EFFECTS OF DEGREE OF SATURATION ON DYNAMIC SOIL PROPERTIES

A DISSERTATION

Submitted in the partial fulfilment of the requirements for the award of the degree of

MASTER OF TECHNOLOGY

in

EARTHQUAKE ENGINEERING

(With specialization in Soil Dynamics)

by

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CANDIDATE’S DECLARATION

I hereby declare that the work carried out in this seminar report entitled, “**Effects of Degree of Saturation on Dynamic Soil properties”,** is being submitted in partial fulfilment of the requirements for the award of degree of “Master of Technology” in Earthquake Engineering with specialization in Soil Dynamics submitted to the Department of Earthquake Engineering, Indian Institute of Technology Roorkee under the supervision of **Dr. B.K. Maheshwari**, Professor, Department of Earthquake Engineering, I.I.T. Roorkee, is an authentic record of my own work carried out during the period of June 2018- June 2019.

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CERTIFICATE

This is to certify that the above statement made by the candidate is correct to the best of my knowledge and belief.

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Place: Roorkee

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ABSTRACT

Failure of soil subjected to dynamic loading is greater. Therefore, it is important to study the response of soil under dynamic loading. Thus the dynamic soil property is an important parameters to be studied. Dynamic soil property is affected by testing methods, method of sample preparation, relative density, confining pressure, degree of saturation of sample, loading frequency, soil type, fines percentage, mineral content etc.

There are various lab tests available for determination of these properties and can be broadly classified as low and high strain testing system. Resonant Column Apparatus (RCA) is used for low strain tests (10^{-4} – 10^{-1} %) and Cyclic Triaxial System (CTS) for high strain tests (10^{-2} - 10^{1} %). Various field tests are also available but the lab tests have an advantage that the various conditions can be simulated and different material can be tested that can be further used for ground improvement where ever required. Present study was carried out on samples of size 50 mm diameter and 100 mm height. The tests are done on three relative densities (40% , 60% & 80%) and three confining pressures (100 kPa, 200 kPa and 300 kPa). The tests were conducted using RCA. The effect of confining pressure, relative density and degree of saturation on dynamic soil property are examined.

Soil properties that influence wave propagation are damping ratio, stiffness, Poisson's ratio and density but among these stiffness and damping ratio are of utmost importance. It is being observed that the shear modulus of sample increases with increasing confining pressure and relative density. Thus decreases with saturation, the damping ratio is observed to decrease with increase in relative density and confining pressure while increases from unsaturated to saturated sample. It is also observed that as the stiffness increases, the strain induced is smaller. The damping ratio obtained in flexure mode of vibration is more than that in torsional mode of vibration.

There is significant differences in behaviour of unsaturated, partially and fully saturated condition as the result of influence of capillarity as the saturation increase there is generation of pore pressure that affect effective stresses on the sample. Various degree of saturation simulates the condition of soil when the water was full there and the later stages where due to evaporation or withdrawal of water from the ground, the water decreases and the degree of saturation reduces. It is observed that the decrement in Shear and Modulus of Elasticity is greater up to 50% degree of saturation but after this saturation there is minor difference between 75% and 100% degree of saturation. There is not much effect of degree of saturation on the damping ratio.

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Introduction

1.1 General

Several researchers are involved in exploring the behaviour of soil in different loading conditions i.e. static and dynamic. Response of soil under dynamic loading is governed by its dynamic properties. Various dynamic soil properties such as stiffness properties, damping properties are required for investigation. Dynamic soil properties are more important as it is observed that the damage is more in dynamic loading e.g. liquefaction of sand during earthquake leading to subsidence of ground.

Dynamic soil properties are also affected by the plasticity index, void ratio, over consolidation ratio, principal effective stress, no of loading cycles, cyclic strain amplitude. With increase in strain it is observed that the stiffness of soil decreases and with increase in confining pressure and relative density it is observed that stiffness of soil increase. As we go deeper in soil the confining pressure increases leading to increase in stiffness of soil.

Damping property of soil is also affected by different stress conditions, plasticity, void ratio etc. Damping ratio decreases with increase in confining pressure, so as we go deeper in soil damping ratio decreases. Poisson's ratio is also an important parameter, it is very important in case of drilling wells, hydraulic fracturing, well instability etc. The value of Poisson's obtained from resonant column apparatus can be used for numerical modelling.

The low strain Young Modulus, Shear Modulus, damping ratio and Poisson's ratio are important properties that are needed for the evaluation of dynamic response of soils. As the influence of water in case of sand is significant due to capillary action, significant differences are observed in the behaviour of unsaturated, partially saturated and fully saturated soils.

The behaviour of soil changes as the degree of saturation increases, its damping ratio increases and stiffness decreases. Degree of saturation can be simulated to the condition where the water starts coming in the soil or being removed and in any stage between the soil is subjected to dynamic loading. So, it is important to study the behaviour of soil in different saturation condition.

The properties of soil also varies when some admixture is added like fibres, fibres can be added to increase the strength of soil. Other waste material like crumbled rubber can be used for strengthening the soil. Lab tests plays an important role as in lab we can use different material and loading condition and its effect can be studied and can be applied on site.

1.2 Objectives of Dissertation

The objective is to find the dynamic soil properties in small strain range using resonant column apparatus. The objective of this report is summarised below.

1. To study the effect of various degree of saturation.
2. To study the effect of confining pressure.
3. To study the effect of relative density.

1.3 Scope of Work

The scope of the report includes conducting resonant column test on Solani sand by simulating actual field conditions in the laboratory to obtain required dynamic properties of sand.

1. Determination of shear modulus and modulus of elasticity by performing torsion and flexure test on the sample.
2. Effect of Relative density on dynamic soil property of solani sand are studied, samples at RD=40%, 60% & 80 % at three confining pressure i.e 100 kPa, 200 kPa, 300 kPa is being tested.
3. Effect of different degree of saturation on dynamic properties is examined, for this samples are prepared at 25 %, 50%, 75% and 100% degree of saturation.
4. Evaluation and comparison of the results obtained from tests on unsaturated, partially and fully saturated samples under different confining pressure and relative densities.

1.4 Organization of Report

This report consists of 6 chapters. Chapter 1 presents introduction and the general work plan of the report. Chapter 2 presents brief description of literature review of dynamic properties Chapter 3 provides details about the test setup and its procedure. Chapter 4 covers the formulation and calibration of resonant column apparatus. Chapter 5 provides the analysis of tests results obtained from conducting resonant test on soil sample. Effects of different degree of saturation, effect of relative density and confining pressures are also discussed in this chapter. Chapter 6 comprises of conclusion drawn, summary of this report and further scope of study.

Chapter-2

Literature Review

The evaluation of dynamic property is of great importance for the soil subjected to dynamic loading such as earthquake, soil under the machine foundation, soil under any heavy machine giving vibrations. The response of soil subjected to any such type of loading is dependent on its dynamic property; particularly those affected by wave propagation, low strains are induced in them.

This chapter includes the past reviews of the work done by the researchers on dynamic soil property using resonant column apparatus. Different work by the researchers on different type of soil and loading condition is being studied in this chapter.

The resonant column apparatus was first developed by Japanese engineers in 1930. It is used to study the dynamic response of soil under low strain. After the work by the authors such as Drnevich et al. (1967), Hardin and Black (1968), Drnevich et al. (1978), the resonant column apparatus became popular.

The resonant column apparatus measures dynamic response of soil which includes shear and elastic modulus which is based on theory of wave propagation. The reduction of data from the resonant column, to obtain the physical properties of interest, is a function of the boundary conditions. The resonant column apparatus measures dynamic response of soils which includes elastic modulus and shear modulus which is based on theory of wave propagation. Longitudinal and torsional vibration are applied on the sample and using the theory of elasticity for solving the equation of wave propagation.

1) Seed et al. (1986) have evaluated the response of soil deposits, and determined the variation of shear modulus and damping ratio with shear strain. Also studied the effect of confining pressure, void ratio and strain levels.

2) Ishibashi and Zhang (1993) have reanalysed the available experimental data and bought into simple unified formulas. The unified formulas express the damping ratio and dynamic shear modulus in terms of maximum shear modulus, cyclic shear strain plasticity index and confining pressure.

3) Cascante et al. (1998) presented equipment modification, data reduction and test procedure in standard torsional resonant column device for flexural excitation; it permits the testing frequencies which are important for near surface studies. High attenuation in flexural mode is measured in partially and fully saturated specimens.

4) Wang et al. (2003) examined the counter electromotive effect and its effect on dynamic soil property calculation. Provided apparatus based corrections to the calculated values from resonant column, particularly to damping ratio. Gave correction charts for resonant frequency and damping ratio for the apparatus.

5) Zhang and Aggour (2004) have conducted tests in RCA using three different types of loading (random, impulse and sinusoidal) under different confining pressures. Main objective was to evaluate the effect of coupling vibrating of compressive waves and shear waves on dynamic properties. The resonant frequencies are obtained from digital frequency meter in longitudinal and torsional directions, using these frequencies the young modulus, shear modulus and damping in flexure and tosional mode is calculated.

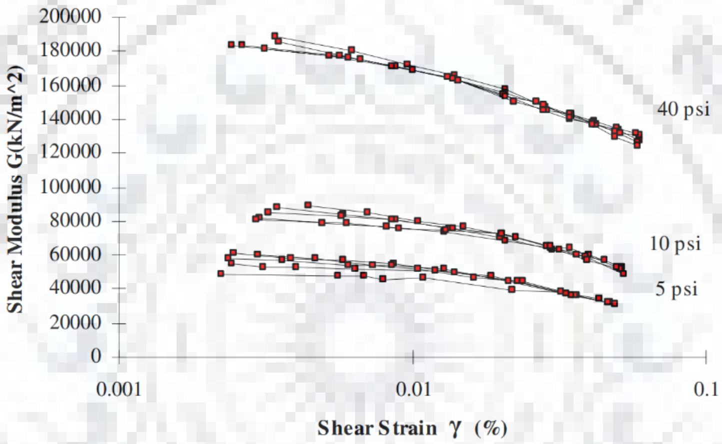

Figure 2.1 Variation of Shear modulus vs shear strain(%) from Coupled Sinusoidal Vibration Tests at different Confining Pressures after Zhang and Aggour, (2004)

6) Khan *et. al.* (2008) has used resonant column apparatus for measuring low and medium strain shear modulus and damping ratio of soils. The resonant column testing was based on the determination of resonant frequency by the measurement of specimen response by giving different excitation frequencies. They have also developed a non-resonance (NR) method, which is based on solution of equation of motion. The method governs the forced vibration of a continuous, homogeneous, and linear viscoelastic cylinder which represents the soil specimen. The results of both the method (standard resonant column test and NR method) are then verified.

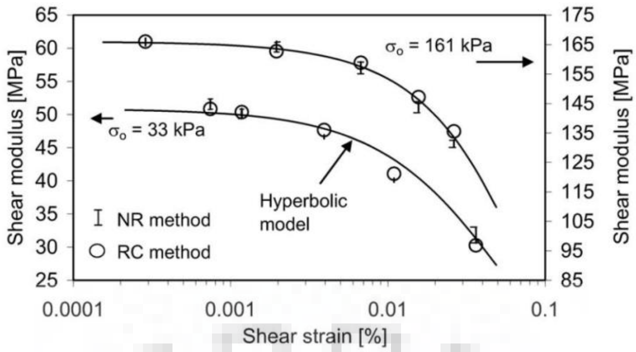

Figure 2.2 Variation of shear modulus with shear strain for both NR method and RD method after Khan et.al.(2008)

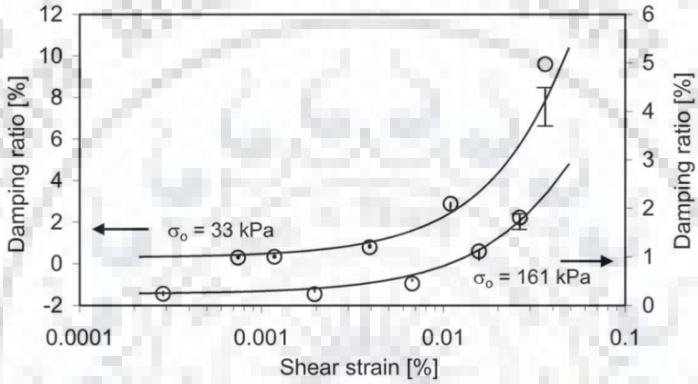

Figure 2.3 Variation of damping ratio with shear strain for both NR method and RD method after Khan et.al.(2008)

7) Kumar and Madhusudhan (2010) have used the basic principle of exciting a cylindrical specimen in its fundamental mode of vibration either in twisting or in bending. And its corresponding frequency and amplitude is measured. They have proposed a new method to calculate the magnitudes of modulus of elasticity and related strains from apparatus.

9) Shen et al. (2013) studied the effect of confining pressure on dynamic property of silty sand using RCA in Dujiangyan, gave the empirical formula of dynamic properties of silty clay in Dujiangyan with confining pressure.

8) Madhusudhan and Senetakis (2016) used resonant column in flexural mode for dynamic characterisation of Banglore Sand. The results showed that material damping is sensitive to the mode of vibration. Flexural damping was higher in magnitude that shear damping and this trend was more pronounced at an increasing confining stress.

Chapter-3

Experimental Set up and Test Procedure

RCA is a lab test that facilitates the determination of low strain dynamic soil property, some other lab tests like ultrasonic pulse test, piezoelectric bender element tests are also available at low strain range. Resonant Column Apparatus can determine the dynamic properties of solid or hollow soil specimen at small strains. Fig. 3.1 represents the schematic diagram of resonant column apparatus. The load on the sample is applied through the electromagnetic system, using which the sinusoidal excitations are applied. Four pair of coils are connected in series, for applying net torque on the soil while during flexural excitations two coils are switched on which apply flexure loading on the sample. Thus these same four coils can be used for flexural and torsional vibration. Fig 3.2 represents the arrangement of coils in flexure and torsion mode.

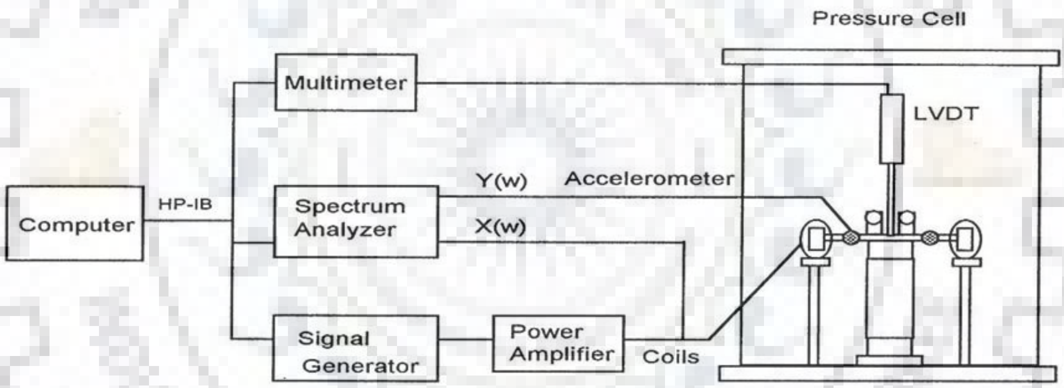

Figure 3.1 Schematic diagram of resonant column apparatus after RCA manual

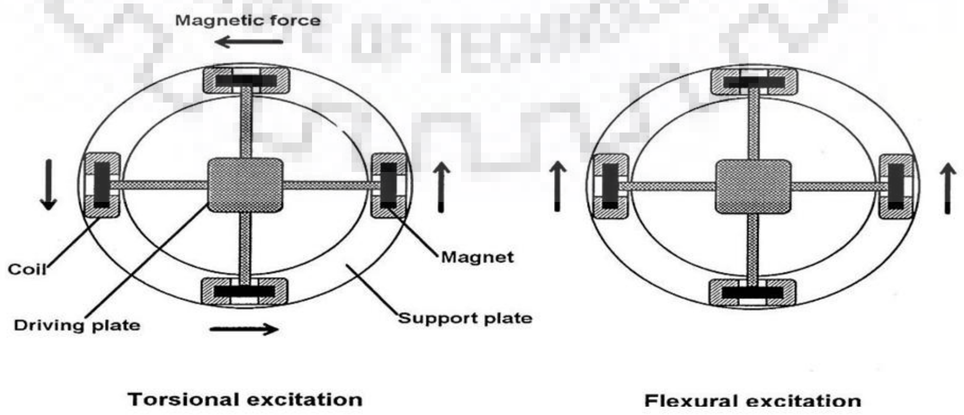

Figure 3.2 Arrangement of coils for torsion and flexure tests after RCA manual

The basic principal of resonant column apparatus is the vibration of the sample in its fundamental mode and noting the frequency and the corresponding strain. The testing is done according to the ASTM D4015. GDS system is software that operates the apparatus and it measures resonance in torsion and flexure mode and also the damping in these modes.

3.1 Description of Test Apparatus

The resonant column apparatus in Fig. 3.3 has been used for computing the dynamic soil properties at low strain levels. RCA consist of electromagnetic system that creates the sinusoidal vibration in torsional or flexure mode using all four magnets or two magnets in series. Thus measuring the resonant frequency and damping at its fundamental mode of vibration. All tests are conducted according to the ASTM D4015 as a standard test. The facilities available in our lab for testing are as:

Resonant test:

Torsion test: In this all four electromagnet are connected in series and the sinusoidal vibrations are created and the resonance frequency and corresponding shear strain are noted. The frequency obtained in this test is used for the determination of Shear modulus.

Flexure test: In this two pair of electromagnet are connected in series and the sinusoidal vibrations are created and the resonance frequency and its corresponding axial strain values are noted. The frequency obtained is used for the calculation of Modulus of Elasticity.

Torsional Shear Test:

This test is different from the resonant test. In this the soil specimen is subjected to applied stress in opposite direction, in which the parallel planes stays parallel but moved in such a way that they are parallel to themselves.

Damping test:

Damping in torsion: The damping in torsional mode of vibrations is obtained from the logarithmic decay curve corresponding to the resonant frequency.

Damping in flexure: The damping in torsional mode of vibrations is obtained from the logarithmic decay curve corresponding to the resonant frequency.

3.2 Terminology

Electromagnetic Frequency: Is the rate at which energy is drawn from a source that supplies the flow of electricity in a circuit. This occurs through the magnetic-flux of the magnets changing, generating an electric field (expressed in volts) in the circuit.

Effective confining pressure: It is the difference of cell pressure and pore water pressure.

Back pressure: It is the pressure applied on the voids of the soil specimen which allows air to get diffused in the water and water is flushed out leading to proper saturation of the sample.

B-value: It is the ratio of change in pore pressure to change in effective confining pressure.

Resonant frequency: This the fundamental frequency at which the strain obtained is maximum.

Shear modulus (G): The ratio of the shearing stress (τ) to the resultant shear strain component (tan θ in the case of simple shear). It basically describes the materials response to shearing strains.

Modulus of Elasticity (E): Is a measure of the stiffness of an isotropic elastic material, through describing the materials response to linear strain. It relates to the prediction of the strain in a component subject to a known stress.

Damping Ratio: The damping ratio is a measure of describing how oscillations in a system die down after a disturbance i.e. how the shear waves generated in the sample die down after a test is complete.

3.3 System Components and Key Features

The system which is installed in the laboratory was manufactured by GDS instruments, UK. The components of RCA system and key features are shown in Table 3.1. Different tranducers are used e.g. transducer for pore water pressure measurement and LVDT for axial displacement measurement.

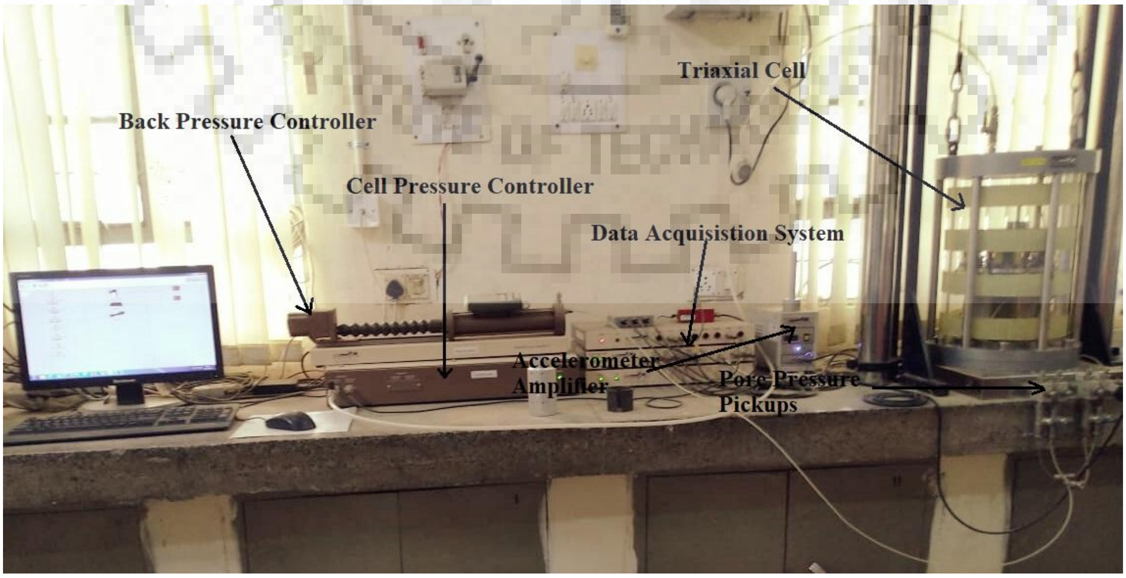

Figure 3.3 Resonant column testing apparatus in soil dynamics lab

Table 3.1 Components of GDS Resonant Column Apparatus

S. No	Components	Utility
1	Standard cell	Enclosing the sample and applying cell pressure up to 1 Mpa
2	LVDT	Measurement of axial displacement
3	Electromagnetic-drive assembly	Neodium iron boron magnet system for applying torque and flexure on the sample with precision.
4	Back pressure controller	Piston controlled measurement of back pressure
5	GDSLAB software	Data input and display of test result
6	Transducers sensitivity controller	Sets sensitivity of accelerometer
7	Dual channel pneumatic regulator	Computer controlled air pressure Max. pressure output is 1000
8	Serial pad	8 channel data recorder of 16 bit data acquisition
9	Specimen Platens	Both active and passive end platens made from non-corrosive material having modulus 10 times the materials
10	Internal mounted, counter-balanced Accelerometer	Acceleration pickups

3.4 Test Setup and Details

The resonant column is used for measurement of dynamic response of soils since the 1930's. Drnevich, Hall & Richard (1967) and Hardin and Black (1968) have used and made popular work in resonant column in 1960's. The reduction of data from the resonant column, to obtain the physical properties of interest, is a function of the boundary conditions. In the majority of cases, research has been undertaken using the fixed-free configuration as in the GDS system. In these configuration, excitation is done to the system in torsion and in flexure at its fundamental frequency. The exciting force is applied by the electromagnetic driven system. From these the velocity and damping value of propagating wave is also measured. The shear modulus is then obtained from the derived velocity and the density of the sample (Anderson and Stokoe, 1978) and testing at high confining stresses.

3.4.1 Material used

The sand used for testing is Solani sand which is collected from the river bed of Solani river near Roorkee. The soil is graded as SP (Poorly graded sand). Index properties of Solani sand is given in Table 3.2 and grain size distribution curve is given in Fig. 3.4. It can be observed that the sand is poorly graded and classified as SP.

Table 3.2 Index properties of Solani sand after Kirar (2016)

Sr. no	Particulars	Notations	Value
1	Soil type	SP	Poorly Graded Sand
2	Specific gravity	G	2.68
3	Uniformity coefficient	C_u	1.96
4	Coefficient of curvature	C_c	1.15
5	Grain size	D_{10}	0.120 mm
		D_{30}	0.180 mm
		D_{50}	0.210 mm
		D_{60}	0.235 mm
6	Maximum Void Ratio	e_{max}	0.850
7	Minimum Void Ratio	e_{min}	0.540

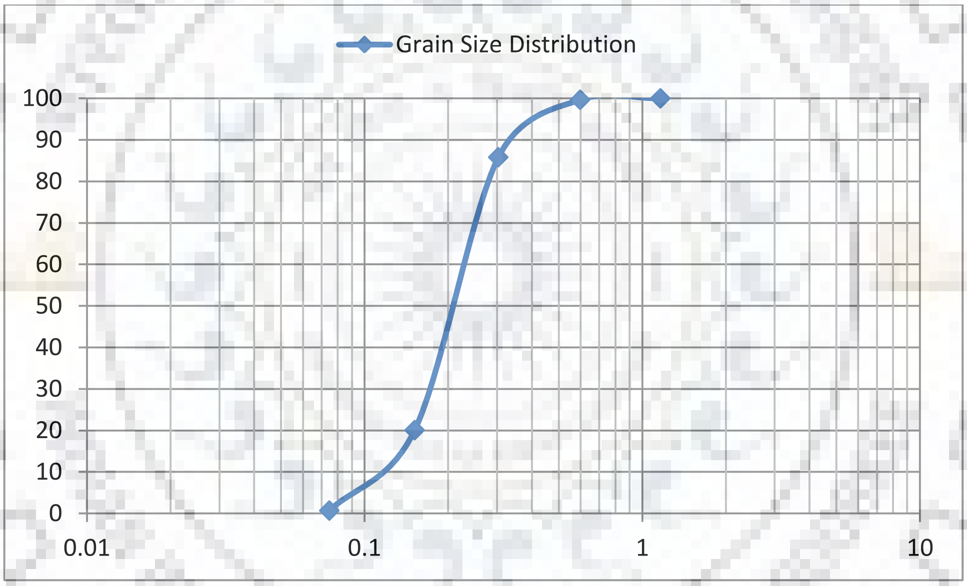

Figure 3.4 Grain size distribution for Solani sand after Kirar (2016)

3.4.2 Details of test

The resonant test in both flexure and torsion mode of vibration are performed on a sample of Solani sand. The samples were prepared for three relative densities viz. 40%, 60% and 80% and are tested under a confining pressure of 100 kPa, 200 kPa and 300 kPa. The sample was prepared for different saturation condition i.e 0%, 25%, 50 %, 75% and 100%.

The method of sample preparation is wet tamping method. The sand is spread in five different layers and the amount of water required for different degree of saturation is spread equally in five layers and then tamped properly.

3.4.3 Testing Programme

All the tests performed using resonant column apparatus to fulfil the objective of this dissertation. The sample is of diameter 50 mm and height 100 mm. The test in performed in two phases. In first phase the calibration of instrument is done and in next phase testing on sand sample is done. Resonant and damping test is performed on the sample in flexure and torsional mode. The calibration is done to find the polar moment of inertia as it is difficult to find it mathematically due to the complexity of the system.

The details of the test performed for calibration is given in Table 3.3 and the details of test performed is given in Table 3.4

Table 3.3 Tests performed for Calibration of Apparatus

Tests	Diameter of Calibration Bars	No of brass weights
Torsion Test	15 mm, 12.5 mm and 10 mm	3
Flexure Test		1
Total no of test performed =18 (12 torsion and 6 flexure)		

Further many test were performed for the learning purpose and understanding the operation of the apparatus and then the final tests were conducted for the dissertation work. During the learning phase the problems coming in operating is observed and also some issues related to testing and sample preparation is observed.

3.5 Sample Preparation and Test Procedure

3.5.1 Sample Preparation and Setup

The sample is prepared at 25%, 50%, 75% and 100% degree of saturation. The sample is prepared in five different layers each having equal thickness of 20mm to prepare the complete sample. Each layer is tamped increasing the no of tamping as height increases and checking the level of the sample using level tube.

The following steps have been used for the sample preparation of sand for different saturation condition of given relative density is done:

a) The relative density of sand is determined by using formulae

$$D_r = \frac{e_{max-e}}{e_{max}-e_{min}} \tag{3.1}$$

b) The void ratio for a given relative density is calculated by

$$e = e_{max} - D_r(e_{max} - e_{min}) \tag{3.2}$$

c) The dry unit weight r_d can be calculated by

$$r_d = \frac{G r_w}{1+e} \quad (3.3)$$

Where r_w=unit weight of water and G =Specific gravity of solids

d) The water content (w) required for saturation (S_r) is calculated as

$$e \times S_r = G \times w \quad (3.4)$$

For different degree of saturation viz. 25%, 50%, 75% and 100% , water content (w) is calculated.

e) Quantity of water (W_W) is given by:

$$W_W = \mathrm{w} \times \mathrm{W_d} \quad (3.5)$$

$\mathrm{W_d}$= weight of dry sand

Amount of water required calculated for different saturation condition is calculated and the calculated amount of water is divided in five equal parts and sprinkled over each layer. Pouring water at each layer and tamping it using the tamping rod, proper height is maintained.

(f) Now the membrane is placed on the rigid base pedestal of resonant column apparatus with the help of rubber rings i.e. O rings at the bottom of pedestal and mould of 100 mm height

(g) We calculate the amount of dry sand required for sample preparation from above given equations. In these tests, sample is prepared in five layers and all the layers is tamped gently. Number of blows for lower layer will be higher than the upper layer so that uniform sample is prepared. After this the top cap is attached with porous stone is placed correctly and its alignment is checked with the help of bubble tube

The sample is prepared using the mould and the rubber membrane, the sand is spread in five layers and tamped and proper height is maintained. For further stabilising the sample a negative pressure of 20 kPa is given for completing the setup when is later released slowly after closing the cell. The final place of top cap on the sample is shown in Fig 3.5 and Fig 3.6 shows the driven assembly and the glass chamber for enclosing the sample with water for applying cell pressure.

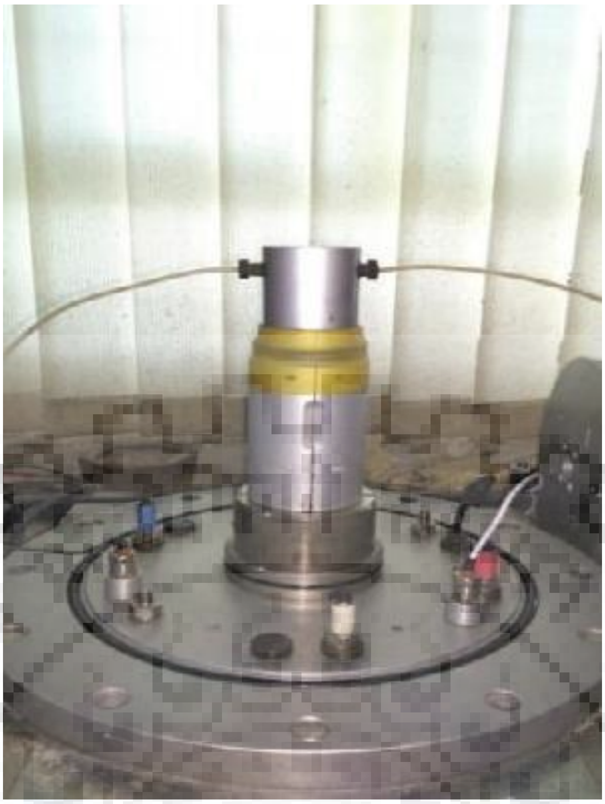

Figure 3.5 Placing of sample and top cap

The accelerometer is then attached to the arm and the coils are attached to the system. After all the connections has been made place the top plate and tighten it. After placing the top cap place the LVDT for measuring the axial displacement, and connect the LVDT to the system. After checking all the connections pull down the main cell and take care of the any disturbance due to it and tightening it so that there is no air leak after applying the cell pressure.

The water in the glass cell provides uniform cell pressure on the sample. The driven assembly is properly tightened, then the level of the sample is checked before placing the driven system. Before placing the driven system on the assembly its level is checked. Then the driven system is place over the assembly. The screws attached to the lever arm of the driven system is tightened to the top cap of the sample. Then, the driven system is moved slightly to position it for further screw tightening and arranging for proper placing of the electromagnets. The driven system and its assembly is shown in Fig 3.7.

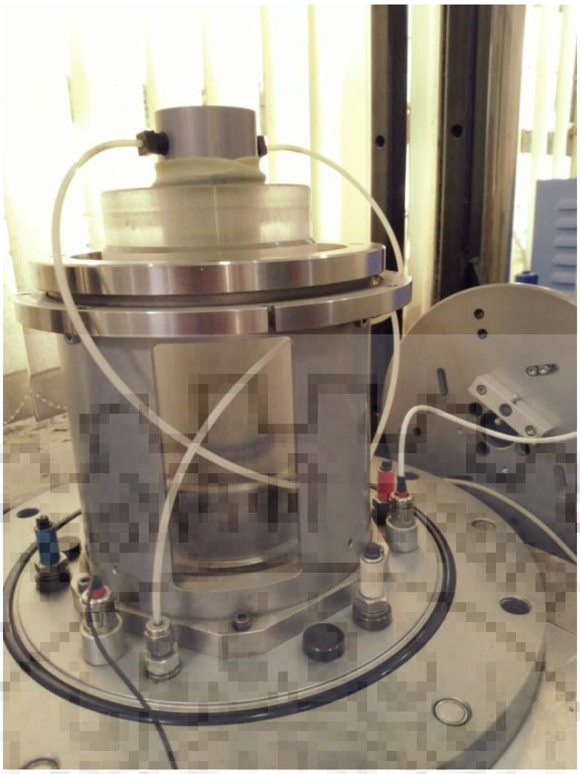

Figure 3.6 Placing of Driven assembly and glass chamber

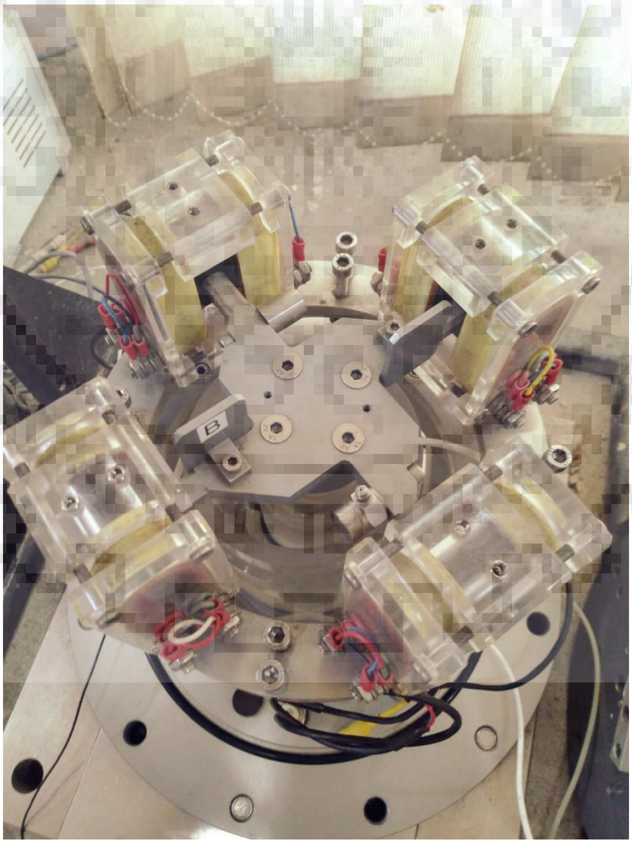

Figure 3.7 Placing Driven system and connecting the coils.

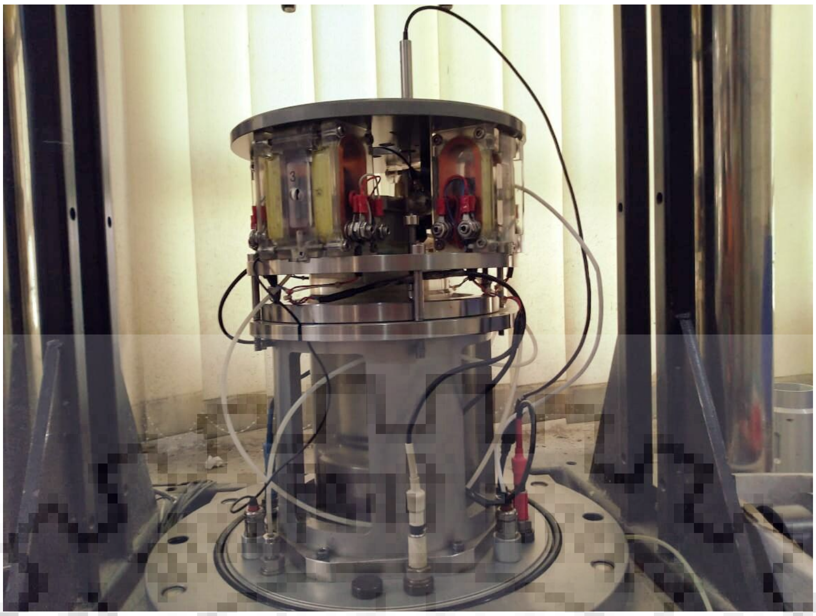

Figure 3.8 Placing of top plate and connections

3.5.2 Flushing

The water is passed from the top of the sample to the bottom to remove all the air present for full saturation of the sample. The cell pressure is applied which is controlled by the pressure controlled system which is operated by the GDS software, the cell pressure is given through air compressor. The water is pushed into the sample using the back pressure control system which is controlled by the GDS software, a difference of 20 kPa is maintained between the cell pressure and back pressure.

3.5.3 Saturation and Consolidation

During flushing almost all the voids are filled with water but the B-value is not reached. So, saturation of the sample is further done by maintaining the difference of 10Kpa between cell and back pressure, allowing further saturation without settlement of sample. Then the B-value is checked. The saturation is done till the B-value reaches 0.95.

Consolidation stage is to apply the effective confining pressure to the sample. In this the effective confining pressure at which the test is to be conducted is given and this stage continues either a maximum of 60 minutes or the volume change is less than $5mm^3$ for five minutes. After this stage test is performed.

3.5.4 Resonant Test

The testing is now done after the consolidation stage and the resonant frequency is determined at different voltage that is applied to the electromagnet. The software allows user to run a broad sweep to find the range of resonant frequency and then at that frequency fine sweep is run that gives the exact very near value of resonant frequency.

Broad Sweep

In this we can give the start and end frequency and the frequency increment. This frequency is further run in fine sweep so that the required resonant frequency can be obtained. Fig 3.9 shows the broad sweep screen

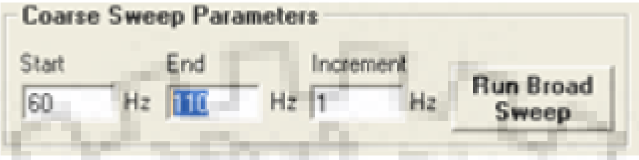

Figure 3.9 Broad sweep after RCA manual

Fine Sweep

The frequency obtained from the broad sweep is further run in fine sweep. This window automatically takes the frequency from broad sweep and in fine sweep we can set the increment and the value to set the domain of fine sweep. The frequency can be entered manually by placing the cursor at the maximum amplitude and noting the frequency. Fig 3.10 shows the broad sweep screen

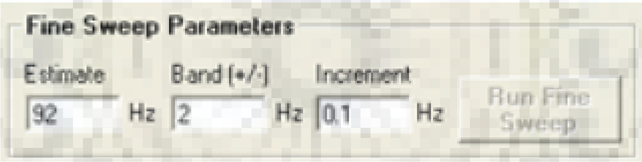

Figure 3.10 Fine sweep after RCA manual

Fig 3.11 show the screen of torsion testing at 0.1 V and the reading of the accelerometer reading. It sweeps for given frequency range as explained above.

Fig 3.12 shows the frequency obtained from the peak amplitude position. This frequency obtained is used for calculation of dynamic property of soil. The voltage value is varied from 0.001 V to 0.3 V and under these conditions the resonant frequency and shear strain value is obtained. The Shear modulus vs shear strain curve is plotted.

Similarly, the flexure test is performed and the calculations are done. At these resonant frequency damping test is performed to find the damping in flexure and torsion mode.

Resonant Test in Torsion mode is for the calculation of Shear modulus and Flexure mode for the calculation of Modulus of Elasticity. In case of torsion mode we get shear strain and in flexure mode we get axial strain. In Damping Test, Damping ratio for both flexure and torsion mode is calculated at the same resonant frequency.

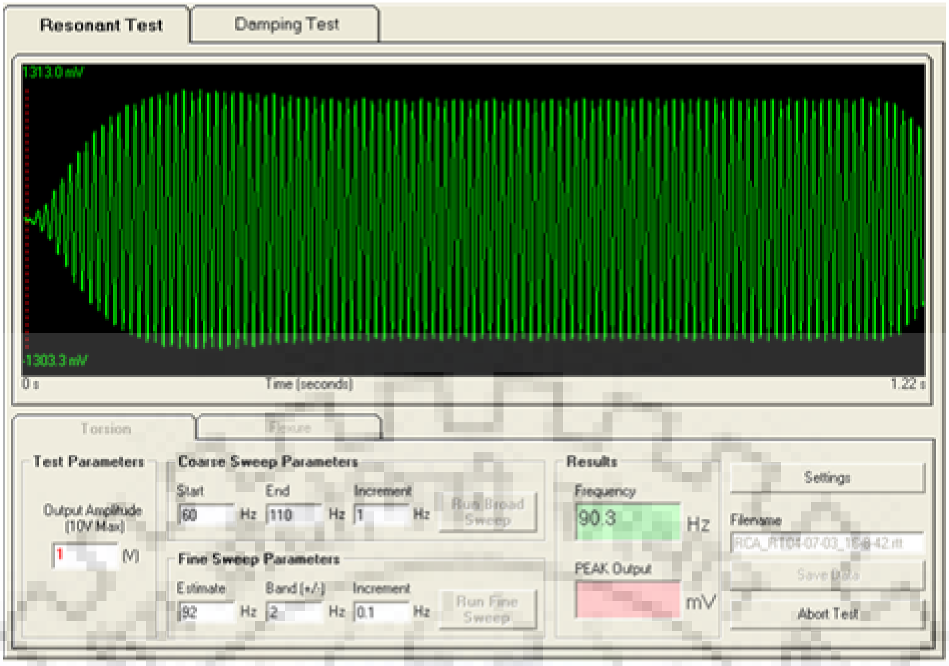

Figure 3.11 Running torsion test after RCA manual

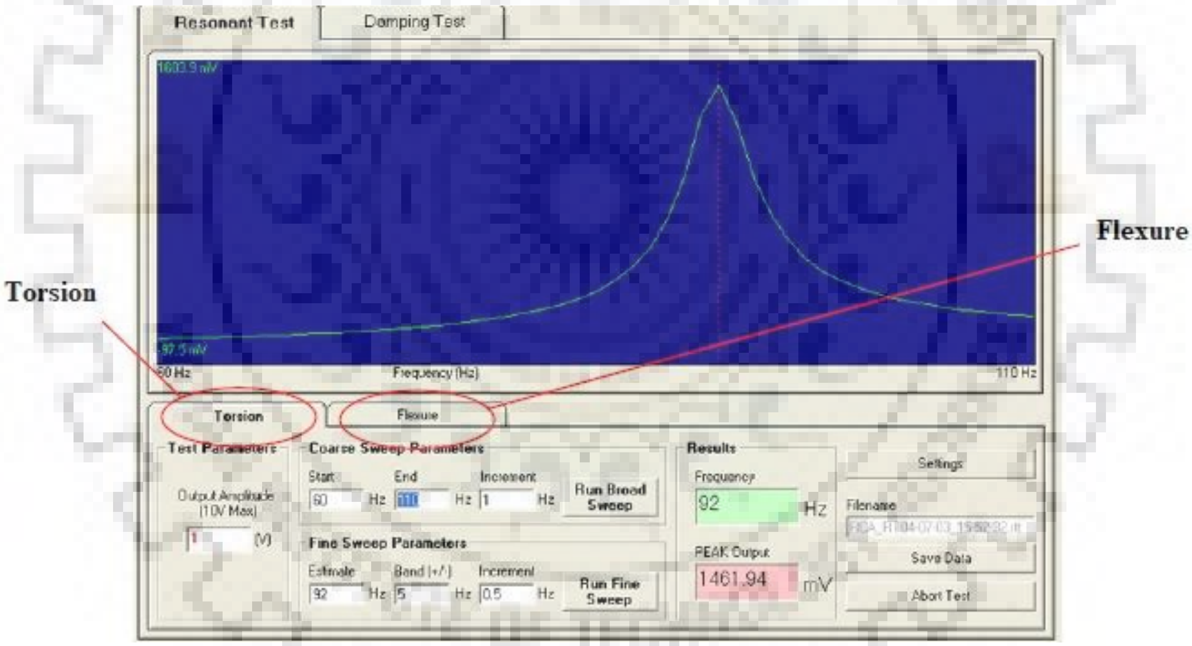

Figure 3.12 Displaying resonant frequency after torsion test after RCA manual

3.5.5 Removal of load and specimen

After performing the tests, the pressure applied is released through the saturation stage and after all the pressure is released, back pressure valves are opened to release the back pressure. The cell is now removed and then the driven system and assembly is removed. The sample is removed from the bottom keeping in mind further spread of sand on the setup. Then the setup is cleaned for further any sand presence.

Chapter-4

Formulations and Calibration of RCA

4.1 Stiffness (G, E) and Damping (ξ) Analysis

From the resonant frequency obtained from the testing in flexure and torsional mode of vibration various formulas are required for the calculation of Shear modulus and Modulus of Elasticity. The formulations used are as:

4.1.1 Torsional Stiffness (Shear modulus, G)

The mass polar moment of inertia of the specimen (I), is used in the one dimensional torsional wave equation. The specimen used is cylindrical and polar moment of inertia is given by Eq. 4.1 and Eq. 4.2 for solid and hollow specimen respectively.

$$I = \frac{md_o^2}{8} \tag{4.1}$$

$$I = \frac{m(d_o^2 + d_i^2)}{8} \tag{4.2}$$

Where

d_o= outside diameter of the solid specimen (m)

d_i = inside diameter of the hollow specimen (m)

m= mass of the specimen (kg)

Basic equation (Eq. 4.3) for the fixed free resonant column is as follows:

$$I/I_o = \beta \tan(\beta) \tag{4.3}$$

Where

I = mass polar moment of inertia of solid specimen

I_o = mass polar moment of inertia of resonant column drive system

As the resonant column system is a very complex system it is not easy to find the mass polar moment of inertia of the drive system mathematically so it can be found out experimentally. The calibration of the instrument is done using the cylindrical aluminium specimen. From the table provided, using the value of I/I_o , β can be determined.

Using the resonant frequency obtained from the test and the value of β, Shear wave velocity is calculated using Eq. 4.4.

$$V_s = \frac{2\pi f h}{\beta} \tag{4.4}$$

Where

f= Natural frequency of sample as found from the test (Hz)

h= Height of the specimen (m)

From the Shear wave velocity (V_s), Shear modulus can be obtained using Eq. 4.5,

$$G = \rho V_s^2 \tag{4.5}$$

Where

ρ= bulk density (Mg/m^3)

4.1.2 Flexural Stiffness (Modulus of Elasticity, E)

The behaviour of the system is assumed elastic, thus no energy is lost and the total energy remains constant. Thus the 'Rayleigh's energy method' can be applied. For the reduction of data for flexural excitation, the drive mechanism and the specimen is considered as an elastic column with a lumped mass at its free end.

From CASCANTE (1998), the circular resonant frequency for a cantilever beam of length L can be obtained using Rayleighs's method and considering N distributed masses m_i (i.e. top bar, top cap, drive and then an additional added mass) using Eq. 4.6:

$$w^2 = \frac{3EI_b}{L^3\left[\frac{133m_r}{140} + \sum_{i=1}^{N} Nm_i h(h_{o,}h_1)\right]} \tag{4.6}$$

Where

E = Young's Modulus

I_b = Area moment of inertia

m_T = Mass of the specimen.

h_{0i} and h_{1i} are heights at the bottom and top respectively of mass I as measured from the top of the soil specimen.

Above equation is used to find the Young's modulus, E, for the flexural excitation to be estimated based on measurement of resonant frequency of flexural vibration and the geometric properties of the specimen and apparatus.

Using the Eq.4.7 , longitudinal wave velocity in bounded medium, V_{rod} is calculated as follows:

$$V_{rod} = \sqrt{(E_{flex}/\rho)} \tag{4.7}$$

Relation between P-wave velocity, V_s and V_{rod} is given by Eq. 4.8:

$$V_p = V_{rod} \times \sqrt{\frac{(1-\nu)}{(1+\nu)(1-2\nu)}} \tag{4.8}$$

Where ν = Poisson's ratio and is found out using Eq.4.9

$$\nu = 0.5 \times \frac{V_{rod}^2}{V_s^2} - 1 \tag{4.9}$$

The constrained modulus (M) is calculated by Eq. 4.10:

$$M = \rho V_p^2 \tag{4.10}$$

From the constrained modulus (M), modulus of elasticity is calculated using Eq. 4.11:

$$E = M \frac{(1+\nu)(1-2\nu)}{(1-\nu)} \tag{4.11}$$

4.2 Calibration of RCA

The calibration of the apparatus is necessary to be carried before conducting tests on the sample. As the resonant column system is a very complex system so to find its polar moment of inertia is also a tough task , that's why we calibrate the system using the Aluminium bars. After using the system for a long time there may be some breakage, slippage or the screw connection might be different that may effect the polar moment of inertia. RCA is a low strain apparatus so if a slight error comes then it might effect the result a lot. So, there is need to calibrate the system prior to testing the actual samples so that good result can be obtained. Three different diameter aluminium bars are used and also three different brass weights are used. Fig 4.2 represents the calibration bar and weights that are used for calibration.

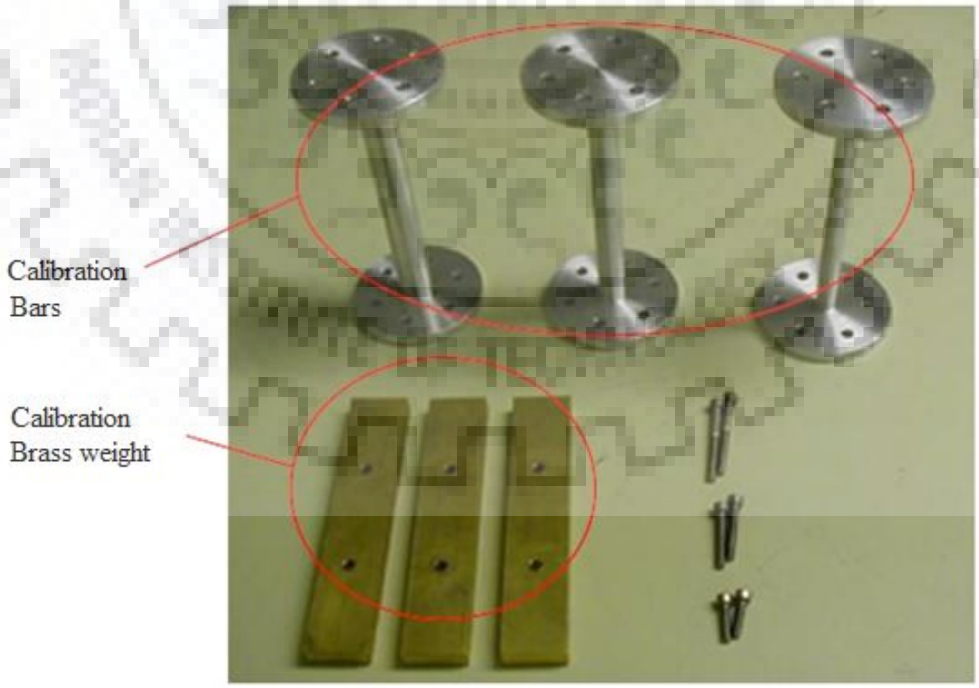

Figure 4.1 Calibration bars and weights after RCA manual

Tests are performed using aluminium bar and brass weight are used and tests are performed in both flexure and torsion. Test are conducted following cases:

1) Without using any calibration mass

2) With addition of one calibration mass,

3) With addition of two calibration masses, and

4) With addition of three calibration masses.

4.2.1 Torsional Calibration

In place of soil sample the aluminium bar is placed and resonant test are performed in torsion mode and the resonance frequency is noted. Different diameter bars and different masses are added and resonant frequency is noted for each condition. The Eq. 4.13 of can be given as:

$$\omega_n = \sqrt{\frac{k}{I}} \tag{4.13}$$

where

k = polar stiffness of specimen

ω_n = natural frequency

I = polar moment of inertia of the bars and masses under different conditions

Polar moment inertia of the bars along with masses can be expressed as Eq. 4.14:

$$I_m = I_o + k \,/\, \omega^2 \tag{4.14}$$

Plot of I_m and $1 \,/\, \omega^2$will give the intercept as I_o and gradient as k.

Usually 2 or 3 calibrations are performed and the average value of I_o is used.

4.2.2 Flexural Calibration

Due to complex geometry of the drive system, the area moment of inertia I_y is determined is determined experimentally. A single metal calibration specimen and single added calibration mass used to measure using Eq. 4.15:

$$\omega_f^2 = \frac{3EI_b}{L^3\left[\frac{133m_r}{140} + \sum_{i=1}^{N} Nm_i h(h_{o,}h_1)\right]} \tag{4.15}$$

The calibration process are as follows:

1) Note the resonant frequency of the calibration bar alone (ω_1)

2) Note the resonant frequency of the calibration bar with a single added mass (ω_2)

Now using the two equations the m_x can be found out:

$$\omega_1^2 = \frac{3EI_b}{L^3\left[\frac{133}{140}m_T + m_a + m_b + m_x\right]} \quad (4.16)$$

$$\omega_2^2 = \frac{3EI_b}{L^3\left[\frac{133}{140}m_T + m_a + m_b + m_x + m_{am}\right]} \quad (4.17)$$

Where,

m_T = mass of specimen

m_a = mass of top disk (top of calibration specimen)

m_b = mass of top cap

m_x = mass of drive (currently unknown)

m_{am} = mass of added mass (added calibration mass)

The calculation for I_y and the calculation to find out modulus of elasticity (E) can also be found out from the spreadsheet provided by the GDS. Table 4.1 and 4.2 gives the calibration data.

Table 4.1 Calibration of apparatus in Torsion

Element	**I of the system (Kg-m^2)**	**Frequency, *f* (Hz)**	**Intercept *(I_o)***
15 mm bar			-0.0031663
Top plate	8.2774E-06	91	
Weight 1	0.0001144	88.5	
Weight 2	0.0001144	87.5	
Weight 3	0.0001144	86.5	
12.5 mm bar			-0.0039816
Top plate	8.2774E-06	64	
Weight 1	0.0001144	63	
Weight 2	0.0001144	62	
Weight 3	0.0001144	61.5	
10 mm bar			-0.0033044
Top plate	8.2774E-06	41.5	
Weight 1	0.0001144	40.5	
Weight 2	0.0001144	40	
Weight 3	0.0001144	39.5	
Average			-0.0035402

Table 4.2 Calibration of apparatus in Flexure

Element	Frequency, *f* (Hz)	I_y
15 mm bar		0.008123676
Resonant frequency with added mass	53	
Resonant frequency without added mass	49.5	
12.5 mm bar		0.008158769
Resonant frequency with added mass	36	
Resonant frequency without added mass	34	
10 mm bar		0.0076644034
Resonant frequency with added mass	24	
Resonant frequency without added mass	22	

Chapter-5

Effects of Various Parameters

This chapter deals with the effect of different parameters on dynamic soil properties. The resonant and damping tests were performed on sample of height 100 mm and diameter 50 mm for Solani sand. The sample were prepared by pouring the sand in five layers and tamping it properly for three different relative densities (40%, 60% & 80%). Samples were tested under three different confining pressures i.e 100 kPa, 200 kPa & 300 kPa. Effects of relative density, confining pressure and degree of saturation on stiffness characteristics and damping characteristics are examined. Variation of damping and stiffness with degree of saturation and effect of mode of vibration is investigated. The details of test conducted are given in Table 5.1.

Table 5.1 Details of tests conducted

S. No.	Type of tests	Mode of Test	Degree of Saturation (%)	Relative Density (%)	Confining Pressure (kPa)	Number of Tests
1	Triaxial Test	Cyclic Shear Test	Dry	60%	100kPa (γ=0.05%, 0.06%, 0.5%, 1%)	8
					300kPa (γ=0.05%, 0.07%, 0.5%, 1%)	
2	Resonant test on RCA	Torsion	0, 25, 50, 75, 100	40, 60, 80	100, 200, 300	45
		Flexure				
3	Damping test on RCA	Torsion	0, 25, 50, 75, 100	40, 60, 80	100, 200, 300	45
		Flexure				

Following test results are presented by varying the different condition and its effect on stiffness and damping parameters under torsion and flexure mode of vibration, they are presented in groups:

(a) Variation of shear modulus and damping ratio are shown with shear strain for torsion test.

(b) Variation of modulus of elasticity and damping ratio are shown with axial strain for flexure test.

(c) Effect of confining pressure on damping and stiffness characteristics in torsion and flexure test.

(d) Effect of relative density on damping and stiffness characteristics in torsion and flexure test.
(e) Effect of mode of vibration on damping characteristics in torsion and flexure test.
(f) Variation of stiffness and damping characteristics with degree of saturation in torsion and flexure test.
(g) Effect of degree of saturation on the Poisson's ratio.

5.1 Validation of Test Data of RCA

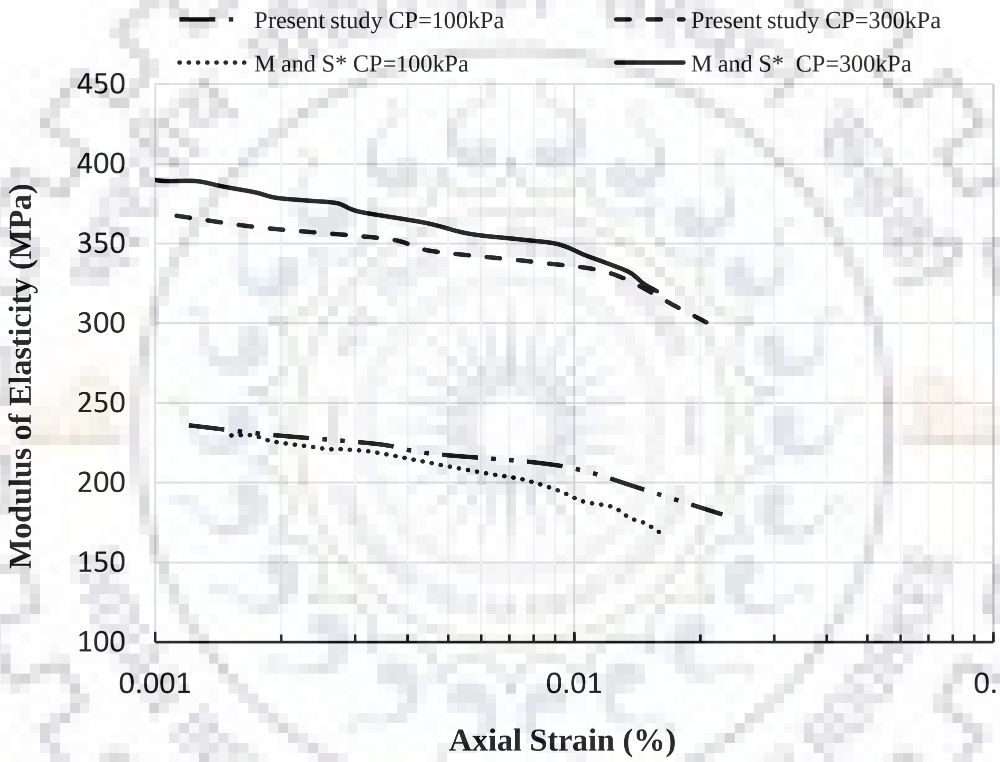

Figure 5.1 Comparison of Present Study with literature
*M and S= Madhusudhan and Senetakis (2016)

For the validation of the result, the results obtained from the present study using flexure test are compared with that of Madhusudhan and Senetakis (2016) in Fig 5.1. It can be observed that the trend of the results are similar. It shall be noted that the results presented by Madhusudhan and Senetakis (2016) are for Bangalore sand while the result of present study are of Solani sand. The comparison of index properties for both the sands are listed in Table 5.2, it can be observed that the index properties of both the sands are comparable therefore the results are compared and found in good agreement. Though comparison is not in the same order at both the confining pressure.

Table 5.2 Index properties of Bangalore Sand and Solani sand

Sr. no	Particulars	Notations	Value Bangalore Sand	Value Solani Sand
1	Soil type	SP	Poorly Graded Sand	Poorly Graded Sand
2	Specific gravity	G	2.69	2.68
3	Uniformity coefficient	C_u	2.01	1.96
4	Coefficient of curvature	C_c	1.10	1.15
5	Grain size	D_{10}	0.170 mm	0.120 mm
		D_{30}	0.250 mm	0.180 mm
		D_{60}	0.340 mm	0.235 mm
6	Maximum Void Ratio	e_{max}	0.97	0.850
7	Minimum Void Ratio	e_{min}	0.59	0.540

5.2 Effect of Saturation

This has been examined at three relative densities and three confining pressure in following sections. The samples were tested at 0, 25, 50, 75 and 100% saturation condition for each relative density and confining pressure.

5.2.1 At RD=40% and CP=100 kPa

Torsion Test

Fig. 5.2 (a) and 5.2 (b) shows the variation of shear modulus and damping ratio with shear strain respectively for different degree of saturation (S).

It can be observed that shear modulus decreases while damping ratio increases with shear strain irrespective of the degree of saturation. Thus the basic characteristics of soil remain intact with the increase in value of Saturation (S).

The effect is saturation is significant up to 50% degree of saturation but later it decreases. Effect of saturation on damping ratio is not much significant.

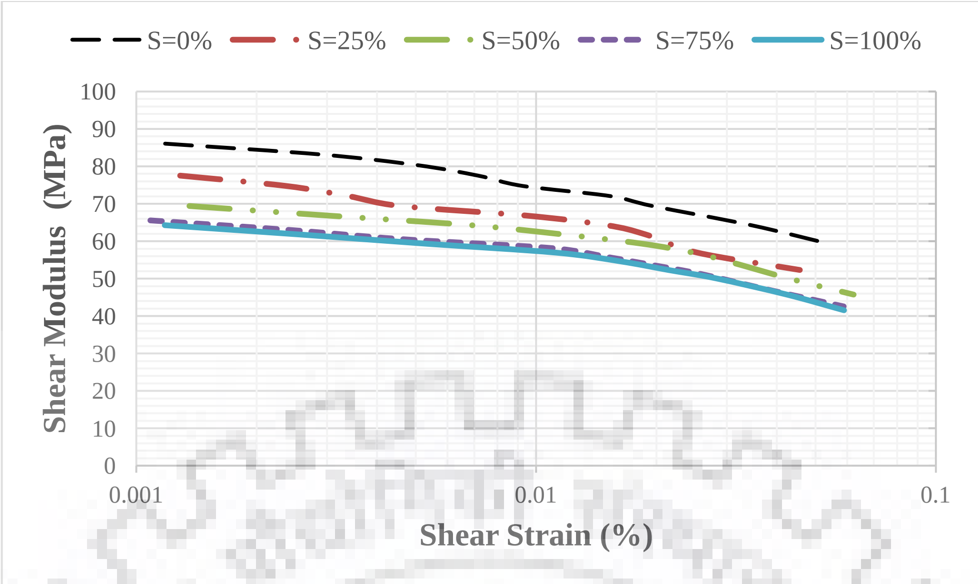

Figure 5.2 (a) Effect of Saturation on Shear modulus vs shear strain at RD=40% and CP=100kPa

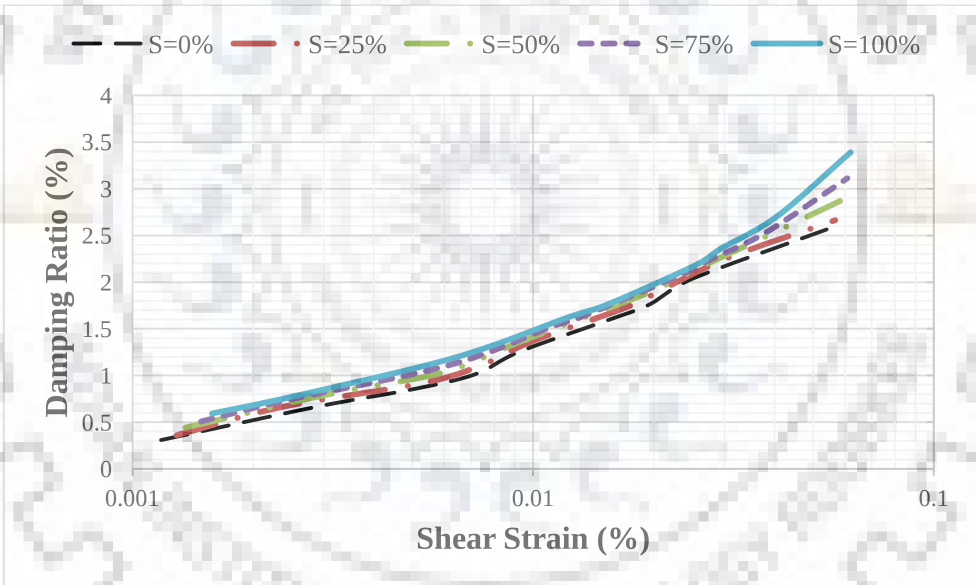

Figure 5.2 (b) Effect of Saturation on Damping ratio vs shear strain at RD=40%and CP=100kPa

Flexure test

Fig. 5.3 (a) and Fig. 5.3 (b) shows the variation of modulus of elasticity of soil and damping ratio with axial strain. It can be observed that the modulus of elasticity decreases with increase in axial strain, following pattern is due to the slippage of particle with increasing axial strain. Effect of saturation is more up to 50 % degree of saturation after while in case of damping ratio the effect is not much significant. Fig 5.3(c) shows the variation of Poisson's ratio with axial strain. As observed from the test results that the Poisson's ratio increases with increase in axial strain. Further, the poisson's ratio increases with degree of saturation at a particular strain. The effect of saturation seems to be prominent after 50% degree of saturation.

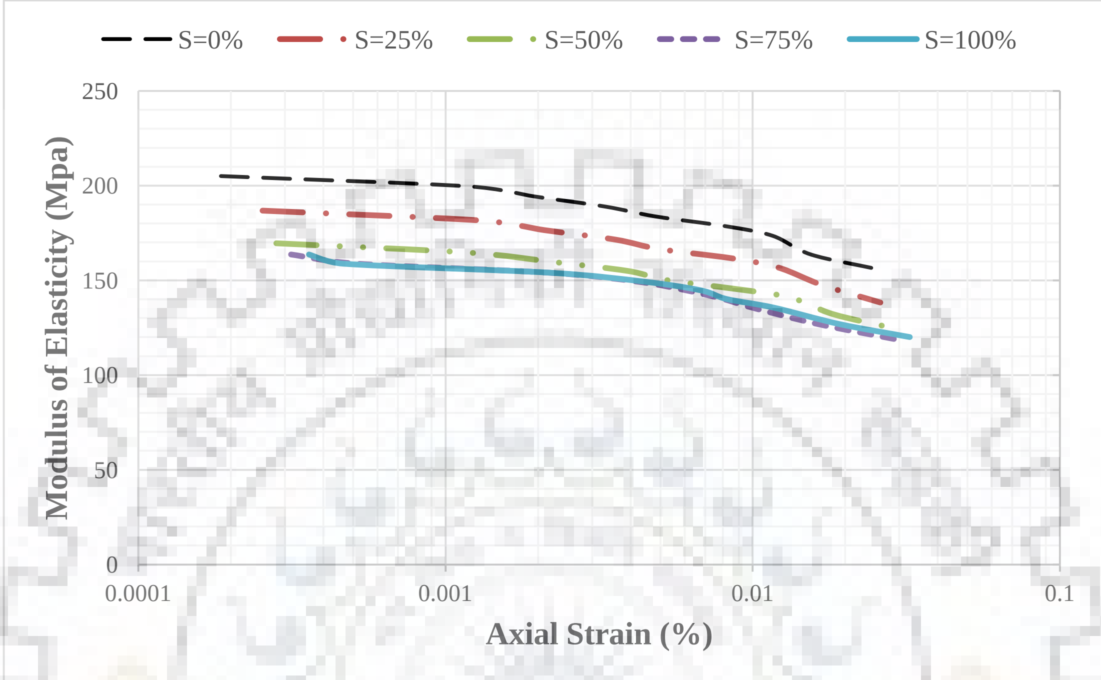

Figure 5.3(a) Effect of Saturation on Modulus of elasticity vs axial strain at RD=40% and CP=100kPa

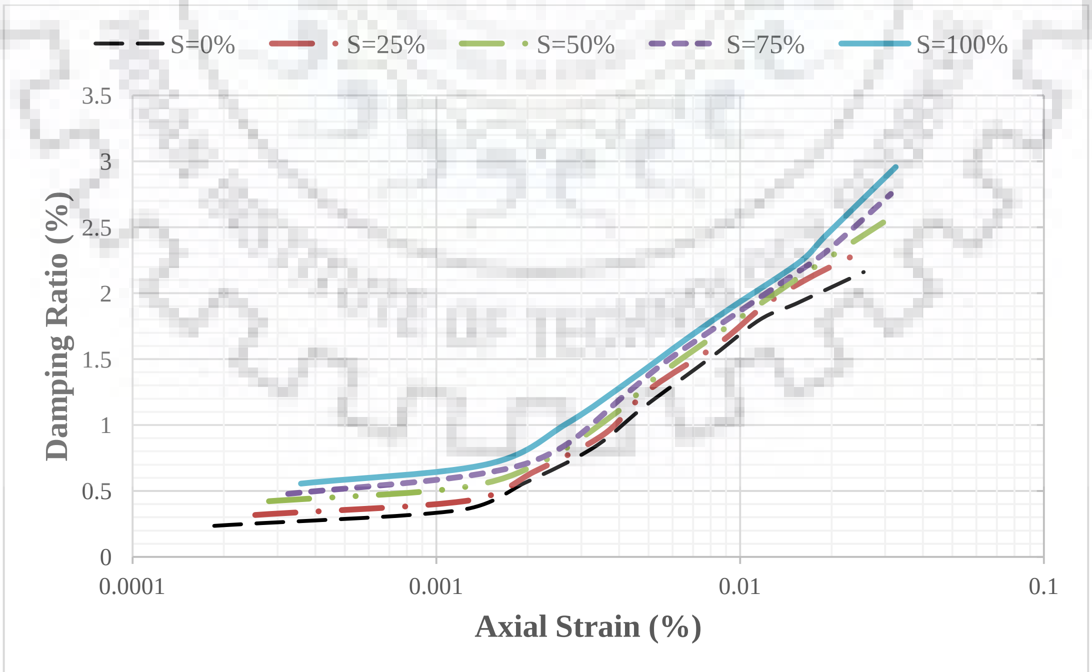

Figure 5.3 (b) Effect of Saturation on Damping ratio vs axial strain at RD=40% and CP=100kPa

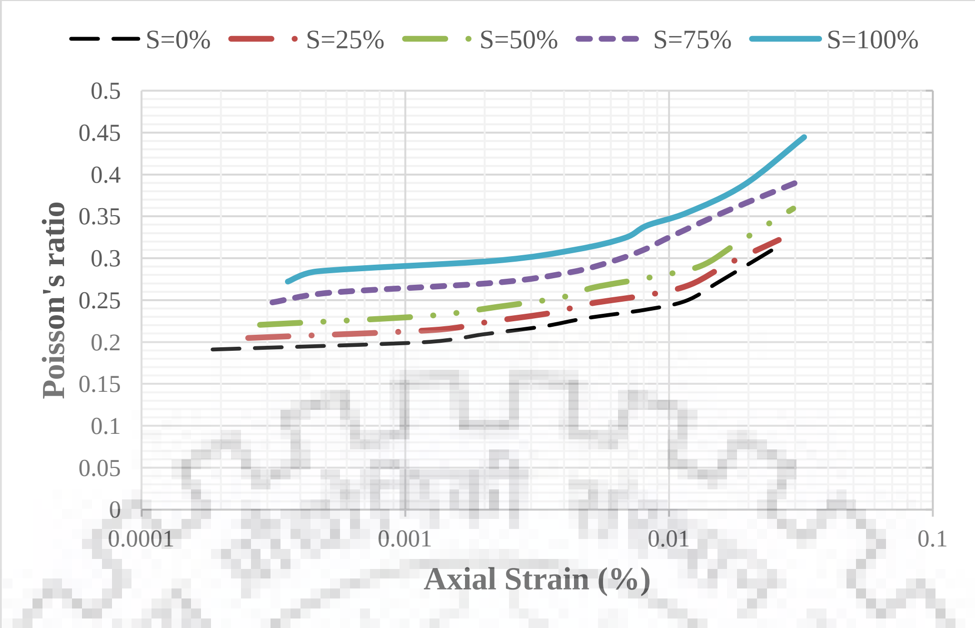

Figure 5.3 (c) Effect of Saturation on Poisson's ratio vs axial strain at RD=40% and CP=100kPa

5.2.2 At RD=40% and CP=200kPa

Torsion Test

Fig. 5.4(a) and 5.4(b) shows the variation of shear modulus and damping ratio with shear strain, respectively.

The variation of damping ratio and shear modulus is similar as observed earlier. The effect of saturation for shear modulus is observed to be more up to 50% degree of saturation, further increasing the saturation has not much effect on the shear modulus. The shear modulus for 75% and 100% degree is saturation is approximately similar. The effect of saturation is not much on damping ratio, increase in damping ratio is very less with each increment of saturation but there is difference in damping from dry and fully saturated condition

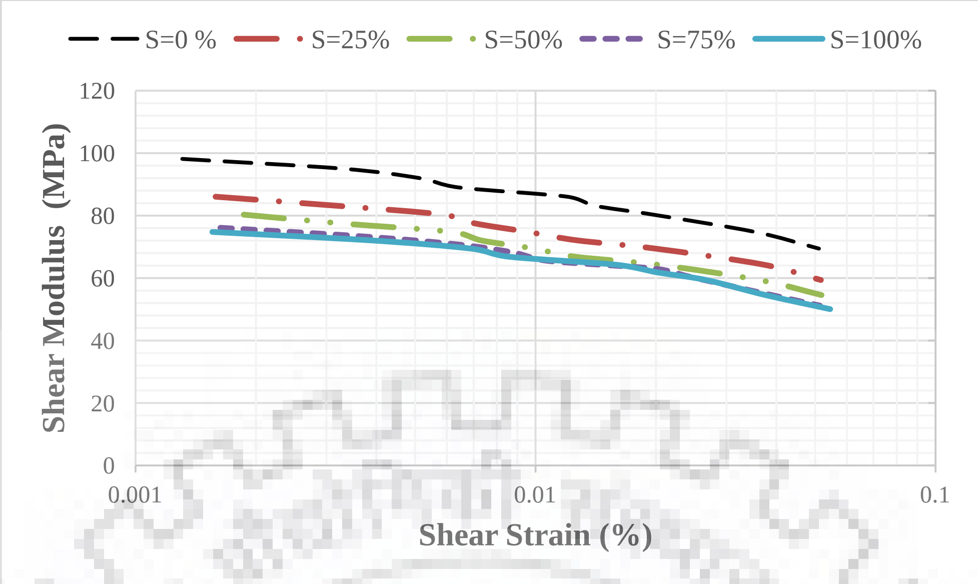

Figure 5.4 (a) Effect of Saturation on Shear modulus vs shear strain at RD=40% and CP=200kPa

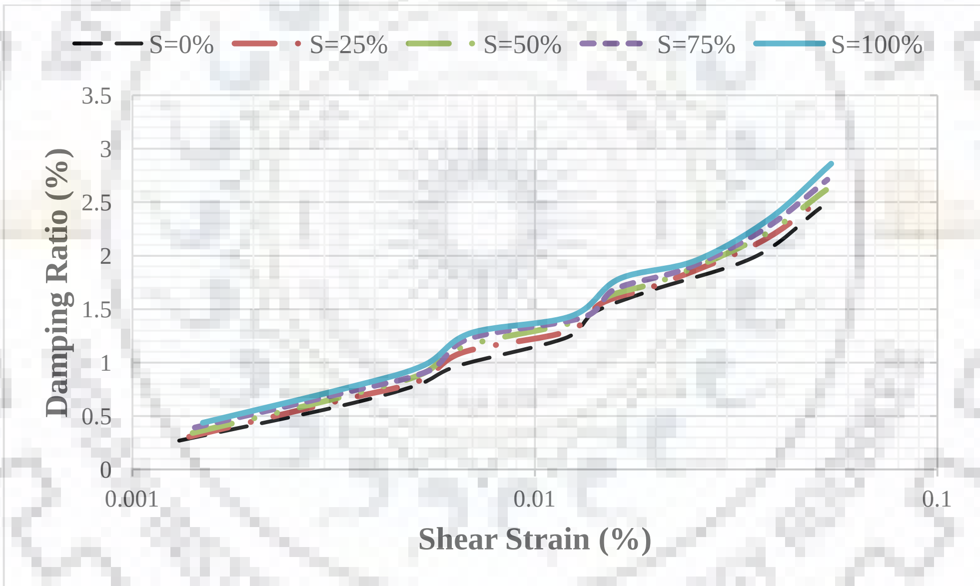

Figure 5.4 (b) Effect of Saturation on Damping ratio vs shear strain at RD=60%and CP=200kPa

Flexure Test

Fig. 5.5(a) and Fig. 5.5(b) shows the variation of modulus of elasticity of soil and damping ratio with axial strain.

The effect of saturation seems to be prominent up to 50% saturation condition, the variation in saturation is very less between 50% saturation condition and 75% saturation. The modulus of elasticity observed is approximately similar for 75% and 100% saturation condition. The damping is not much effected by varying the degree of saturation but there is difference between the fully saturated and dry condition.

Fig 5.5 (c) shows the variation of Poisson's ratio with axial strain for different degree of saturation. The difference in Poisson's ratio is more upto 50% saturation , but the difference is very less between 25% and 50% saturation.. As observed there is difference between dry and 25%saturation condition. Saturation effect is observed to be very less between 25% and 50% saturation condition.

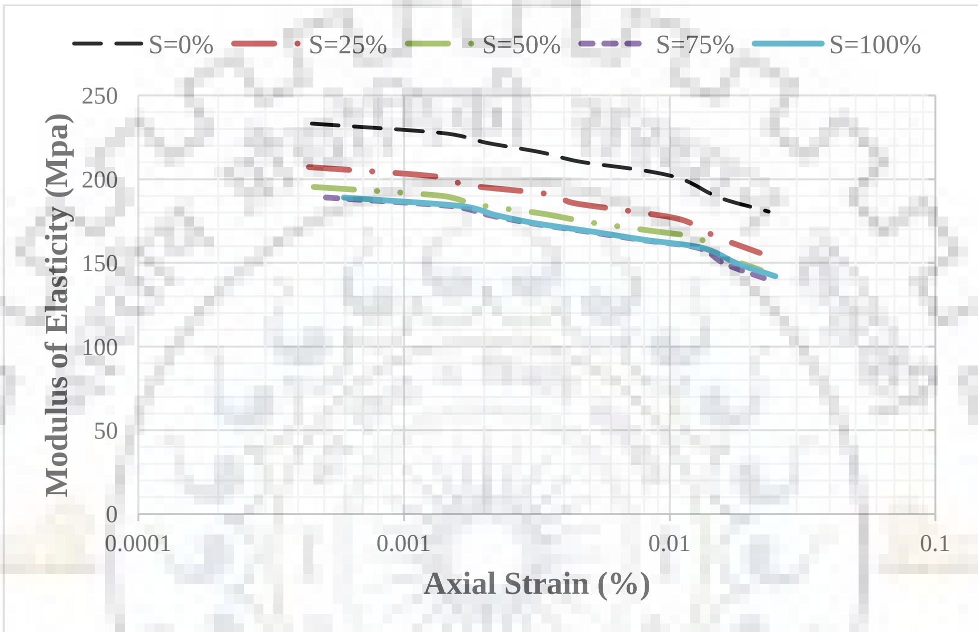

Figure 5.5(a) Effect of Saturation on Modulus of elasticity vs axial strain at RD=40% and CP=200kPa

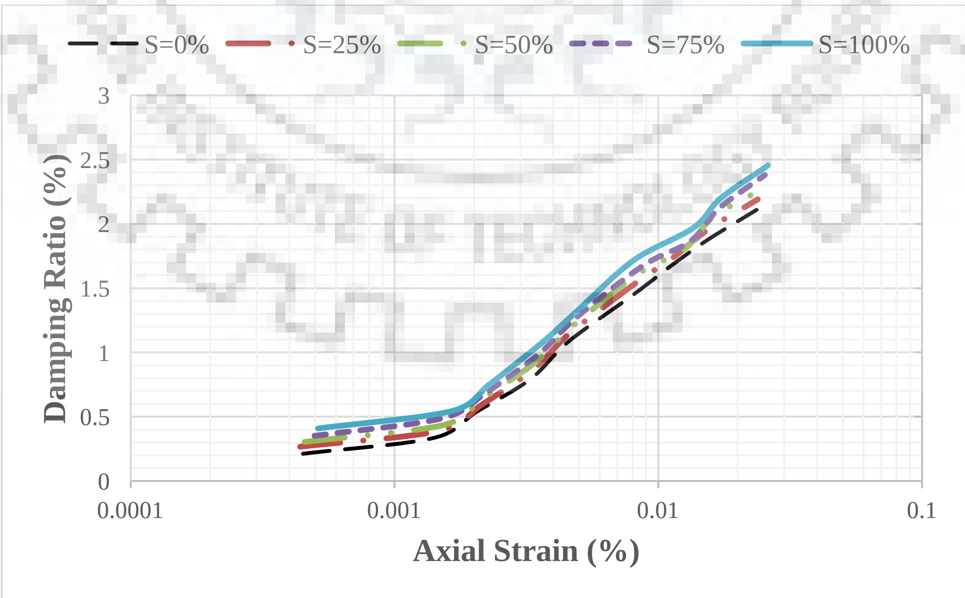

Figure 5.5 (b) Effect of Saturation on Damping ratio vs axial strain at RD=40% and CP=200kPa

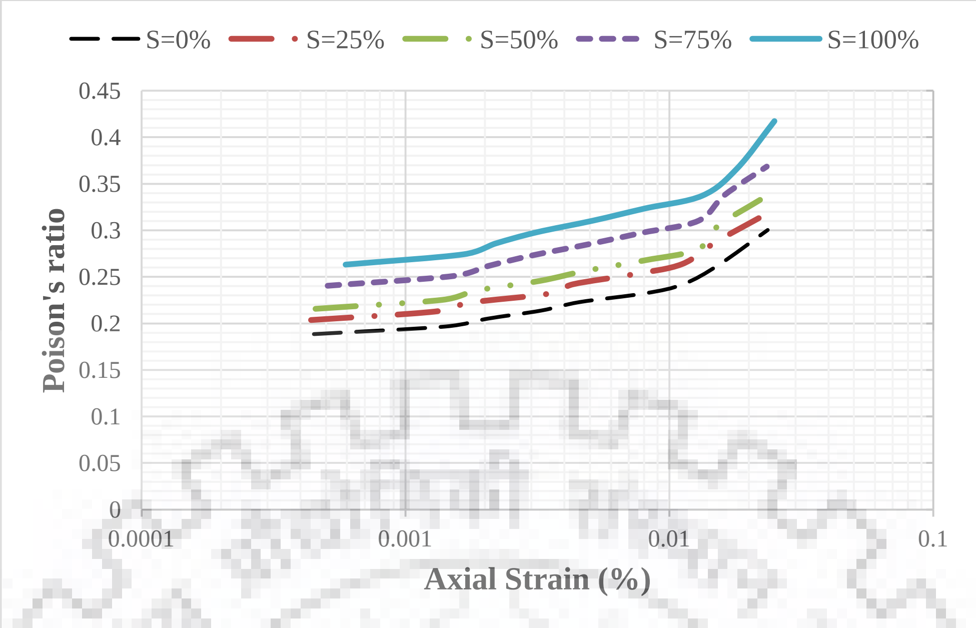

Figure 5.5 (c) Effect of Saturation on Poisson's ratio vs axial strain at RD=40% and CP=200kPa

5.2.3 At RD=40% and CP=300kPa

Torsion Test

Fig. 5.6(a) and 5.6(b) shows the variation of shear modulus and damping ratio with shear strain, respectively.

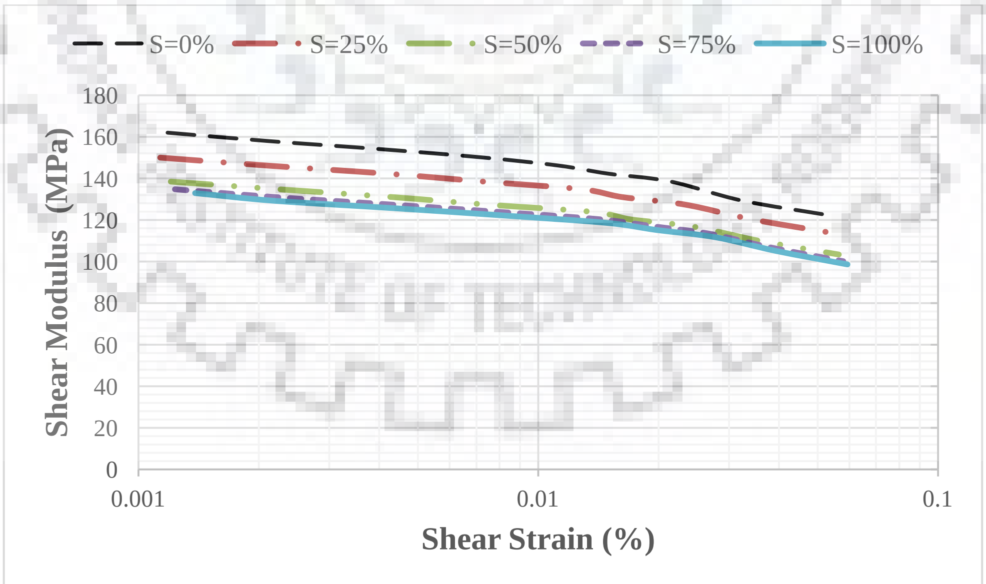

Figure 5.6 (a) Effect of Saturation on Shear modulus vs shear strain at RD=40% and CP=300kPa

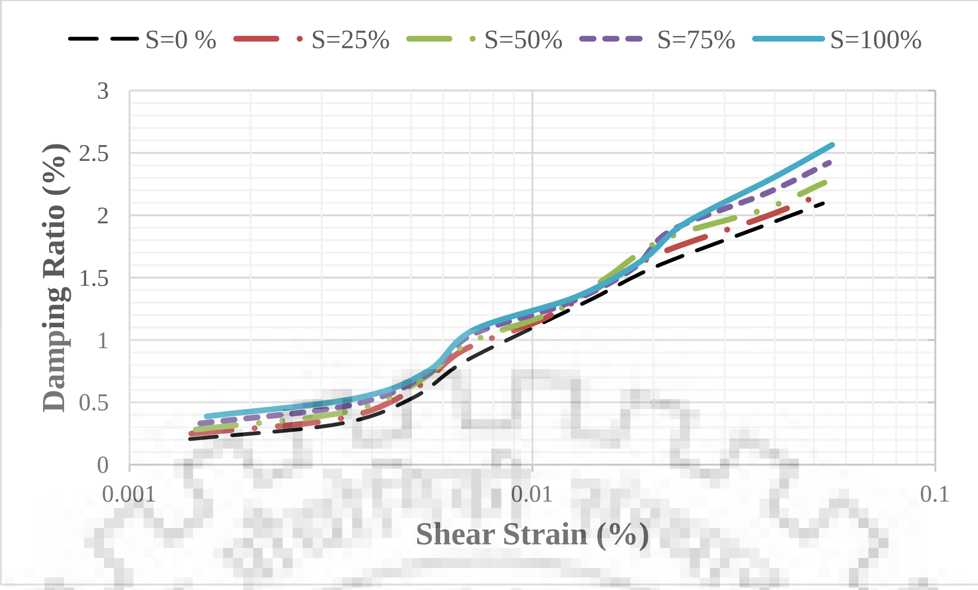

Figure 5.6 (b) Effect of Saturation on Damping ratio vs shear strain at RD=40%and CP=300kPa

The trend observed for shear modulus and damping with shear strain is same as expected. The effect of saturation seems to be more prominent upto 50% saturation condition lateron the effect is very less, between 75% and 100% saturation the effect of saturation is almost negligible. However, the effect of saturation on damping ratio is very less, but there is considerable difference between dry and fully saturated condition.

Flexure Test

Fig. 5.7(a) and Fig. 5.7(b) shows the variation of modulus of elasticity of soil and damping ratio with axial strain.

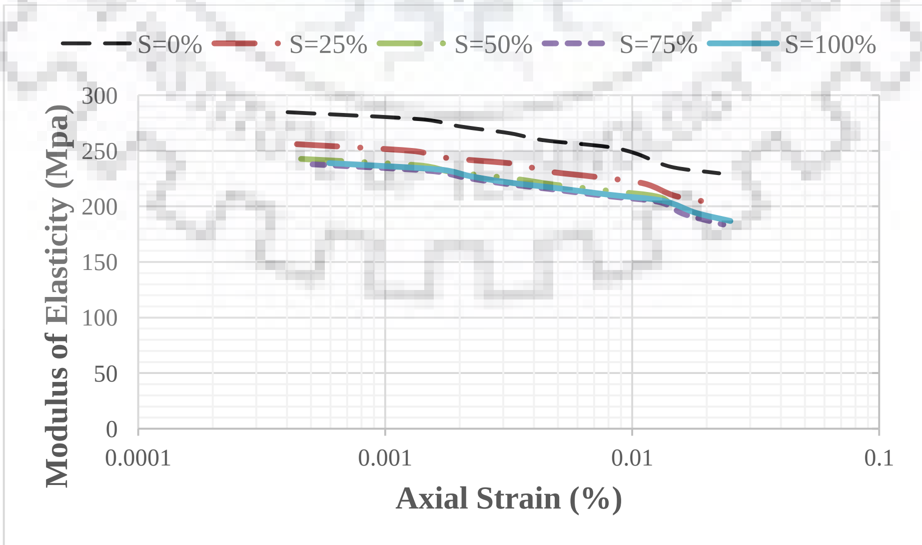

Figure 5.7(a) Effect of Saturation on Modulus of elasticity vs axial strain at RD=40% and CP=200kPa

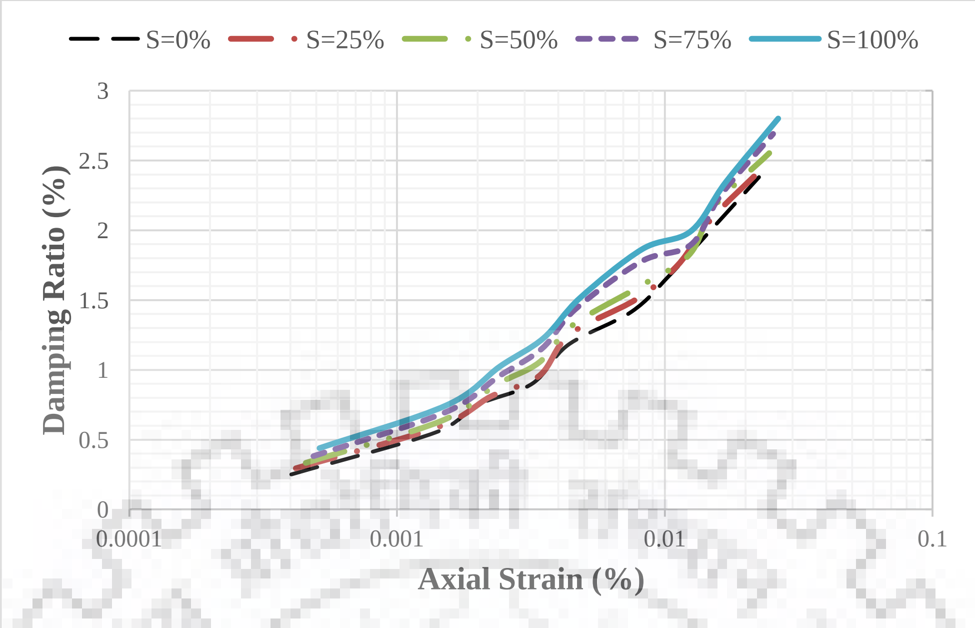

Figure 5.7 (b) Effect of Saturation on Damping ratio vs axial strain at RD=40% and CP300kPa

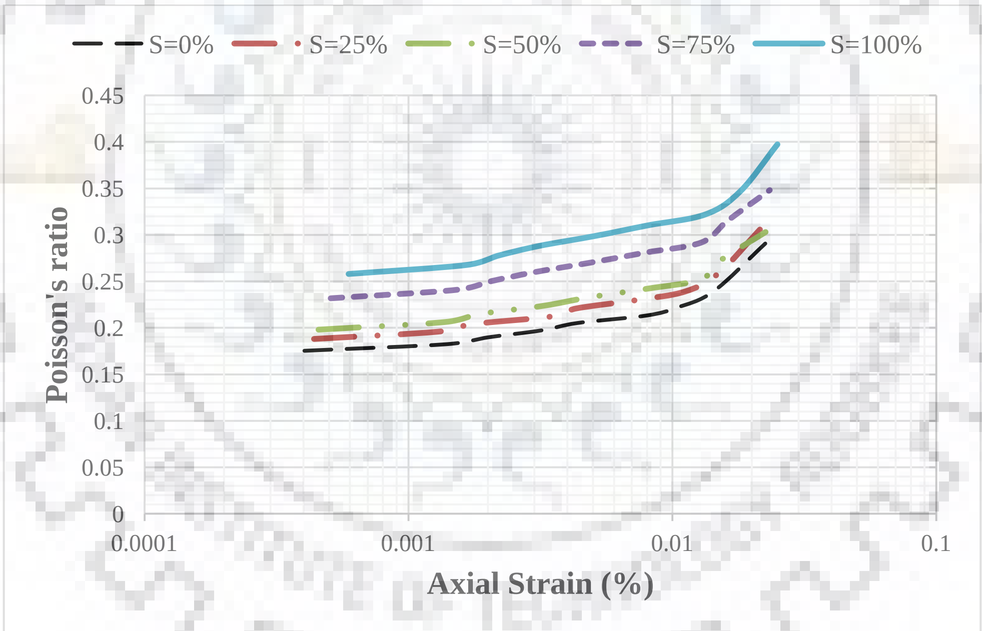

Figure 5.7 (c) Effect of Saturation on Poisson's ratio vs axial strain at RD=40% and CP300kPa

With increase in degree of saturation modulus of elasticity decreases whereas damping ratio increases. The effect of saturation on modulus of elasticity is more up to 50% saturation condition, later on the effect is negligible. The effect of saturation on damping ratio is not much, only we can consider the difference between fully saturated and dry condition.

Fig 5.7 (c) shows the variation of Poisson's ratio with axial strain . The effect of saturation up to 50% saturation condition is not much, but there is considerable difference after that.

5.2.4 At RD=60% and CP=100kPa

Torsion test

Fig. 5.8(a) and 5.8(b) shows the variation of shear modulus and damping ratio with shear strain, respectively.

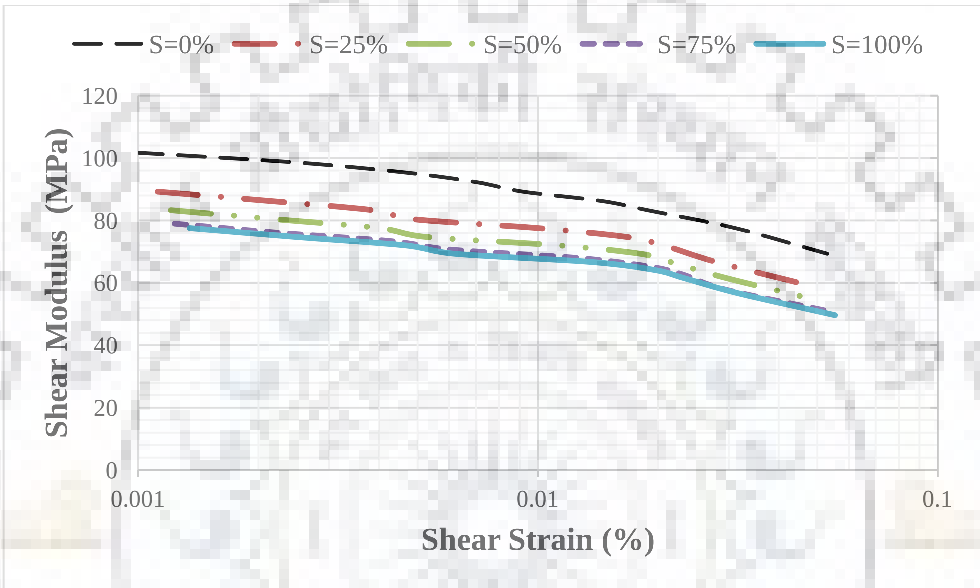

Figure 5.8 (a) Effect of Saturation on Shear modulus vs shear strain at RD=60% and CP=100kPa

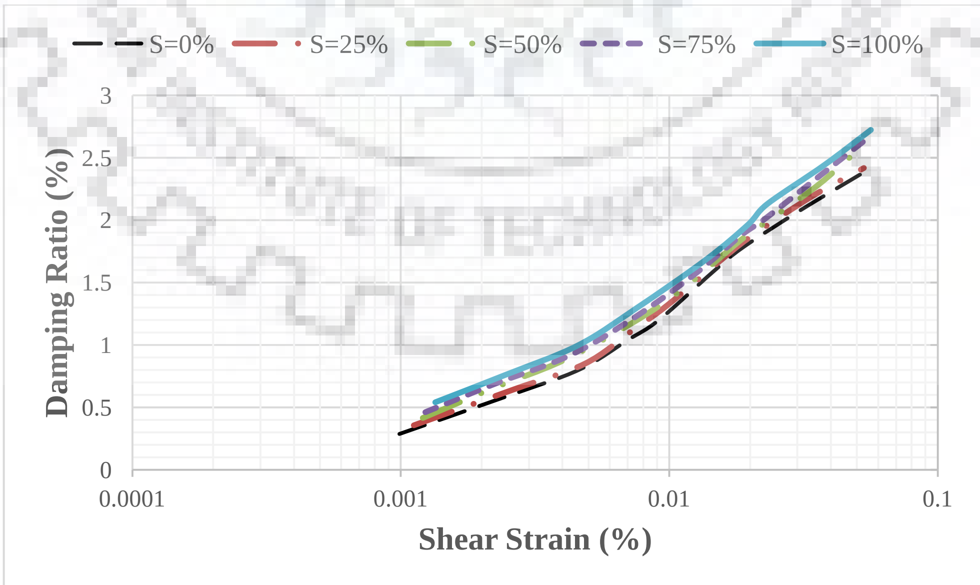

Figure 5.8 (b) Effect of Saturation on Damping ratio vs shear strain at RD=60%and CP=100kPa

As observed shear modulus decreases and damping ratio increases with increase in degree of saturation. The effect of saturation on shear modulus seems to be more prominent up to 50% saturation but later on the effect is negligible whereas the effect of saturation is not much in case of damping ratio.

Flexure test

Fig. 5.9(a) and Fig. 5.9(b) shows the variation of modulus of elasticity of soil and damping ratio with axial strain for different saturation condition.

Fig 5.9(c) shows the variation of Poisson’s ratio with axial strain for different saturation condition.

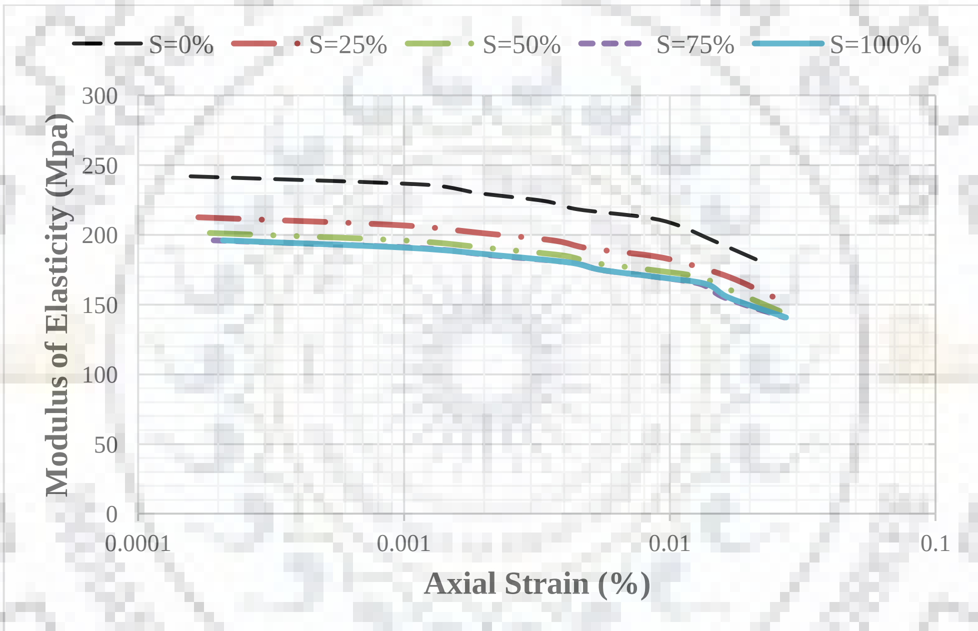

Figure 5.9 (a) Effect of Saturation on Modulus of elasticity vs axial strain at RD=60% and CP=100kPa

With increase in degree of saturation modulus of elasticity decreases but the damping ratio and Poisson’s ratio increases with saturation. The effect of saturation is considerable up to 75% degree of saturation later on the effect is very less, whereas the difference between dry and saturated condition the damping ratio is considerable. The effect of Poisson’s ratio is observed to be negligible between 0% and 25 % saturation, but difference is minor for 25% and 50 % saturation, later on the effect is considerable

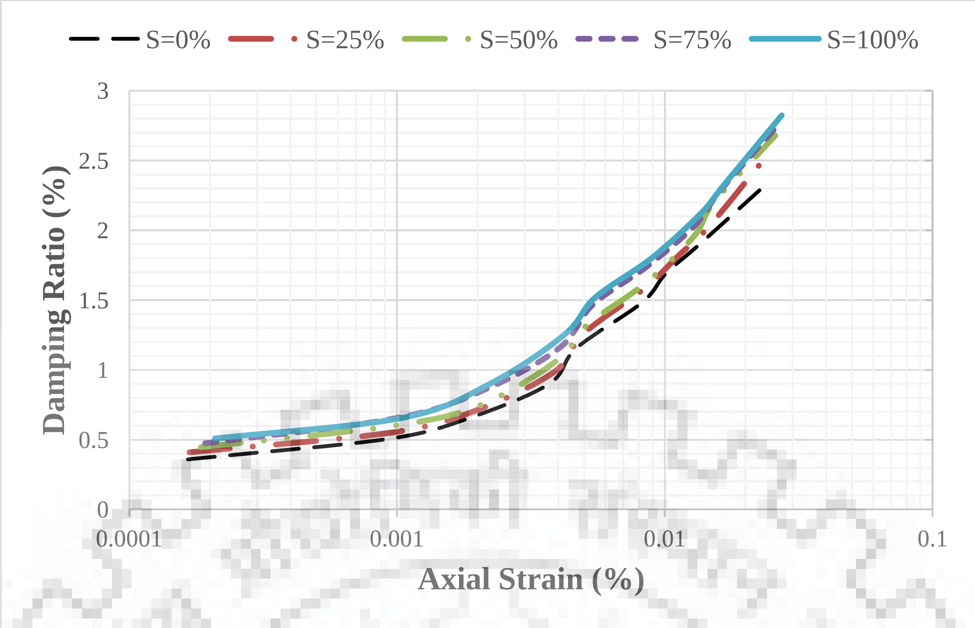

Figure 5.9 (b) Effect of Saturation on Damping ratio vs axial strain at RD=60% and CP=100kPa

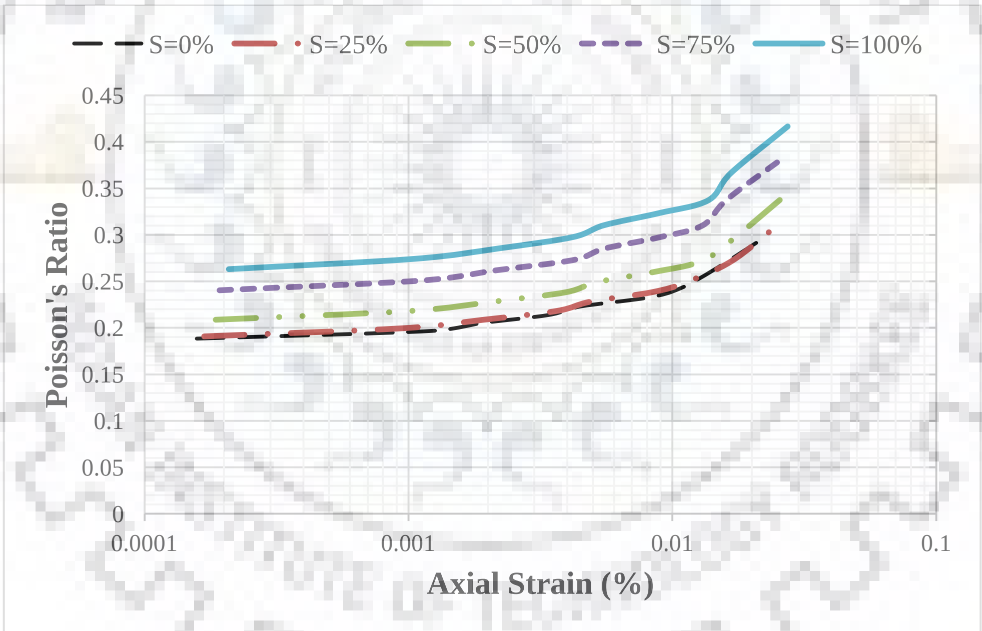

Figure 5.9 (c) Effect of Saturation on Poisson's ratio vs axial strain at RD=60% and CP=100kPa

5.2.5 At RD=60% and CP=200kPa

Torsion Test

Fig. 5.10(a) and 5.10(b) shows the variation of shear modulus and damping ratio with shear strain, respectively.

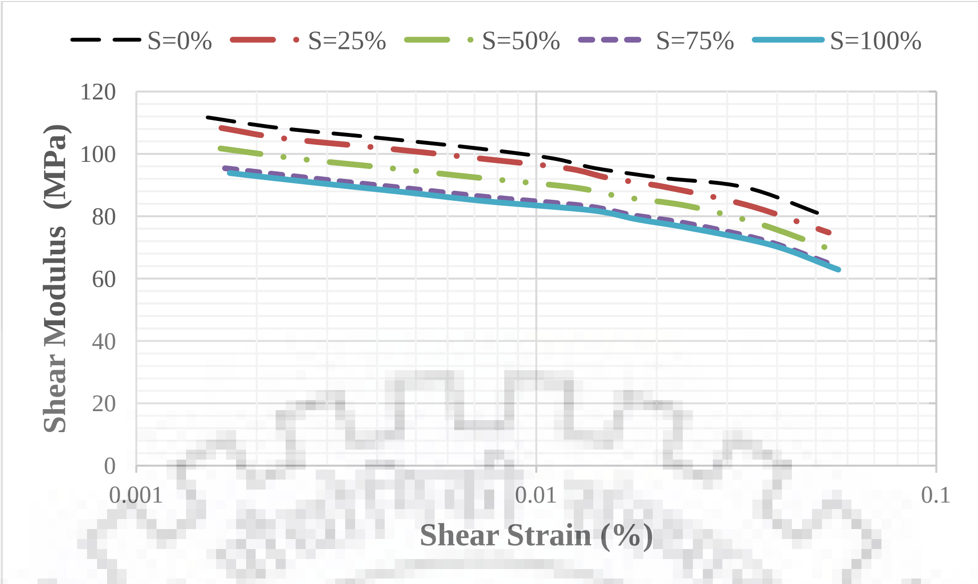

Figure 5.10 (a) Effect of Saturation on Shear modulus vs shear strain at RD=60% and CP=200kPa

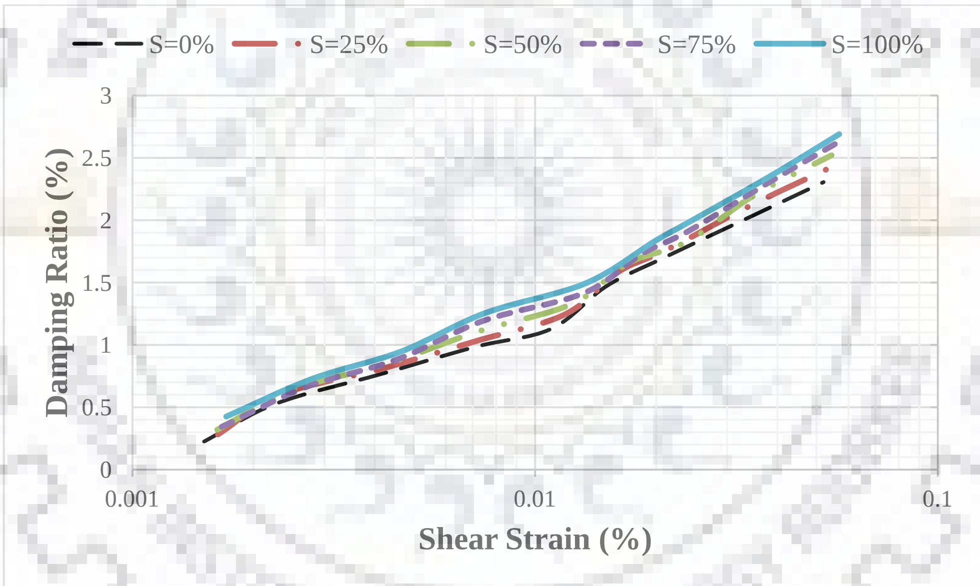

Figure 5.10 (b) Effect of Saturation on Damping ratio vs shear strain at RD=60%and CP=200kPa

As observed from the test results obtained shear modulus decreases with increase in degree of saturation, the effect is more up to 50% saturation condition while damping ratio increases with increase in saturation but the increase with saturation is very less. There is considerable difference in damping ratio for dry and fully saturated condition. Shear modulus for 75% and 100% saturation values are approximately same.

Flexure Test

Fig. 5.11(a) and Fig. 5.11(b) shows the variation of modulus of elasticity of soil and damping ratio with axial strain,Fig 5.11 (c) shows the variation of Poisson's ratio with axial strain for varying degree of saturation.

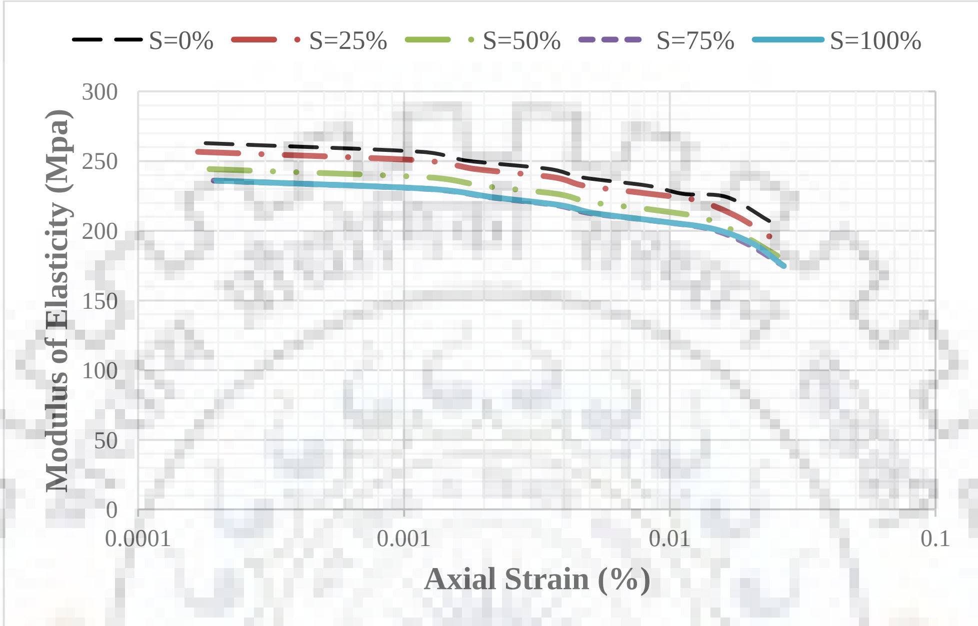

Figure 5.11(a) Effect of Saturation on Modulus of elasticity vs axial strain at RD=60% and CP=200kPa

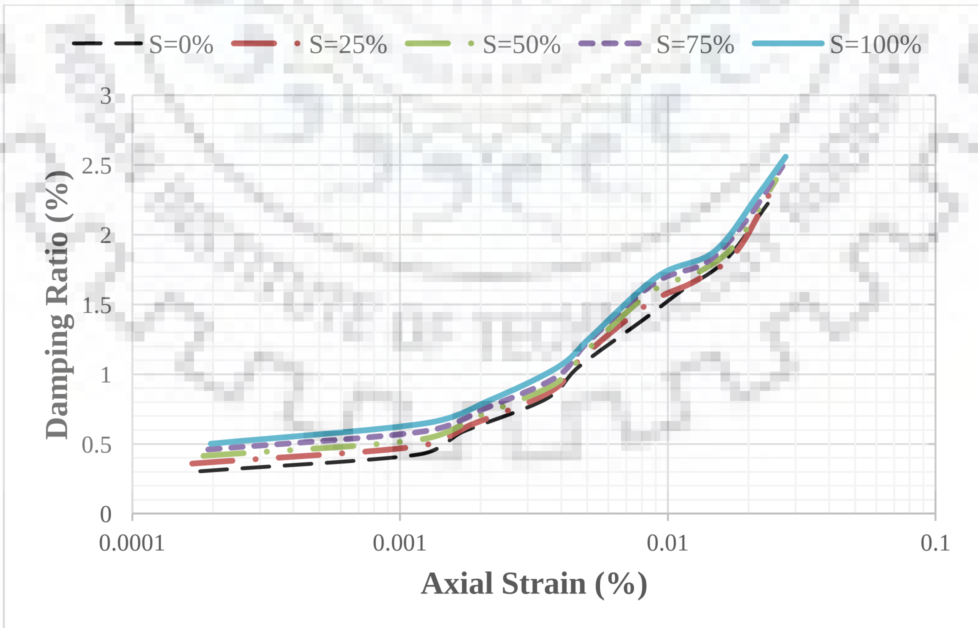

Figure 5.11 (b) Effect of Saturation on Damping ratio vs axial strain at RD=60% and CP=200kPa

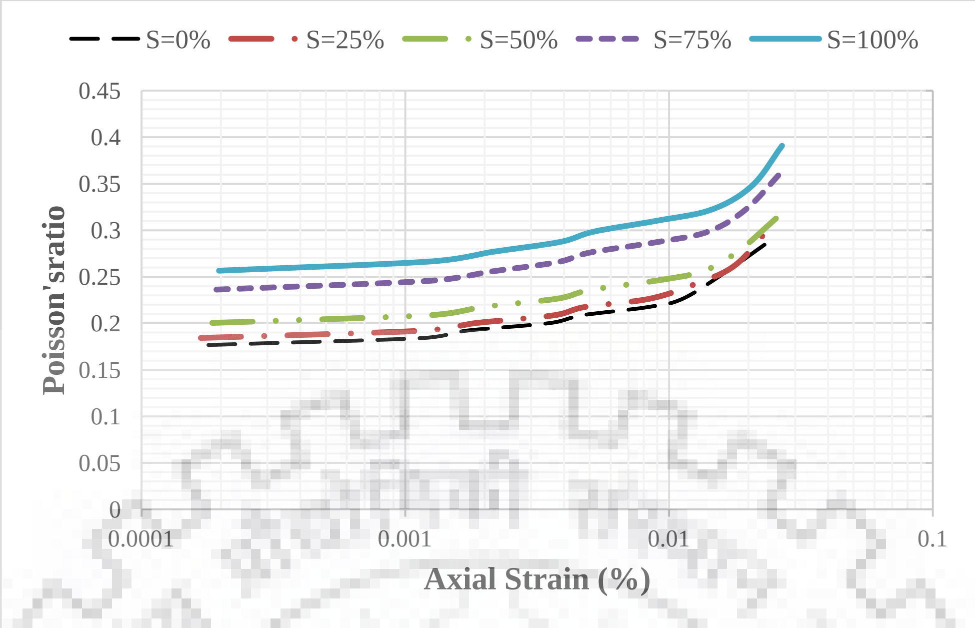

Figure 5.11 (c) Effect of Saturation on Poisson's ratio vs axial strain at RD=60% and CP200kPa

With increase in degree of saturation modulus of elasticity is observed to be decreasing but damping ratio and Poisson's ratio increases. The effect of saturation on shear modulus is observed to be more up to 50% saturation, later on the shear modulus is approximately similar. The effect of saturation on damping ratio is almost very less but there is considerable difference between dry and fully saturated condition. Effect of saturation on Poisson's ratio is observed to be less up to 50% saturation, but it is considerable after 50% saturation.

5.2.6 At RD=60% and CP=300kPa

Torsion Test

Fig. 5.12(a) and 5.12(b) shows the variation of shear modulus and damping ratio with shear strain, respectively for varying saturation condition.

Shear modulus decreases but damping ratio increases with degree of saturation. The effect of saturation is observed to be up to 50% later the value of shear modulus obtained is not much different for higher saturation condition. Damping ratio observed is not varying much with degree of saturation , but the difference between dry and fully saturated is considerable

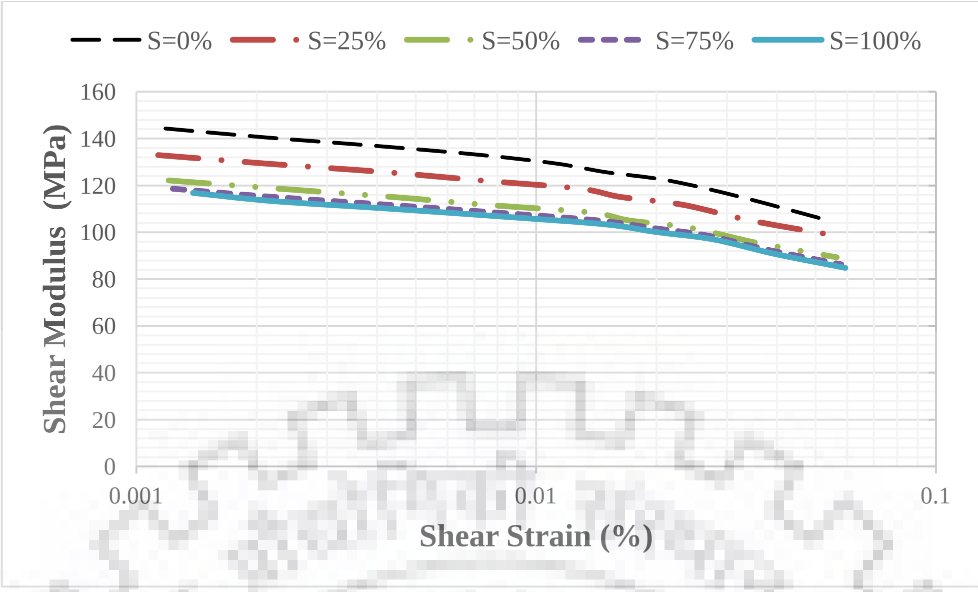

Figure 5.12 (a) Effect of Saturation on Shear modulus vs shear strain at RD=60% and CP=300kPa

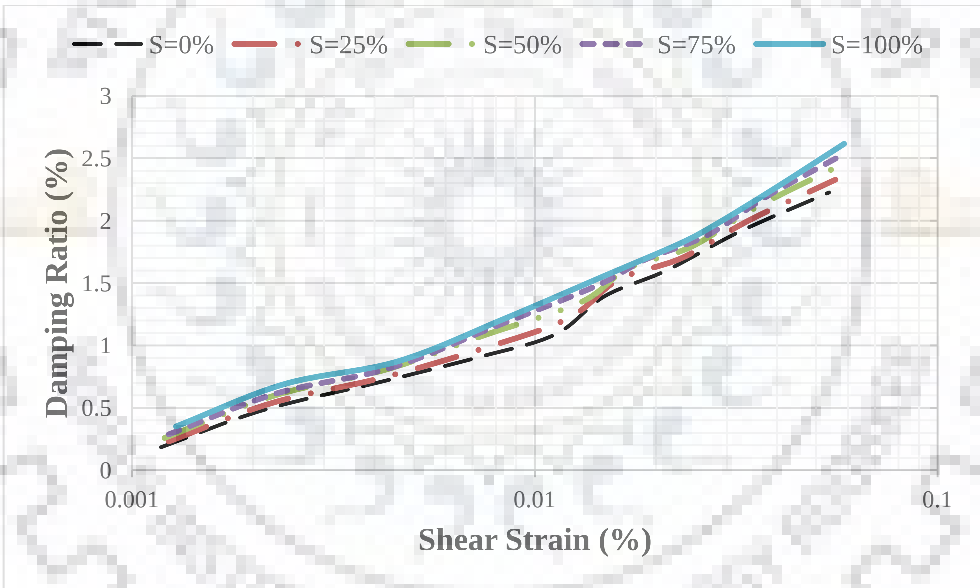

Figure 5.12 (b) Effect of Saturation on Damping ratio vs shear strain at RD=60%and CP=300kPa

Flexure Test

Fig. 5.13(a) and Fig. 5.13(b) shows the variation of modulus of elasticity of soil and damping ratio with axial strain, Fig 5.13(c) shows the variation of Poisson's ratio with axial strain for varying degree of saturation. It can be observed from Fig 5.13(a) that the variation in modulus of elasticity is observed more up to 50% saturation but later there is very less difference between 75% and 100% saturation condition. From Fig. 5.13(b) it is observed that the damping ratio is increases as degree of saturation increases but the increment is very less for increment in saturation. Poisson's ratio obtained up to 50% saturated condition is very less but after 50% saturation the increment in Poisson's ratio is considerable

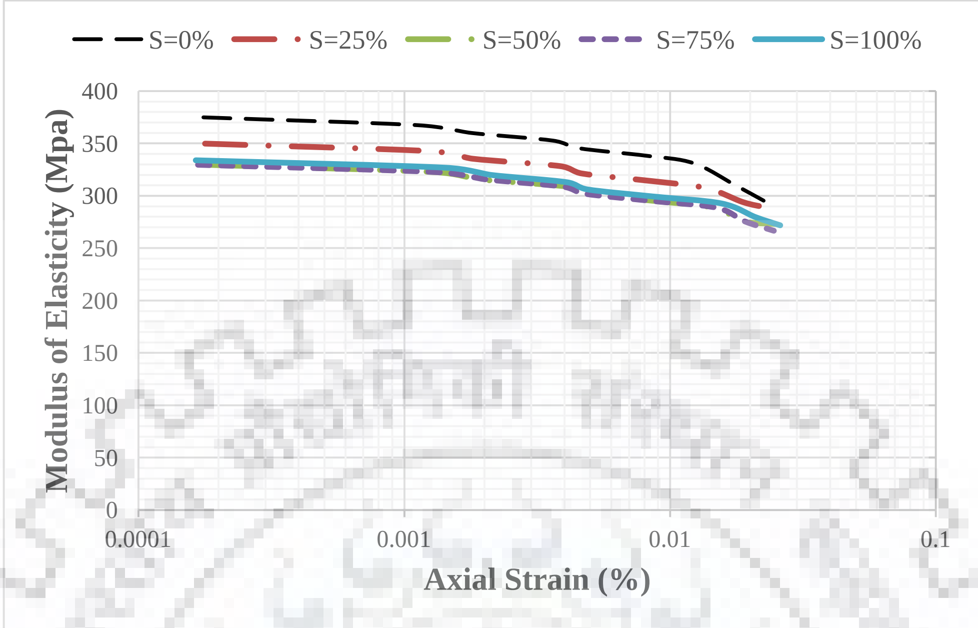

Figure 5.13(a) Effect of Saturation on Modulus of elasticity vs axial strain at RD=60% and CP=300kPa

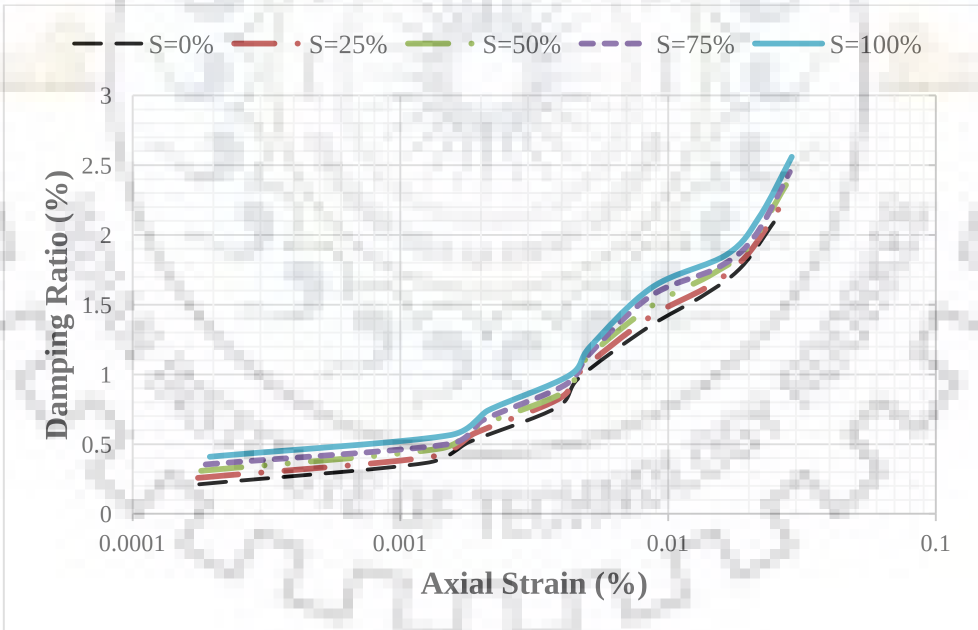

Figure 5.13 (b) Effect of Saturation on Damping ratio vs axial strain at RD=60% and CP300kPa

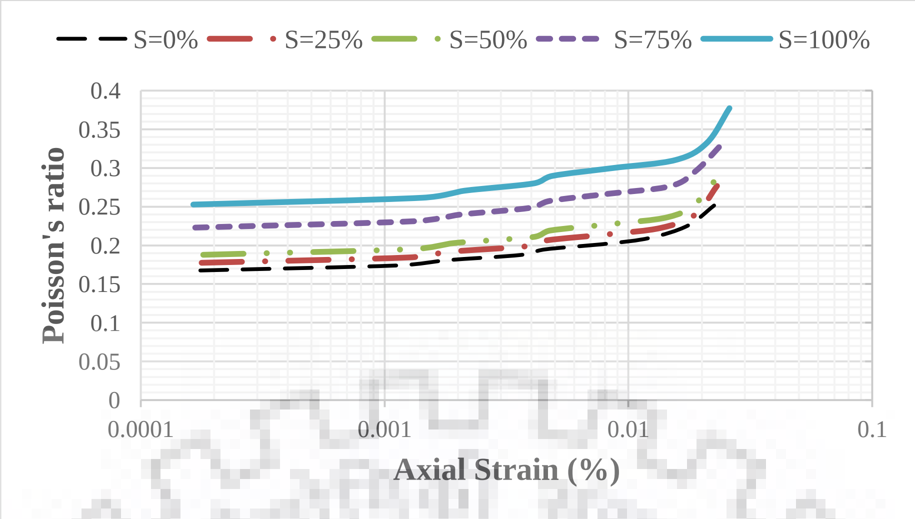

Figure 5.13 (c) Effect of Saturation on Poisson's ratio vs axial strain at RD=60% and CP300kPa

5.2.7 At RD=80% and CP=100kPa

Torsion test

Fig. 5.14(a) and 5.14(b) shows the variation of shear modulus and damping ratio with shear strain, respectively. As observed from the test results, shear modulus decreases with increasing the degree of saturation. The effect is seen more up to 50% saturation and the variation is minimal between 75% and 100% saturation. Damping ratio is not much effected by saturation.

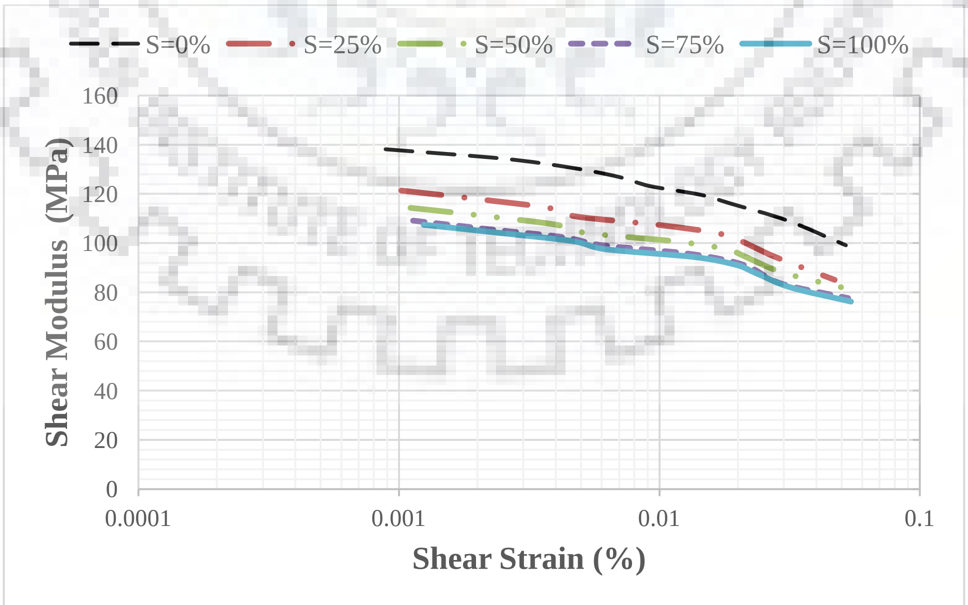

Figure 5.14 (a) Effect of Saturation on Shear modulus vs shear strain at RD=80% and CP=100kPa

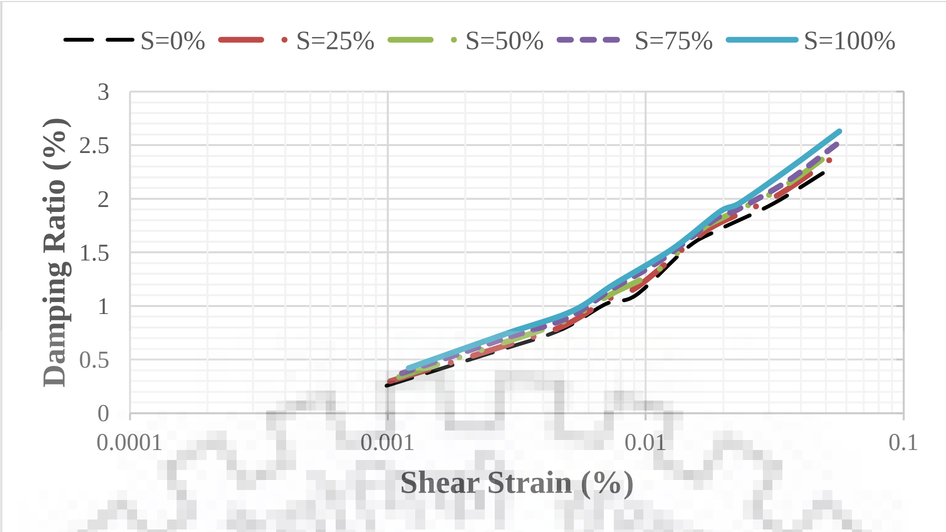

Figure 5.14 (b) Effect of Saturation on Damping ratio vs shear strain at RD=80%and CP=100kPa

Flexure test

Fig. 5.15(a) and Fig. 5.15(b) shows the variation of modulus of elasticity of soil and damping ratio with axial strain for different degree of saturation. Fig 5.15(c) shows the variation of Poisson's ratio with axial strain for different degree of saturation.

With increase in saturation modulus of elasticity decreases and damping ratio increases. Effect of saturation on modulus of elasticity is observed up to 50% saturation after that the effect is minimum. Damping ratio is not much effected by varying saturation. Poisson's ratio increases with increase in saturation, the effect is more after 25% saturation.

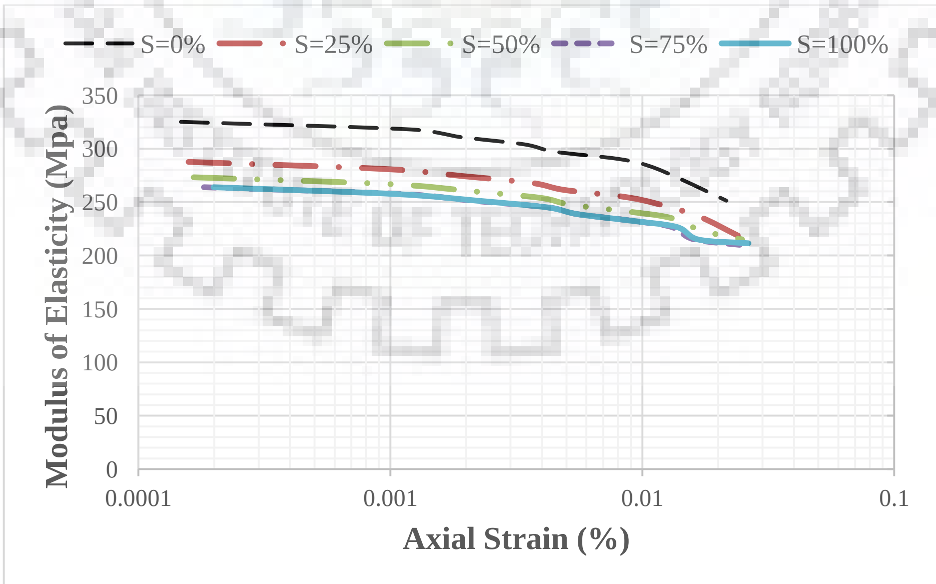

Figure 5.15(a) Effect of Saturation on Modulus of elasticity vs axial strain at RD=80% and CP=100kPa

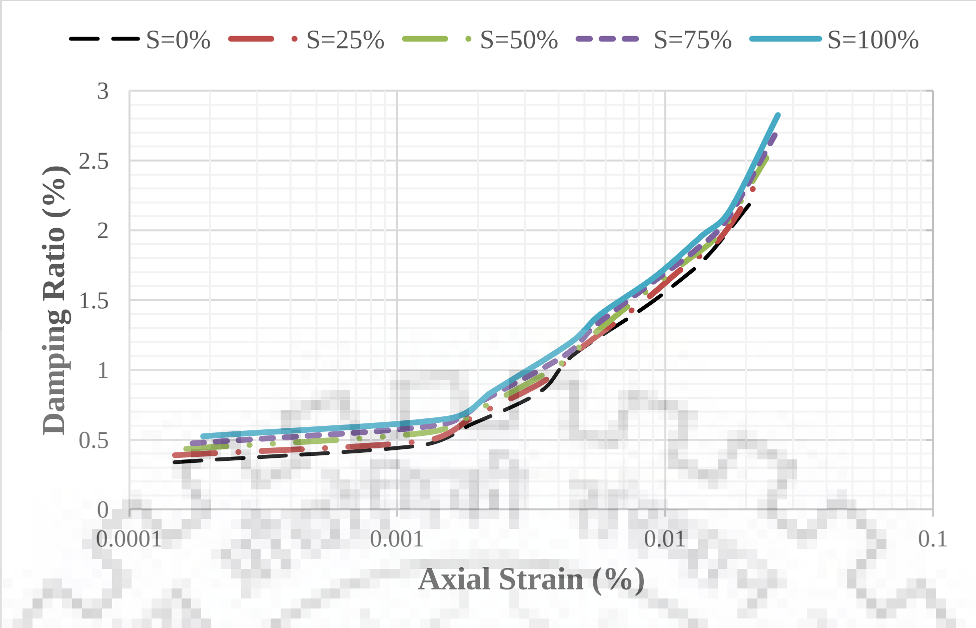

Figure 5.15 (b) Effect of Saturation on Damping ratio vs axial strain at RD=80% and CP=100kPa

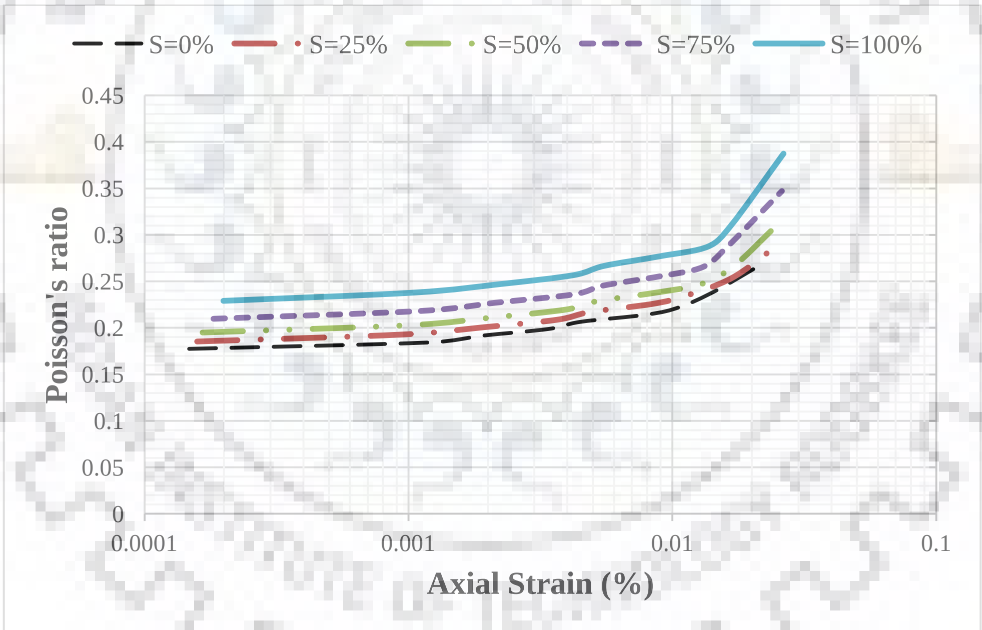

Figure 5.15 (c) Effect of Saturation on Poisson's ratio vs axial strain at RD=80% and CP=100kPa

5.2.8 At RD=80% and CP=200kPa

Torsion Test

Fig. 5.16(a) and 5.16(b) shows the variation of shear modulus and damping ratio with shear strain, respectively. As observed from the test results, shear modulus decreases with increasing the degree of saturation. The effect is seen more up to 50% saturation and the variation is minimal between 75% and 100% saturation. Damping ratio is not much effected by varying degree of saturation., the difference between dry and fully saturated condition is considerable.

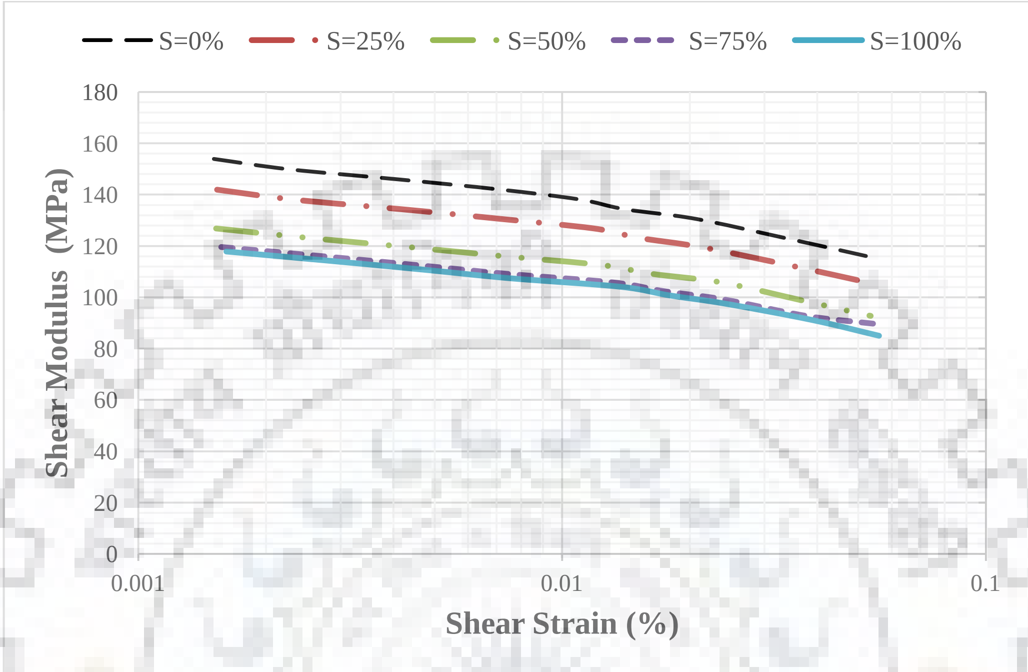

Figure 5.16 (a) Effect of Saturation on Shear modulus vs shear strain at RD=80% and CP=200kPa

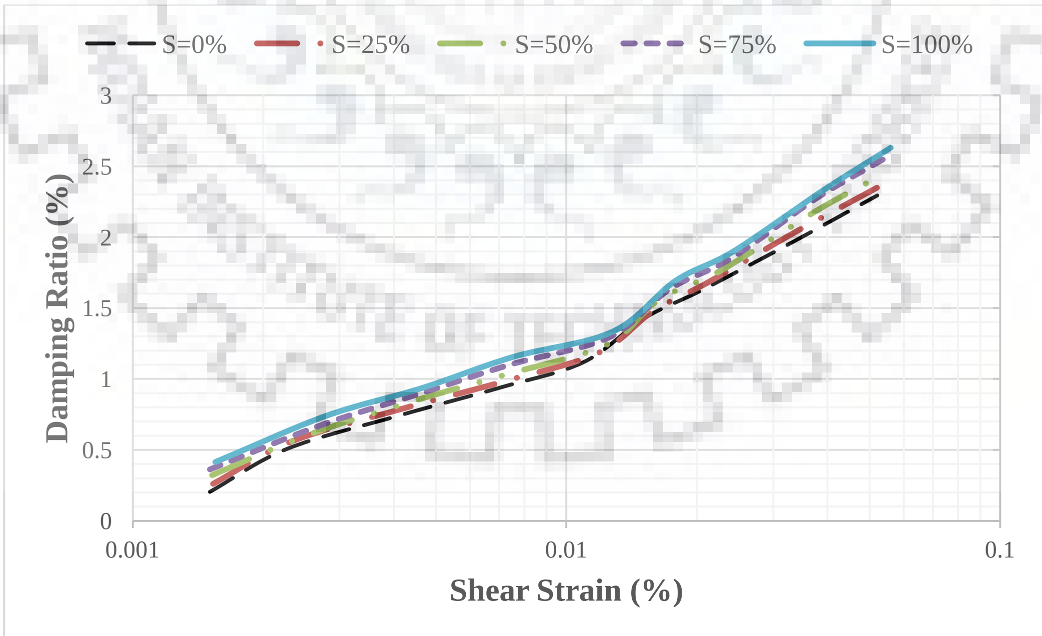

Figure 5.16 (b) Effect of Saturation on Damping ratio vs shear strain at RD=80%and CP=200kPa

Flexure Test

Fig. 5.17(a) and Fig. 5.17(b) shows the variation of modulus of elasticity of soil and damping ratio with axial strain for different degree of saturation. Fig 5.17 (c) shows the variation of Poisson's ratio with axial strain for different degree of saturation. With increase in saturation modulus of elasticity decreases, the effect is seen more up to 50% saturation condition, later the effect is minimum. Damping ratio doesn't vary much with degree of saturation. As observed from, the effect of saturation is seen after 25% saturation, after that the increment in Poisson's ratio is more with varying saturation

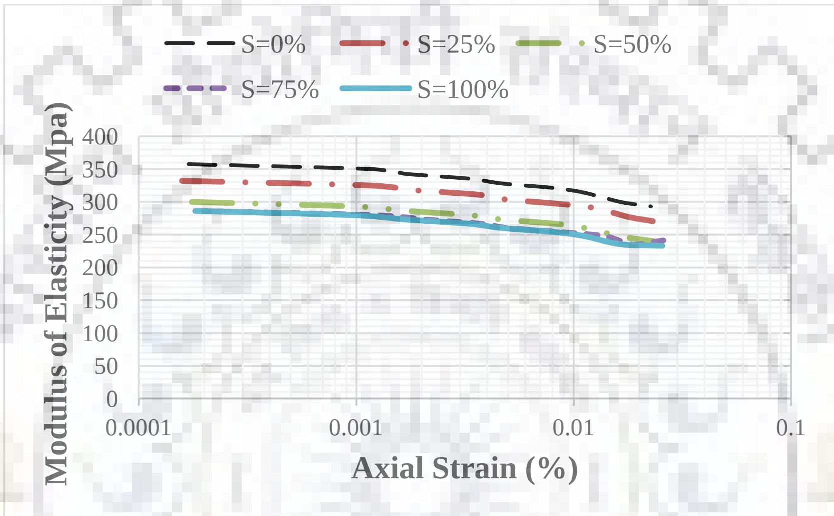

Figure 5.17 (a) Effect of Saturation on Modulus of elasticity vs axial strain at RD=80% and CP=200kPa

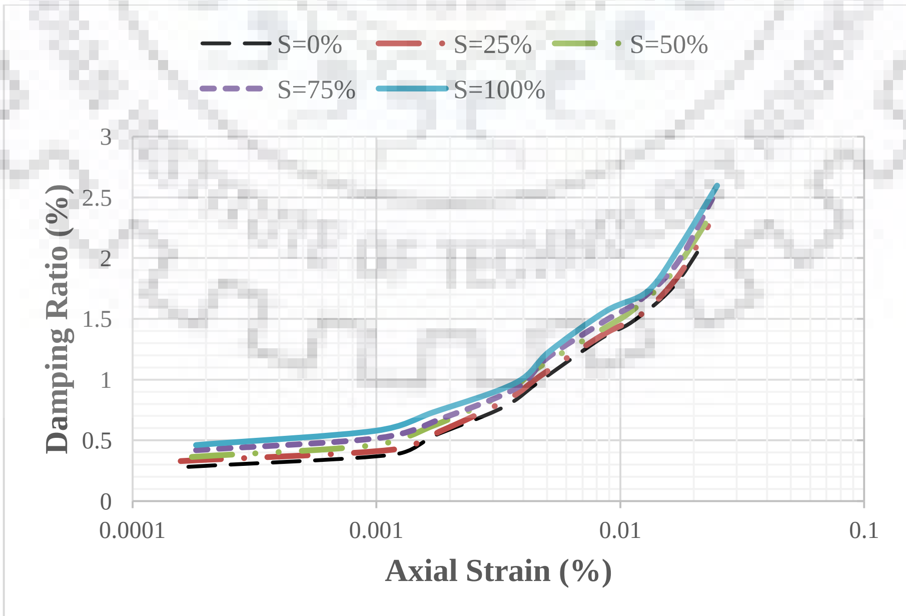

Figure 5.17 (b) Effect of Saturation on Damping ratio vs axial strain at RD=80% and CP200kPa

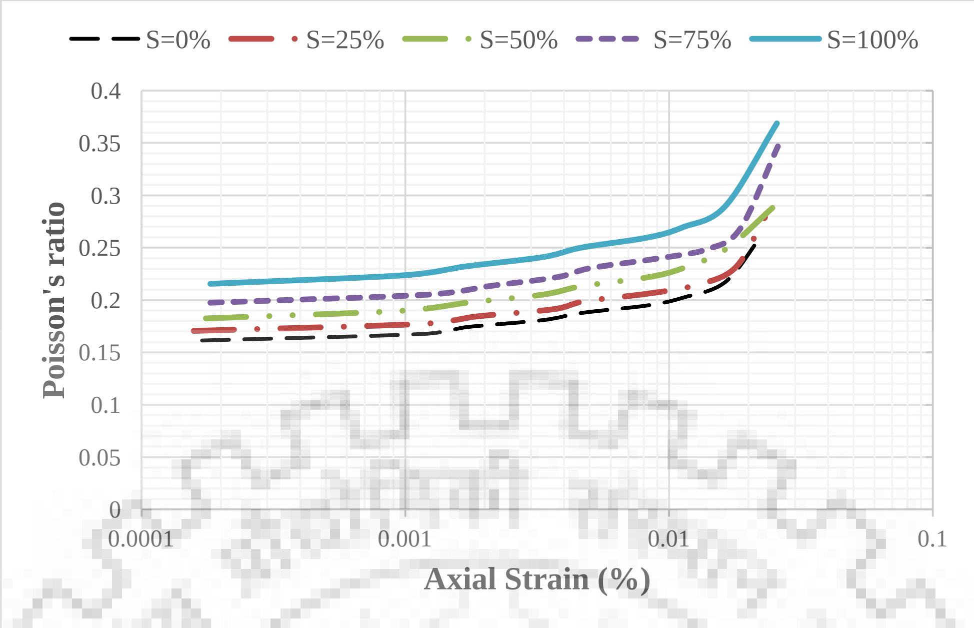

Figure 5.17 (c) Effect of Saturation on Poisson's ratio vs axial strain at RD=80% and CP=200kPa

5.2.9 At RD=80% and CP=300kPa

Torsion Test

Fig. 5.18(a) and 5.18(b) shows the variation of shear modulus and damping ratio with shear strain, respectively. As observed from the test results, shear modulus decreases with increasing the degree of saturation, the effect is seen more up to 50% saturation while the damping ratio is not much effected by saturation.

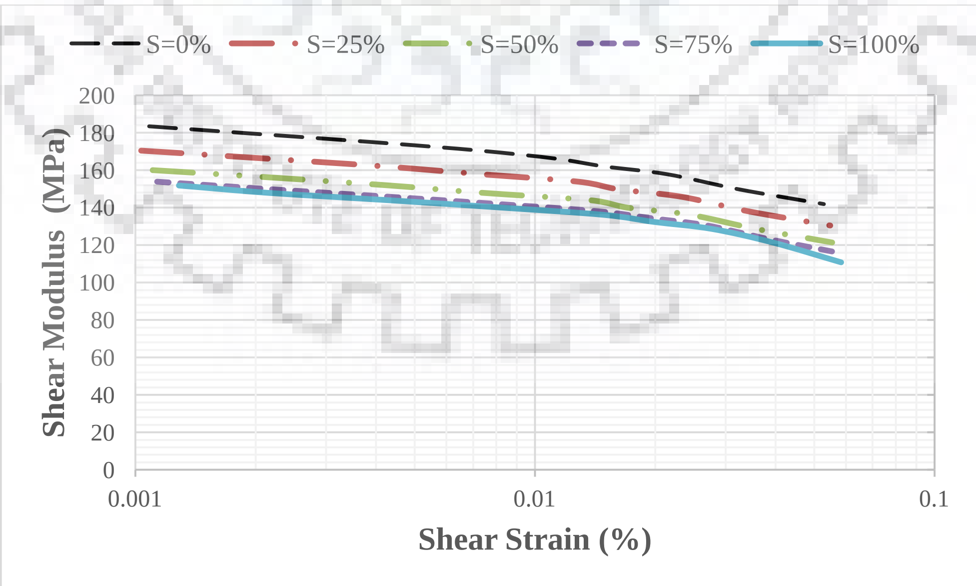

Figure 5.18 (a) Effect of Saturation on Shear modulus vs shear strain at RD=80% and CP=300kPa

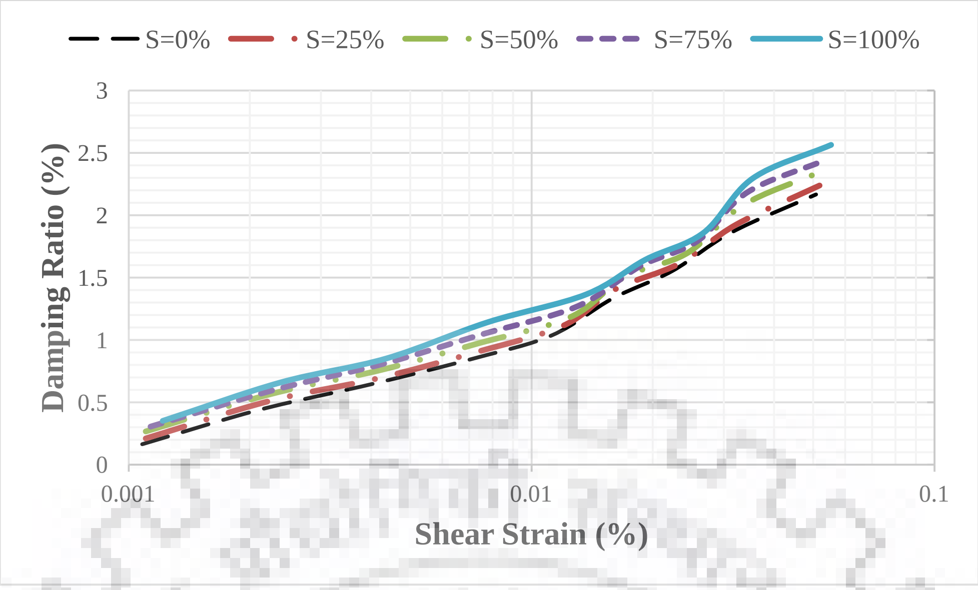

Figure 5.18 (b) Effect of Saturation on Damping ratio vs shear strain at RD=80%and CP=300kPa

Flexure Test

Fig. 5.19(a) and Fig. 5.19(b) shows the variation of modulus of elasticity of soil and damping ratio with axial strain. It can be observed that the variation in modulus of elasticity is observed more up to 50% saturation , after this modulus of elasticity remains approximately similar .It can be observed that the damping ratio is increases as degree of saturation increases but the increment is very small for different saturation increment . Poisson's ratio remains not much affected up to 50% saturation condition, but later the effect is more with increment in saturation.

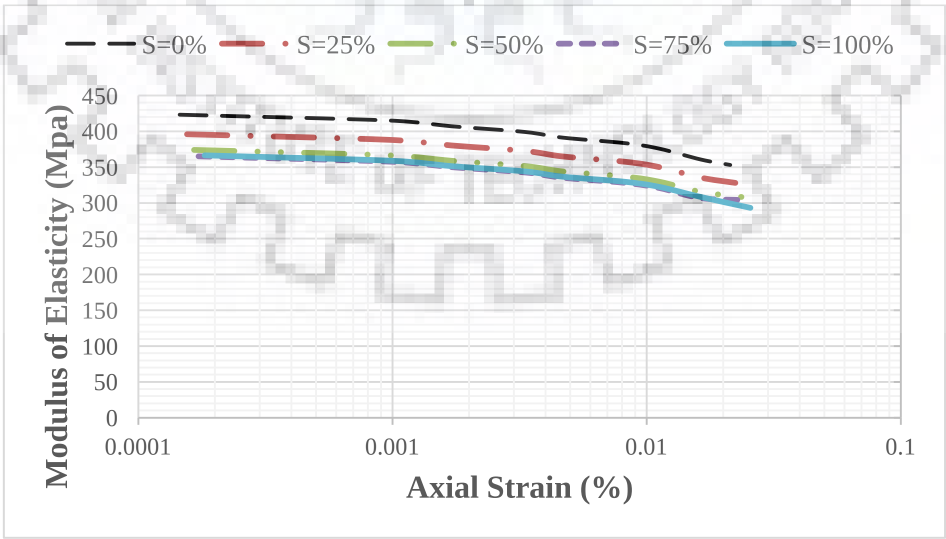

Figure 5.19 (a) Effect of Saturation on Modulus of elasticity vs axial strain at RD=80% and CP=200kPa

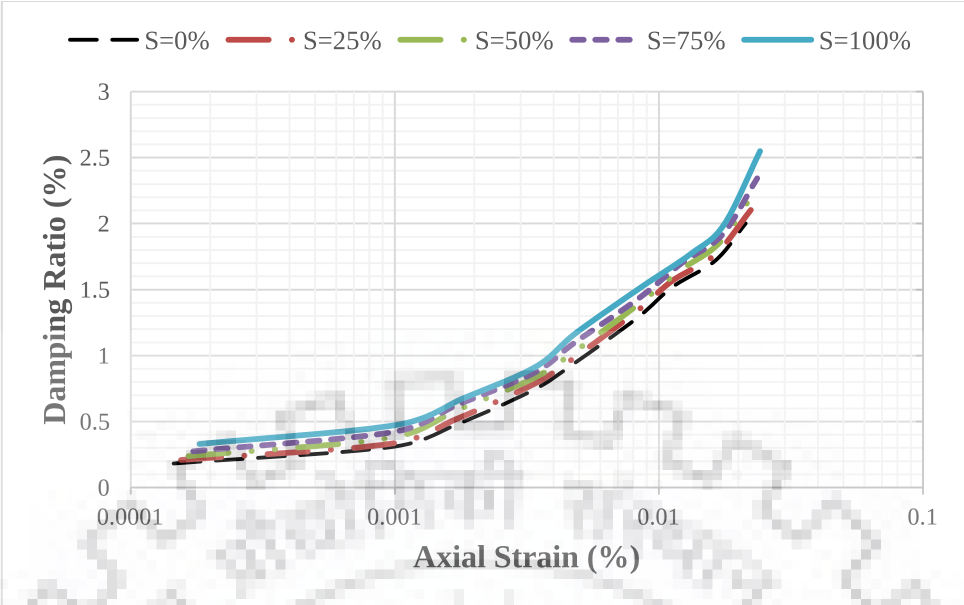

Figure 5.19 (b) Effect of Saturation on Damping ratio vs axial strain at RD=80% and CP=300kPa

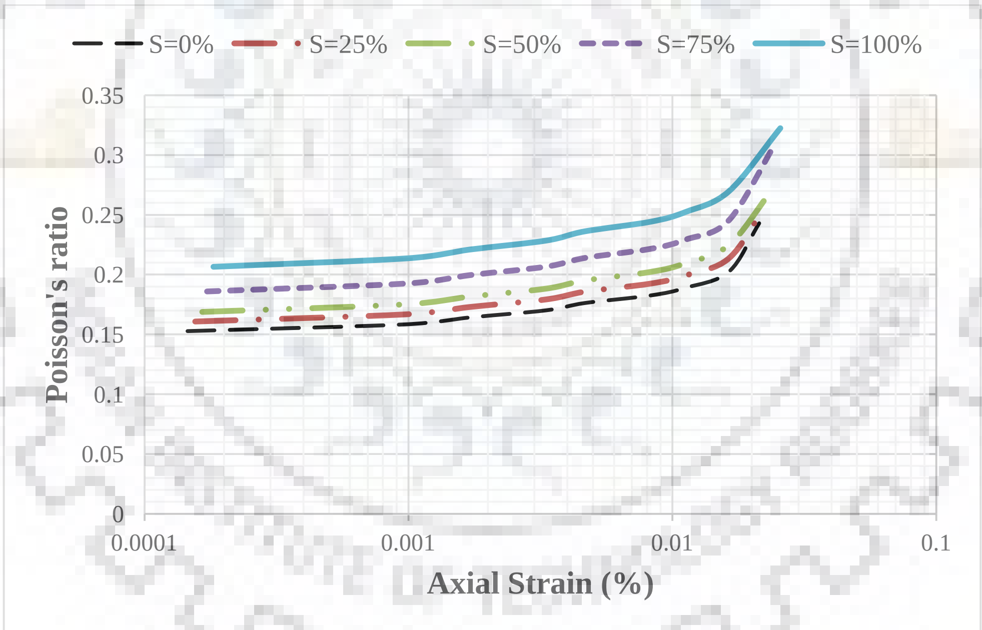

Figure 5.19 (c) Effect of Saturation on Poisson's ratio vs axial strain at RD=80% and CP=300kPa

5.2.10 Summary

The degree of saturation for optimum value of shear modulus (in torsion), Young's Modulus (in flexure) and Poisson's ratio for all the cases is presented in section 5.2.1 to 5.1.9 are summarized in Table 5.3. Here the optimum value of degree of Saturation is defined as follows:

a) Maximum value of saturation upto which decrease in Shear modulus and modulus of elasticity is significant.

b) Minimum value of saturation after which increase in Poisson's ratio is Significant.

Table 5.3 Summary of results

S. No.	Relative Density	Confining Pressure	Saturation (%)		
			Shear Modulus	Modulus of Elasticity	Poisson's ratio
1	40	100	50	50	50
2	40	200	50	50	50
3	40	300	50	50	50
4	60	100	50	50	25
5	60	200	75	50	25
6	60	300	50	50	50
7	80	100	50	50	25
8	80	200	50	50	25
9	80	300	50	50	50

It is observed from the Table 5.3 for all three confining pressures and relative densities; the effect of saturation is maximum up to 50% degree of saturation condition. As observed earlier, The difference in shear modulus and modulus of elasticity is very less for 50% and 75% saturation, whereas the results obtained for 75% and 100% saturation are nearly same.

The effect of degree of saturation on damping ratio is not much, but the difference in the values for dry and saturated is considerable. Up to 50% saturation, Poisson's ratio is much effected for relative density 40% but for higher relative density 60% and 80% the effect of saturation is negligible up to 25% saturation. The results at 300 kPa for 60% and 80% relative density shows not much variation in Poisson's ratio up to 50% saturation.

5.3 Variation of Confining Pressure

Fig 5.20(a) and Fig 5.20(b) shows the variation of shear modulus and modulus of elasticity with confining pressure at different saturation condition respectively.

As observed from the test results, with increase in confining pressure there is increase in shear modulus and elastic modulus. With increase in confining pressure, there is more confining to the samples leading to less strain development and more strength development leading to more shear and young modulus. There is increase in grain contact with increase in confining pressure leading to more strength development. Shear modulus and modulus of Elasticity is approximately similar for 50% saturation and 100% saturation condition.

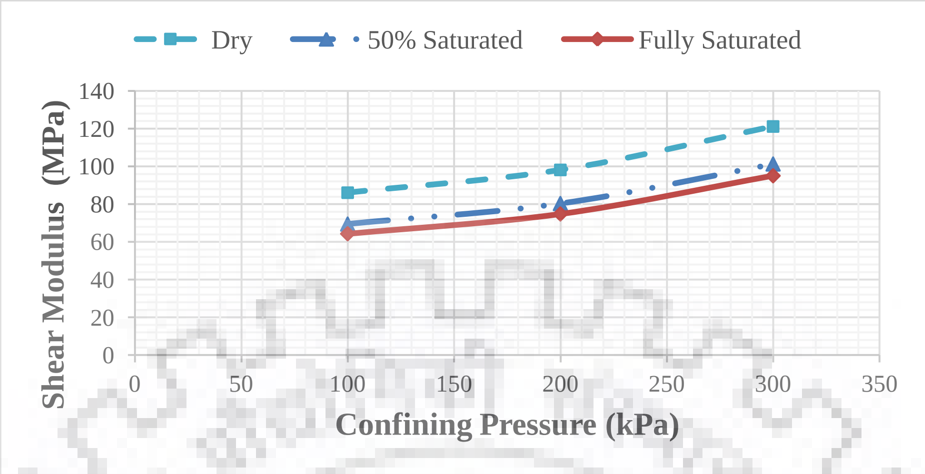

Figure 5.20 (a) Shear Modulus with confining pressure at RD=40%

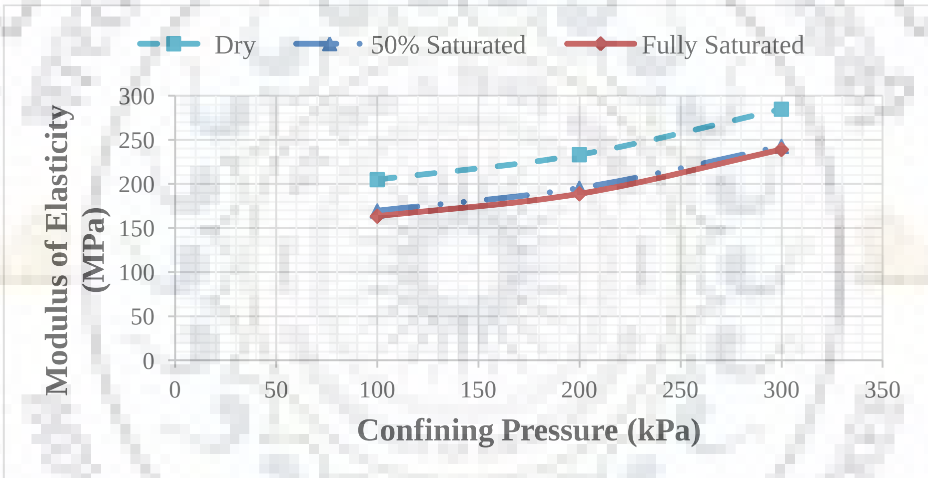

Figure 5.20 (b) Modulus of Elasticity with confining pressure at RD=40%

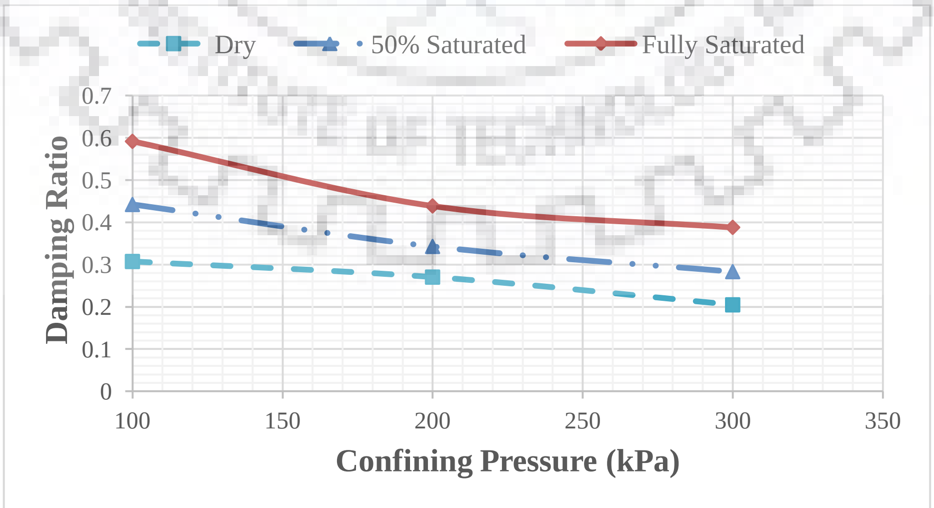

Figure 5.21 (a) Torsional damping with confining pressure at RD=40%

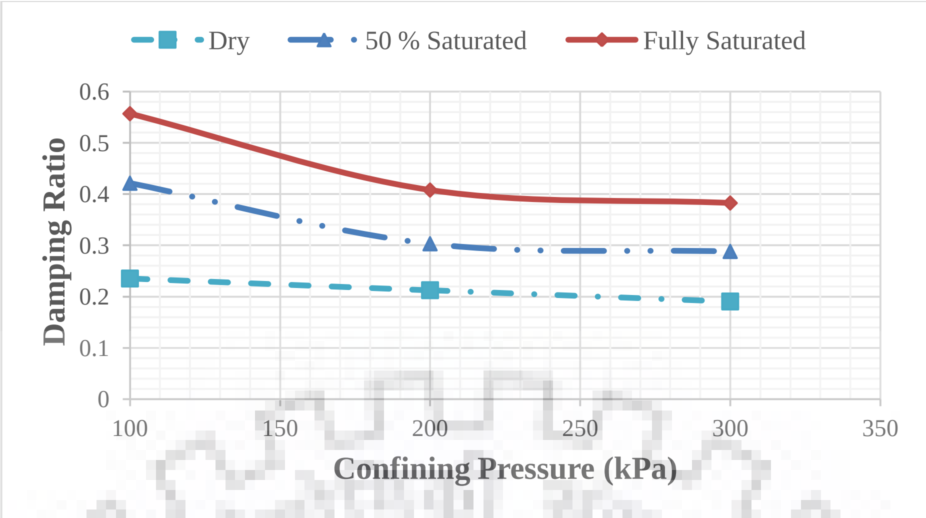

Figure 4.21 (b) Flexural damping with confining pressure at RD=40%

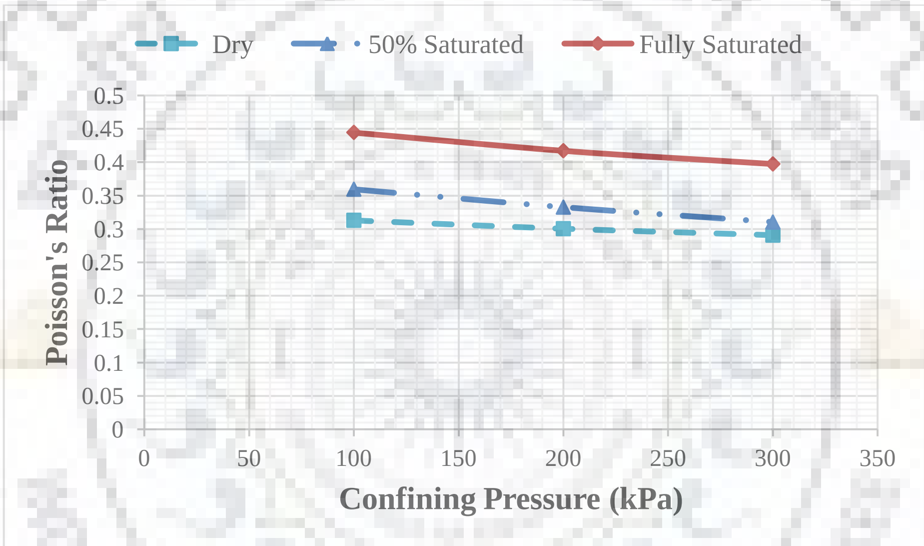

Figure 4.21 (c) Poisson's ratio with confining pressure at RD=40%

Fig 5.21(a) and Fig 5.21(b) shows the variation of Damping ratio in torsion and flexure mode with confining pressure for different saturation. The variation in damping rato is more for saturated condition and decreases for dry condition.

Fig 5.21 (c) shows the variation of Poisson's ratio with confining pressure at relative density 40%, it is observed that the effect of saturation is observed after 50%.

For a given density, with increase in pressure there is decreases in damping, this is due to faster wave propagation path and less attenuation of waves as with increase in confining pressure this is due to the increase in grain contacts.

5.4 Variation of Relative Density

Fig 5.22 (a) and Fig 5.22 (b) shows the variation of shear modulus and modulus of elasticity with relative density respectively for different saturation condition.

Fig 5.23(a) and Fig 5.23 (b) shows the variation of damping ratio with relative density in torsion and flexure mode respectively. The shear modulus and modulus of elasticity seems to be approximately similar for 50% and fully saturated condition for relative density increment.

From the test results, with increase in relative density the shear modulus and modulus of elasticity increases as with increase in relative the amount of sand increases for the same volume thus strength increases as the void reduces with increases relative density. As the relative density increases damping ratio decreases this is due to increase in density there is more soil particle for given volume thus denser packing and denser packing has more grain contact.

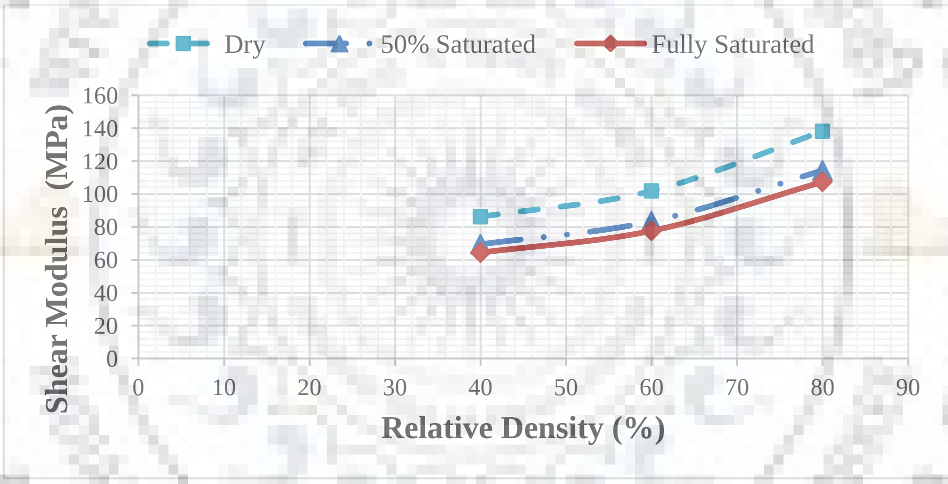

Figure 5.22 (a) Shear Modulus with relative density at Confining Pressure=100kPa

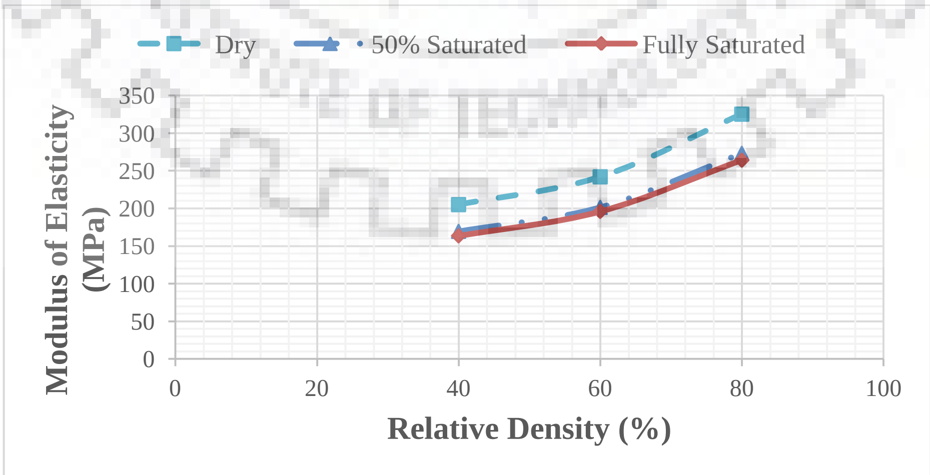

Figure 5.22 (b) Modulus of Elasticity with relative density at CP=100kPa

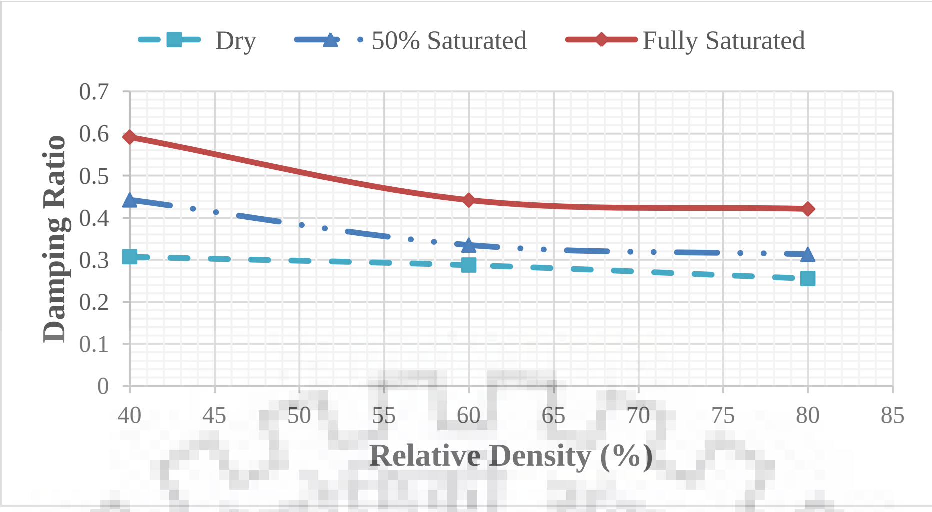

Figure 5.23 (a) Torsional damping with relative density at CP=100kPa

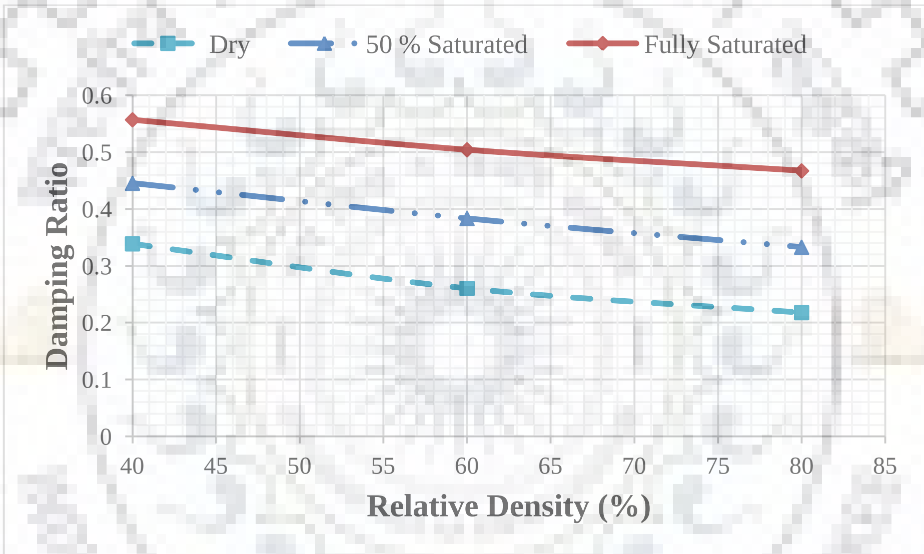

Figure 5.23 (b) Flexural damping with relative density at CP=100kPa

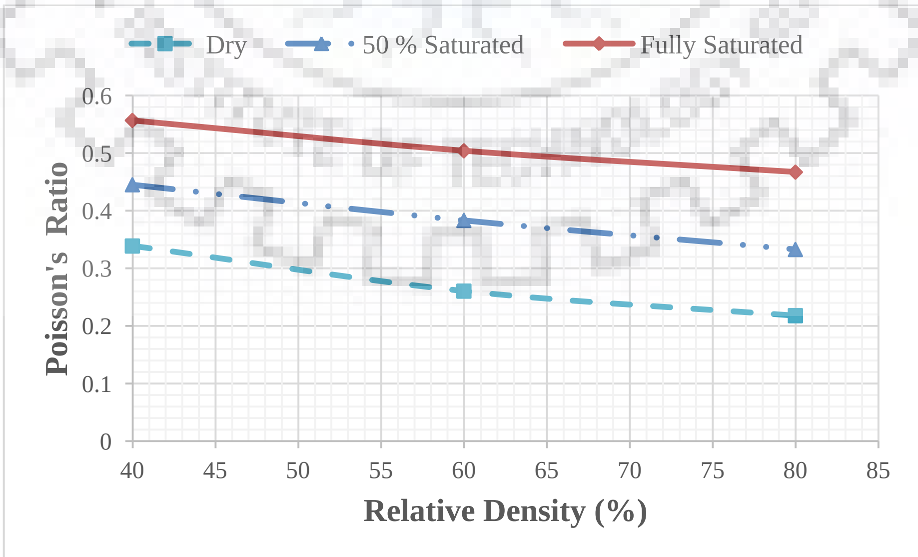

Figure 5.23 (c) Poisson’s ratio with relative density at CP=100kPa

5.5 Variation of Dynamic Soil Property with Degree of Saturation

Fig 5.25 (a) , 5.25 (b) and Fig 5.25 (c) shows the variation of shear modulus , young's modulus and damping ratio with degree of saturation for different confining pressure.

Fig 5.26 (a) , 5.26 (b) and Fig 5.26 (c) shows the variation of shear modulus , young's modulus and damping ratio with degree of saturation for different relative density.

As there is decrease in degree of saturation causes the outer menisci to be pulled inward, which leads to an increase in both matric suction and effective stress on sample. With increase in degree of saturation the shear modulus decreases. With decrease in degree of saturation matric suction decreases thus inclusion of air takes place in pore water body, thus effective stress increases with decrease in degree of saturation. The reason for this variation is, as the saturation decreases the overall effective area covered by the water droplets for the given cross sectional area of particle results in decrease of net effective stress, which will result in decrease in shear modulus. The damping ratio as observed is increasing very less with degree of saturation the, this is due to the presence of more pores filled with water in place of air on increasing the degree of saturation but the damping ratio is approximately similar for 75% and 100 % saturation as after 75% saturation almost all the voids are filled with water so on further increasing the saturation not much effect is observed.

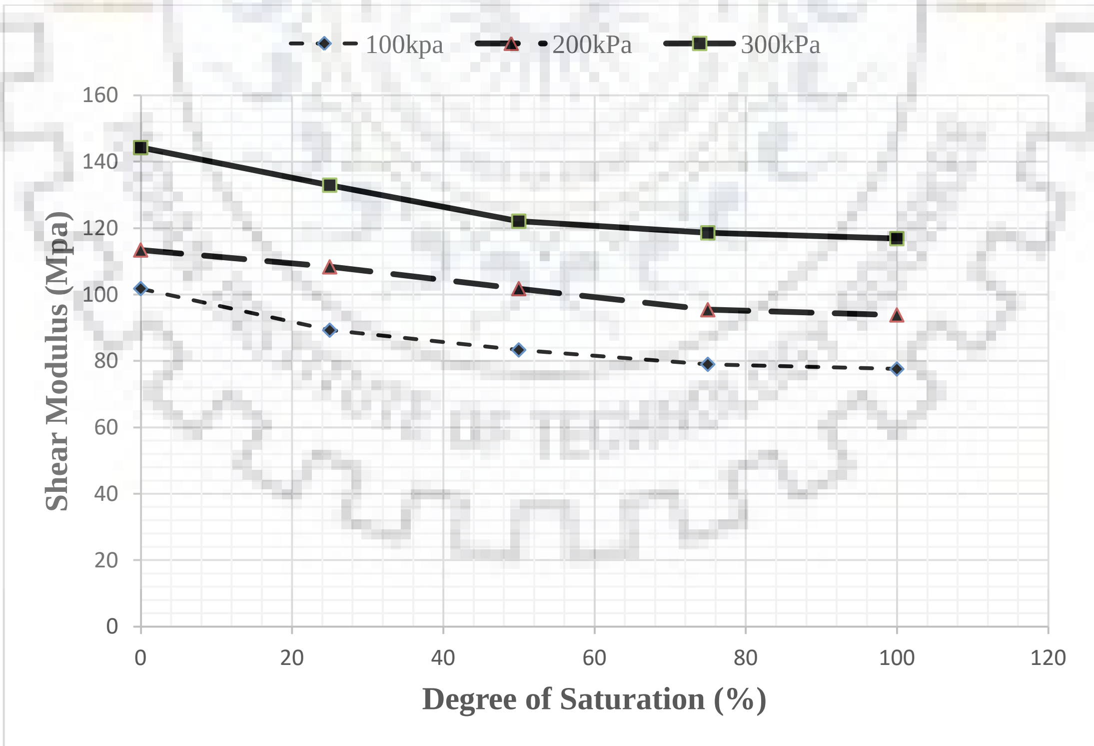

Figure 5.24 (a) Shear Modulus with degree of saturation at RD=40%

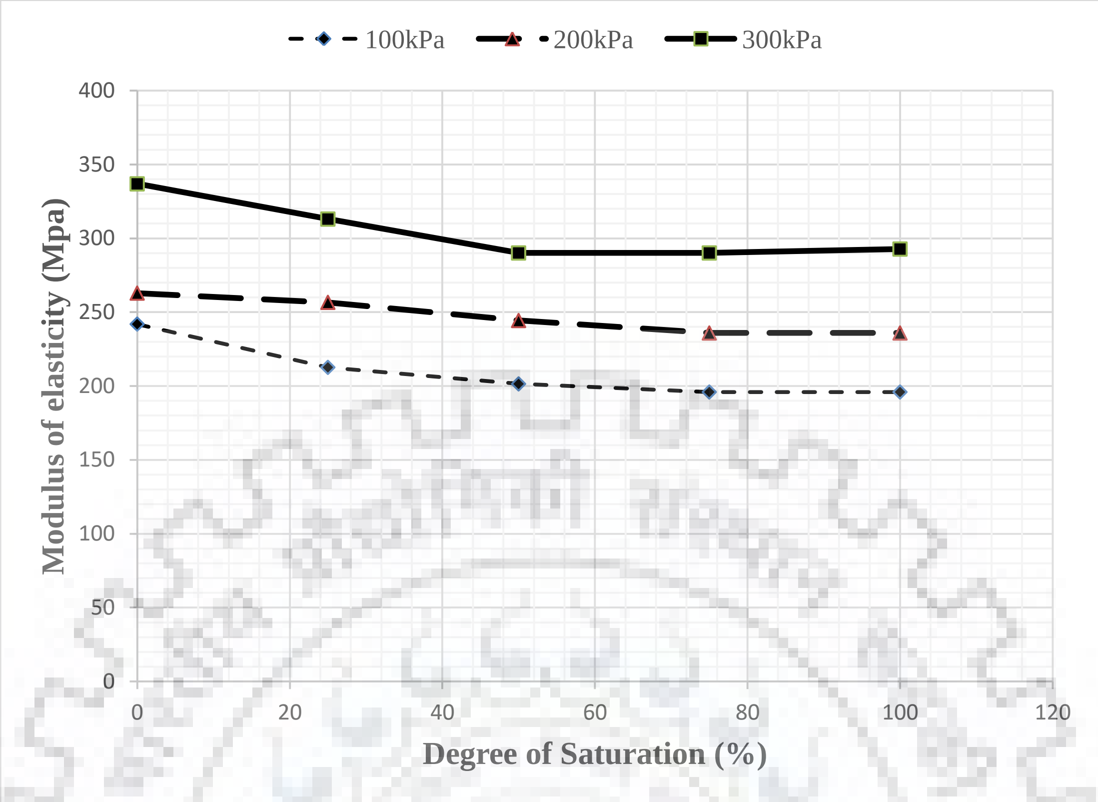

Figure 5.24 (b) Modulus of Elasticity with degree of saturation at RD=40%

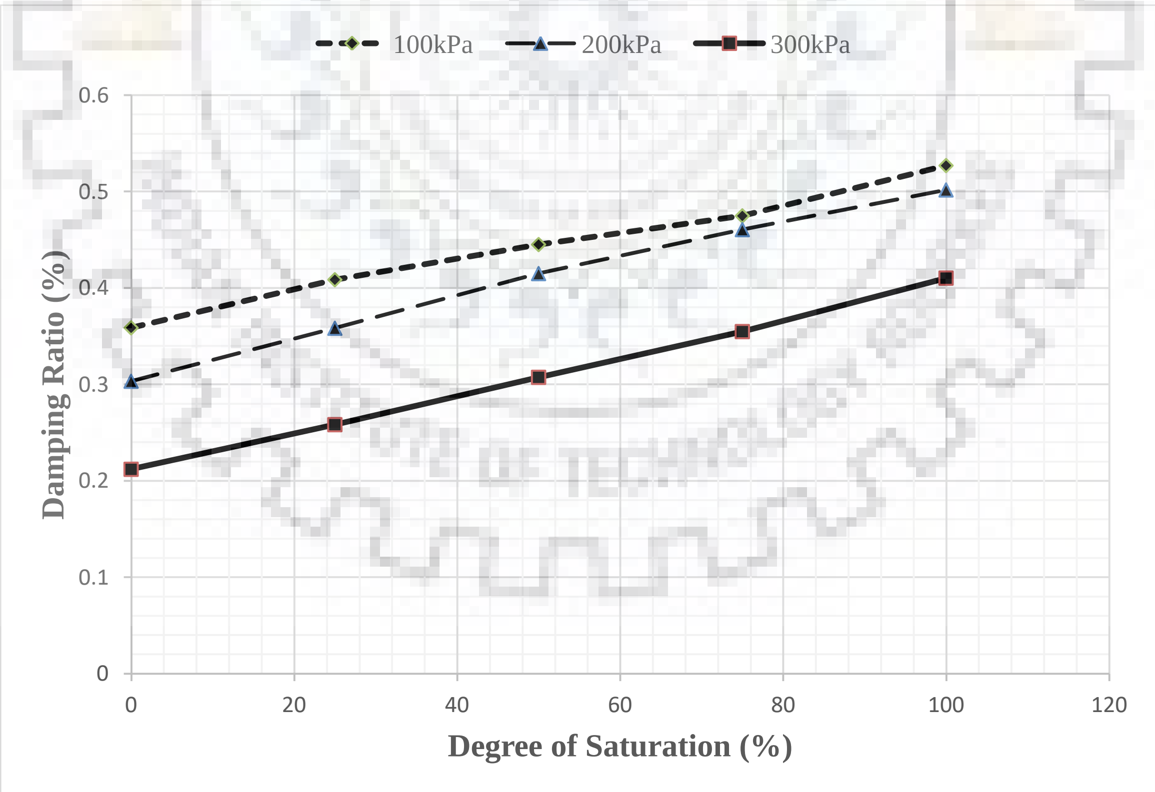

Figure 5.24 (c) Damping Ratio with degree of saturation at RD=40%

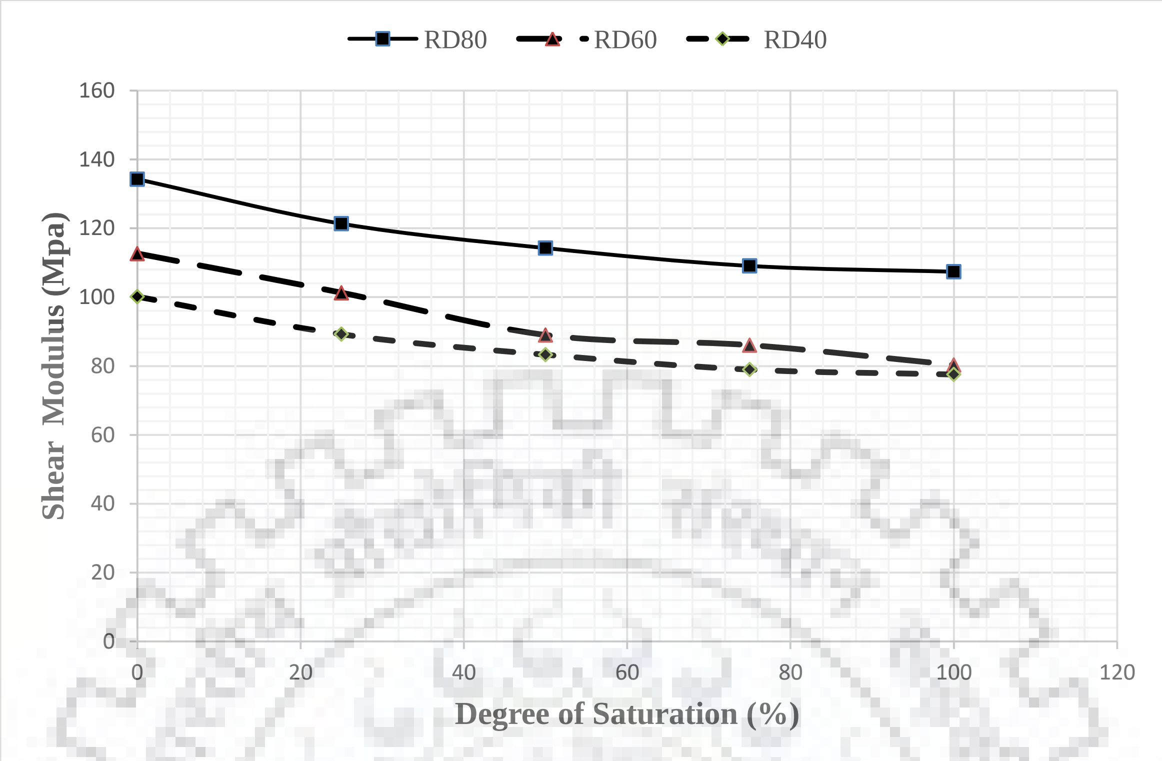

Figure 5.25 (a) Shear Modulus with degree of saturation at CP=100kPa

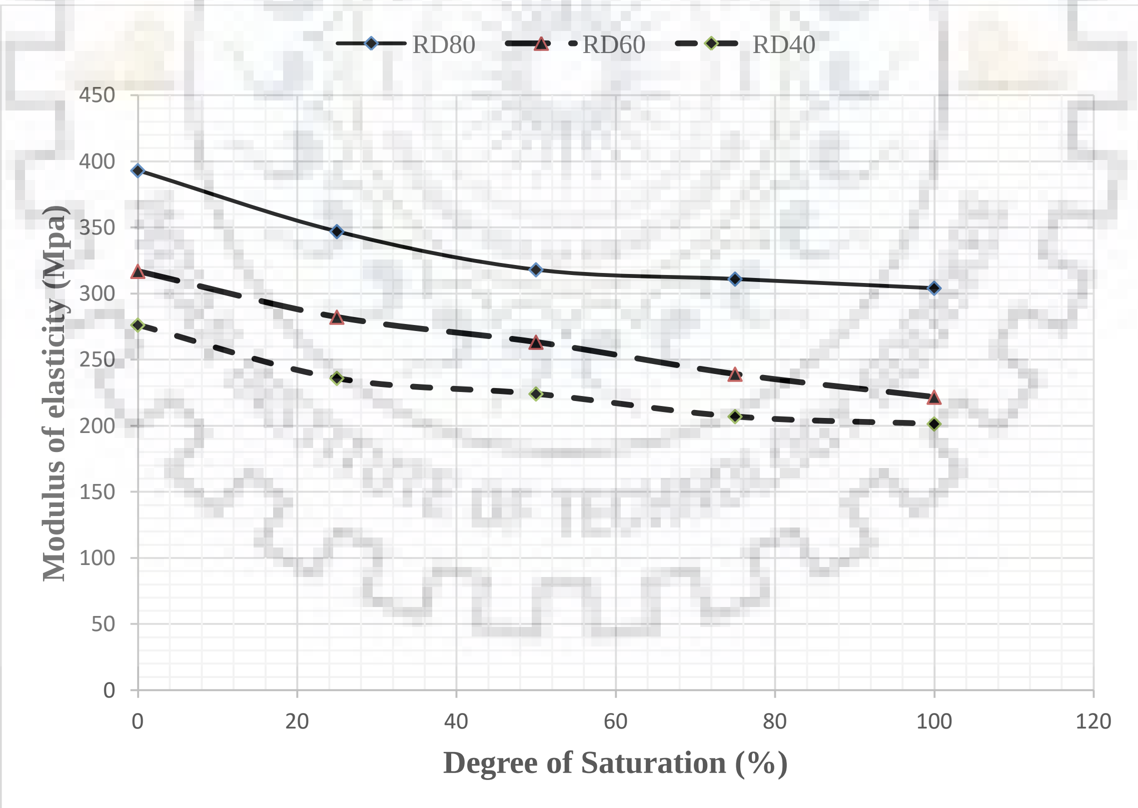

Figure 5.25 (b) Modulus of Elasticity with degree of saturation at CP=100kPa

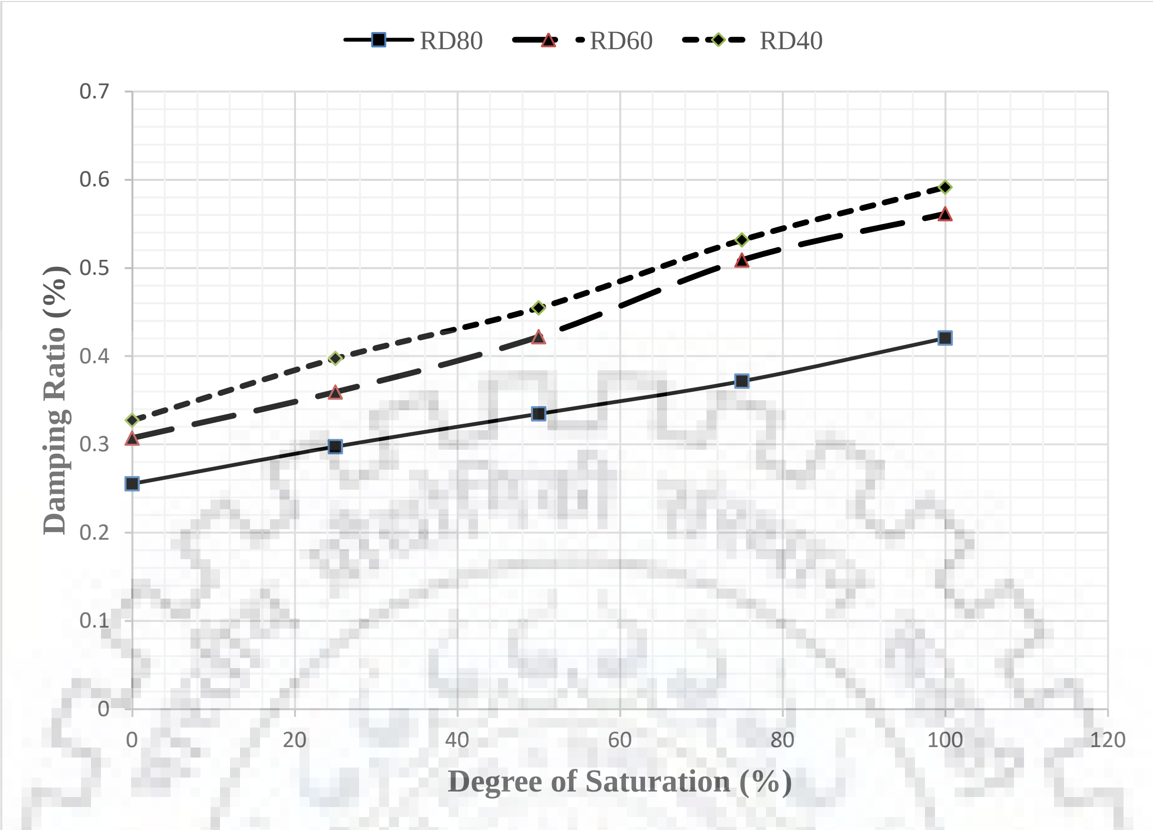

Figure 5.25 (c) Damping Ratio with degree of saturation at CP=100kPa

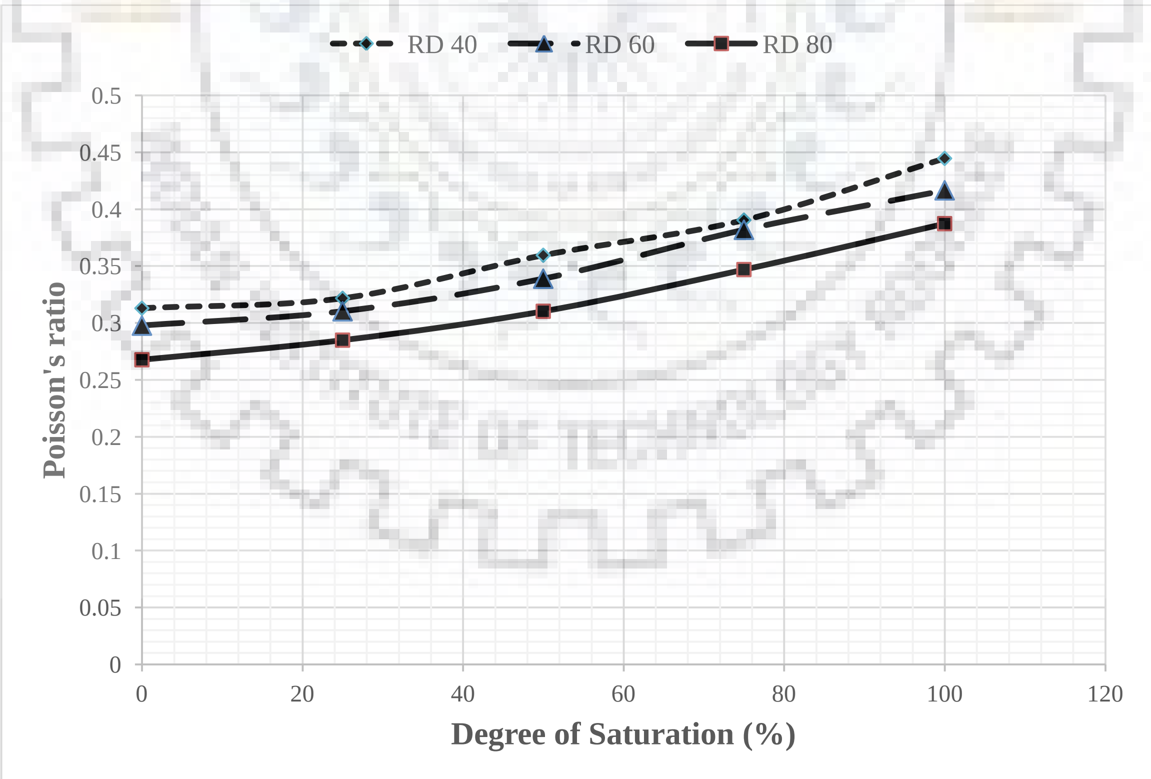

Figure 5.25 (d) Poisson's ratio with degree of saturation at CP=100kPa

5.6 Verification of Poisson's Ratio

The value of Shear and Young's Modulus obtained is used to verify the value of Poisson's ratio obtained from the apparatus using the Eq. 5.1. Fig 5.26 shows the variation of Shear Modulus and Young's Modulus with axial strain. The Shear strain obtained from the torsion test is converted to axial strain using Eq. 5.2. and axial strain is obtained, Shear and Young's Modulus is plotted.

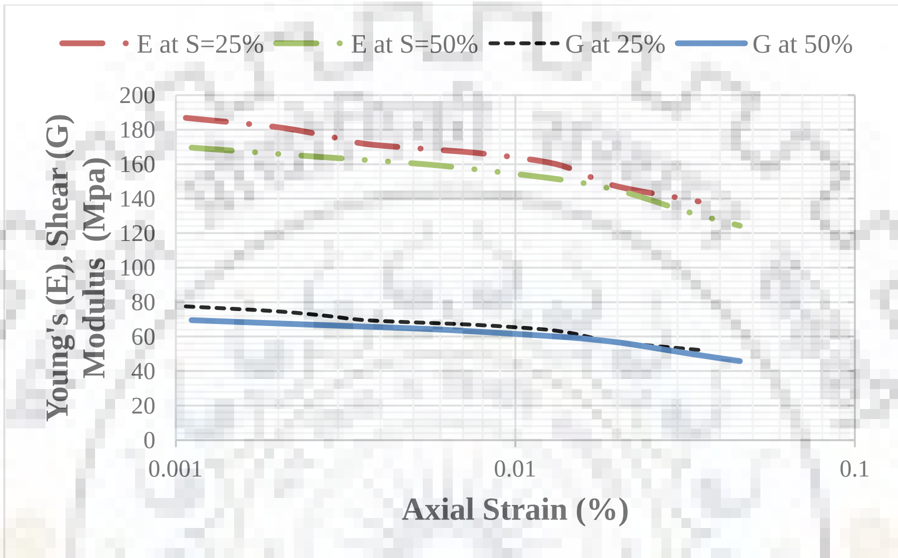

Figure 5.26 Shear and Young's Modulus with Axial Strain

Using Formula,

$$E=2*G*(1+\nu) \quad (5.1)$$

$$\gamma = (1+\nu)\varepsilon \quad (5.2)$$

Where,

γ, ε= Shear and Axial Strain respectively.

ν= Poisson's Ratio

E,G= Young's and Shear Modulus respectively

To show a sample calculation, values of Shear modulus and Young's modulus at 0.01 % axial strain at S=50 % is calculated from Fig 5.27

Young's Modulus= 154.93 Mpa, Shear Modulus= 60 Mpa

$$\nu = \frac{E}{2G} - 1 = 0.29$$

From Fig 5.3 (c), at axial strain= 0.01%, ν=0.28.

The difference in values obtained from the equation and the value of Poisson's ratio directly from the apparatus is 0.01. Thus, the results are found in good agreement.

5.7 Cyclic Shear Test on CTS

The Cyclic Shear tests were conducted using Cyclic Triaxial System (CTS) on dry samples (Relative Density=60%) at 1% , 0.5% , 0.05%, 0.064% for samples of 100kPa confining pressure and for samples subjected to 300 kPa shear strains are 1%, 0.5%, 0.05%, 0.07%. All tests were conducted at a frequency of 0.5 Hz.

From the shear modulus and shear strain curves i.e Fig. 5.27 (a) it is observed that the strength is higher for the sample subjected to higher confining pressure. From Fig. 5.27 (b) plot of damping ratio and shear strain , the sample with higher confining pressure has a lower damping ratio.

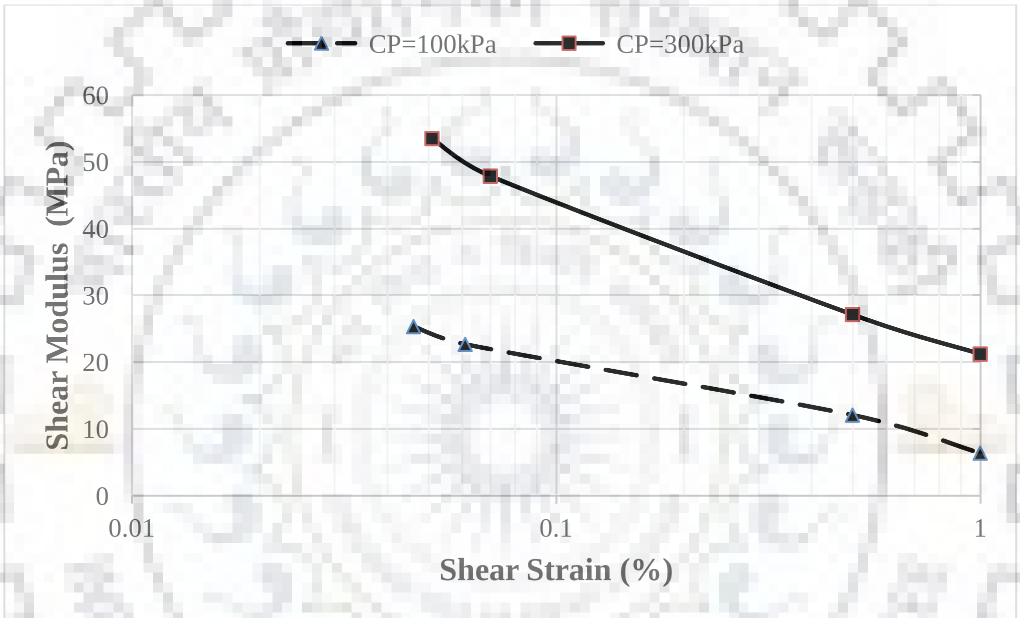

Figure 5.27 (a) Shear modulus with shear strain at relative density 60% & dry sand

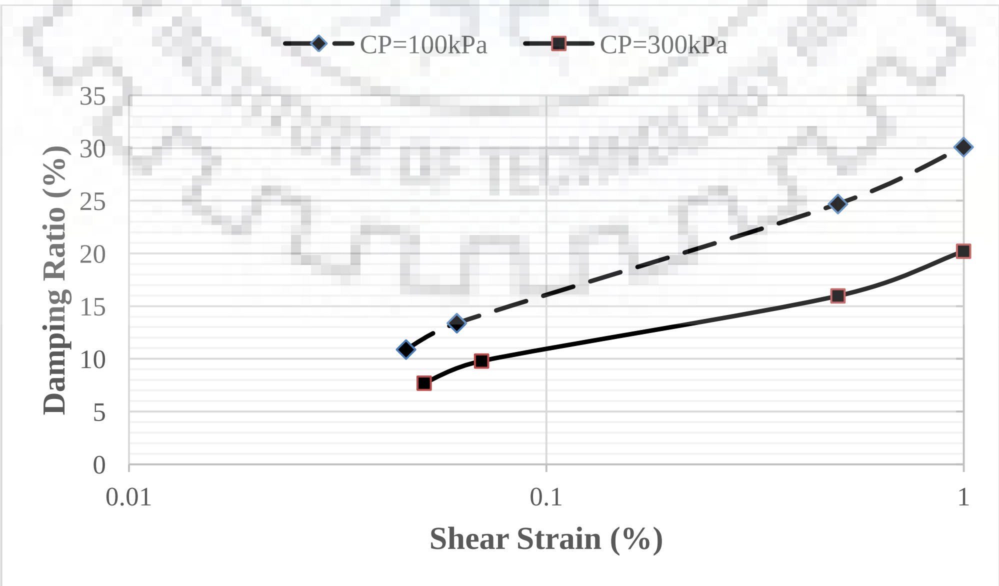

Figure 5.27 (b) Damping Ratio with shear strain at relative density 60% & dry sand

5.8 Effect of System Compliance

To determine dynamic soil properties, tests are available either in low strain range (using resonant column apparatus) and high strain range (using cyclic triaxial system). The range of low strain is (0.0001 % to 0.01%), or in high strain is (0.01 % to 10 %).Since, both the testing systems are laboratory test, various testing conditions can be created in the laboratory to find the dynamic properties and it can be applied in the field for the design purpose of site subjected to dynamic loading. Medium strain range is important for medium severity earthquake and this region is expected to have minor strength degradation and pore water pressure generation and stabilisation occurs in comparison to high strain range where there is much increment of pore water pressure.

Determination of dynamic soil properties in this range is important.It shall be noted that none of single apparatus cover the full range and to cover the range both the testing system are used viz. Resonant column apparatus, cyclic triaxial system. But while using both the apparatus at the common strain values it is found that the magnitude of dynamic properties obtained have a significant difference. This difference so obtained is said as system compliance effect.

The system compliance effect is important to take care as the values of dynamic properties to be used by the designer for using in dynamic loading prone areas is such that it would lead to economic design. The system compliance can be of due to the testing system but it can be also due to the membrane used for testing, the effect of membrane will be maximum in the gravel size particles due to sticking of membrane in the gaps but it would be very less for fine to medium coarse grained soil. There can also be some other reason for causing system compliance like the accuracy of LVDT, Volume change measurement device, Pore Pressure measuring device or if there is any kind of effect on the movement of actuator in case of cyclic triaxial system. The significant error introduced in measuring resonant frequency may be due to the compliance of many parts like the drive mechanism, support, calibration bar and compliance between apparatus and specimen. (Man Bui, 2010)

To cater out the effect of system compliance the more accurate measuring device using in both the testing system could be used, that might lead to somewhat help in reducing effect of system compliance. These is a need to investigate the effect of base rigidity, calibration bar design and insufficient base mass in case of resonant column apparatus. The test was conducted at the same strain viz. 0.05%, 0.064% for 100kPa confining pressure and 0.051%, 0.07% for 300kPa for dry samples using both CTS and RCA, the difference in both the value is the test apparatus compliance due to which the shear modulus and damping ratio is obtained are different.

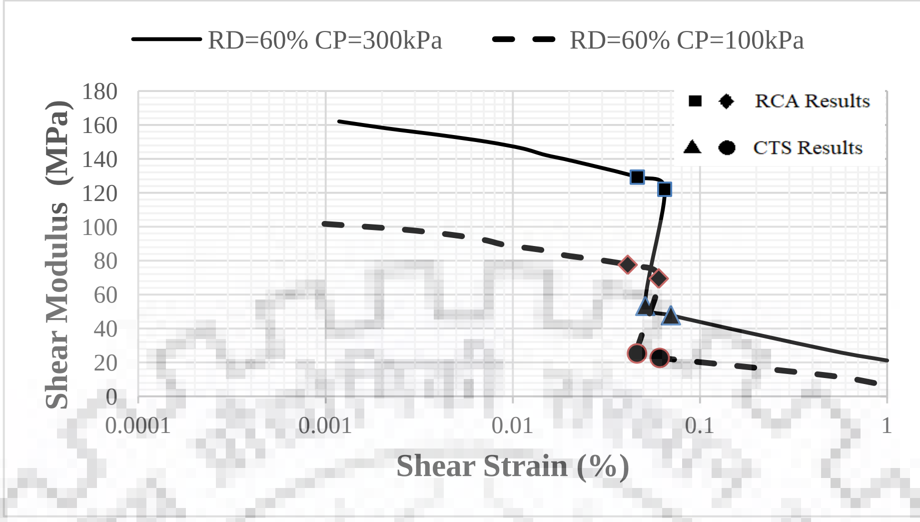

Figure 5.28 (a) Shear modulus vs shear strain at relative density 60% & Dry Sand

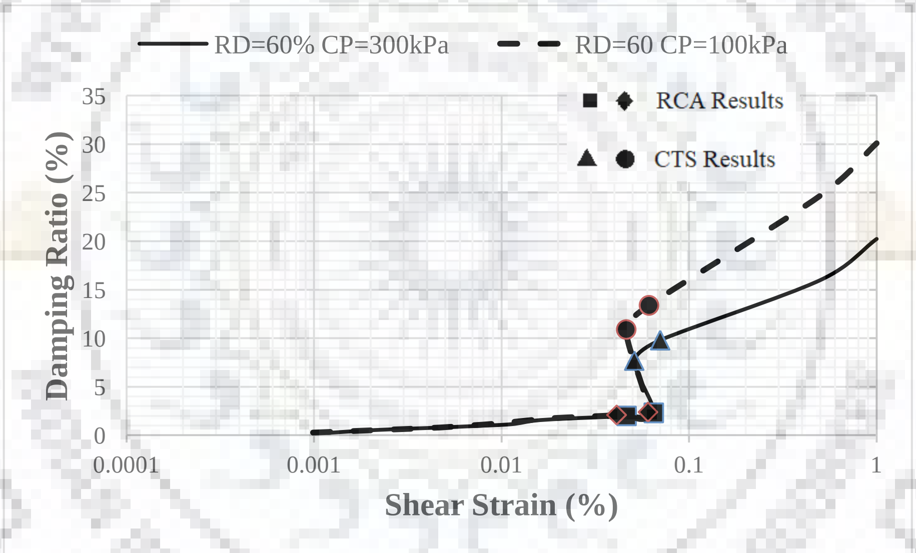

Figure 5.28 (b) Damping Ratio vs shear strain at relative density 60% & Dry Sand

From Fig. 5.28 (a) and 5.28 (b), due to system compliance effect the shear modulus and damping ratio are found to be different at same shear strain.

Table 5.4 Effect of System Compliance on Shear Modulus

S No.	Shear Strain (%)	Confining Pressure (kPa)	Shear Modulus (Mpa)		Difference (Mpa)	Percentage Decrease (%)
			RCA	CTS		
1	0.05	100	69.35	25.32	44.03	63.49
2	0.06	100	61.27	22.66	38.61	63.02
3	0.05	300	125.04	53.485	71.515	57.212
4	0.07	300	115.02	49.855	65.165	56.65

Table 5.5 Effect of System Compliance on Damping Ratio

S No.	Shear Strain (%)	Confining Pressure (kPa)	Damping Ratio (%)		Difference (%)	Percentage Increase
			RCA	CTS		
1	0.05	100	2.38	10.89	8.51	357.6
2	0.06	100	2.58	13.39	10.89	422.11
3	0.05	300	2.31	7.9	5.59	241.99
4	0.07	300	2.59	9.8	7.21	278.38

It can be observed from the Table 5.4 and 5.5, the Shear modulus obtained is smaller from cyclic triaxial system while the damping ratio is higher at the same strain level. This difference is due to the differnece in type of loading thus the method of calulation of stiffness and damping parameters. RCA gives stiffness from the resonant test, thus calulating the shear wave velocity and from that finding the shear modulus, and damping ratio is calulated from the logarithmic decrement curve while in case of CTS the stiffness and damping parameters are calculated from the hysteresis curve plotted from the cyclic loading data. In addition to the loading the compliance in value obtained is due to the sensitivity of the different measuring devices.

Also with the increment in shear strain the system compliance effect seems to increase while with increase in confining pressure its effect is reducing. The effect of increase in confining pressure leads to increase in stiffness sample is getting less disturbed when subjected to laoding so shear modulus and damping ratio obtained has lesser differnce.

Chapter-6

Summary and Conclusion

The tests were conducted on Solani Sand using Resonant Column Apparatus. The effect of saturation, confining pressure and relative density is observed. In addition to it, the effect of mode of vibration on damping ratio is being studied. Following observations are made:

- Stiffness decreases with increase in strain.
- Damping ratio increases with strain.
- Poisson's ratio increases with strain

Effect of Saturation:

- It is observed that the stiffness decreases more up to 50 % saturation but there is minor difference in 75% and 100% saturation condition.
- The damping ratio variation is almost linear and very small with increment in degree of saturation, but the difference in dry and fully saturated condition is considerable.
- Poisson's ratio increases with increase in saturation, the effect of saturation is less up to 50% saturation but after this the effect is more for Relative Density 40, this value reduces to 25 % for relative density 60% and 80 %.

Effect of Confining Pressure:

- With increase in confining pressure Shear modulus and Modulus of Elasticity increases.
- With increase in confining pressure the damping ratio in both mode of vibration decreases.
- With increase in confining pressure the Poisson's ratio in both mode of vibration decreases.

Effect of Relative Density:

- With increase in relative density Shear modulus and Modulus of Elasticity increases.
- With increase in confining pressure the damping ratio in both mode of vibration decreases.
- With increase in confining pressure the Poisson's ratio in both mode of vibration decreases.

Effect of System Compliance:

- Percentage difference in the shear modulus is less for higher strains while for damping ratio is more for higher strains for both the CTS and RCA.

- Percentage difference in the shear modulus and damping ratio decreases with increase in confining pressure.

Future Scope:

- Dynamic Soil Property of Clay in Low strain range.
- Torsional Shear Test on Sand using RCA.
- Effect of inclusion of waste material on Dynamic soil property in low strain range.
- Effect of Degree of Saturation on all above points.

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