



DYNAMIC PROPERTIES OF COMPACTED COHESIVE SOIL BASED ON RESONANT COLUMN STUDIES

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ABSTRACT: Dynamic properties of compacted cohesive soils are required in most of the civil engineering constructions. These include construction of dams, dikes, embankments, liners and levees. Dynamic properties are highly important for determining the engineering behaviour under dynamic as well as cyclic loading. In the present study a series of resonant column tests were performed on compacted cohesive soil to determine its dynamic properties. The dynamic properties studied were shear modulus, damping ratio and Poisson's ratio of soil. The effects of confining pressure and shear strain on the dynamic properties of the compacted cohesive soil are discussed. It is observed that there is increase in shear modulus and decrease in damping ratio as well as Poisson's ratio of the soil with the increase in confining pressure. It is also observed that there is reduction in shear modulus and increase in damping ratio and Poisson's ratio of the soil with increase in shear strain.

Keywords: shear modulus, damping ratio, Poisson's ratio, resonant column test, cohesive soil

1 INTRODUCTION

Dynamic properties of compacted cohesive soils are required in most of the civil engineering constructions. These include construction of dams, dikes, embankments, liners and levees (Inci et al. 2003). Dynamic properties are highly important for determining the engineering behavior under dynamic as well as cyclic loading. The most important dynamic properties of soil are shear modulus (G), damping ratio (D) and Poisson's ratio (ν) of the soil. The most widely used laboratory test to determine the dynamic properties of soil is the resonant column test in which a soil specimen is loaded harmonically. The main advantage of performing resonant column test is that it can be used to determine the dynamic properties of soil for a wide range of shear strain from 10^{-4} % to 10^{-1} %. The testing procedure and data reduction are dealt in lot of studies [ASTM D4015-92, Drnevich et al. 1978]. Poisson's ratio (ν) of the soil can be estimated by performing the resonant column tests in both torsional and flexural mode of excitation. The data reduction for flexural mode of excitation had been shown by Cascante et al. (1998). Many studies had been conducted to determine the parameters which influence the dynamic properties of cohesive soil (Hardin and Black 1968, Seed and Idriss 1970, Hardin and Drnevich 1972, Kokusho et al. 1982, Vucetic and Dobry 1991, Zhang et al. 2005). The important parameters which influence the dynamic properties of cohesive soil are effective confining pressure, shear strain and plasticity index of the soil. Other factors which influence the dynamic properties of cohesive soil but its influence is found to be less significant are frequency of loading, number of loading cycles, void ratio, degree of saturation, overconsolidation ratio, grain characteristics etc. (Sas et al. 2015). In the present study, a series of resonant column tests were performed on compacted cohesive soil to determine its dynamic properties. The effects of confining pressure and shear strain on shear modulus (G), damping ratio (D) and Poisson's ratio (ν) of the compacted cohesive soil are also discussed. The variation of confining pressure was made from 25 kPa to 200 kPa and the shear strain variation was made from 0.0001 % to 0.1%.

2 MATERIAL PROPERTIES

A dark brown colored clayey soil having a natural moisture content of 5 % is used in the present study. The soil is having a free swell index of 50 % and can be classified as a moderately expansive soil. The specific gravity of the soil (G_s) is 2.8. Standard Proctor's optimum moisture content is 22 % and maximum dry density is 1.68 g/cc. The fines content (passing 75 μ size) of the soil is 70 % and clay fraction is 40 %. The liquid limit, plastic limit and plasticity index of the soil are 58 %, 20 % and 38 % respectively. The soil classification based on AASHTO and USCS is A-7-6 and CH respectively.

3 SPECIMEN PREPARATION

The soil samples were prepared in a constant volume mould of size 50 mm \times 100 mm. During sample preparation, the soil sample was first mixed properly with desired quantity of water which is calculated



from the optimum moisture content of the soil obtained and cured for water equilibrium. The sample was then compacted to its maximum dry density under a static compaction under a triaxial loading frame. Figure 1 gives the triaxial loading frame used to prepare samples by static compaction. The prepared specimen was cured for 24 hours in a humidity chamber and then placed in the resonant column pedestal for testing.

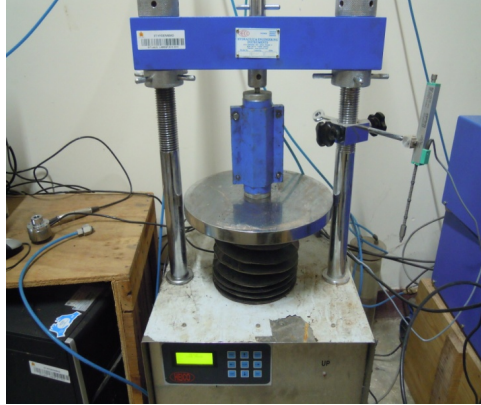


Figure 1: Static compaction performed in triaxial loading frame

4 RESONANT COLUMN APPARATUS

The resonant column test has been widely used to determine the dynamic properties of soil way back from 1930's, when it was developed by two Japanese engineers (Ishimoto and Iida 1936, 1937). The technique has been refined subsequently by a lot of researchers from then onwards (Hardin and Richart 1963; Drnevich and Richart 1970; Stokoe et al. 1994). In resonant column test, a cylindrical soil specimen is excited by an electromagnetic drive system to vibrate in one of its natural modes (Das and Ramana 2011). Resonant column apparatus can be used to perform tests under both torsional and flexural modes of excitation. The drive system consists of four electromagnets. For performing the test in both torsional as well as flexural mode, four electromagnets were used in two different directions. During the torsional mode the four pair of magnets work in series which apply a net torque to the soil specimen. For applying the flexural mode only two pair of magnetic coils work to apply a net horizontal force at the top of the specimen.

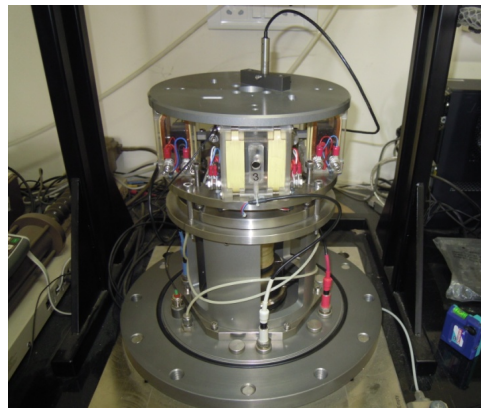


Figure 2: Fixed-Free resonant column used in the study

4.1 Determination of Shear Modulus

The shear modulus, G is determined from the resonant frequency and specific characteristics of the device.

$$G = \rho \cdot V_s^2 \quad (1)$$

where, G = shear modulus of the soil sample; V_s = shear wave velocity.



Shear wave velocity can be obtained from the resonant frequency.

$$V_s = \frac{2\pi fL}{\beta} \quad (2)$$

where, f = resonant frequency (Hz); L = length of the specimen; β = a factor that can be obtained from equation (3).

$$\frac{I}{I_o} = \beta \cdot \tan(\beta) \quad (3)$$

where, I = mass polar moment of inertia of the soil specimen; and I_o = mass polar moment of inertia of the electromagnetic drive system.

4.2 Determination of Damping Ratio

After the resonant frequency was determined, the excitation power is switched off and the specimen was allowed to freely vibrate. The damping is determined by logarithmic decrement method from the free vibration curve.

$$D(\%) = \frac{1}{2\pi n} \ln\left(\frac{Z_o}{Z_n}\right) \quad (4)$$

where, D = damping ratio; Z_o = vibration amplitude after excitation power is switched off; Z_n = vibration amplitude after n^{th} cycle; n = number of cycles.

4.3 Determination of Poisson's Ratio

Resonant column tests have to be performed in both torsional and flexural modes of excitation for determining the Poisson's ratio of the soil sample.

Cascante et al. (1998) gave the circular resonant frequency for a soil specimen of length L by using Rayleigh's method and considering N distributed mass m_i as:

$$\omega_f^2 = \frac{3EI_b}{L^3 \left[\frac{33}{140} m_T + \sum_{i=1}^n m_i h(h_{0i}, h_{1i}) \right]} \quad (5)$$

$$h(h_{0i}, h_{1i}) = m_i \left[1 + 3 \frac{(h_{1i} + h_{0i})}{2L} + \frac{3}{4} \left(\frac{h_{1i}^2 + h_{1i}h_{0i} + h_{0i}^2}{L} \right)^2 \right] \quad (6)$$

where, h_{0i} and h_{1i} are the heights at the bottom and top respectively, of mass i , measured from the top of the soil specimen; ω_f = circular resonant frequency in flexural mode; E = Young's modulus of the soil specimen; I = area moment of inertia; m_T = mass of the soil specimen.

Equation (6) can also be expressed in terms of centre of gravity, y_{ci} and area moment of inertia, with respect to centre of gravity, I_{yi} of each mass, m_i .

$$h(y_{ci}, I_{yi}) = 1 + \frac{3y_{ci}}{L} + \frac{9}{4L^2} \left[\frac{I_{yi}}{m_i} + y_{ci}^2 \right] \quad (7)$$

Due to complex geometry, area moment of inertia I_y for the drive system is determined experimentally.

Now the Poisson's ratio is determined using:

$$\nu = \frac{1}{2} \frac{V_{LF}^2}{V_s^2} - 1 \quad (8)$$



Where, V_{LF} = longitudinal wave velocity which can be calculated using equation (9).
 V_s = shear wave velocity calculated using equation (2).

$$V_{LF} = \sqrt{\frac{E}{\rho}} \quad (9)$$

where, E = Young's modulus of the soil specimen determined using equation (5); ρ = density of the soil specimen.

5 RESULTS AND DISCUSSIONS

Figure 3 (a) gives the variation of shear modulus (G) with shear strain. It is seen that with the increase of shear strain, there is reduction in shear modulus (G) of the soil. This is due to loss of stiffness of the soil with the increase in shear strain. In the present study, the strain variation was made from 0.0001% to 0.1%. Taylor and Parton (1973), Zen et al. (1978), Kokusho et al. (1982) posited that strain dependent variation of shear modulus (G) of cohesive soil is very less up to shear strain of 0.001 % and after that it reduces drastically. Similar observation is made in the present study for different values of confining pressures. Figure 3 (b) gives the variation of normalized shear modulus (G/G_{max}) with shear strain for different confining pressures. It is observed that, there is degradation of normalized shear modulus (G/G_{max}) with the increase in shear strain. However there is increase of normalized shear modulus (G/G_{max}) with the increase in confining pressure.

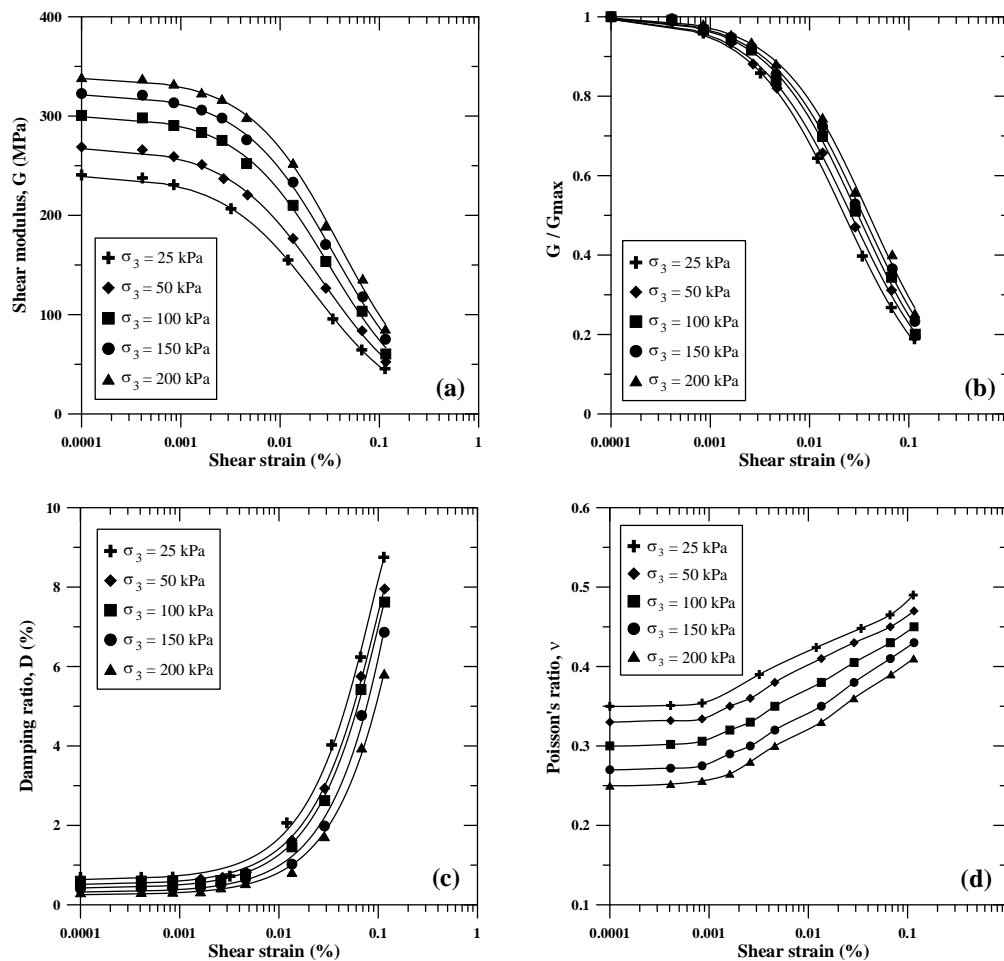


Figure 3: (a) Variation of shear modulus (G) with shear strain (b) Variation of normalized shear modulus (G / G_{max}) with shear strain (c) Variation of damping ratio (D) with shear strain (d) Variation of Poisson's ratio (v) with shear strain



Figure 3 (c) gives the variation of damping ratio (D) with shear strain. It is observed that damping ratio (D) of cohesive soil increases with the increase in shear strain. Damping of soil signifies the amount of energy dissipated during cyclic loading. With the increase in shear strain, higher is the degree of particle slippage and particle rearrangement, hence higher is the damping ratio (D) of the soil (Fahoum et al. 1996). However the increase in damping ratio (D) with shear strain is less upto shear strain of .01 % and with further increase in shear strain there is significant increase in damping ratio (D). Figure 3 (d) shows the variation of Poisson's ratio (ν) of cohesive soil with shear strain. It is seen that with the increase with the increase of shear strain, Poisson's ratio (ν) of the soil increases. Similar observation was made by Sas et al. (2013) by performing resonant column tests on clayey sand. It is seen that increase in Poisson's ratio of soil is very less upto shear strain of 8×10^{-4} %. This may be due to the reason that the soil behaves in a linear elastic manner upto a shear strain of 10^{-3} %.

Figure 4 (a) gives the variation of maximum shear modulus (G_{max}) with confining pressure. It is seen that maximum shear modulus increases monotonically with the increase in confining pressure. Maximum shear modulus (G_{max}) is determined at a shear strain of 0.0001%. The increase in confining pressure results in increased number of particle-particle bonds which provides resistance to the specimen to deformation (Mitchell 1976). This means that there is an increased stiffness of the soil specimen with increase in the confining pressure. Figure 4 (b) gives the variation of minimum damping ratio (D_{min}) and Poisson's ratio (ν) with confining pressure. It is observed that there is decrease of minimum damping ratio (D_{min}) as well as Poisson's ratio (ν) of the soil with the increase in confining pressure. There is considerable reduction in damping ratio as compared to Poisson's ratio (ν) of soil with the increase in confining pressure. This is because increase in confining pressure increases the rigidity of the soil specimen and reduces the strains induced in the soil resulting in lower value of damping ratio and Poisson's ratio of the soil.

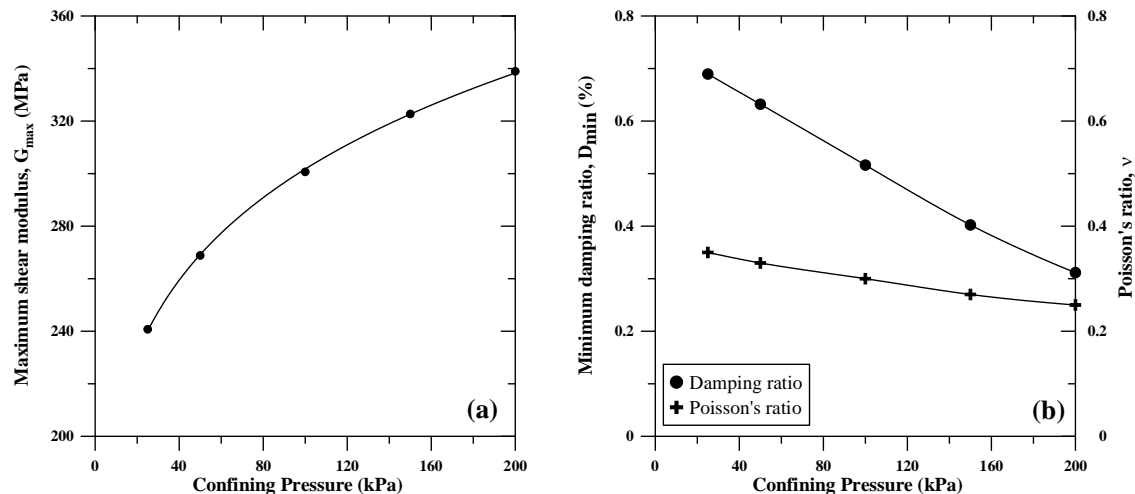
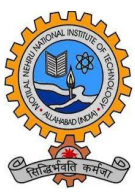


Figure 4: (a) Variation of maximum shear modulus (G_{max}) with confining pressure (b) Variation of minimum damping ratio (D_{min}) and Poisson's ratio (ν) with confining pressure

6 CONCLUSIONS

In the present study a series of resonant column tests were performed to determine the dynamic properties of compacted cohesive soil. The dynamic properties determined were shear modulus (G), damping ratio (D) and Poisson's ratio (ν) of soil. It is observed that shear modulus (G) of soil decreases whereas damping ratio (D) and Poisson's ratio (ν) of soil increases with the increase in shear strain. This is due to loss of stiffness of the soil with the increase in shear strain. There is degradation of normalized shear modulus (G/G_{max}) with the increase in shear strain. There is marginal increase of normalized shear modulus (G/G_{max}) with the increase in confining pressure. With the increase in confining, there is increase in maximum shear modulus (G_{max}) and decrease in damping ratio (D_{min}) and Poisson's ratio (ν) of soil. There is considerable reduction in damping ratio (D_{min}) as compared to Poisson's ratio (ν) of soil with the increase in confining pressure.



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