01%). However, data fall with in the band proposed by Seed and Idriss (1970) for sands.

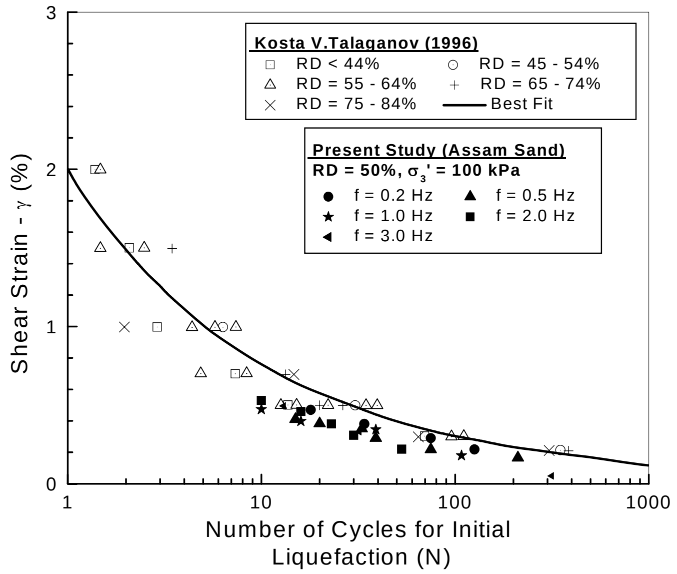


Figure 9: Relationship between shear strain and number of cycles for initial liquefaction at varying frequencies

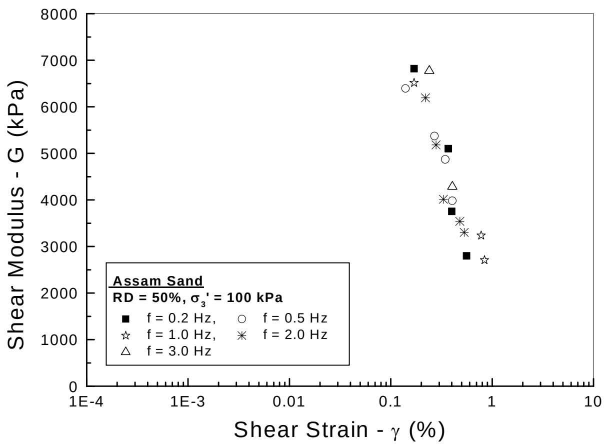


Figure 10: Effect of frequency on shear Modulus of sand

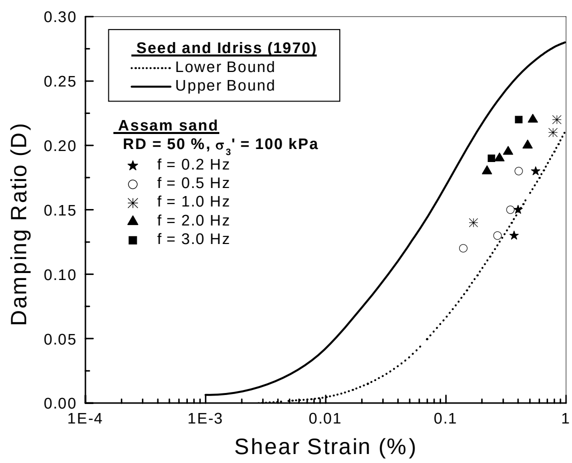


Figure 11: Effect of frequency on damping ratios of sand

CONCLUDING REMARKS

A detailed experimental investigation were carried out using cyclic triaxial testing to study the effect of frequency of cyclic loading on excess pore water pressure generation, liquefaction potential and strain dependent dynamic properties sandy soils using strain-controlled technique. The results of the studies on excess pore water pressure build up in sands under varying loading frequencies show that the difference between the magnitudes of pore water pressures at any given cycle is not much varied with the frequency of cyclic loading. Also, there exists single relationship between normalized pore water pressures and cycle ratios regardless of loading frequencies. The results of the study at ten cycles fall well with in the band suggested by Dobry (1985) indicating no effects of frequency on pore water pressure build up. Further, for various frequencies data compare well with the relationship proposed by Talaganov (1996) despite a wide range of shear strains. The test results show that the liquefaction potential of sands is independent of frequency of cyclic loading in the range of frequencies adopted. Further, the frequency of cyclic loading does not affect significantly the shear modulus values. However, the damping ratios are affected to some extent by the frequency of loading in the range of frequencies tested. Higher damping ratios are noticed for higher frequency of loading.

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