DYNAMIC PROPERTIES OF SOLANI SAND AT SMALL STRAINS USING RESONANT COLUMN APPARATUS

B. Kirar[(1)] and B.K. Maheshwari[(2)]

[(1)] *Research Scholar, Dept. of Earthquake Eng., IIT Roorkee, India bablu_iitg@yahoo.in*

[(2)] *Professor, Dept. of Earthquake Eng. and Head, Centre of Excellence in Disaster Mitigation and Management, IIT Roorkee, India bkmahfeq@iitr.ac.in*

Abstract

Dynamic properties of soils vary significantly with the level of strain. During earthquakes, the behaviour of soil is much dependent on its dynamic characteristics. The behaviour of soils are very different at small and large strains. For laboratory tests, the resonant column apparatus (RCA) is a fairly precise device and widely used to measure the shear modulus and damping ratio of soils at low and medium strains. Conventional resonant column testing is based on the determination of the resonant frequency of a soil specimen by measuring the specimen response at different excitation frequencies. Himalayan region is a seismically active zone and Roorkee city in North India falls under its subduction zone. The city has experienced effect of earthquakes in the past and faces the danger of severe seismic threat in future also. Large area of Roorkee is covered by soil from the bed of Solani River i.e. Solani sand.

In this paper, the strength characteristics of Solani sand has been investigated by a series of resonant column tests, which has been never reported in the literature. The fixed-free torsional resonant column tests were performed using a resonant column device and its associated software, GDSLAB. A number of resonant column tests were performed on cylindrical soil specimens to evaluate dynamic soil properties viz. shear modulus and damping ratio of the Solani sand. The paper presents, effects of two key parameters i.e. relative density and confining pressure on dynamic properties of Solani sand in the small shear strain range (0.001 % to 0.1 %). The effect of both relative density and confining pressure on the shear modulus is significant; however, effect of these parameters on the damping ratio is not so significant.

Keywords: resonant column apparatus; shear modulus; damping ratio; Solani sand; relative density; confining pressure

1. Introduction

Determination of dynamic properties of soils is very important for various geotechnical earthquake engineering problems. The behaviour of soils is strain dependent, as a result characteristics of soils are different at low and high strains [1]. Earlier a number of researchers [2-6] have reported usage of resonant column apparatus (RCA) for dynamic soil properties. The method has been standardized by ASTM [7]. The fixed-free torsional resonant-column device is widely used to measure shear modulus (G) and damping ratio (ξ) of soils at low and medium strains (0.001 % to 0.1 %) [4]. The effect of various parameters such as relative density and confining pressure on dynamic soil properties in large strain is studied in detail using cyclic triaxial tests. However, the effect of these parameters in low and medium strain range using RCA is hardly reported. This paper presents the effect of relative density and confining pressure on dynamic properties of Solani sand at low and medium strains. It was observed that the effect of relative density and confining pressure on shear modulus is significant.

2. Material used

The sand used in this study was collected from Solani river bed (NH-58) near Roorkee, India. The Solani sand is classified as poorly graded sand i.e. SP. Grain size distribution and other index properties like Specific Gravity, Maximum and Minimum void Ratio, Coefficient of uniformity and Coefficient of curvature etc. are reported in Kirar et al. [8].

3. Test Procedure and Formulation

The test procedures typically involve the torsional vibration of a cylindrical soil specimen enclosed within a triaxial cell. The specimen is fixed at its base while its top is torsionally vibrated until its resonant frequency is found. The soil's shear modulus at the corresponding strain level may then be determined using one-dimensional shear-wave propagation theory [1]. Damping ratio may also be determined using a variety of different methods, such as the half-power bandwidth method or the logarithmic decrement method [9].

In this study, the fixed-free torsional resonant column tests were performed using an advanced resonant column device and its associated software, GDSLAB. The characteristics of the equipment pertinent to the generation and interpretation of the presented data are summarized. For complete operational details, the reader is referred to the resonant column device handbook provided by the commercial manufacturer [10]. Cylindrical soil specimens (50 mm diameter, 100 mm length) are placed within the resonant column device's triaxial cell using two scored end platens: the bottom platen affixes the specimen to the resonant column base, and the top platen connects the top free end of the specimen to an electromagnetic drive motor such that it may be torsionally harmonically excited. Resonant column apparatus used in the present study is shown in Fig. 1.

The user input to the electromagnetic drive motor is specified via an input voltage with a value between 0 and 1 V. The device then sweeps through a range of harmonic torsional loads of varying frequencies until shear strain (γ) maximizes, indicating the torsional resonant frequency, f (in Hz). The GDSLAB software post-calculates the value of γ from data from an accelerometer connected to the top platen given by

$$\gamma = \frac{FCVR}{(2\pi f)^2 LA} \tag{1}$$

where F = nonuniform strain correction factor equal to 0.80; C = device-specific accelerometer calibration factor (in m/s^2); V = accelerometer output in volts; R = specimen radius (in m); L = specimen length (in m); and A = accelerometer offset distance from the center of the specimen (m) [10]. The soil's shear modulus at this strain level, G(γ), is then determined by GDSLAB using standard one-dimensional torsional shear-wave propagation theory as [1, 7].

$$G(\gamma) = \rho V_s^2 = \rho \left(\frac{2\pi f L}{\beta} \right)^2 \tag{2}$$

where ρ = specimen's total mass density; V_s = shear wave velocity and β = device-specific calibration factor used to remove the extraneous moment of inertia contributions from the device's end platens and the electromagnetic drive motor [10]. The torsional excitation is then halted, and GDSLAB analyzes the decay free vibration response using the logarithmic decrement method to determine the strain-dependent damping ratio, ξ(γ) [6, 7, 9]. Kirar et al. [11] reported shear wave velocity in the region.

The maximum shear modulus (G_{max}) is also calculated by the following empirical equation [12]

$$G_{\max} = 1230 \times \frac{(2.973 - e)^2}{(1 + e)} (OCR)^k \sqrt{\sigma'_m} \tag{3}$$

where *e* is the void ratio; *OCR* is the overconsolidation ratio; σ_m' is the mean principal effective stress. In Eq. 3, both G_{max} and σ_m' are in pounds per square inch (psi), and k is a constant which depends upon the PI of clay, its value may be taken as zero for sand.

In Eq. 3 for sand (k=0) and to use in SI units, equation is revised as follows

$$G_{\max} = 3230 \times \frac{(2.973 - e)^2}{(1 + e)} \sqrt{\sigma'_m} \tag{4}$$

Where, now G_{max} and σ_m' are in kPa.

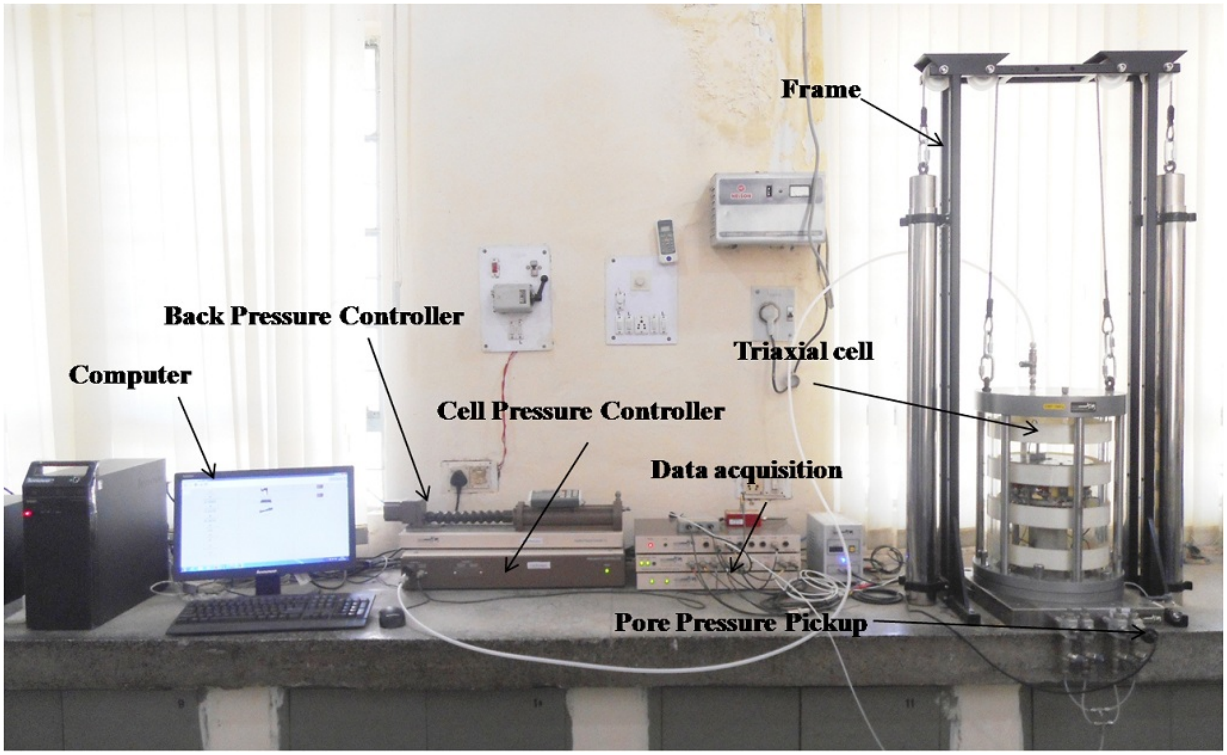

Fig. 1 - Resonant column apparatus used in the present study

4. Effect of Relative Density

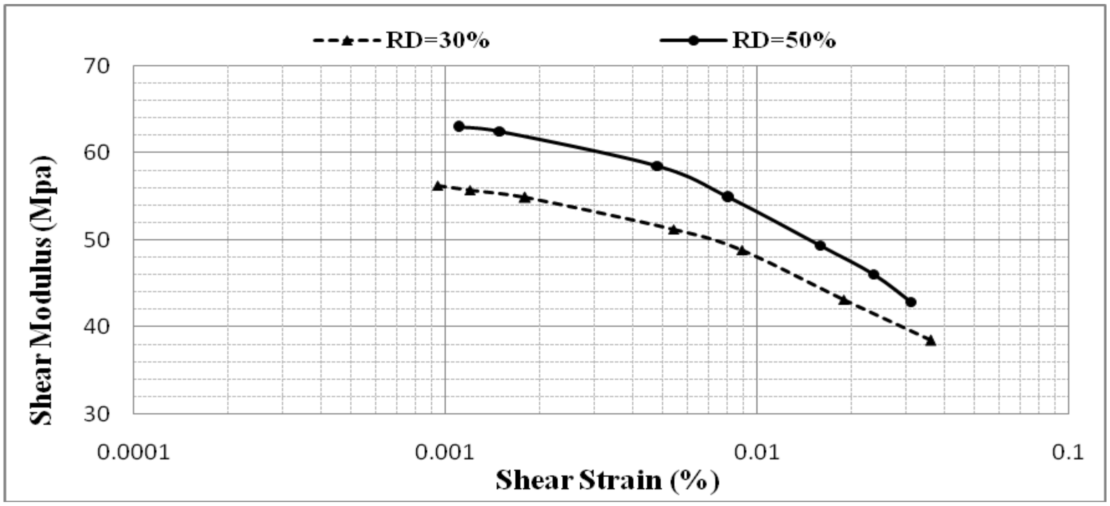

Fig. 2a - Influence of relative density on shear modulus with shear strain at CP=50 kPa

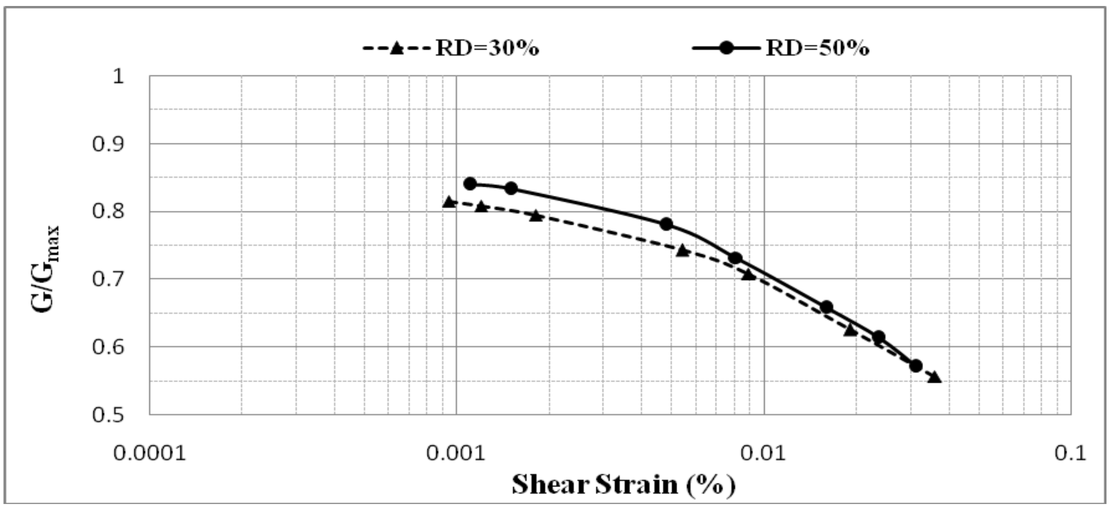

Fig. 2b - Influence of relative density on modulus reduction curves at CP=50 kPa

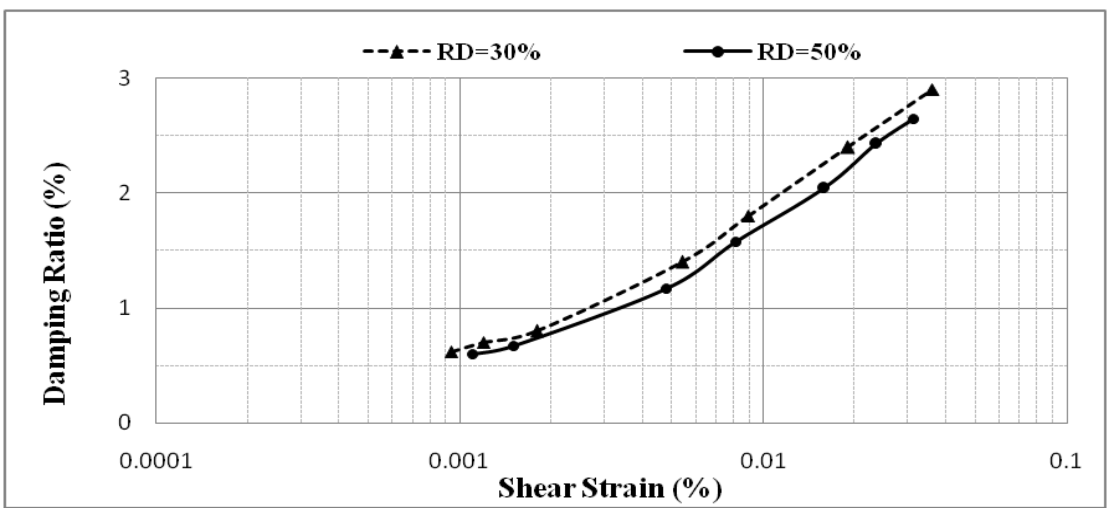

Fig. 2c - Influence of relative density on damping ratio with shear strain at CP=50 kPa

Effect of relative density on dynamic properties is examined with two different relative densities of 30% and 50% at the same confining pressure of 50 kPa. Figs. 2 a-c show the variations of shear modulus, shear modulus ratio (G/G_{max}) and damping ratio with shear strains respectively at different relative densities. From Figs. 2 a-c, it can be observed that as the shear strain increases, the shear modulus and shear modulus ratio (G/G_{max}) decreases while damping ratio increases. From Figs. 2(a) and 2(b), it can be observed that shear modulus and shear modulus ratio (G/G_{max}) increases due to increase in relative density at all the shear strains, though this is quite significant at low strain. As the shear strain increases, the shear modulus decreases and falls in a narrow band in the large strain range. Also from Fig. 2(c) it can be observed that damping ratio decreases marginally with relative density.

Though, the effect of relative density is significant on shear modulus and shear modulus ratio (G/G_{max}) but not so on damping ratio. For example at 0.002% strain, shear modulus increases from 54 kPa to 62 kPa due to increase in relative density i.e. by a margin of 15% and at 0.01% strain, shear modulus increases from 48 kPa to 53.3 kPa due to increase in relative density i.e. by a margin of 11%.

5. Effect of Confining Pressure

The influence of confining pressure on dynamic properties is examined with three different confining pressures of 50 kPa, 100 kPa and 150 kPa at the same relative density of 50%. Variations of shear modulus, shear modulus ratio (G/G_{max}) and damping ratio with shear strains at different confining pressure are shown in Figs. 3 a-c. From Figs. 3 a-c, it can be observed that, the shear modulus and shear modulus ratio (G/G_{max}) increases while damping ratio decreases with the confining pressure. However, effect is more significant on shear modulus than on the damping ratio. For example increase in shear modulus when CP increases to 100 kPa and 150 kPa are at 0.02% shear strain from 62 kPa to 95 kPa and 127 kPa, respectively, i.e. increase by a margin of 53% and 105%. Thus the effect of CP is quite significant.

The percentage increase in shear modulus due to increase in confining pressure (CP) can be represented as ratio

$$\%Increase = \frac{\Delta G}{G_{50}} = \frac{G_{CP} - G_{50}}{G_{50}} \tag{5}$$

Here G_{CP} and G_{50} are values of G at a given CP and at a CP=50 kPa respectively, at a particular shear strain considered.

Fig. 4 shows the percent increase in shear modulus with shear strain for confining pressures equal to 100 kPa and 150 kPa. It can be observed that the influence of confining pressure increases as the level of shear strain increases. The effect is the maximum at the highest shear strain considered.

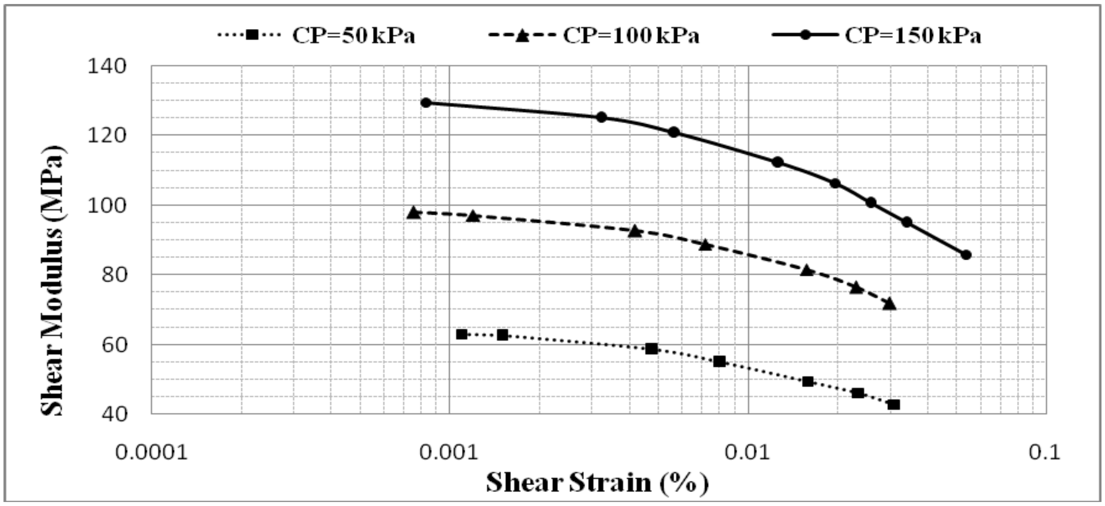

Fig. 3a - Influence of confining pressure on shear modulus with shear strain at RD=50%

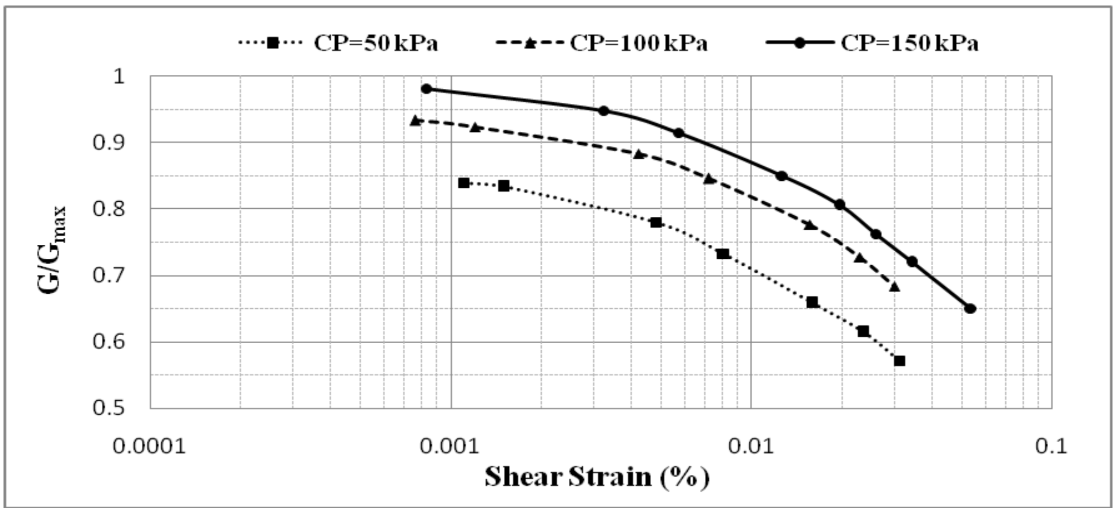

Fig. 3b - Influence of confining pressure on modulus reduction curves at RD=50%

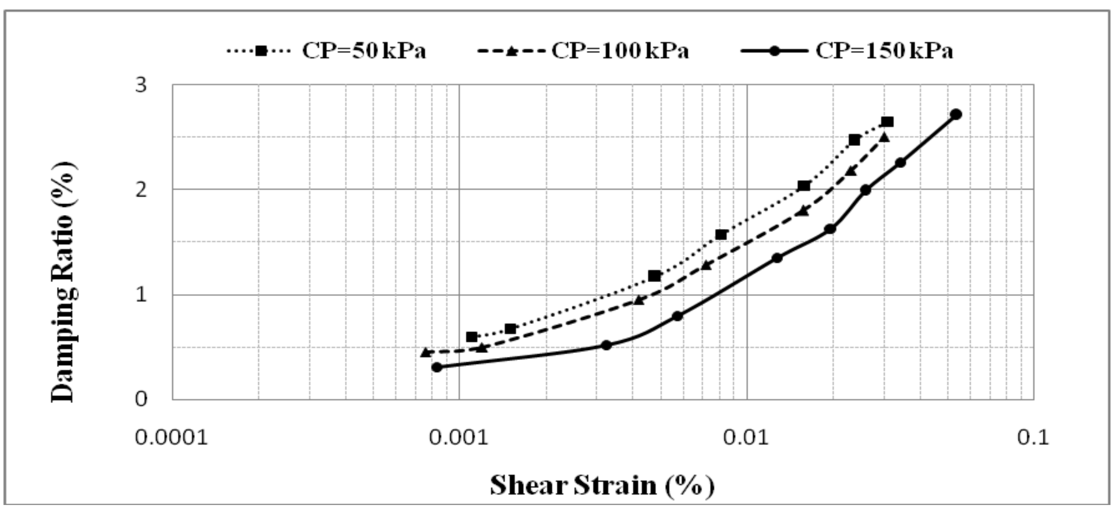

Fig. 3c - Influence of confining pressure on damping ratio with shear strain at RD=50 %

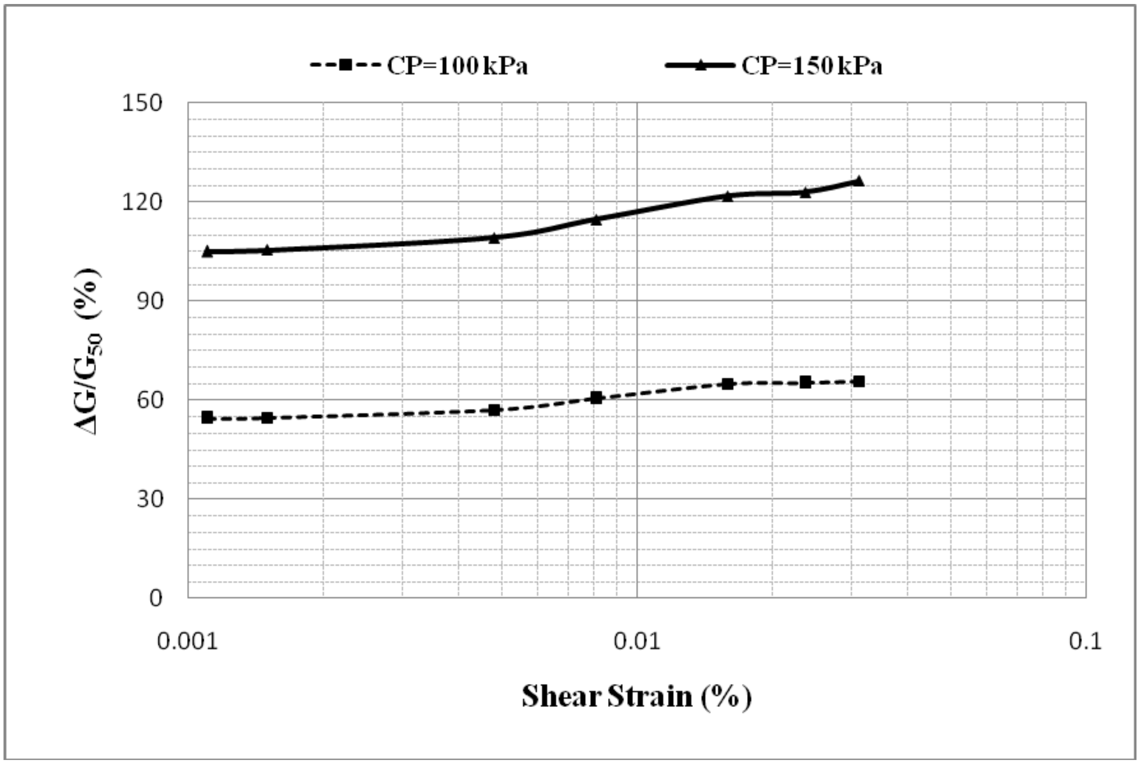

Fig. 4 - Percent increase in shear modulus with confining pressure at different shear strains

5. Summary and Conclusions

This paper presents the results of fixed-free torsional resonant-column tests conducted on Solani sand with different relative density and different confining pressure. The main conclusions that can be drawn based on this study are summarized as:

- Shear modulus and shear modulus ratio (G/G_{max}) decreases while damping ratio increases with shear strain, this is as expected.
- In general, both shear modulus and shear modulus ratio increases with relative density and confining pressure. However, there is no significant effect of relative density on damping ratio. The damping ratio slightly decreases due to increase in confining pressure.
- In general, the effect of both relative density and confining pressure on the shear modulus is relatively greater at high shear strain.

Effect of both relative density and confining pressure has practical application as one can use these curves in low strain range for dynamic analyses. However, authors acknowledge that the data presented here is small and further study is required.

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