Study of stress-dependent dynamic properties of jointed rock using resonant column apparatus

Sakshi Rohilla
Indian Institute of Technology Ropar, Rupnagar, India

Resmi Sebastian
Indian Institute of Technology Ropar, Rupnagar, India

ABSTRACT:Field stress conditions have a significant impact on the mechanical characteristics of jointed rock masses. This paper investigates and discusses the effects of joint spacing and confining pressure on the dynamic properties of a jointed rock mass. The RCA was used to test jointed gypsum material at varied confining pressures and strain amplitudes. The normalised shear modulus and material damping ratio curves for various joint spacings and confining pressures have been produced. The modified hyperbolic and Ramberg-Osgood models were used to fit curves based on experimental data collected at various shear strain amplitudes and confining pressures. This study presents the best-fitted parameters showing the link amongst shear modulus and shear strain, in addition to damping ratio and shear strain for varied joint spacing. The eminence of confining pressure on shear modulus and damping ratio at various strain levels has been studied using the power function.

Keywords: Jointed rock, Shear modulus, Damping ratio, Confining pressure, Joint spacing.

1 INTRODUCTION

The ubiquity of joints and additional discontinuities alters the potency of rock and reduces its integrality and stiffness. The effectuality of these joints is determined by both the stress conditions and the strain amplitudes to which they are subjected. Fratta and Santamarina (2002)investigated long-wavelength shear wave propagation using an instrument employing the resonant frequency mechanism. Following this, shear wave velocities and damping ratios were quantified by imparting torsional vibrations of differing normal stress magnitudes to a cylindrical column of rocks. An exploration of the propagation of longitudinal waves for various joint situations under various confining stress magnitudes but at a specific strain amplitude was examined by Cha et al. (2009). The rock structure may be exposed to numerous strain amplitudes somewhere within the elastic range, relying on the source of vibration, the proximity of the object of concern to the origin of vibration, the material's properties, and other variables. Sebastian and Sitharam (2016) evaluated the wave propagation under various stress conditions linked to various strain amplitudes using the

Resonant Column Apparatus (RCA). In this study, the Ramberg-Osgood model (RO) and a modified hyperbolic model (MH) have been used to characterize the dynamic properties of plain jointed rock samples obtained using resonant column apparatus, under various confining pressures.

2 MATERIALS AND METHODOLOGY

Plaster of Paris (POP) was utilised as a model material in this work to scrutinize the progression of shear waves across jointed rocks. Rocks are frequently simulated with model materials. Indraratna and Haque (2000) utilised gypsum plaster to explore the shear behaviour of rock joints, while Cha et al. (2009) utilised dental gypsum discs to carry out the resonance investigations on rocks. Accessibility, repeatability, customization, and rapid hardening are all advantages of POP samples. Even though POP samples behave similarly to soft rocks, they are significantly less stiff than usual rocks. POP samples were made by libating a POP and water mix slurry into readily available split molds, which were later recovered after the samples had set.The samples were then dried for 12–14 days at typical ambient temperature and humidity conditions in order to get a consistent weight. The gypsum plaster specimens employed in this study contain joints that are present at spacings of 50 mm, 33 mm, 25 mm, and 20 mm, respectively.Sebastian and Sitharam (2016)explored the effect of joint spacing on the propagation of waves across filled and frictional joints. The UCS value of the intact POP sample reveals that the material is classed as very weak rock byISRM 1978, and the joint spacing of 20 to 50 mm falls under very close spacing.

GDS Instruments, UK, London, supplied the resonant column apparatus for this research. In a resonant column apparatus (RCA), the upper portion of the specimen is exposed to a net torsional stress by a coil-magnet drive system, while the bottom remains fixed. The top and bottom pieces of the solid or hollow test specimen are glued with epoxy to the rough surfaces of the top and bottom plates to prevent the specimen from slipping (Khan et al., 2008). This allows the topmost section of the specimen to rotate with the driving plate when torque is applied, while the bottommost section remains stationary with the base pedestal. To inspect the implications of confining pressure at various joint spacings, confining pressures of 0 MPa, 0.5 MPa, 1 MPa, 1.5 MPa, 2 MPa, and 2.5 MPa were applied.

3 RESULTS AND DISCUSSION

3.1 Influence of confining pressure

The effect of confining pressure on the dynamic characteristics of jointed rock has been investigated across a broad spectrum of strain amplitudes. Shear modulus values raised with the hikes in the confining pressure, however damping ratios reduced across the board for all jointing conditions. Furthermore, it was discovered that an escalation in the values of the shear modulus and declination of damping ratio with rising confining pressure followed the power function, which can be written as $y=a*x^b$. In this equation, ‘a’ represents the shear modulus/damping ratio at a confining pressure of 1 kPa, and ‘b’ represents the exponent that indicates how sensitive the shear modulus and damping ratio are to changes in the confining pressure. Figures 1 and 2 demonstrate how the shear modulus and damping ratio vary with the confining pressures at various strain amplitudes, specifically 0.00001%, 0.0001%, 0.001%, 0.01%, and 0.1%, for 1-jointed, 2-jointed, 3-jointed, and 4-jointed samples. The curve fitting parameters of the power function are presented with a confidence level of 95% in the tables that accompany each graph. Figure 1 demonstrates that the value of ‘a’ declines as the number of joints rises, while the value of ‘b’ rises, indicating that the sensitivity of the change in shear modulus with confining pressure increases as the number of joints increases. This is demonstrated by the fact that the value of shear modulus reduces as the number of joints rises. This exploratory study reiterates the findings of Cha (2009) as well as Sebastian and Sitharam (2016). Figure 2, which is quite similar to Figure 1, indicates that the value of ‘a’ hikes as the confining pressure rises, while the value of ‘b’ reduces. This suggests that the damping ratio values climb, while the sensitivity lowers, as the number of joints increases. In addition, the data presented in Figure 1 illustrates that the values of the 'a' and 'b' parameters shift in response to an increase in the strain level in every joint configuration. Figure 2 also includes a description of the situation in reverse.

3.2 Curve fitting models

The elastoplastic response of materials is frequently depicted using the Ramberg-Osgood (RO) model (Jennings, 1965). For the Ramberg-Osgood elastoplastic material model proposed by Idriss et al., 1978, the secant shear modulus and material damping ratio from the backbone curve may be reported as:

$$\frac{G}{G_{max}} = \frac{1}{\left(1 + \alpha \left|\frac{G}{G_{max}} \frac{\gamma}{\gamma_y}\right|^{r-1}\right)}; \ D = \frac{2}{\pi} \frac{r-1}{r+1} \alpha \frac{\left|\frac{G}{G_{max}} \frac{\gamma}{\gamma_y}\right|^{r-1}}{1 + \alpha \left|\frac{G}{G_{max}} \frac{\gamma}{\gamma_y}\right|^{r-1}} \tag{1}$$

Where the constants α and r have values of 0 and 1, respectively, and γ is the shear strain, γ_y, the reference shear strain, G, the shear modulus, and G_{max} the maximum shear modulus.

The parameter γ_y must be specified precisely since it determines the point of greatest curvature of the backbone curve and the hysteresis curve form (Ueng and Chen, 1992). The value of γ_y for geomaterials varies depending on the type of material. The reference shear strain value, γ_y, affects the dynamic characteristics of the material, the G and D.

Numerous researches on geomaterials indicated that when shear strain amplitudes grow, the dynamic shear modulus, G, will reduce and the damping ratio, D, will rise (e.g., Bolton Seed & Idriss, 1970; Darendeli, 2001). To determine the nonlinear response of the geomaterials, the modified hyperbolic model (Darendeli, 2001) (MH) have been widely adapted. The expression of MH model for normalized shear modulus and material damping ratio can be described as follows:

$$\frac{G}{G_{max}} = \frac{1}{1 + \left(\frac{\gamma}{\gamma_y}\right)^a}; \ D = \frac{4}{\pi}\left[1 + \frac{1}{\left(\frac{\gamma}{\gamma_y}\right)}\right]\left[1 - \frac{ln(1 + \frac{\gamma}{\gamma_y})}{\frac{\gamma}{\gamma_y}}\right] - \frac{2}{\pi} \tag{2}$$

Where γ_y is the reference shear strain, corresponding to the G/G_{max} value of 0.5.

Figure 3 depicts the normalised modulus reduction and damping ratio curves for 1-jointed, 2-jointed, 3-jointed, and 4-jointed samples alongwiththe usual upper and lower bounds of curves derived by fitting experimental data at varied confining pressure values ranging from 0 to 2.5MPa. The experimentally observed normalised modulus reduction curves fit well with the RO model and MH model.The generated damping ratio curves indicate that the modified hyperbolic model is more accurate than the Ramberg-Osgood model at high strain levels. The ramberg-Osgood model underestimates the value of damping ratio at higher strain levels, i.e., >0.1%.

Table 1 shows the results of fitting experimental data to the RO and MH models. The curve fitting of the RO model revealed that the value of 'r' grows with the number of joints.Moreover, the outcomes of curve fitting for the modified hyperbolic model demonstrate that the value of 'γ_y' falls as the number of joints increases.

4 CONCLUSIONS

The effects of joint spacing and confining pressure on the dynamic characteristics of jointed rocks have been investigated. Resonant column testing was carried out on the model material, namely gypsum plaster, with 1 to 4 joints and confining pressure values ranging from 0 to 2.5 MPa. The transformation of shear modulus and damping ratio with confining pressure follows a power function that was discovered to be appropriate for all joint conditions. The value of 'b' for shear modulus increased while damping ratio decreased as number of joints increased. And the same was true when the strain amplitude increased. Furthermore, the Ramberg-Osgood model (RO) and a modified hyperbolic model (MH) were utilized to fit the experimental results. Both models show a fair match to the normalized modulus reduction curve, however the RO model underestimates the value of damping ratio at higher strain levels. With an addition in the number of joints, the value of 'r' in the RO model rises while 'γ_y' in the MH model falls.

REFERENCES

Fratta, D. and Santamarina, J.C., 2002. Shear wave propagation in jointed rock: state of stress. Géotechnique, 52 (7), 495–505. doi:10.1680/geot.2002.52.7.495

Cha, M., Cho, G., and Santamarina, J.C., 2009. Long wavelength P-wave and S-wave propagation in jointed rock masses. Geophysics, 74 (5), E205–E214. doi:10.1190/1.3196240

Indraratna, B. and Haque, A., 2000. Experimental and numerical modeling of shear behavior of rock joints. In: GeoEng 2000, an international conference on geotechnical & geological engineering, Pennsylvania, vol. 1.

ISRM, 1978. International society for rock mechanics commission on standardization of laboratory and field tests. International Journal Rock Mechanics and Mining Sciences & Geomechanics Abstracts, 15, 319–368.

Khan, Z.H., Cascante,G., and El – Naggar, H., 2008. Evaluation of the first mode of vibration and base fixidity in resonant column testing. Geotechnical Testing Journal ASTM, 31 (1), 1–11.

Jennings, Paul C. (1965). Earthquake Response of a Yielding Structures. Journal of the Engineering Mechanics Division, **91(4)**, 41–68. https://doi.org/10.1061/JMCEA3.0000649

Idriss, I. M., Ricardo, D., &Singh, R. D. (1978). Nonlinear Behavior of Soft Clays during Cyclic Loading. Journal of the Geotechnical Engineering Division, 104(12), 1427–1447.https://doi.org/10.1061/AJGEB6.0000727

Ueng, T.& Chen, J.C. (1992). Computational Procedures for Determining Parameters in Ramberg-Osgood Elastoplastic Model Based on Modulus and Damping Versus Strain. Engineering, http://doi.org/10.2172/6496483. Lawrence Livermore National Lab, 22.

Seed, H. B., Idriss, I. M., Shannon & Wilson., & Agbabian-Jacobsen Associates. (1970). Soil moduli and damping factors for dynamic response analyses. University of California Berkeley Structural Engineers and Mechanics, NTIS No. PB197869, California University, Berkeley, [Report No. EERC70-10], p.48.

Darendeli, M. B. (2001). Development of a New Family of Normalized Modulus Reduction and Material Damping Curves. Ph.D. Dissertation, University of Texas at Austin, 362p.

Sebastian, R., & Sitharam, T. G. (2016). Long-wavelength propagation of waves in jointed rocks - study using resonant column experiments and model material. Geomechanics and Geoengineering, 11(4), 281–296. https://doi.org/10.1080/17486025.2016.1139753

Table 1. Outcomes of curve fitting parameters obtained from Ramberg-Osgood and modified hyperbolic model.

Curve fitting parameters					
Number of joints		**Ramberg-Osgood Model**		**Modified hyperbolic model**	
		r	**α**	**γ_y**	**a**
1	Upper bound	1.605	0.130	0.208	0.715
	Lower bound	1.524	0.297	0.159	0.705
2	Upper bound	1.607	0.303	0.185	0.795
	Lower bound	1.702	0.105	0.082	0.725
3	Upper bound	1.687	0.202	0.155	0.795
	Lower bound	1.742	0.125	0.083	0.762
4	Upper bound	1.717	0.223	0.149	0.802
	Lower bound	1.732	0.134	0.085	0.651

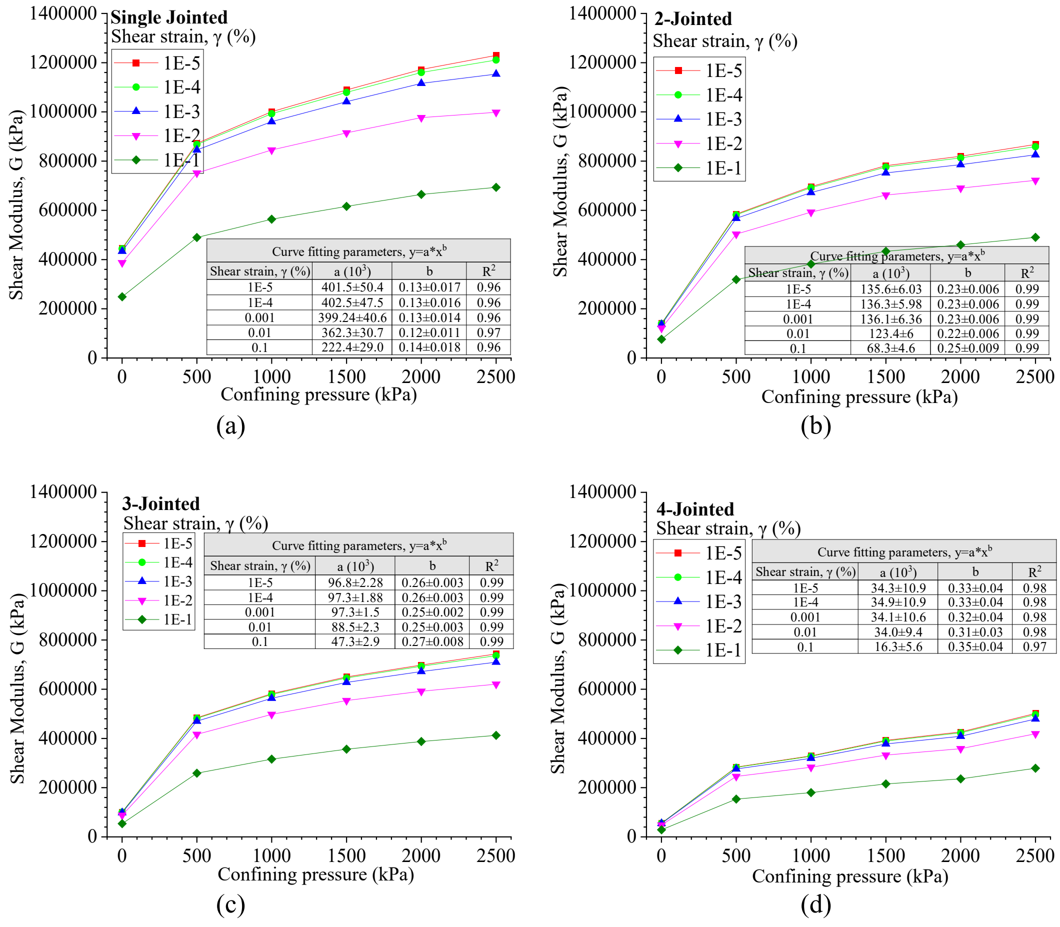
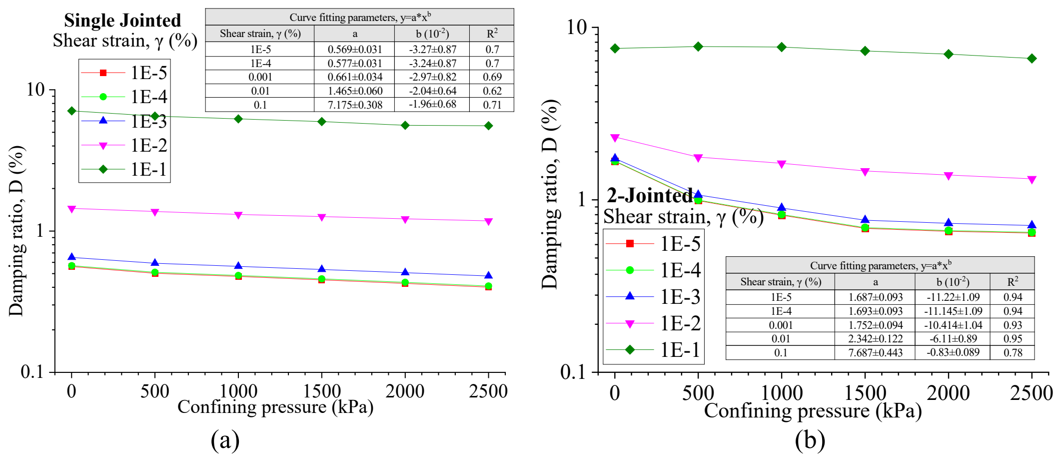
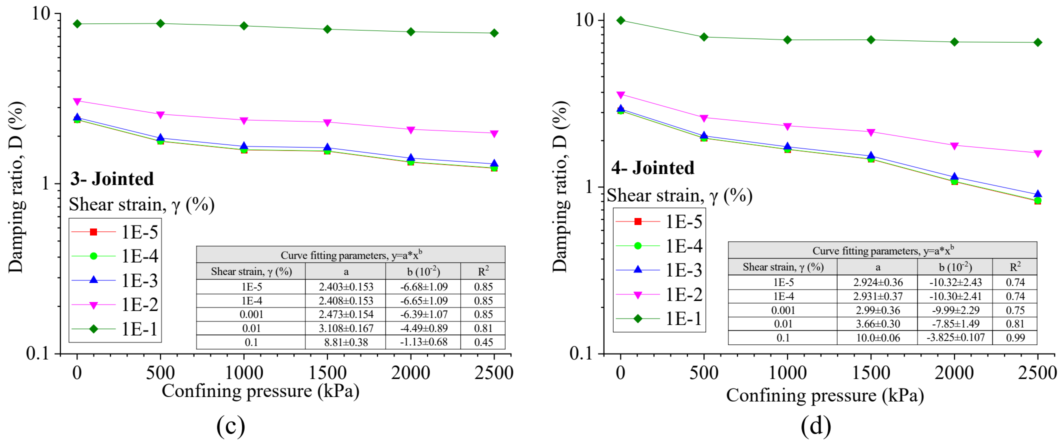


Figure 1. Variation of Shear modulus with confining pressure for, (a) single jointed; (b) 2-jointed; (c) 3-jointed; and (d) 4-jointed gypsum plaster.





Curve fitting parameters, $y=a*x^b$ (c)			
Shear strain, γ (%)	a	b (10^{-2})	R^2
1E-5	2.403±0.153	-6.68±1.09	0.85
1E-4	2.408±0.153	-6.65±1.09	0.85
0.001	2.473±0.154	-6.39±1.07	0.85
0.01	3.108±0.167	-4.49±0.89	0.81
0.1	8.81±0.38	-1.13±0.68	0.45

Curve fitting parameters, $y=a*x^b$ (d)			
Shear strain, γ (%)	a	b (10^{-2})	R^2
1E-5	2.924±0.36	-10.32±2.43	0.74
1E-4	2.931±0.37	-10.30±2.41	0.74
0.001	2.99±0.36	-9.99±2.29	0.75
0.01	3.66±0.30	-7.85±1.49	0.81
0.1	10.0±0.06	-3.825±0.107	0.99

Figure 2. Variation of Damping ratio with confining pressure for, (a) single jointed; (b) 2-jointed; (c) 3-jointed; and (d) 4-jointed gypsum plaster.

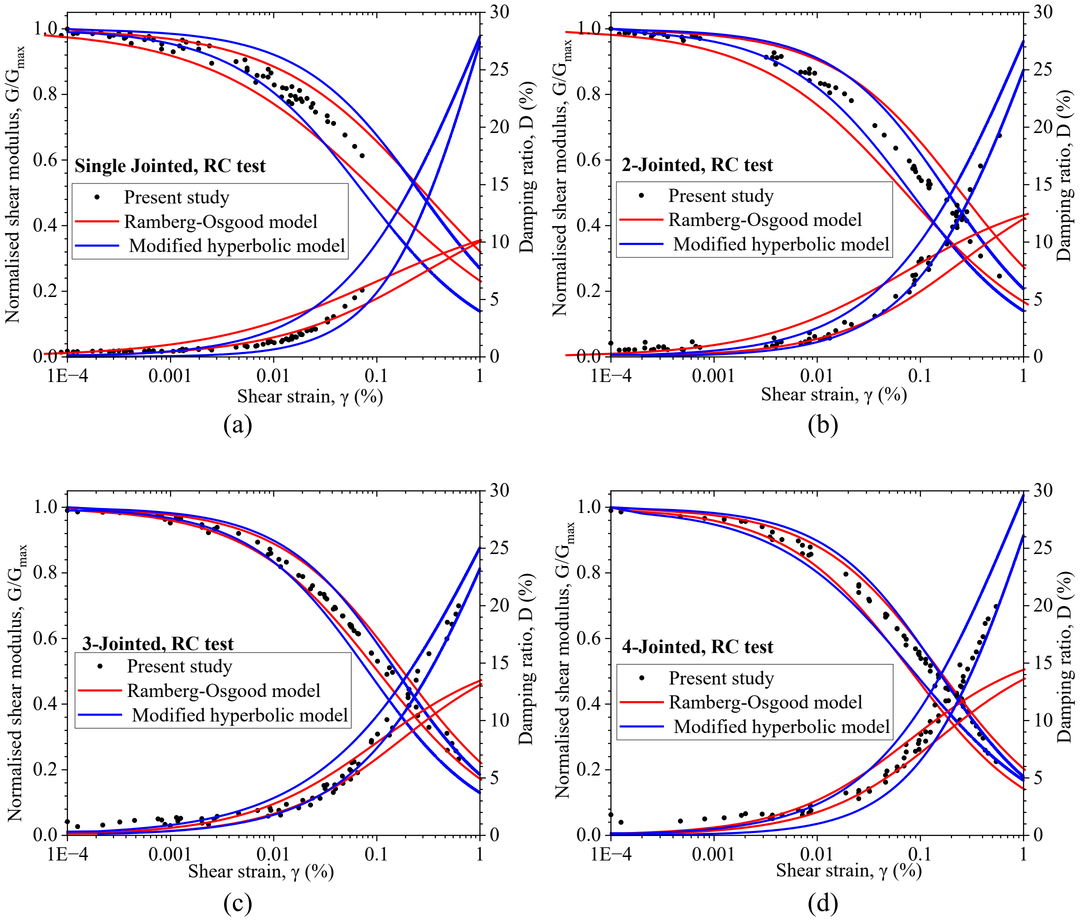


Figure 3. Normalised shear modulus and damping ratio curves for, (a) single jointed; (b) 2-jointed; (c) 3-jointed; and (d) 4-jointed gypsum plaster.