Dynamic properties of silty-sand varying saturation in a cyclic triaxial test

Kunjari Mog, & Anbazhagan P
Department of Civil Engineering, Indian Institute of Science, Bangalore 560012, India

ABSTRACT
The cyclic triaxial tests on partially saturated to fully saturated silty-sands were carried out to investigate the effect of saturation on dynamic soil parameter (such as shear modulus and damping ratio). The surface liquefied silty-sand which were erupted to the ground surface due to the 3rd January 2017, Manu earthquake, Tripura, India is used in the present study. Though the earthquake was of moderate magnitude with Mw 5.7, it produced liquefaction in the river bed as well as agricultural farmland adjacent to the Manu River. A constant volume split mold of size 50.1 mm internal diameter and 102 mm height was used in preparing the test specimens. The tests were carried out for two different relative densities (50 %, 30 %) with varying cyclic shear strain amplitudes. The reconstituted soil specimens prepared at partially saturated to fully saturated states were subjected to sinusoidal loading at 1 Hz frequency and results were compared. The same effective confining pressure of 100 kPa was maintained for all the tests specimen.

1 INTRODUCTION

The response of soils mainly controlled by the mechanical properties of the soil when subjected to cyclic and dynamic loadings. The mechanical properties include shear modulus, damping ratio, Poisson ratio, density, of which shear modulus and damping properties are the governing parameters which basically characterizes the dynamic behavior of soils. Hence, measurement of the dynamic soil properties such as shear modulus and damping ratio is vital for performing any geotechnical dynamic analysis or in the numerical modeling of soil-structure interaction studies. For this purpose, various laboratory tests, as well as field geophysical methods have been developed by several investigators. Generally, in the laboratory environment, small strain dynamic properties measurement is done using resonant column test, pulse wave test or bender element test and medium to large strain measurement is performed using cyclic triaxial test, cyclic simple shear and cyclic torsional shear apparatus. Often, small strain cyclic loading tests can also be conducted by introducing a high sensitivity gap- sensors or proximeters in the advanced-type triaxial apparatus (Kokusho 1980). On the other hand, in-situ small strain soil properties (shear wave velocity) can be measured by seismic down-hole method, cross-hole method, suspension method, refraction method, reflection method, surface wave method (Multichannel Analysis of Surface Wave (MASW), Spectral Analysis of Surface Wave (SASW). Though there has been a rapid development in the methods of field measurement of small strain soil properties (shear modulus), yet, the methods for direct measurement of the in-situ soil damping ratio do not exist.

Numerous past studies on shear modulus and damping properties of different types of soils are available in the literature, mostly, either on dry or saturated samples (Seed, 1970, Hardin & Drnevich,1972, Iwasaki et al. 1978, Kokusho 1980, Ellis et al. 2000, Menq & Stokoe, 2003, Wichtmann et al. 2010, Senetakis et al. 2013, Wichtmann et al. 2015). However, soils above the water table, subgrade soils of roads and railways can exist in a partially saturated state where voids between the soil particles are filled with a mixture of air and water. A few of previous studies exist on the static behaviour of partially saturated soils (e.g. MeiBner, & Becker, 1970); and few studies available on the effect of saturation on the dynamic properties of soils (Madhusudan & Kumar, 2013, Sharma & Maheshwari 2018. It is noted that in the previous studies as reported by authors Madhusudan & Kumar, 2013, there is an insignificant variation in the results of small strain dynamic soil properties between the dry and fully saturated condition; while Sharma & Maheshwari, 2018, reported that shear modulus is more for dry samples as compared to the saturated samples and exactly opposite trend was shown for the damping ratio. However, Seed, 1970, in their studies reported that damping ratio is observed to be higher for dry sand than those of saturated sands with a variation of 0 – 20 %. Since, most of the earlier studies were restricted to the small strain ranges and provides somewhat contradictory results, the study of dynamic soil properties by varying degree of saturation significant at large shear strain levels.

Hence, this study presents the investigations of the dynamic properties of silty-sand at large shear strains while it varies from partially saturated to fully saturated state. The strain-controlled cyclic triaxial test was performed on the surface liquefied silty-sand of Tripura, India. All the tests were conducted under the drained condition at a different level of saturation ratio viz. 0.25, 0.35, 0.50, 0.75, 0.96 and at different relative densities. An effective confining pressure of 100 kPa was maintained and sinusoidal loading frequency of 1 Hz is considered for conducting all the test specimens. The dynamic shear modulus and damping ratio were evaluated as a function of large shear strain, saturation ratio and number of cycles.

2 TEST MATERIAL

The test material chosen in the present study is surface liquefied silty-sand, which were ejected to the ground surface during the 3rd January 2017, Manu earthquake of Tripura, India. Though the earthquake was of moderate importance with a moment magnitude (Mw) of 5.7, it caused liquefaction in the river bed as well as agricultural farmland adjacent to the Manu River. Tripura is situated in the north-eastern part of India and located in the seismically active region adjacent to the Himalayan belt. Due to its geographic location, it has witnessed several earthquakes in the past. Hence, the study of dynamic soil properties is imperative for this region. The grain size distribution test of the collected sample used in this study is performed based on Indian Standard IS 2720 (1983). Based on the grain size analysis, the soil is classified as silty-sand. The basic index properties of the tested material are enumerated in Table 1.

Table 1. Physical properties of the tested material

Property Description	Value
Specific gravity, (G_s)	2.636
Grain Size Distribution	
Fine Sand	79.753
Silt & Clay	20.247
Silt	19.837
Clay	0.410
Uniformity coefficient (C_u)	2.903
Coefficient of Curvature (C_c)	0.861
Plastic limit	Non-Plastic
Maximum dry unit weight, (γ_{dmax})	1.741 g/cc
Minimum dry unit weight, (γ_{dmin})	1.395 g/cc
Indian standard classification	Silty-sand

3 SAMPLE PREPARATION

The dry-temping method is adopted to prepare all the tests specimen. At first, an appropriate amount of air-dried sample is weighed and divided into six equal parts. The soil sample is then poured into the cylindrical mold and compacted into six equal layers. The split mold of 50.4 mm internal diameter and 102 mm height is used so as to maintain the height to diameter ratio close to 2. A temping rod of 31 mm in diameter is employed to compact the soil sample into different layers. In order to maintain a uniform thickness throughout the specimen, each of the six layers was compacted at equal thickness. With the help of temping and by varying the number of blows, a total height of 102 mm is controlled throughout the specimen preparation. Before removal of the split mold, a constant vacuum pressure of 15 – 30 kPa was applied to the bottom of the specimen to keep the sample intact. The samples were prepared at two different relative densities viz. 30 %, and 5 0% respectively. After the sample preparation, each time the specimen diameter and height were checked with 0.01 mm Vernier caliper. Afterward, the triaxial cell is assembled, it filled with water and cell pressure is applied. During application of the cell pressure, vacuum pressure is released simultaneously, and the flow of CO_2 is permitted to pass from the bottom to the top of the specimen. CO2 can expedite the saturation process as it is heavier than air and easily soluble in water. This CO_2 saturation is let on to continue for about 15 – 20 minutes and subsequently, de-aired water is flushed through the bottom of the specimen. The flushing of de-aired water was continued until the collected water equals twice the specimen volume.

Saturation process is then performed by incremental increase of the cell pressure and back pressure while maintaining the effective confining stress 10 kPa. After each increment of the cell pressure, the value of B or Skempton pore-pressure parameter (B) is calculated to ensure the saturation status. The process of increasing both the cell pressure and back pressure was then repeated until the required B value is achieved. Specimens were prepared at two different relative densities and saturation was done for a Skempton's B value of 0.25, 0.35, 0.50, 0.75, 0.96 restively.

It is to be mentioned here that specimen is considered to be fully saturated when B value exceeds 0.95. After the saturation process is completed for a chosen B value, isotropic consolidation is then performed to the desired confining stress by increasing the cell pressure and keeping the back-pressure constant. The consolidation is continued for about 30 minutes to 1 hour or it is stopped when the volume change of the specimen is no longer significant. In this study, an effective confining pressure of 100 kPa was maintained for all the tests specimen. Finally, cyclic loading is then applied to the consolidated specimens under the drained condition.

4 CYCLIC TRIAXIAL TESTING EQUIPMENT

The GCTS resonant column cum cyclic triaxial equipment is used for testing all the soil specimens. The equipment is servo-controlled capable of performing the stress-controlled and strain-controlled test under both static and cyclic loading conditions. The cyclic axial stress is produced by means of a pneumatic loading system. A view of the equipment set up with control unit and data acquisition system is shown in Figure 1. In this system, the piston movement is controlled by means of an air regulator with desired amplitude and frequency. It can generate irregular loading waveform, sinusoidal, triangular and square type waveform. The load cell capacity is 10 kN with a frequency range varies from 0.01 Hz – 10 Hz. The maximum capacity of the three pressure transducers to measure the cell pressure, back pressure and pore pressure is 1000 kPa. The change in volume can also be measured by the automatic volume change sensor. For the present study, the strain-controlled cyclic triaxial test was selected to investigate the dynamic properties of silty-sand for varying saturation levels. The sinusoidal loading waveform with a loading frequency of 1 Hz is chosen for conducting all tests.

Figure 1. View of Triaxial set-up at Soil Mechanics Lab, IISc

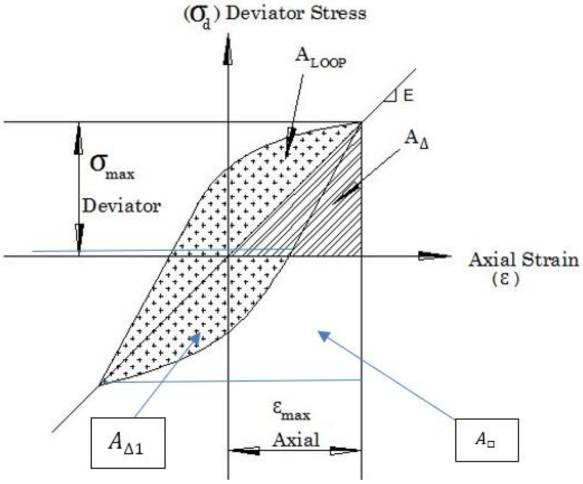

Figure 2. Typical hysteresis loop for one cycle of loading

The plot of deviator stress (σ_d) versus axial strain (ε) is the output which can be obtained from any cyclic triaxial test. It is also referred to as the hysteresis loop. The nature of the typical hysteresis loop for one cycle of loading is shown in Figure 2. From this, initially modulus of elasticity, E is determined using $E = \sigma_d/\varepsilon$. Once E is determined, the value of shear modulus can be calculated using the following expression:

$$G = E/2\ (1 + \mu) \qquad [1]$$

Here, μ =Poisson's ratio. Its value ranges between 0.1 – 1.0 for sand and gravelly sand (Bowles). However, in the present study, Poisson's ratio is assumed as 0.5 for both saturated & partially saturated specimens. Again, referring to Figure 3, from the same hysteresis loop, the damping ratio (D) which is the energy dissipation property of the material can be calculated from the following conventional equation:

$$D = \frac{A_{loop}}{4\pi A_\Delta} \qquad [2]$$

Here, A_{loop}= Area of the hysteresis loop and A_Δ= Area of the triangle. The above equation may be used only for the symmetrical hysteresis loop as also suggested by Kumar et al. 2017, however, for non-symmetrical loop, the following modified equation can be used:

$$D^* = \frac{A_{loop}}{\pi(A_\Delta + A_{\Delta 1} + A_\square)} \qquad [3]$$

Here, D^* = Damping ratio considering non-symmetrical loop, A_{loop}= Area enclosed by the hysteresis loop and $A_\Delta + A_{\Delta 1}$= Area of the two triangles, $A_\square$ = Area of the rectangle. The damping ratio determined from Equation 3 is reported in this study.

5 TEST RESULTS AND DISCUSSION

Strain-controlled cyclic triaxial tests were conducted on reconstituted consolidated silty-sand specimens. All the tests were performed under the drained condition. Each specimen was subjected to 10 number of cycles of shear stress application with a loading frequency of 1 Hz as in most earthquakes, the number of significant cycles is likely to be less than 20. The shear modulus (G) and damping ratio (D) obtained at 10th cycles of loadings are considered as a representative value (Iwasaki et al. 1978, Kokusho 1980) for comparing G & D curves with respect to shear strain amplitude. The tests were conducted at two different relative densities viz. 30 % & 50 % respectively, at an effective confining pressure of 100 kPa. The summary of tests conducted at various conditions is presented in Table 2.

Table 2. Summary of cyclic triaxial tests conducted on silty-sand

Relative Density (Dr)	Skempton's B value	Shear Strain Amplitude (%)
30%	0.25	0.09, 0.30, 0.45, 0.60, 0.75, 0.90, 1.0. 1.5, 3.0, 4.5, 6.0
30%	0.50	
30%	0.75	
30%	0.96	
50%	0.35	
50%	0.50	
50%	0.75	
50%	0.96	

5.1 Effect of Number of Cycles on Shear Modulus and Damping at large shear strain and at different saturation levels

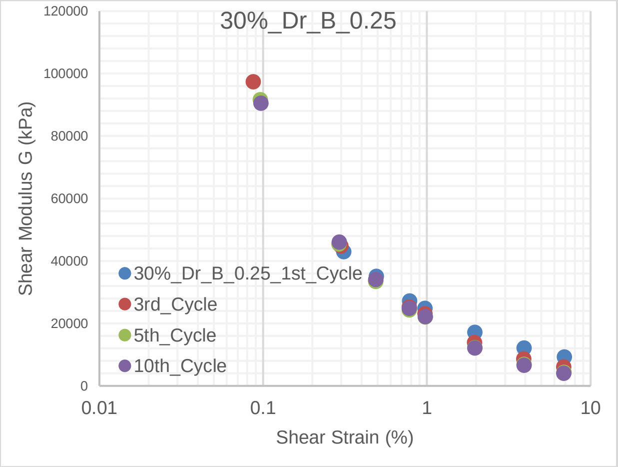

Figure 3 (a). Influence of number of cycles on shear modulus

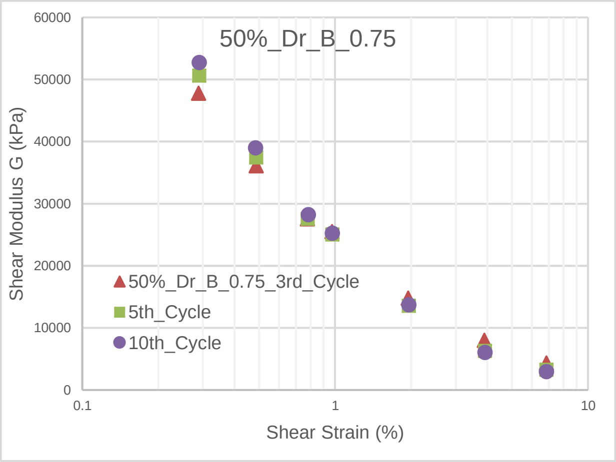

Figure 3 (b). Influence of number of cycles on shear modulus

The strain-controlled drained cyclic triaxial tests were conducted to investigate the effect of the number of cycles on dynamic properties of partially saturated to fully saturated state. The Skempton's B parameter was chosen as 0.25, 0.50, 0.75 and 0.96 respectively. Two types of relative density (30 % & 50 %) with an effective confining pressure of 100 kPa is considered. Fig. 3 shows a plot of shear modulus G with respect to cyclic shear strain amplitude for different number cycles i.e., 1st, 3rd, 5th, and 10th cycle on a loose sand specimen (Dr=30 %). The saturation ratio considered is B = 0.25. From the Figure 3(a), it can be observed that for a given value of confining stress and number of cycles of stress application, the value of shear modulus decreases with the amplitude of shear strain. It can also be observed that the variation of shear modulus is nearly equal between the number of cycles N = 1 to 10 for a shear strain range 0.08 to 1% for a loose specimen. However, only a slight variation in the value of G can be noticed after 1% of shear strain between the cycle 1 & 10 which can be neglected, while testing is conducted in the pneumatic loading system. Likewise, an insignificant variation in the value of shear modulus is noticed at 3rd, 5th, and 10th, cycles of loading for different saturation levels considered in this study.

Similarly, samples were tested for 50% relative density at different saturation levels (B=0.25, 0.50, 0.75, 0.96) and result is shown in Figure 3(b). In order to avoid the overlapping in the data, the results pertaining to saturation ratio, B = 0.75 is presented. From the plot of G versus shear strain, as illustrated in Figure 3(b) for a medium dense sample, it can be observed that for a given value of shear strain, the magnitude of G increases with the increasing number of cycles (3rd, 5th, 10th cycles); though, the difference is small. The similar trend is reported in the literature by Silver and Seed, 1971. The same trend is observed for other test samples as well at different saturation ratio. Hence, from this result, it can be stated that the number of cycles does not have much effect on the value of shear modulus for a given shear strain amplitude and at 100 kPa confining stress, while 10 number of cycles of loading is considered to obtained G value. This result is in accordance with the findings of Kokusho (1980) at small strain levels. Even for a partially saturated to fully-saturated conditions, the effect of number of cycles on G at large shear strain is insignificant.

The influence of the number of cycles on the damping ratio is discussed in this section. The nature of the stress versus shear strain behavior of loose sand under different shear strain levels for 10th cycles of loading is shown in Figure 4 (a) – (f). Considering the hysteresis loop of this type and using Equation 3, the hysteretic damping obtained from the cyclic triaxial test for a relative density of 30 % and 50 % are shown in Figure 5 (a) & (b). It can be clearly observed from Figure 5 that the magnitude of the damping ratio decreases with the increasing number of cycles for a given value of shear strain amplitude. This trend is observed for both loose and medium dense specimen. It can also be seen that the value of damping ratio decreases with the increase of shear strain amplitude at large shear strain (beyond 1% Strain), but strain levels of up to 1 %, magnitude of damping increases with the increase of shear strain (Silver & Seed 1971, Mog & Anbazhagan 2018). The difference is rather small. The details about increasing and decreasing trend of damping ratio at medium to large shear strain levels are explained in the subsequent subsection.

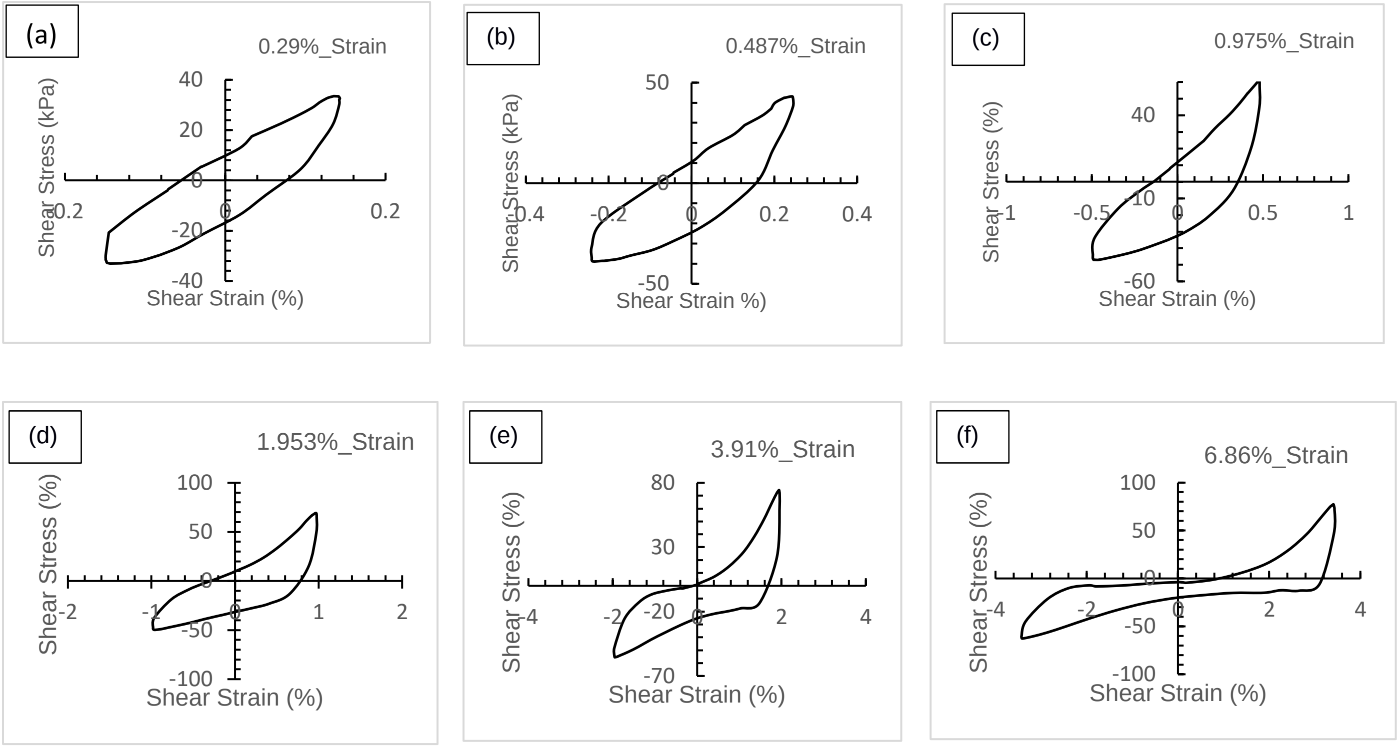

Figure 4. Typical Stress-strain behavior of loose sand at 10th Cycles of loading for partially-saturated condition at B value 0.25

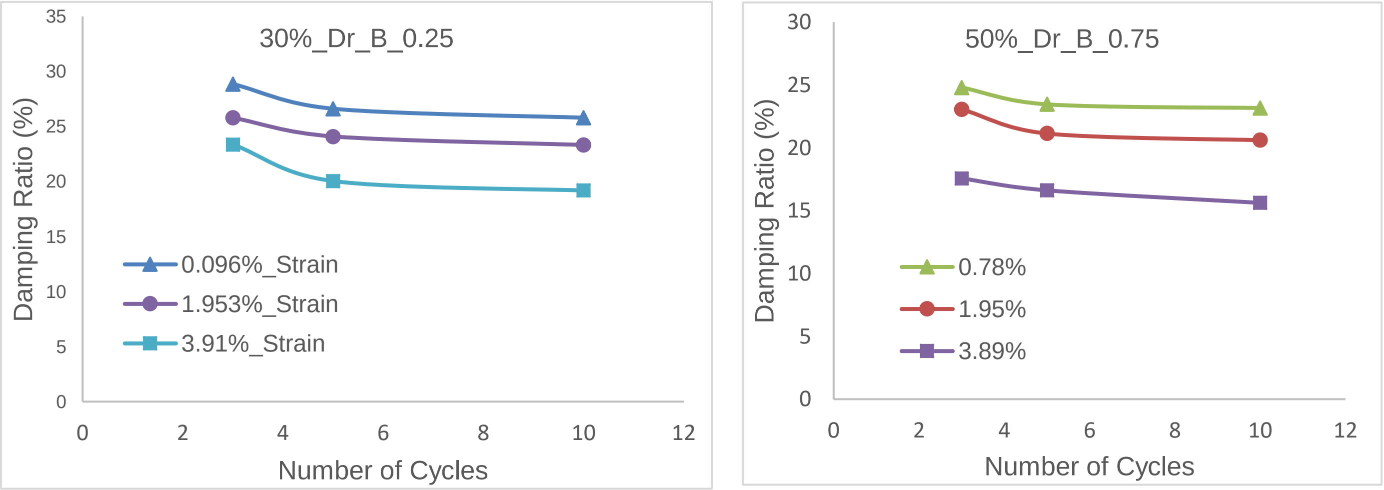

Figure 5 (a). Influence of number of cycles on damping ratio (D) at different shear strain levels at 30% relative density for B value 0.25. Figure 5 (b). Influence of number of cycles on D at different shear strain levels at 30% relative density for B value 0.75

5.2 Effect of Saturation on shear modulus and damping properties

The effect of saturation on shear modulus at large shear strain was investigated by performing the strain-controlled cyclic triaxial test at two different relative densities under different saturation levels such as B = 0.25, 0.50, 0.75, 0.96 respectively. The tests were carried out under drained condition at an effective confining pressure of 100 kPa and at 1 Hz loading frequency. The magnitude of the shear modulus and damping versus saturation ratios are presented in Figure 6.

From Figure 6 (a) it can be observed that the value of shear modulus remains nearly same in three different levels of saturation viz. B=0.25, 0.50 and 0.75, at large shear strain amplitudes. Similar observations were made by Kumar & Madhusudan, 2012, Tatsuoka et al. 1979 in small strain measurement. In contrast to the partially-saturated condition, an increase in the value of G can be observed at the fully-saturated level (when B value is 0.96). This is due to a decrease in the height of specimens under the drained condition with the increasing number of shear stress application, which eventually causes a reduction in the void ratio and little stiffening of the specimens. For example, it can be seen from the Figure 6 (c) & 6 (d) that in drained conditions, the volume change in the saturated specimen (B=0.96) is slightly higher than that of the unsaturated specimen (B = 0.25). Also, it has been observed that the difference in G values between partially-saturated and saturated silty-sand specimen is less than 10% and hence, for all practical purposes, this difference can be negligible while using the normalized shear modulus reduction curves.

Figure 6 (b) illustrates the damping ratio variation with different saturation levels for 30% relative density at the 10th cycle. It can be observed that for a given confining pressure of 100 kPa, the difference in the damping ratio between the fully-saturated and partially saturated silty-sand varies from 2 – 10 %. The fully saturated soil specimens exhibit higher damping values than the partially saturated specimens. This result appears to be in accordance with the findings of Madhusudan & Kumar, 2013 at small shear strain ranges. It can also be seen that at a saturation ratio of 0.5, the magnitude of damping for different strain amplitudes tends to merge together. However, this need further investigation. Hence, based on the results obtained under drained condition, it can be inferred that variations in the saturation ratio (B value 0.25 to 0.96) have a negligible effect on the magnitude of the shear modulus of silty-sand. However, the degree of saturation tends to show little effect on the damping properties at large shear strain.

5.3 Effect of Relative Density on shear modulus and damping at various saturation ratio

The effect of relative density on dynamic properties of partially saturated to fully-saturated silty-sand is investigated under strained controlled cyclic triaxial testing. Two types of relative density such as 30 % and 50 % are

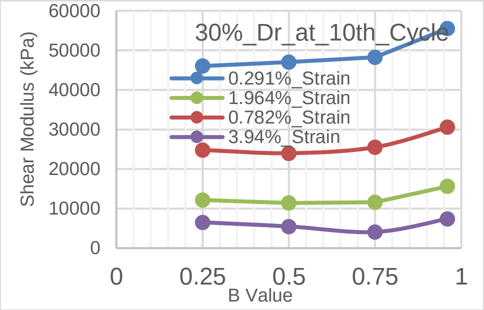

Figure 6 (a). Effect of saturation on shear modulus

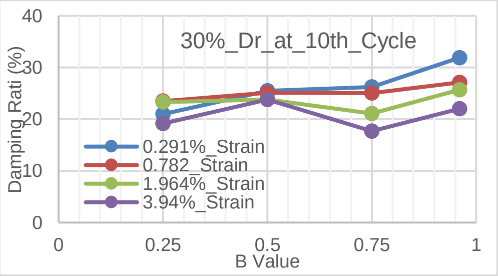

Figure 6 (b). Effect of saturation on damping ratio

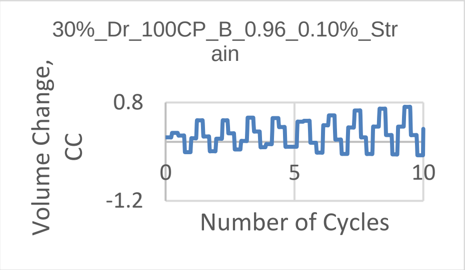

Figure 6 (c) Volume change vs. number of cycles at B value 0.96

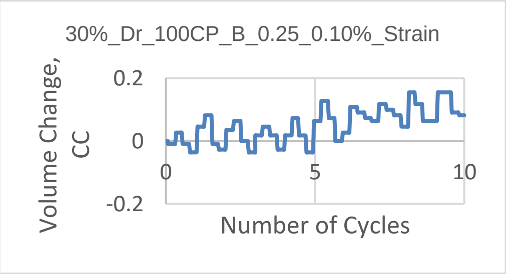

Figure 6 (d) Volume change vs. number of cycles at B value 0.25

considered for this purpose. The variation of shear modulus and damping ratio against the shear strain amplitude are illustrated in Figure 7 for 50 % relative density and combined results for both 30 % and 50 % relative density is presented in Figure 8. It can be observed from Figure 7 (a) that the magnitude of shear modulus decreases with an increase in shear strain amplitudes irrespective of various saturation levels considered. The value of shear modulus is higher for partially saturated specimens than that of the fully-saturated specimen. However, the difference in the value of G between partially saturated and fully saturated specimens reduces significantly beyond 0.1 % of shear strain. These observations are also valid for 30 % relative density samples under 100 kPa confining pressure which is also shown in Figure 8 (a).

Similarly, Figure 7 (b) illustrates the variation of damping ratio with shear strain amplitudes. It has been observed from Figure 7 (b) that at a given shear strain amplitude for a saturation ratio 0.35 to 0.75, a minute increase in damping value is noticed, though the difference is insignificant. The damping ratio is observed to be higher for the fully-saturated specimen (for B = 0.96) compared to the partially saturated specimens. Figure 7 (b) also indicates that the magnitude of damping is increased up to a shear strain level of 1 %, after which a decreasing trend in the value of damping is followed. A similar trend is also reported by Mog & Anbazhagan 2018 and Kumar et al. 2017. This increasing and decreasing trend in the value of damping with shear strain amplitude is observed for both partially saturated and fully-saturated silty-sand samples.

Figure 8 shows the comparison of the dynamic properties of silty-sand at two different relative densities under various saturation levels. The variation of shear modulus versus shear strain for both 30 % and 50 % relative density is illustrated in Figure 8 (a).

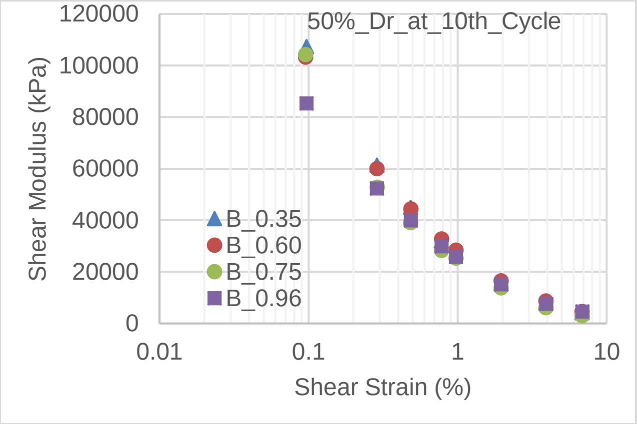

Figure 7 (a). Variation of G for various saturation levels at 50% relative density

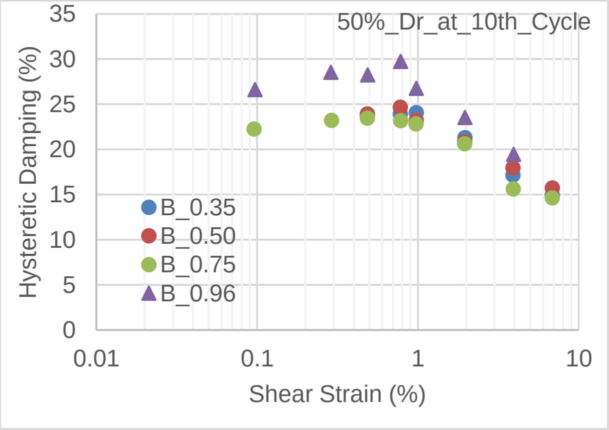

Figure 7 (b). Variation of D for various saturation levels at 50% relative density

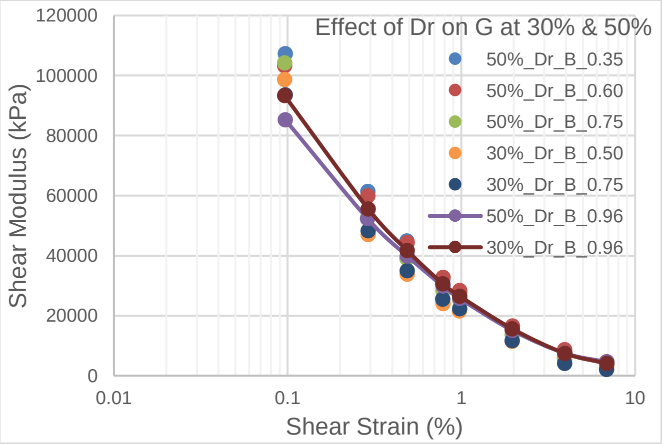

Figure 8 (a). Effect of saturation on G under different saturation levels and two relative densities

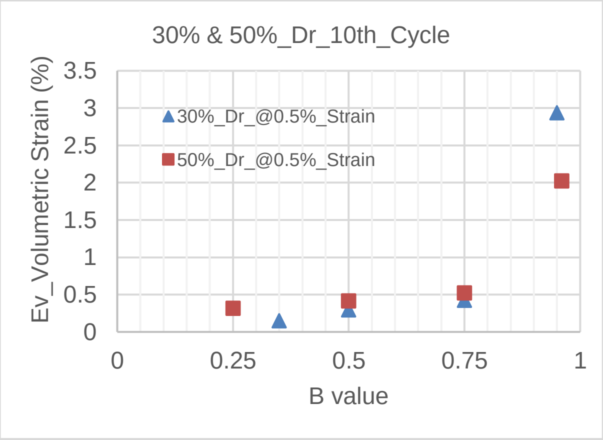

Figure 8 (b) Volumetric strain versus B parameter for 30% & 50% relative density at 0.5% strain level

It can be observed that at fully saturated condition (i.e., B = 0.96) the magnitude of the shear modulus of the loose specimen is little higher than the medium dense specimen, though the difference is insignificant. This is due to the decrease in height of saturated loose specimens at the beginning of the testing that stiffens the sample under drained condition. It is evident from the plot between the volumetric strain versus saturation ratio as shown in Figure 8 (b) for two different relative densities (30% & 50%). It can be observed from the Figure 8 (b) that the loose specimen in fully saturated condition undergoes more volume change than medium dense specimen resulting in increase of the shear modulus. However, shear modulus (Figure 8 (a)) for partially saturated samples (B = 0.25 to 0.75) is observed to be slightly higher for medium dense specimens (50 %) compared to the loose specimens (30 %). At shear strain levels lesser than 0.1 % or close to that the shear modulus variation is noticeable for partially saturated samples. The reason may be attributed to the suction effect at shear strain levels lesser than 0.1 %. The difference in the shear modulus value between partially saturated and fully-saturated condition is about 15 % at strain levels lesser than 0.1%, however, beyond 0.1 % the difference is less than 10%. Hence, it can be concluded that relative density does not have a significant influence on the shear modulus at large shear strain for varying saturation conditions.

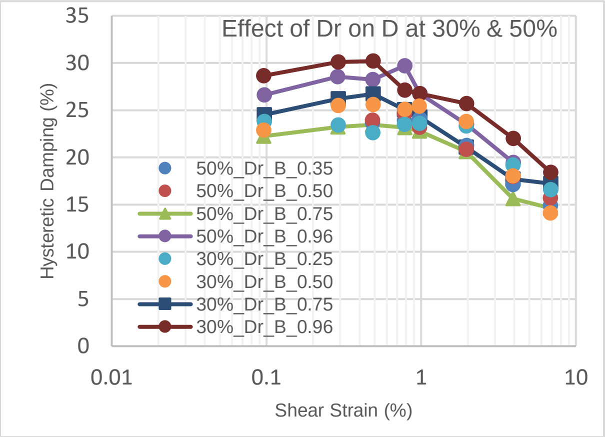

Figure 8 (c). Effect of saturation on D under different saturation levels and two relative densities

Figure 8 (c) shows the variation of damping ratio with shear strain at various saturation levels. It can be observed that the damping ratio is higher for loose samples than those of medium dense samples at fully-saturated condition (B value 0.96). Similarly, for partially saturated condition (B value 0.25 to 0.75), the magnitude of damping is observed to be higher for loose specimens. In 8 (c), the square box with a smooth line represents for 30 % relative density and triangular symbol represents for 50 % relative density at the same saturation ratio B = 0.75. The damping ratio for the fully-saturated samples is about 5 – 8 % higher than the partially saturated samples. From Figure 8 (c), it can also be seen that the degree of saturation has little influence on damping ratio variation at large shear strain amplitudes for the two relative density tested under drained condition. It may be mentioned here that in general, the matric suction and shear strength are directly related; as the matric suction increases, the shear strength of a sample increases (Fredlund et al., 2013). However, the influence of matric suction is not reported in the present studies, though it may have influence on the results of partially saturated specimens.

6 CONCLUSIONS

The dynamic properties of silty-sand for partially saturated to fully-saturated states are investigated in the cyclic triaxial instrument under drained condition. Based on the obtained results at large shear strain levels, it can be concluded that the degree of saturation has an insignificant effect on the magnitude of shear modulus and damping ratio of silty-sand at 10th cyclic of loading or less. Also, the number of cycles does not have significant effect on the value of shear modulus and damping (as shown in Figure 3 and Figure 5) for a given shear strain amplitude and at 100 kPa confining stress, while 10 number of cycles of loading is considered.

It has been observed that the variations in the saturation ratio (for B value 0.25 to 0.96) have a negligible effect on the magnitude of the shear modulus of silty-sand. However, the degree of saturation tends to show little effect on the damping properties at large shear strain levels. The fully saturated soil specimens tend to show higher damping values than the partially saturated specimens. The difference in the damping ratio between the fully-saturated and partially saturated silty-sand is observed to be varied from 2 – 10 %.

It has also been observed that the magnitude of shear modulus decreases with an increase in shear strain amplitudes irrespective of various saturation levels considered. The value of shear modulus is lesser for partially saturated specimens than that of the fully-saturated specimen, though the difference is small and can be ignored.

The damping ratio is observed to be higher for fully-saturated specimen (for B = 0.96) compared to the partially saturated specimens (B = 0.25, 0.50, 0.75). Also, the magnitude of damping is increased up to a shear strain level of 1%, after which a decreasing trend in the value of damping is observed. A similar trend was also reported by Mog & Anbazhagan 2018.

It can also be concluded that relative density does not have a significant influence on the shear modulus at large shear strain for partially saturated to fully saturated conditions. However, it has little influence on the value of damping ratio at large shear strain amplitudes. The damping ratio for the fully-saturated samples is about 5 – 8% higher than the partially saturated samples.

REFERENCES

Bowles, J. E. (1976). Foundation Analysis and Design., 1996. *Peoria, Illinois*.

Ellis, E. A., Soga, K., Bransby, M. F., & Sato, M. (2000). Resonant column testing of sands with different viscosity pore fluids. *Journal of Geotechnical and Geoenvironmental Engineering*, *126*(1), 10-17.

Fredlund, D. G., Rahardjo, H., & Fredlund, M. D. (2013). Unsaturated soil mechanics in engineering practice. *대한토목학회지,* 61(5), 101-101.

Hardin, B. O., & Drnevich, V. P. (1972). Shear modulus and damping in soils: measurement and parameter effects. *Journal of Soil Mechanics & Foundations Div*, *98*(sm6).

IS: 2720 (Part 4): Methods of test for soils: Grain size analysis. *Bureau of Indian Standards (BIS)*, New Delhi (1983).

Iwasaki, T., Tatsuoka, F., & Takagi, Y. (1978). Shear moduli of sands under cyclic torsional shear loading. *Soils and Foundations*, *18*(1), 39-56.

Kokusho, T. (1980). Cyclic triaxial test of dynamic soil properties for wide strain range. *Soils and foundations*, 20(2), 45-60.

Kumar, J., & Madhusudhan, B. N. (2012). Dynamic properties of sand from dry to fully saturated states. *Geotechnique*, *62*(1), 45-54.

Kumar, S. S., Krishna, A. M., & Dey, A. (2017). Evaluation of dynamic properties of sandy soil at high cyclic strains. *Soil Dynamics and Earthquake Engineering*, *99*, 157-167.

Kumar, S. S., Krishna, A. M., & Dey, A. (2017). Evaluation of dynamic properties of sandy soil at high cyclic strains. *Soil Dynamics and Earthquake Engineering*, *99*, 157-167.

Madhusudhan, B. N., & Kumar, J. (2013). Damping of sands for varying saturation. *Journal of Geotechnical and Geoenvironmental Engineering*, *139*(9), 1625-1630.

MeiBner, H., & Becker, A. (1970). Dynamic behaviour of partially saturated sand. *WIT Transactions on The Built Environment*, *15*.

Menq, F. Y., & Stokoe, K. H. (2003). Linear dynamic properties of sandy and gravelly soils from large-scale resonant tests. *Deformation characteristics of geomaterials*, 63-71.

Mog, K., & Anbazhagan, P. (2018, November). Dynamic Properties of Surface Liquefied Site Silty-Sand of Tripura, India. In *International Congress and Exhibition" Sustainable Civil Infrastructures: Innovative Infrastructure Geotechnology"*(pp. 140-154). Springer, Cham.

Seed, HB (1970). Soil moduli and damping factors for dynamic response analysis. *EERC*.

Senetakis, K., Anastasiadis, A., & Pitilakis, K. (2013). Normalized shear modulus reduction and damping ratio curves of quartz sand and rhyolitic crushed rock. *Soils and Foundations*, *53*(6), 879-893.

Sharma, P., & Maheshwari, B. K. (2019). Effect of Saturation on Dynamic Properties of Solani Sand. In *Soil Dynamics and Earthquake Geotechnical Engineering* (pp. 51-55). Springer, Singapore.

Silver, M. L., & Seed, H. B. (1971). Deformation characteristics of sands under cyclic loading. *Journal of Soil Mechanics & Foundations Div*.

Wichtmann, T., Hernández, M. N., & Triantafyllidis, T. (2015). On the influence of a non-cohesive fines content on small strain stiffness, modulus degradation and damping of quartz sand. *Soil Dynamics and Earthquake Engineering,* 69, 103-114.

Wichtmann, T., Niemunis, A., & Triantafyllidis, T. (2010). On the “elastic” stiffness in a high-cycle accumulation model for sand: a comparison of drained and undrained cyclic triaxial tests. *Canadian Geotechnical Journal*, *47*(7), 791-805.

Authors' response to comments from reviewer

The authors thank the editor and reviewer for providing the valuable comments on the article. All recommended revisions have been implemented. The responses to reviewer comments are provided as follows:

1 INTRODUCTION:

1. **Reviewer:** One word (geotechnical)

   Authors' response: As per suggestion, it is corrected in the revised version. Pls see in the Introduction section.

2. It is well recognized that the response of soil-foundation-structural systems is not that sensitive to the variations in the value of Poisson's ratio. Typically, it's value ranges from 0.25 – 0.35 for cohesion-less soils and 0.35 -0.45 for cohesive soils.
   Reviewer: This statement is not clear for me. Please, clarify and support it with references.

   Authors' response: As the source is not authentic, to avoid the ambiguity, it is removed from the text.
   It was referred from the following internet source:
   https://webcache.googleusercontent.com/search?q=cache:-xcW-xekfN8J:https://www.ikbooks.com/home/samplechapter%3Ffilename%3D33_Sample_Chapter.pdf+&cd=2&hl=en&ct=clnk&gl=in

3 SAMPLE PREPARATION Section:

3. **Reviewer:** Please, explain the procedure that you used to target the effective confining pressure to 100 kPa for diffident B values.

   Authors' response: To obtain different saturation ratio i.e., B value equals to 0.25,0.50,0.75, at first, Cell Pressure (CP) = 40, Back Pressure (BP) = 30 is applied and kept for some time. After 25-30 minutes, CP is increased to 60 kPa (drainage valve is closed), while BP of 30 kPa is held constant. As confining pressure is applied with an increment of 20 kPa (i.e., 40 kPa to 60 kPa), the pore-water-pressure of the soil specimen increases by Δu (as drainage is prevented). This increase in the pore water pressure is measured & B value is calculated using the expression $B = {}^{\Delta u}/_{\Delta_{\sigma 3}}$ where, B is referred to Skempton's pore pressure parameter, Δu as change in pore pressure and $\Delta_{\sigma 3}$ as change in confining pressure.

   In the next increment, (drainage valve is opened) CP = 60, BP = 50 is applied and after about 30 minutes, (drainage valve is closed) B value is checked by increasing the CP to 80 and keeping the BP constant (50 kPa). This incremental increase (20 kPa each time) of the CP & BP was then repeated until the required B value is achieved. The difference between the CP & BP is maintained as 10 kPa throughout the saturation process. Also, it should be mentioned here that to obtain the B value greater than 0.95 or to achieve fully saturated condition, an incremental increase of 30 kPa is maintained, as it was difficult to achieve B value greater than 0.95 when 20 kPa incremental increase is maintained to the CP & BP.

   After the saturation process is completed for different B values, isotropic consolidation is performed (drainage valve is opened) by increasing the CP while keeping the constant BP. Here, constant BP refers to the pore water pressure reached during the final saturation B-check. The cell pressure is then applied in such a way that the difference between the CP & BP meet the target effective confining pressure, which is 100 kPa in this study. The consolidation is continued for about 30 minutes to 1 hour or it is stopped when the volume change of the specimen is no longer significant (Please see Figure 1). Finally, cyclic loading is then applied to the consolidated specimens under the drained condition. The same procedure is followed (for all the specimens) to conduct the cyclic test under different B values at 100 kPa effective confining pressure. The measurement of the Skempton's parameter B obtained for 50% relative density specimen is enumerated in Table 1. However, due to page limitation, the Table 1 is not given in the revised manuscript.

4. **Reviewer:** Did B values maintain constant during the consolidation stage? and cyclic loading? How was it controlled? Please clarify that and provide a consolidation figure.

   Authors' response: During the consolidation and cyclic loading stage, B value was not measured. After achieving the required saturation ratio (i.e., B values of B= 0.95,0.75, 0.50, 0.25), then isotropic consolidation is performed followed by the cyclic loading. The consolidation figure obtained at 30% relative density and B value corresponding to 0.96 is shown in Figure 1 as suggested.

Table 1: Measurement of Skepmton's B value parameter obtained at 50% relative density

Time (Approx.)	**Drainage Valve**	**CP (Cell Pressure)**	**BP (Back Pressure)**	Δu **(Change in Pore Pressure)**	$B = \Delta u / \Delta_{\sigma 3}$
0		40	30	-	-
After 30 minutes	Closed				
		60	35	5	0.25
	Opened				
		60	50	-	-
60 minutes	Closed				
		80	61	11	0.55
	Opened				
		80	70	-	-
90 minutes	Closed				
		100	83	13	0.65
	Opened				
		100	90	-	-
120 minutes	Closed				
		120	104	14	0.7
	Opened				
		120	110	-	-
150 minutes	Closed				
		140	125	15	0.75
	Opened				
		140	110		
220 minutes	Consolidation	210	110		

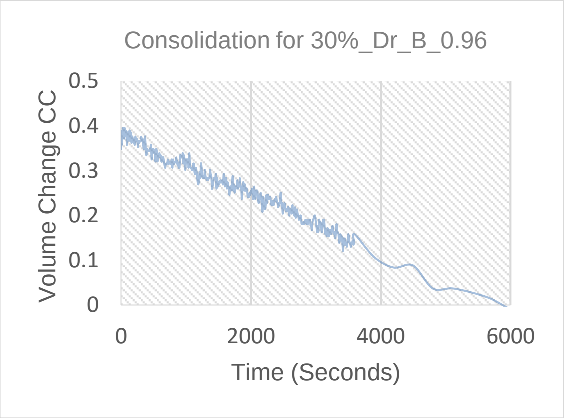

Figure 1. Volume change vs. time for 30 % relative density specimen during consolidation stage at 100 kPa confinement

5. **Reviewer:** What is the influence of matric suction (pore pressure -water pressure) on the results? Did you measure the matric suction? Please clarify that.
   Ref. might help:
   Book: Unsaturated Soil Mechanics in Engineering Practice, by D. G. Fredlund, H. Rahardjo & M. D. Fredlund, 2012, Chapter 11.

Authors' response: Authors thank the reviewer for the valuable comment. The matric suction was not measured for the present studies. However, it can be seen from the results that there was not much variation (less than 10 %) in the shear modulus value with varying degree of saturation at large shear strain levels. It may be possible that matric suction did not have significant influence at large shear strain levels. In future, the effect of matric suction on dynamic response of the same soil will be carried out under different confining pressures and high relative densities. In addition, whether the method of preparation with CO2 saturation & without CO2 saturation has an influence or not will be studied.

The following sentences have been added in the revised manuscript: In general, the matric suction and shear strength are directly related; as the matric suction increases, the shear strength of a sample increases (Fredlund et al., 2013). However, the influence of matric suction is not reported in the present studies, though it may have influence on the results of partially saturated specimens. Please see in the "5.3 Effect of Relative Density on shear modulus and damping at various saturation ratio"

4 CYCLIC TRIAXIAL TESTING EQUIPMENT:

6. Here, μ=Poisson's ratio, which value may be assumed as 0.5 for saturated sand specimens.

Reviewer: Please justify of using the Poisson's ratio of 0.5 in drained condition.

Authors' response: According to Kokusho 1980, the shear modulus and damping ratio for both drained and undrained condition yields relatively coinciding results when Poisson's ratio, μ is assumed as 0.5. It was also mentioned that when μ is assumed as 0.3, the curves are shifted little left along the logarithmic axis of γ resulting no significant difference. Please see the Figure 2 as given below.

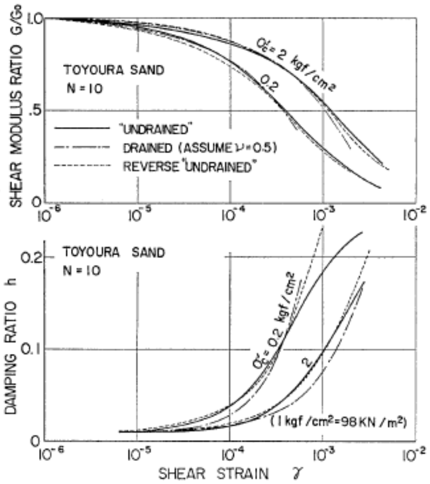

Figure 2. Comparison of undrained tests and drained tests in terms of G/G0 vs. logγ and damping vs. logγ relationships (Kokusho 1980).

Although, Kokusho (1980) is reported for the small shear strain levels, however, it can be expected that at high shear strain level, Poisson's ratio may vary, due to the changes in the soil's cross section. As the drained test in the cyclic triaxial only measures axial strain and young's modulus, it is possible to obtain the shear modulus value by only changing the Poisson's ratio in the following relationship:

$$G = E/2\,(1+\mu) \qquad [1]$$

Figure 3 shows the plot of shear modulus vs. shear strain for two different Poisson's ratios (0.35, 0.50). It can be observed from Figure 3 that G is little high for Poisson's ratio of 0.35 than for 0.50, which is obvious based on the relationship given in equation 1 (above). However, in the present study, cyclic test is conducted assuming the Poisson's ratio as 0.5, considering the results of Kokusho (1980). In future, the same studies will be extended for undrained condition and effects of drainage conditions on the dynamic properties of soil will be reported elsewhere.

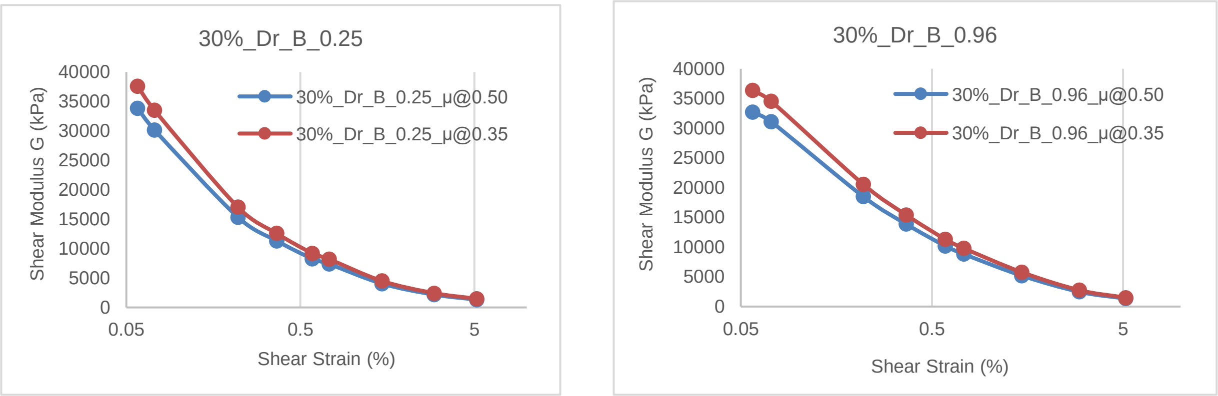

Figure 3. Comparison of shear modulus for two different Poisson’s ratios (0.35 & 0.50)

Reviewer: Also, did you use the same value for unsaturated conditions? Please explain

Authors’ response: Yes, the same value of Poisson’s ratio is used for unsaturated conditions. This is added in the revised version of the manuscript. Please see in “4 cyclic triaxial equipment section”.

5.1 Effect of Number of Cycles on Shear Modulus and Damping at large shear strain and at different saturation levels:

7. Marks are missed, please check the figures. Figure 3(a) & (b).

   Authors’ response: Figures are checked and marked with gridlines.

8. Hence, from this result, it can be stated that the number of cycles does not have much effect on the value of shear modulus for a given shear strain amplitude and confining stress, while 10 number of cycles of loading is considered to obtained G value.

   Reviewer: Please check, is it applied for small shear strain amplitude too?
   Authors’ response: Yes, the number of cycles has little effect on the value of shear modulus (Kokusho 1980). It is applicable for small shear strain amplitude too. This has been added in the revised text.

   Reviewer: The results do not show the effect of no. of cycles on the shear modulus for different confining pressures? Please justify the statement or provide references.
   Authors’ response: The authors agree with the reviewer comment that the results do not show the effect of number of cycles on the shear modulus for different confining pressures, as the present study is conducted only at 100 kPa confining pressure. The sentence is corrected in the revised version.

9. **Reviewer:** Please be more detail of the figure title. Figure 5(a) & 5(b).

   Authors’ response: It has been modified in the revised manuscript.

5.2 Effect of Saturation on shear modulus and damping properties:

10. **Reviewer:** From Figure 6 (a) it can be observed that the value of shear modulus remains nearly identical in three different levels of saturation viz. B=0.25, 0.50 and 0.75, at large shear strain amplitudes.

    Reviewer: Do you mean "same".
    Authors’ response: Yes. The “identical” word is replaced with “same” in the revised version.

11. In contrast to the partially-saturated condition, an increase in the value of G can be observed at the fully-saturated level (when B value is 0.96). This is due to a decrease in the height of specimens under the drained condition with the increasing number of shear stress application, which eventually causes a reduction in the void ratio and little stiffening of the specimens.

Reviewer: Please, provide more information such as volume change/void ratio figure that explain the variations. Sorry it is not clear for me that G and D increase for saturated sample, please explain more and provide more information.

Authors' response: The volume change vs. number of cycles at 0.10% shear strain is comapred in Figure 4 for both fully-saturated and partially saturated condition. It can be seen from the Figure 4 that in drained conditions, the volume change in the saturated specimen (B=0.96) is slightly higher than that of the unsaturated specimen (B = 0.25). This volume change in saturated samples causes the specimen height to decrease which eventually increases the specimen stiffness. This has been added in the revised manuscript.

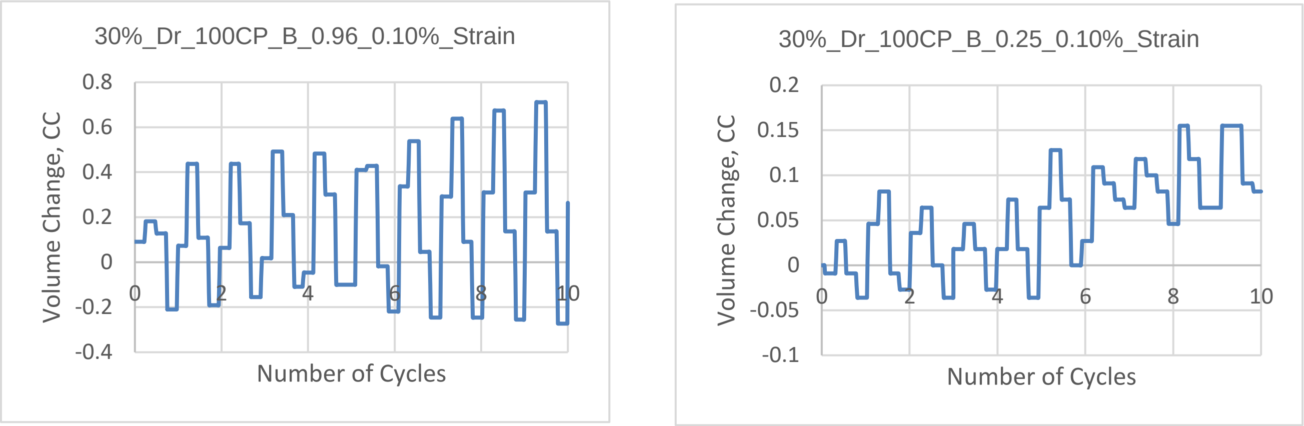

Figure 4. Volume change vs. number of cycles for fully-saturated specimen (B = 0.96) and partially-saturated specimen (B = 0.25) at 30% relative density.

12. The fully saturated soil specimens exhibit higher damping values than the partially saturated specimens.
    Reviewer: Your study is at high shear strain level!
    Authors' response: Yes, the study is at high shear strain level.

13. It can also be seen that at a saturation ratio of 0.5, the magnitude of damping for different strain amplitudes tends to merge together.
    Reviewer: Can You explain why?

    Authors' response: It is an experimental observation based on the results obtained from 30 % relative density specimen. We feel sorry to not able to comment on this as further investigation will be carried out on the same.

5.3 Effect of Relative Density on shear modulus and damping at various saturation ratio:

14. **Reviewer:** Please, fix the figures. Figure 8(a) & 8(b).
    Authors' response: It has been corrected. The Figure 8 (b) is now became to Figure 8 (c) as one additional Figure is added as per suggestion.

15. It can be observed that at fully-saturated condition (at B = 0.96), the magnitude of the shear modulus of the loose specimen is little higher than the medium dense specimen, though the difference is insignificant. This is due to the decrease in height of saturated loose specimens at the beginning of the testing that stiffens the sample under drained condition.
    Reviewer: Please provide more information such as figure to support that you get opposite finding due to significant change of volumetric strain in loose specimens.

    Authors' response: The plot between the volumetric strain versus saturation ratio is shown in 5 (Figure 8 (b) in the revised manuscript) at two different relative densities (30% & 50%). It can be observed from the Figure that the loose specimen in fully saturated condition undergoes more volume change than medium dense specimen resulting in increase of the shear modulus.

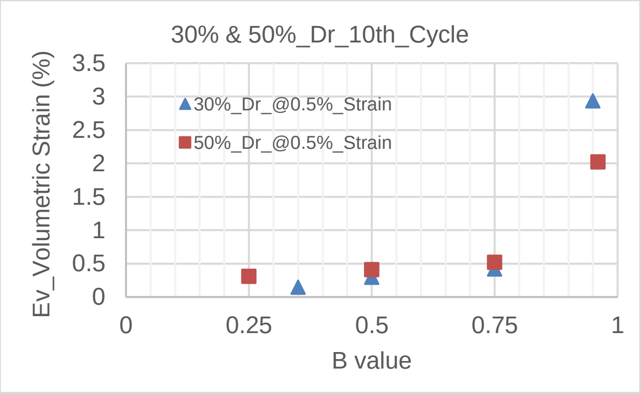

Figure 5. (Figure 8 (b) in the revised manuscript) Volumetric strain versus B parameter for 30% & 50% relative density at 0.5% strain level

16. These differences in G value at different relative densities would be diminished when G is normalized with Gmax value.
    Reviewer: Sorry, I do not agree with this statement.

    Authors' response: The sentence has been removed.

17. Similarly, for partially saturated condition (B value 0.25 to 0.75), the magnitude of damping is observed to be higher for loose specimens.
    Reviewer: same comment as for G.

    Authors' response: The specimen prepared at 30% relative density undergoes large deformation due to large volume reduction, and since its damping is calculated using the modified method (using Equation 3 in the manuscript); area underneath the curve (such as shown in Figure 4) decreases in stress vs. strain plot, thereby damping is increases.

18. In Figure 9 (b), the square box with a smooth line represents for 30 % relative density and triangular symbol represents for 50 % relative density at the same saturation ratio B = 0.75. The damping ratio for the fully-saturated samples is about 5 – 8 % higher than the partially saturated samples. From Figure 9 (b), it can also be seen that the degree of saturation has little influence on damping ratio variation at large shear strain amplitudes for the two relative density tested under drained condition.
    Reviewer: You mean Figure 8(b)
    Authors' response: It has been corrected as Figure 8 (c) in the revised manuscript**.**

6 CONCLUSIONS:

19. Hence, shear modulus and damping value can be considered from any of the cycles between N = 2 – 10, when 10 numbers of shear stress application are selected.
    Reviewer: Sorry, I do not get the meaning.

    Authors' response: The sentences have been modified and rephrased in the text as follows:

    The number of cycles does not have significant effect on the value of shear modulus and damping (as shown in Figure 3 and Figure 5) for a given shear strain amplitude and at 100 kPa confining stress, while 10 number of cycles of loading is considered.

20. The value of shear modulus is higher for partially saturated specimens than that of the fully-saturated specimen, though the difference is small and can be ignored.

    Reviewer: Figure 6(a) for Dr=30%, shows the opposite trend.

Authors' response: We thank the reviewer for this comment. The sentence is corrected in the revised version as follows:

The value of shear modulus is lesser for partially saturated specimens than that of the fully-saturated specimen, though the difference is small and can be ignored.

GEO ST.JOHN'S 2019
UNDER LAND & SEA

Dynamic properties of silty-sand varying saturation in a cyclic triaxial test

Kunjari Mog, & Anbazhagan P
Department of Civil Engineering, Indian Institute of Science, Bangalore 560012, India

ABSTRACT
The cyclic triaxial tests on partially saturated to fully saturated silty-sands were carried out to investigate the effect of saturation on dynamic soil parameter (such as shear modulus and damping ratio). The surface liquefied silty-sand which were erupted to the ground surface due to the 3rd January 2017, Manu earthquake, Tripura, India is used in the present study. Though the earthquake was of moderate magnitude with Mw 5.7, it produced liquefaction in the river bed as well as agricultural farmland adjacent to the Manu River. A constant volume split mold of size 50.1 mm internal diameter and 102 mm height was used in preparing the test specimens. The tests were carried out for two different relative densities (50 %, 30 %) with varying cyclic shear strain amplitudes. The reconstituted soil specimens prepared at partially saturated to fully saturated states were subjected to sinusoidal loading at 1 Hz frequency and results were compared. The same effective confining pressure of 100 kPa was maintained for all the tests specimen.

1 INTRODUCTION

The response of soils mainly controlled by the mechanical properties of the soil when subjected to cyclic and dynamic loadings. The mechanical properties include shear modulus, damping ratio, Poisson ratio, density, of which shear modulus and damping properties are the governing parameters which basically characterizes the dynamic behavior of soils. Hence, measurement of the dynamic soil properties such as shear modulus and damping ratio is vital for performing any ~~geo-technical~~ **geotechnical** dynamic analysis or in the numerical modeling of soil-structure interaction studies. For this purpose, various laboratory tests, as well as field geophysical methods have been developed by several investigators. ~~It is well recognized that the response of soil-foundation-structural systems is not that sensitive to the variations in the value of Poisson's ratio~~. ~~Typically, it's value ranges from 0.25 – 0.35 for cohesion-less soils and 0.35 -0.45 for cohesive soils.~~ Generally, in the laboratory environment, small strain dynamic properties measurement is done using resonant column test, pulse wave test or bender element test and medium to large strain measurement is performed using cyclic triaxial test, cyclic simple shear and cyclic torsional shear apparatus. Often, small strain cyclic loading tests can also be conducted by introducing a high sensitivity gap-sensors or proximeters in the advanced-type triaxial apparatus (Kokusho 1980). On the other hand, in-situ small strain soil properties (shear wave velocity) can be measured by seismic down-hole method, cross-hole method, suspension method, refraction method, reflection method, surface wave method (Multichannel Analysis of Surface Wave (MASW), Spectral Analysis of Surface Wave (SASW). Though there has been a rapid development in the methods of field measurement of small strain soil properties (shear modulus), yet, the methods for direct measurement of the in-situ soil damping ratio do not exist.

Numerous past studies on shear modulus and damping properties of different types of soils are available in the literature, mostly, either on dry or saturated samples (Seed, 1970, Hardin & Drnevich,1972, Iwasaki et al. 1978, Kokusho 1980, Ellis et al. 2000, Menq & Stokoe, 2003, Wichtmann et al. 2010, Senetakis et al. 2013, Wichtmann et al. 2015). However, soils above the water table, subgrade soils of roads and railways can exist in a partially saturated state where voids between the soil particles are filled with a mixture of air and water. A few of previous studies exist on the static behaviour of partially saturated soils (e.g. MeiBner, & Becker, 1970); and few studies available on the effect of saturation on the dynamic properties of soils (Madhusudan & Kumar, 2013, Sharma & Maheshwari 2018. It is noted that in the previous studies as reported by authors Madhusudan & Kumar, 2013, there is an insignificant variation in the results of small strain dynamic soil properties between the dry and fully saturated condition; while Sharma & Maheshwari, 2018, reported that shear modulus is more for dry samples as compared to the saturated samples and exactly opposite trend was shown for the damping ratio. However, Seed, 1970, in their studies reported that damping ratio is observed to be higher for dry sand than those of saturated sands with a variation of 0 – 20 %. Since, most of the earlier studies were restricted to the small strain ranges and provides somewhat contradictory results, the study of dynamic soil properties by varying degree of saturation significant at large shear strain levels.

Hence, this study presents the investigations of the dynamic properties of silty-sand at large shear strains while it varies from partially saturated to fully saturated state. The strain-controlled cyclic triaxial test was performed on the surface liquefied silty-sand of Tripura, India. All the tests were conducted under the drained condition at a different level of saturation ratio viz. 0.25, 0.35, 0.50, 0.75, 0.96 and at different relative densities. An effective confining pressure of 100 kPa was maintained and sinusoidal loading frequency of 1 Hz is considered for conducting all the test specimens. The dynamic shear modulus and damping ratio were evaluated as a function of large shear strain, saturation ratio and number of cycles.

2 TEST MATERIAL

The test material chosen in the present study is surface liquefied silty-sand, which were ejected to the ground surface during the 3rd January 2017, Manu earthquake of Tripura, India. Though the earthquake was of moderate importance with a moment magnitude (Mw) of 5.7, it caused liquefaction in the river bed as well as agricultural farmland adjacent to the Manu River. Tripura is situated in the north-eastern part of India and located in the seismically active region adjacent to the Himalayan belt. Due to its geographic location, it has witnessed several earthquakes in the past. Hence, the study of dynamic soil properties is imperative for this region. The grain size distribution test of the collected sample used in this study is performed based on Indian Standard IS 2720 (1983). Based on the grain size analysis, the soil is classified as silty-sand. The basic index properties of the tested material are enumerated in Table 1.

Table 1. Physical properties of the tested material

Property Description	Value
Specific gravity, (G_s)	2.636
Grain Size Distribution	
Fine Sand	79.753
Silt & Clay	20.247
Silt	19.837
Clay	0.410
Uniformity coefficient (C_u)	2.903
Coefficient of Curvature (C_c)	0.861
Plastic limit	Non-Plastic
Maximum dry unit weight, (γ_{dmax})	1.741 g/cc
Minimum dry unit weight, (γ_{dmin})	1.395 g/cc
Indian standard classification	Silty-sand

3 SAMPLE PREPARATION

The dry-temping method is adopted to prepare all the tests specimen. At first, an appropriate amount of air-dried sample is weighed and divided into six equal parts. The soil sample is then poured into the cylindrical mold and compacted into six equal layers. The split mold of 50.4 mm internal diameter and 102 mm height is used so as to maintain the height to diameter ratio close to 2. A temping rod of 31 mm in diameter is employed to compact the soil sample into different layers. In order to maintain a uniform thickness throughout the specimen, each of the six layers was compacted at equal thickness. With the help of temping and by varying the number of blows, a total height of 102 mm is controlled throughout the specimen preparation. Before removal of the split mold, a constant vacuum pressure of 15 – 30 kPa was applied to the bottom of the specimen to keep the sample intact. The samples were prepared at two different relative densities viz. 30 %, and 5 0% respectively. After the sample preparation, each time the specimen diameter and height were checked with 0.01 mm Vernier caliper. Afterward, the triaxial cell is assembled, it filled with water and cell pressure is applied. During application of the cell pressure, vacuum pressure is released simultaneously, and the flow of CO_2 is permitted to pass from the bottom to the top of the specimen. CO2 can expedite the saturation process as it is heavier than air and easily soluble in water. This CO_2 saturation is let on to continue for about 15 – 20 minutes and subsequently, de-aired water is flushed through the bottom of the specimen. The flushing of de-aired water was continued until the collected water equals twice the specimen volume.

Saturation process is then performed by ~~gradually raising~~ incremental increase of the cell pressure and back pressure while maintaining the effective confining stress ~~between~~ 10 ~~– 30~~ kPa. After each increment of the cell pressure, the value of B or Skempton pore-pressure parameter (B) is calculated to ensure the saturation status. The process of increasing both the cell pressure and back pressure was then repeated until the required B value is achieved. Specimens were prepared at two different relative densities and saturation was done for a Skempton's B value of 0.25, 0.35, 0.50, 0.75, 0.96 restively.

It is to be mentioned here that specimen is considered to be fully saturated when B value exceeds 0.95. After the saturation process is completed for a chosen B value, isotropic consolidation is then performed to the desired confining stress by increasing the cell pressure and keeping the back-pressure constant. **The consolidation is continued for about 30 minutes to 1 hour or it is stopped when the volume change of the specimen is no longer significant**. In this study, an effective confining pressure of 100 kPa was maintained for all the tests specimen. Finally, cyclic loading is then applied to the consolidated specimens under the drained condition.

4 CYCLIC TRIAXIAL TESTING EQUIPMENT

The GCTS resonant column cum cyclic triaxial equipment is used for testing all the soil specimens. The equipment is servo-controlled capable of performing the stress-controlled and strain-controlled test under both static and cyclic loading conditions. The cyclic axial stress is produced by means of a pneumatic loading system. A view of the equipment set up with control unit and data acquisition system is shown in Figure 1. In this system, the piston movement is controlled by means of an air regulator with desired amplitude and frequency. It can generate irregular loading waveform, sinusoidal, triangular and square type waveform. The load cell capacity is 10 kN with a frequency range varies from 0.01 Hz – 10 Hz. The maximum capacity of the three pressure transducers to measure the cell pressure, back pressure and pore pressure is 1000 kPa. The change in volume can also be measured by the automatic volume change sensor. For the present study, the strain-controlled cyclic triaxial test was selected to investigate the dynamic properties of silty-sand for varying saturation levels. The sinusoidal loading waveform with a loading frequency of 1 Hz is chosen for conducting all tests.

Figure 1. View of Triaxial set-up at Soil Mechanics Lab, IISc

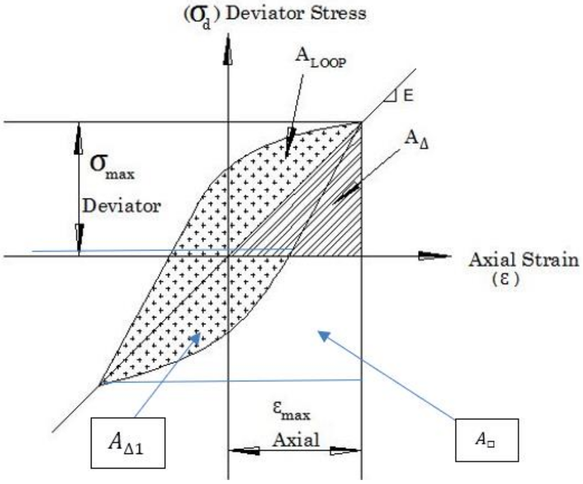

Figure 2. Typical hysteresis loop for one cycle of loading

The plot of deviator stress (σ_d) versus axial strain (ε) is the output which can be obtained from any cyclic triaxial test. It is also referred to as the hysteresis loop. The nature of the typical hysteresis loop for one cycle of loading is shown in Figure 2. From this, initially modulus of elasticity, E is determined using $E = \sigma_d/\varepsilon$. Once E is determined, the value of shear modulus can be calculated using the following expression:

$$G = E/2\,(1+\mu) \qquad [1]$$

Here, μ =Poisson's ratio. **Its value ranges between 0.1 – 1.0 for sand and gravelly sand (Bowles). However, in the present study, Poisson's ratio is assumed as 0.5 for both saturated & partially saturated specimens**. ~~which value may be assumed as 0.5 for saturated sand specimens.~~ Again, referring to Figure 3, from the same hysteresis loop, the damping ratio (D) which is the energy dissipation property of the material can be calculated from the following conventional equation:

$$D = \frac{A_{loop}}{4\pi A_\Delta} \qquad [2]$$

Here, A_{loop}= Area of the hysteresis loop and A_Δ= Area of the triangle. The above equation may be used only for the symmetrical hysteresis loop as also suggested by Kumar et al. 2017, however, for non-symmetrical loop, the following modified equation can be used:

$$D^* = \frac{A_{loop}}{\pi(A_\Delta + A_{\Delta 1} + A_\square)} \qquad [3]$$

Here, D^* = Damping ratio considering non-symmetrical loop, A_{loop}= Area enclosed by the hysteresis loop and $A_\Delta + A_{\Delta 1}$= Area of the two triangles, $A_\square$ = Area of the rectangle. The damping ratio determined from Equation 3 is reported in this study.

5 TEST RESULTS AND DISCUSSION

Strain-controlled cyclic triaxial tests were conducted on reconstituted consolidated silty-sand specimens. All the tests were performed under the drained condition. Each specimen was subjected to 10 number of cycles of shear stress application with a loading frequency of 1 Hz as in most earthquakes, the number of significant cycles is likely to be less than 20. The shear modulus (G) and damping ratio (D) obtained at 10th cycles of loadings are considered as a representative value (Iwasaki et al. 1978, Kokusho 1980) for comparing G & D curves with respect to shear strain amplitude. The tests were conducted at two different relative densities viz. 30 % & 50 % respectively, at an effective confining pressure of 100 kPa. The summary of tests conducted at various conditions is presented in Table 2.

Table 2. Summary of cyclic triaxial tests conducted on silty-sand

Relative Density (Dr)	Skempton's B value	Shear Strain Amplitude (%)
30%	0.25	0.09, 0.30, 0.45, 0.60, 0.75, 0.90, 1.0. 1.5, 3.0, 4.5, 6.0
30%	0.50	
30%	0.75	
30%	0.96	
50%	0.35	
50%	0.50	
50%	0.75	

50%	0.96

5.1 Effect of Number of Cycles on Shear Modulus and Damping at large shear strain and at different saturation levels

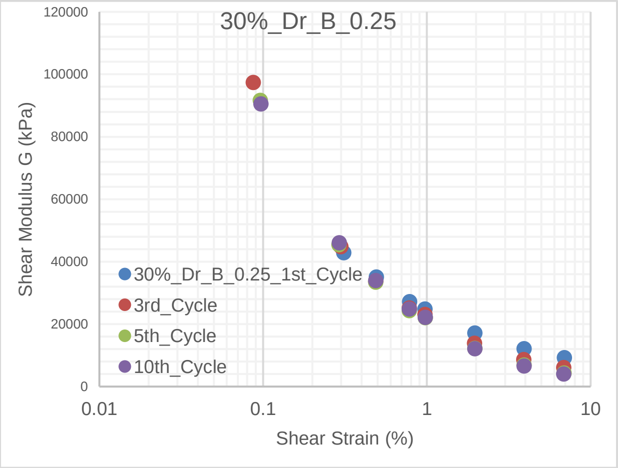

Figure 3 (a). Influence of number of cycles on shear modulus

The strain-controlled drained cyclic triaxial tests were conducted to investigate the effect of the number of cycles on dynamic properties of partially saturated to fully saturated state. The Skempton's B parameter was chosen as 0.25, 0.50, 0.75 and 0.96 respectively. Two types of relative density (30 % & 50 %) with an effective confining pressure of 100 kPa is considered. Fig. 3 shows a plot of shear modulus G with respect to cyclic shear strain amplitude for different number cycles i.e., 1st, 3rd, 5th, and 10th cycle on a loose sand specimen (Dr=30 %). The saturation ratio considered is B = 0.25. From the Figure 3(a), it can be observed that for a given value of confining stress and number of cycles of stress application, the value of shear modulus decreases with the amplitude of shear strain. It can also be observed that the variation of shear modulus is nearly equal between the number of cycles N = 1 to 10 for a shear strain range 0.08 to 1% for a loose specimen. However, only a slight variation in the value of G can be noticed after 1% of shear strain between the cycle 1 & 10 which can be neglected, while testing is conducted in the pneumatic loading system. Likewise, an insignificant variation in the value of shear modulus is noticed at 3rd, 5th, and 10th, cycles of loading for different saturation levels considered in this study.

Similarly, samples were tested for 50% relative density at different saturation levels (B=0.25, 0.50, 0.75, 0.96) and result is shown in Figure 3(b). In order to avoid the overlapping in the data, the results pertaining to saturation ratio, B = 0.75 is presented. From the plot of G versus shear strain, as illustrated in Figure 3(b) for a medium dense sample, it can be observed that for a given value of shear strain, the magnitude of G increases with the increasing number of cycles (3rd, 5th, 10th cycles); though, the difference is small. The similar trend is reported in the literature by Silver and Seed, 1971. The same trend is observed for other test samples as well at different saturation ratio. Hence, from this result, it can be stated that the number of cycles does not have much effect on the value of shear modulus for a given shear strain amplitude and **at 100 kPa** confining stress, while 10 number of cycles of loading is considered to obtained G value. **This result is in accordance with the findings of Kokusho (1980) at small strain levels**. Even for a partially saturated to fully-saturated conditions, the effect of number of cycles on G at large shear strain is insignificant.

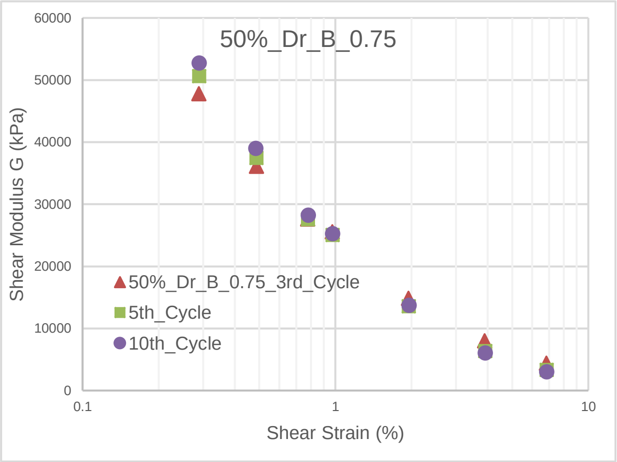

Figure 3 (b). Influence of number of cycles on shear modulus

The influence of the number of cycles on the damping ratio is discussed in this section. The nature of the stress versus shear strain behavior of loose sand under different shear strain levels for 10th cycles of loading is shown in Figure 4 (a) – (f). Considering the hysteresis loop of this type and using Equation 3, the hysteretic damping obtained from the cyclic triaxial test for a relative density of 30 % and 50 % are shown in Figure 5 (a) & (b). It can be clearly observed from Figure 5 that the magnitude of the damping ratio decreases with the increasing number of cycles for a given value of shear strain amplitude. This trend is observed for both loose and medium dense specimen. It can also be seen that the value of damping ratio decreases with the increase of shear strain amplitude at large shear strain (beyond 1% Strain), but strain levels of up to 1 %, magnitude of damping increases with the increase of shear strain (Silver & Seed 1971, Mog & Anbazhagan 2018). The difference is rather small. The details about increasing and decreasing trend of damping ratio at medium to large shear strain levels are explained in the subsequent subsection.

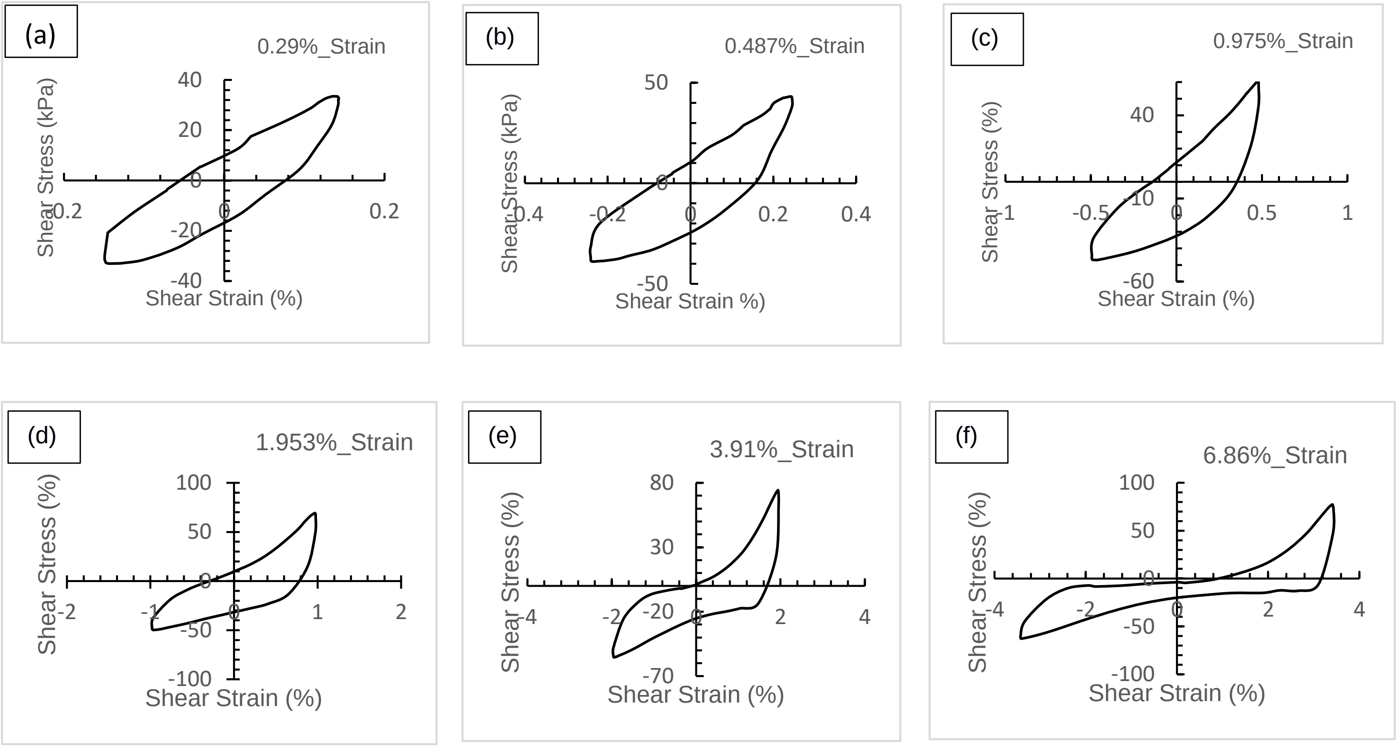

Figure 4. Typical Stress-strain behavior of loose sand at 10th Cycles of loading for partially-saturated condition at B value 0.25

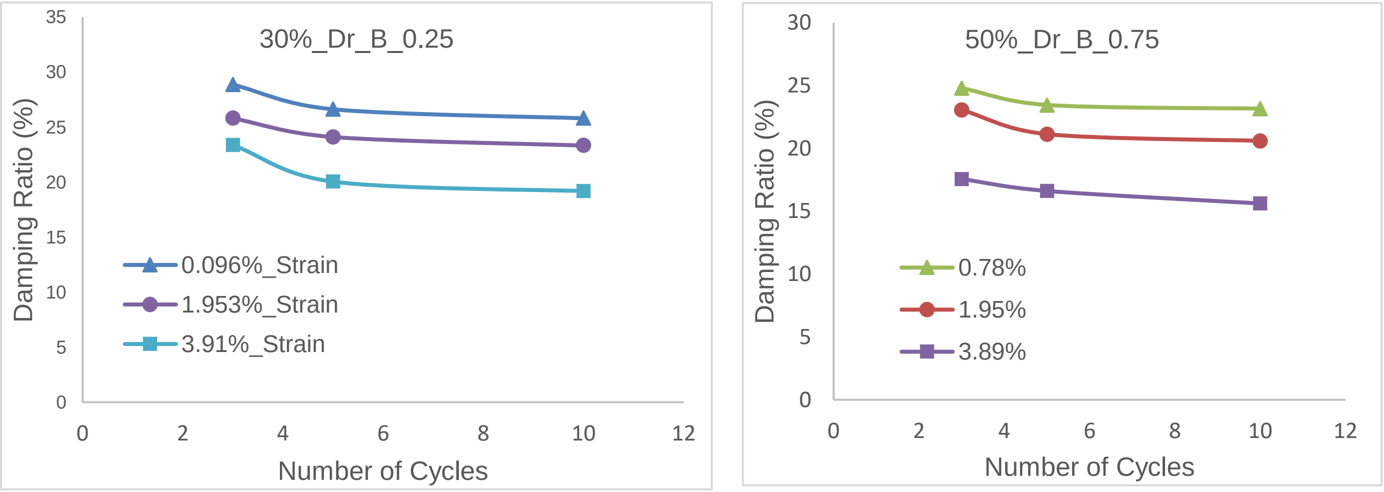

Figure 5 (a). Influence of number of cycles on damping ratio (D) at different shear strain levels at 30% relative density for B value 0.25. Figure 5 (b). Influence of number of cycles on D at different shear strain levels at 30% relative density for B value 0.75

5.2 Effect of Saturation on shear modulus and damping properties

The effect of saturation on shear modulus at large shear strain was investigated by performing the strain-controlled cyclic triaxial test at two different relative densities under different saturation levels such as B = 0.25, 0.50, 0.75, 0.96 respectively. The tests were carried out under drained condition at an effective confining pressure of 100 kPa and at 1 Hz loading frequency. The magnitude of the shear modulus and damping versus saturation ratios are presented in Figure 6.

From Figure 6 (a) it can be observed that the value of shear modulus remains nearly ~~identical~~ **same** in three different levels of saturation viz. B=0.25, 0.50 and 0.75, at large shear strain amplitudes. Similar observations were made by Kumar & Madhusudan, 2012, Tatsuoka et al. 1979 in small strain measurement. In contrast to the partially-saturated condition, an increase in the value of G can be observed at the fully-saturated level (when B value is 0.96). This is due to a decrease in the height of specimens under the drained condition with the increasing number of shear stress application, which eventually causes a reduction in the void ratio and little stiffening of the specimens. **For example, it can be seen from the Figure 6 (c) & 6 (d) that in drained conditions, the volume change in the saturated specimen (B=0.96) is slightly higher than that of the unsaturated specimen (B = 0.25).** Also, it has been observed that the difference in G values between partially-saturated and saturated silty-sand specimen is less than 10% and hence, for all practical purposes, this difference can be negligible while using the normalized shear modulus reduction curves.

Figure 6 (b) illustrates the damping ratio variation with different saturation levels for 30% relative density at the 10^{th} cycle. It can be observed that for a given confining pressure of 100 kPa, the difference in the damping ratio between the fully-saturated and partially saturated silty-sand varies from 2 – 10 %. The fully saturated soil specimens exhibit higher damping values than the partially saturated specimens. This result appears to be in accordance with the findings of Madhusudan & Kumar, 2013 at small shear strain ranges. It can also be seen that at a saturation ratio of 0.5, the magnitude of damping for different strain amplitudes tends to merge together. **However, this need further investigation**. Hence, based on the results obtained under drained condition, it can be inferred that variations in the saturation ratio (B value 0.25 to 0.96) have a negligible effect on the magnitude of the shear modulus of silty-sand. However, the degree of saturation tends to show little effect on the damping properties at large shear strain.

5.3 Effect of Relative Density on shear modulus and damping at various saturation ratio

The effect of relative density on dynamic properties of partially saturated to fully-saturated silty-sand is investigated under strained controlled cyclic triaxial testing. Two types of relative density such as 30 % and 50 % are

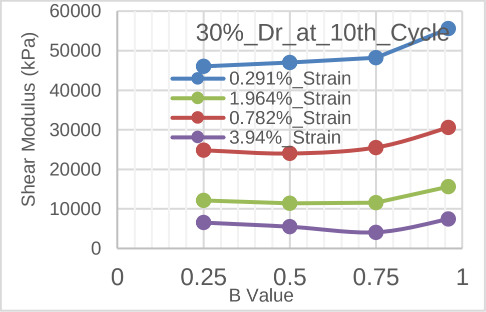

Figure 6 (a). Effect of saturation on shear modulus

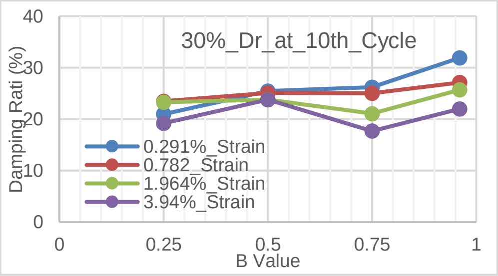

Figure 6 (b). Effect of saturation on damping ratio

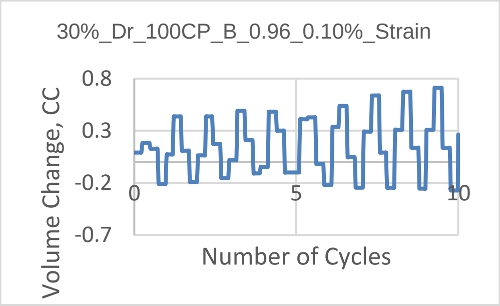

Figure 6 (c) Volume change vs. number of cycles at B value 0.96

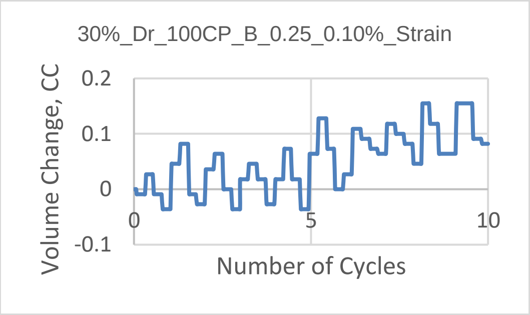

Figure 6 (d) Volume change vs. number of cycles at B value 0.25

considered for this purpose. The variation of shear modulus and damping ratio against the shear strain amplitude are illustrated in Figure 7 for 50 % relative density and combined results for both 30 % and 50 % relative density is presented in Figure 8. It can be observed from Figure 7 (a) that the magnitude of shear modulus decreases with an increase in shear strain amplitudes irrespective of various saturation levels considered. The value of shear modulus is higher for partially saturated specimens than that of the fully-saturated specimen. However, the difference in the value of G between partially saturated and fully saturated specimens reduces significantly beyond 0.1 % of shear strain. These observations are also valid for 30 % relative density samples under 100 kPa confining pressure which is also shown in Figure 8 (a).

Similarly, Figure 7 (b) illustrates the variation of damping ratio with shear strain amplitudes. It has been observed from Figure 7 (b) that at a given shear strain amplitude for a saturation ratio 0.35 to 0.75, a minute increase in damping value is noticed, though the difference is insignificant. The damping ratio is observed to be higher for the fully-saturated specimen (for B = 0.96) compared to the partially saturated specimens. Figure 7 (b) also indicates that the magnitude of damping is increased up to a shear strain level of 1 %, after which a decreasing trend in the value of damping is followed. A similar trend is also reported by Mog & Anbazhagan 2018 and Kumar et al. 2017. This increasing and decreasing trend in the value of damping with shear strain amplitude is observed for both partially saturated and fully-saturated silty-sand samples.

Figure 8 shows the comparison of the dynamic properties of silty-sand at two different relative densities under various saturation levels. The variation of shear modulus versus shear strain for both 30 % and 50 % relative density is illustrated in Figure 8 (a).

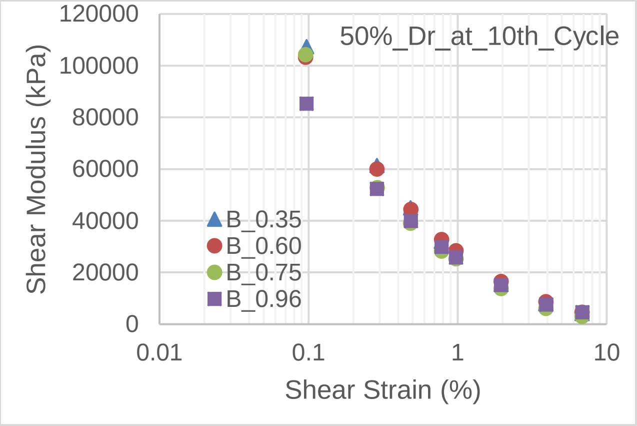

Figure 7 (a). Variation of G for various saturation levels at 50% relative density

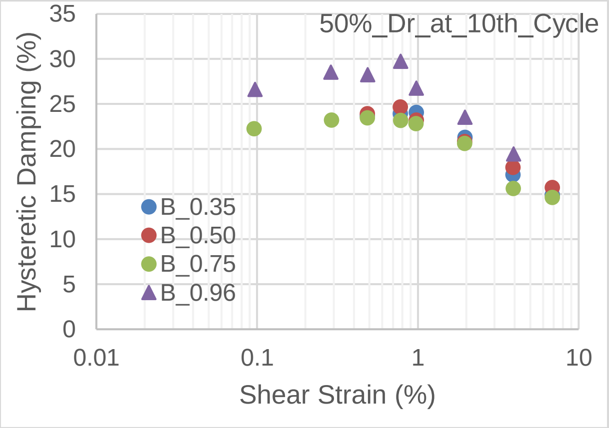

Figure 7 (b). Variation of D for various saturation levels at 50% relative density

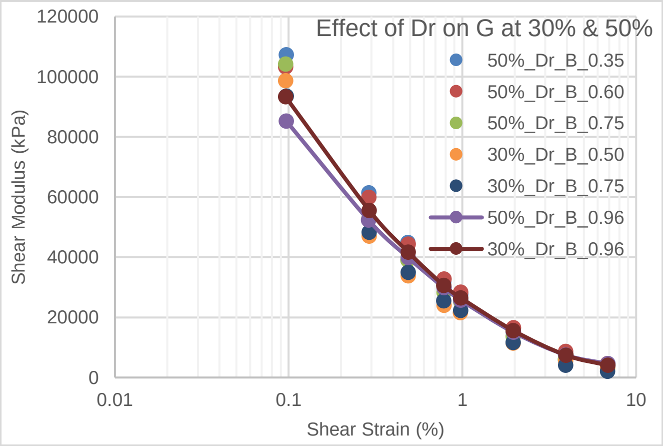

Figure 8 (a). Effect of saturation on G under different saturation levels and two relative densities

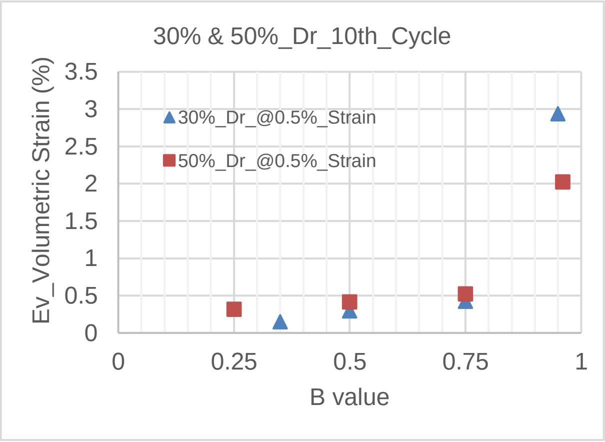

Figure 8 (b) Volumetric strain versus B parameter for 30% & 50% relative density at 0.5% strain level

It can be observed that at fully saturated condition (i.e., B = 0.96) the magnitude of the shear modulus of the loose specimen is little higher than the medium dense specimen, though the difference is insignificant. This is due to the decrease in height of saturated loose specimens at the beginning of the testing that stiffens the sample under drained condition**. It is evident from the plot between the volumetric strain versus saturation ratio as shown in Figure 8 (b) for two different relative densities (30% & 50%). It can be observed from the Figure 8 (b) that the loose specimen in fully saturated condition undergoes more volume change than medium dense specimen resulting in increase of the shear modulus.** However, shear modulus (**Figure 8 (a))** for partially saturated samples (B = 0.25 to 0.75) is observed to be slightly higher for medium dense specimens (50 %) compared to the loose specimens (30 %). At shear strain levels lesser than 0.1 % or close to that the shear modulus variation is noticeable for partially saturated samples. The reason may be attributed to the suction effect at shear strain levels lesser than 0.1 %. The difference in the shear modulus value between partially saturated and fully-saturated condition is about 15 % at strain levels lesser than 0.1%, however, beyond 0.1 % the difference is less than 10%. ~~These differences in G value at different relative densities (30% & 50%) would be diminished when G is normalized with G_{max} value.~~ Hence, it can be concluded that relative density does not have a significant influence on the shear modulus at large shear strain for varying saturation conditions.

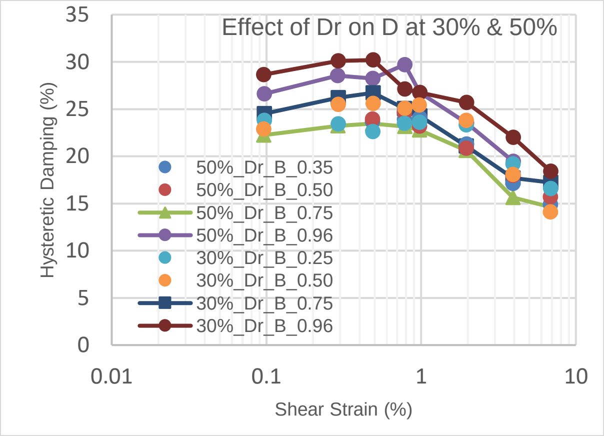

Figure 8 (c). Effect of saturation on D under different saturation levels and two relative densities

Figure 8 (c) shows the variation of damping ratio with shear strain at various saturation levels. It can be observed that the damping ratio is higher for loose samples than those of medium dense samples at fully-saturated condition (B value 0.96). Similarly, for partially saturated condition (B value 0.25 to 0.75), the magnitude of damping is observed to be higher for loose specimens. In ~~Figure 9 (b)~~ **8 (c),** the square box with a smooth line represents for 30 % relative density and triangular symbol represents for 50 % relative density at the same saturation ratio B = 0.75. The damping ratio for the fully-saturated samples is about 5 – 8 % higher than the partially saturated samples. From Figure ~~9 (b)~~ **8 (c)** , it can also be seen that the degree of saturation has little influence on damping ratio variation at large shear strain amplitudes for the two relative density tested under drained condition. **It may be mentioned here that in general, the matric suction and shear strength are directly related; as the matric suction increases, the shear strength of a sample increases (Fredlund et al., 2012). However, the influence of matric suction is not reported in the present studies, though it may have influence in the partially saturated specimens.**

6 CONCLUSIONS

The dynamic properties of silty-sand for partially saturated to fully-saturated states are investigated in the cyclic triaxial instrument under drained condition. Based on the obtained results at large shear strain levels, it can be concluded that the degree of saturation has an insignificant effect on the magnitude of shear modulus and damping ratio of silty-sand at 10th cyclic of loading or less. ~~Hence, shear modulus and damping value can be considered from any of the cycles between N = 2 – 10, when 10 numbers of shear stress application are selected.~~ **Also, the number of cycles does not have significant effect on the value of shear modulus and damping (as shown in Figure 3 and Figure 5) for a given shear strain amplitude and at 100 kPa confining stress, while 10 number of cycles of loading is considered.**

It has been observed that the variations in the saturation ratio (for B value 0.25 to 0.96) have a negligible effect on the magnitude of the shear modulus of silty-sand. However, the degree of saturation tends to show little effect on the damping properties at large shear strain levels. The fully saturated soil specimens tend to show higher damping values than the partially saturated specimens. The difference in the damping ratio between the fully-saturated and partially saturated silty-sand is observed to be varied from 2 – 10 %.

It has also been observed that the magnitude of shear modulus decreases with an increase in shear strain amplitudes irrespective of various saturation levels considered. The value of shear modulus is ~~higher~~ **lesser** for partially saturated specimens than that of the fully-saturated specimen, though the difference is small and can be ignored.

The damping ratio is observed to be higher for fully-saturated specimen (for B = 0.96) compared to the partially saturated specimens (B = 0.25, 0.50, 0.75). Also, the magnitude of damping is increased up to a shear strain level of 1%, after which a decreasing trend in the value of damping is observed. A similar trend was also reported by Mog & Anbazhagan 2018.

It can also be concluded that relative density does not have a significant influence on the shear modulus at large shear strain for partially saturated to fully saturated conditions. However, it has little influence on the value of damping ratio at large shear strain amplitudes. The damping ratio for the fully-saturated samples is about 5 – 8% higher than the partially saturated samples.

REFERENCES

Bowles, J. E. (1976). Foundation Analysis and Design., 1996. *Peoria, Illinois*.

Ellis, E. A., Soga, K., Bransby, M. F., & Sato, M. (2000). Resonant column testing of sands with different viscosity pore fluids. *Journal of Geotechnical and Geoenvironmental Engineering*, *126*(1), 10-17.

Fredlund, D. G., Rahardjo, H., & Fredlund, M. D. (2013). Unsaturated soil mechanics in engineering practice. *대한토목학회지,* 61(5), 101-101.

Hardin, B. O., & Drnevich, V. P. (1972). Shear modulus and damping in soils: measurement and parameter effects. *Journal of Soil Mechanics & Foundations Div*, *98*(sm6).

IS: 2720 (Part 4): Methods of test for soils: Grain size analysis. *Bureau of Indian Standards (BIS)*, New Delhi (1983).

Iwasaki, T., Tatsuoka, F., & Takagi, Y. (1978). Shear moduli of sands under cyclic torsional shear loading. *Soils and Foundations*, *18*(1), 39-56.

Kokusho, T. (1980). Cyclic triaxial test of dynamic soil properties for wide strain range. *Soils and foundations*, 20(2), 45-60.

Kumar, J., & Madhusudhan, B. N. (2012). Dynamic properties of sand from dry to fully saturated states. *Geotechnique*, *62*(1), 45-54.

Kumar, S. S., Krishna, A. M., & Dey, A. (2017). Evaluation of dynamic properties of sandy soil at high cyclic strains. *Soil Dynamics and Earthquake Engineering*, *99*, 157-167.

Kumar, S. S., Krishna, A. M., & Dey, A. (2017). Evaluation of dynamic properties of sandy soil at high cyclic strains. *Soil Dynamics and Earthquake Engineering*, *99*, 157-167.

Madhusudhan, B. N., & Kumar, J. (2013). Damping of sands for varying saturation. *Journal of Geotechnical and Geoenvironmental Engineering*, *139*(9), 1625-1630.

MeiBner, H., & Becker, A. (1970). Dynamic behaviour of partially saturated sand. *WIT Transactions on The Built Environment*, *15*.

Menq, F. Y., & Stokoe, K. H. (2003). Linear dynamic properties of sandy and gravelly soils from large-scale resonant tests. *Deformation characteristics of geomaterials*, 63-71.

Mog, K., & Anbazhagan, P. (2018, November). Dynamic Properties of Surface Liquefied Site Silty-Sand of Tripura, India. In *International Congress and Exhibition" Sustainable Civil Infrastructures: Innovative Infrastructure Geotechnology"*(pp. 140-154). Springer, Cham.

Seed, HB (1970). Soil moduli and damping factors for dynamic response analysis. *EERC*.

Senetakis, K., Anastasiadis, A., & Pitilakis, K. (2013). Normalized shear modulus reduction and damping ratio curves of quartz sand and rhyolitic crushed rock. *Soils and Foundations*, *53*(6), 879-893.

Sharma, P., & Maheshwari, B. K. (2019). Effect of Saturation on Dynamic Properties of Solani Sand. In *Soil Dynamics and Earthquake Geotechnical Engineering* (pp. 51-55). Springer, Singapore.

Silver, M. L., & Seed, H. B. (1971). Deformation characteristics of sands under cyclic loading. *Journal of Soil Mechanics & Foundations Div*.

Wichtmann, T., Hernández, M. N., & Triantafyllidis, T. (2015). On the influence of a non-cohesive fines content on small strain stiffness, modulus degradation and damping of quartz sand. *Soil Dynamics and Earthquake Engineering,* 69, 103-114.

Wichtmann, T., Niemunis, A., & Triantafyllidis, T. (2010). On the “elastic” stiffness in a high-cycle accumulation model for sand: a comparison of drained and undrained cyclic triaxial tests. *Canadian Geotechnical Journal*, *47*(7), 791-805.