Effect of scale and in-situ stress ratio on the deformation modulus of rock mass around tunnels

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ABSTRACT: Assessment of rock mass modulus is an essential part of analysis and design of tunnels. An in-house study was conducted to understand the variation of rock mass modulus around a tunnel to changing joint characteristics and far-field in-situ stress ratios. In each test, tunnel support pressures and displacements at the boundary of the test specimen were monitored. An exhaustive analysis of test results revealed that the deformation modulus is more sensitive to varying in-situ stress ratio than joint orientations. The modulus is found to decrease with increasing stress ratio. In addition to in-house study tests, analysis of the laboratory test results on jointed rock and small-scale rock mass specimens from literature proved a profound scale effect on deformation modulus.

Keywords: Tunnels, Rock mass modulus, Joints, Joint factor, Scale effect.

1 INTRODUCTION

Several tunnels are being constructed through fragile rock masses of the Indian Himalayas to meet the surging energy needs and increase connectivity. Often, these rock masses exhibit anisotropic behaviour due to the inevitable existence of geological discontinuities such as joints, foliations, and bedding planes. The orientation of these discontinuities along with in-situ stress state affects the strength and deformational characteristics of rock mass. Accurate estimation of the rock mass parameters is essential to precisely characterize the anisotropic behaviour of rock mass, which would facilitate a safe and economical tunnel design.

Rock mass modulus is among the most important parameters that govern the design of tunnels. The determination of the modulus at site is often expensive, laborious, and challenging. Alternatively, empirical correlations based on intact rock properties and joint attributes are used. These approaches are derived from field and laboratory studies. In this article an experimental study is discussed to have better understanding of the rock mass modulus around a tunnel.

A total of nine tests were performed on large specimens of rock mass by varying far-field in-situ stress ratio (SR) and joint orientation. The observed data on boundary deformations were analyzed to obtain rock mass modulus in horizontal and vertical directions. In addition, modulus was calculated from empirical correlations available in literature. The comparison of results revealed a striking dependence of the scale of testing on rock mass modulus. The effect of in-situ stress ratio and joint orientation on deformation modulus of rock mass based on the test results is discussed.

2 EXPERIMENTAL PROGRAMME

2.1 Experimental Setup

An experimental setup was devised to investigate the strength and deformational behaviour of rock mass surrounding a D-shaped tunnel (Choudhari, 2007). The experimental setup, as shown in Figure 1, consists of a reaction frame designed to withstand a 500kN load and accommodates the test specimen with cross-sectional dimensions of 750 x 750 mm and extending 150 mm along the tunnel axis.

The test specimen is a jointed mass of small individual elemental blocks measuring 25 x 25 x 75 mm. The blocks are systematically arranged to form two orthogonal sets of joints, allowing the study of the anisotropic behaviour of rock mass. The positioning of the blocks was varied to create different orientations of the joints. A model material was used to simulate intact rock. Plaster of Paris was used as model material. The properties of the model material are described in Table 1.

The in-situ stress was simulated by a gradual load increase using hydraulic jacks connected with the test specimen using loading platens. Two sets of dial gauges, H.D.1, H.D.2, V.D.1 and V.D.2 are placed on the horizontal and vertical platens, respectively, to measure the boundary displacements. The crown, invert and walls of the tunnel support are made of iron and held in place using vertical and horizontal load gauges (V.Lc., H.Lc.) while assembling the specimen to simulate excavation.

A total of nine tests were performed by varying joint orientations and stress states. Three different joint configurations, namely 00/90°, 45/135°, and 60/150° were used in the study. The angles of the joints are measured with the horizontal axis in the anti-clockwise direction. The behaviour of the test specimen under bi-axial conditions is studied by varying stress ratios from 1.00, 1.33, to 2.00.

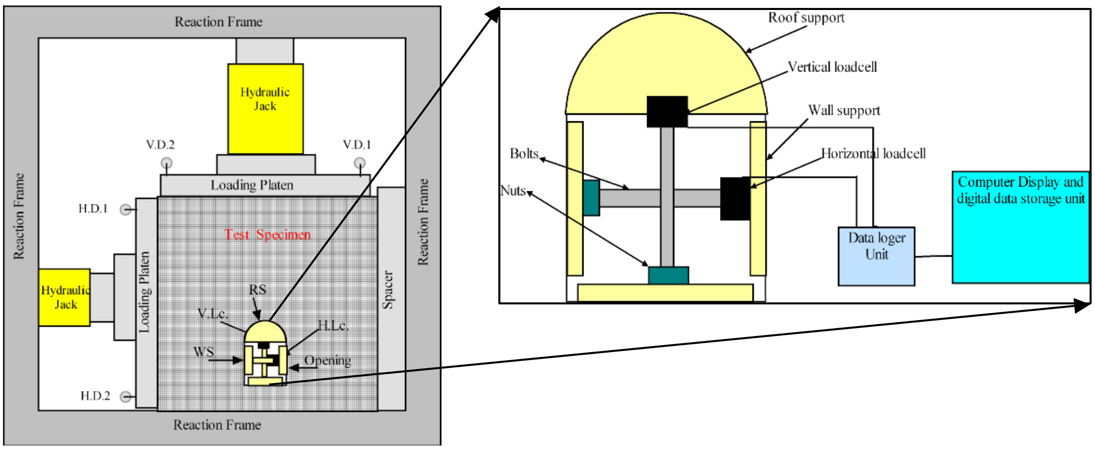

Figure 1. Test setup highlights the arrangement of hydraulic jacks, dial gauges, load gauges and loading platens within a reaction frame.

Table 1. Engineering and physical properties of the model material.

Property	Value	Property	Value
Dry density, kN/m^3	18.5	*At low normal stress $\sigma_n \leq 0.55\ MPa$	
Poisson's ratio	0.25	Joint cohesion, c_j, (MPa)	0
Specific gravity	2.52	Joint friction angle, φ_j °	39.0
Tangent modulus, E_i, (MPa)	2200	*At high normal stress $\sigma_n > 0.55\ MPa$	
UCS (MPa)	7	Joint cohesion, c_j, (MPa)	0.1
Cohesion, c_i, (MPa)	2	Joint friction angle, φ_j °	37.0
Friction angle, φ_i °	33	*σ_n is the normal stress	

2.2 Calculation of Deformation Modulus

The test specimen was loaded gradually in seven steps until the desired horizontal (P_h) and vertical (P_v) pressures reached pre-determined in-situ stresses. Loads and respective boundary deformations were recorded. The moduli of deformation of rock mass under uniaxial loading conditions in the lateral (Eh_j) and vertical direction (Ev_j) were calculated using plane-stress relations according to equations 1 and 2 as given in Obert & Duvall (1967).

$$E_{h_j} = \left(\frac{P_h * (1 - \mu^2)}{\mu \varepsilon_v + \varepsilon_h} \right) \tag{1}$$

$$E_{v_j} = \left(\frac{P_v * (1 - \mu^2)}{\mu \varepsilon_h + \varepsilon_v} \right) \tag{2}$$

Where ε_h and ε_v are the strains measured at the boundaries in horizontal and vertical direction and μ is poisson's ratio. The variation of moduli values with increasing stress ratio at different joint orientations is plotted in Figure 2. The stresses applied at the boundaries, calculated deformation moduli, measured support pressures at the crown (P_{sr}) and wall (P_{sw}), along with deformations obtained at horizontal (δH) and vertical (δV) boundaries are listed in Table 2.

Table 2. List of tests performed and obtained deformation moduli, support pressures for varied joint orientations and stress ratios.

Test	Orientation (°)	Stress Ratio	P_h (MPa)	P_v (MPa)	E_{hj} (MPa)	E_{vj} (MPa)	P_{sw} (MPa)	P_{sr} (MPa)	δH (mm)	δV (mm)
1	0-90	1.00	1.72	1.72	163	203	1.44	1.72	16.75	7.11
2	45-135	1.00	2.22	2.22	152	238	1.80	1.56	10.99	8.35
3	60-150	1.00	2.13	2.13	136	210	1.85	2.10	11.41	7.46
4	0-90	1.33	2.13	1.6	170	203	1.72	1.44	9.98	4.50
5	45-135	1.33	2.13	1.6	135	246	2.11	1.32	11.29	2.49
6	60-150	1.33	2.13	1.6	147	208	1.66	1.19	13.47	3.38
7	0-90	2.00	2.13	1.07	157	141	1.97	0.87	12.37	4.17
8	45-135	2.00	1.78	0.89	105	146	2.03	0.78	15.51	0.66
9	60-150	2.00	2.13	1.07	121	177	1.52	1.00	16.32	4.52

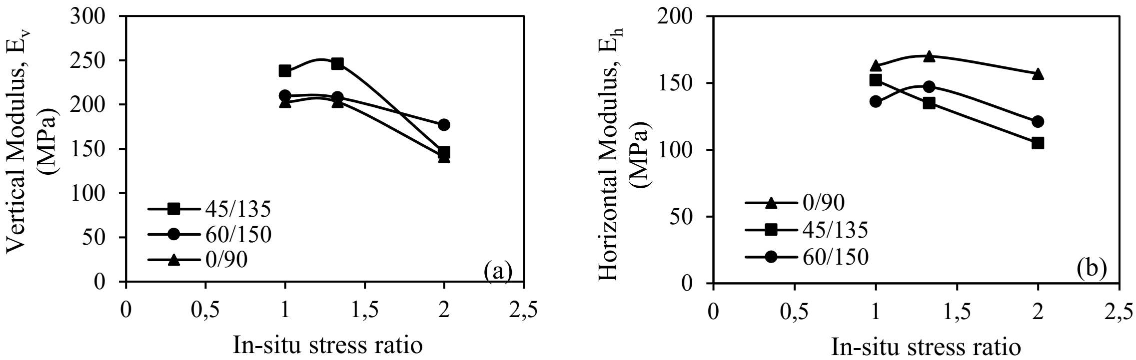

Figure 2. Variation of vertical (a) and horizontal (b) modulus with in-situ stress ratio for different joint orientations.

2.3 *Applicability of Joint Factor (Jf)*

Ramamurthy & Arora (1994) proposed an empirical approach to assess equivalent continuum modulus of jointed rocks. A weakness coefficient, 'Joint Factor' was defined which clubs three most important parameters of joints (orientation, frequency and surface roughness) into one. The joint factor is defined as given in equation 3.

$$J_f = \frac{J_n}{n * r} \tag{3}$$

The following correlation (4) was suggested to get rock mass modulus (Ej) based on tests conducted on small cylindrical specimens of size 38 x 76 mm.

$$\frac{E_j}{E_i} = exp(-0.0115 * \mathrm{J_f}) \tag{4}$$

Later Singh et al. (2002) extended the joint factor concept to rock mass specimens by testing specimens of 150 x 150 x 150 mm. A correlation (5) was suggested based on their study for different failure patterns. As per the guidelines given in Singh et al. (2002), in the case of splitting and shearing, coefficient 'a' is taken as -0.02, and -0.035 in the case of sliding along the joints. Sitharam et al. 2001 have applied the Jf concept successfully to determine rock mass modulus from the modulus of intact rock (E_i).

$$\frac{E_j}{E_i} = exp(-\mathrm{a} * \mathrm{J_f}) \tag{5}$$

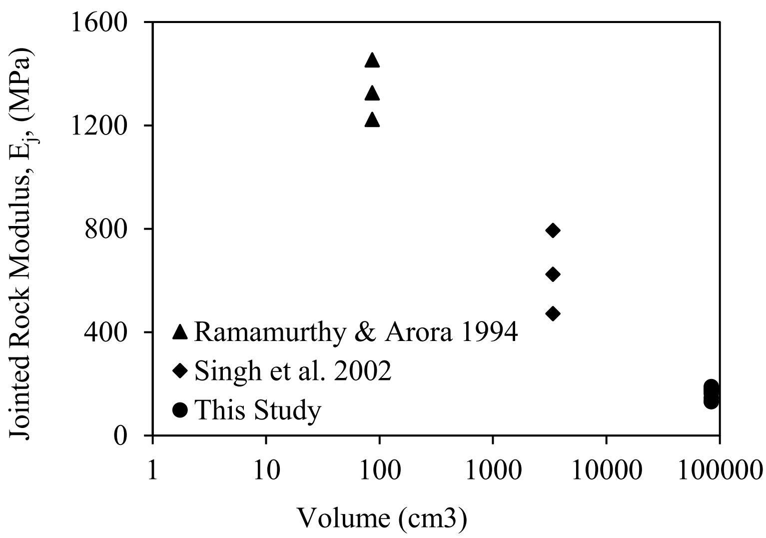

Figure 3. Effect of scale on jointed rock modulus with volume of test specimen.

The joint factor calculated for different joint orientations from this study is used in equations 4 and 5 to estimate the rock mass modulus and plotted in Figure 3. It is observed that the jointed rock modulus obtained from previous studies, when compared with test results of the current study depicts a decreasing trend with an increasing volume of the test specimen, providing incontrovertible proof of scale effect and thereby proves the efficacy of the joint factor concept in estimating the rock mass modulus using an equivalent continuum approach.

2.4 Effect of stress ratio and joint orientation

A typical decrease in horizontal and vertical moduli values is observed with an increasing stress ratio as shown in Figure 2. In situ conditions, where large stress anisotropy exists due to faults, decrease in in-situ rock mass modulus compared to hydro-static conditions is expected. The anisotropy in horizontal modulus increases rapidly with stress ratio compared to vertical modulus. In addition, suppression of anisotropy in vertical modulus and increment in anisotropy in horizontal modulus due to change in joint orientation is observed.

3 NUMERICAL MODELLING

Numerical modelling is done for analysis and design of support systems in tunnels. Before applying numerical modelling in tunnel design, it is necessary to validate its applicability through field or laboratory observations. In present study, an attempt has been made to numerically model the laboratory tests to have insight into the intricacies of rock mass deformation surrounding the tunnel.

Several researchers have resorted to equivalent characterization of rock mass to model its behaviour as a continuum (Zhang & Einstein 2004). Similarly, in this study, anisotropy induced due to the presence of joints is modelled using transversely isotropic constitutive model.

3.1 Establishment of model geometry

A three-dimensional model of the test specimen was developed in finite element software MIDAS GTS NX ver 2021 to validate the experimental findings. The size of the typical model was 0.75 m x 0.75 m x 0.15 m for the case of 0/90° joint orientation. The height and width of the model increases slightly for the joint orientations 45/135° and 60/150°.

3.2 Mesh

Discretization and mesh generation are among the key steps in generating an accurate model. It is suggested to mesh elements that require a finer mesh followed by the regions that require coarser mesh. The mesh size in the present finite element model varies from 4 mm near load gauges and gradually increased to 12 mm at the boundaries.

3.3 Loading and Boundary conditions

In-situ stresses were applied to the model as a pressure at the horizontal and vertical boundaries. The self-weight of the specimen is considered by activating gravity. Although, it is observed that the boundary displacements are not sensitive to the effect of self-weight compared to in-situ stresses.

The boundary conditions were determined by an iterative procedure to minimize its effect on boundary displacements of the test specimen. The bottom boundary was restricted in the vertical direction and allowed to deform in the horizontal direction. Similarly, the right boundary was fixed in horizontal direction and allowed to deform in the vertical direction.

The average values of the displacements observed at the boundaries of the specimen are compared with that of the experimental results as shown in Figure 4. The horizontal displacements were predicted to be within 5%, and vertical displacements within an error of 22% with a probability of 75%.

In majority of simulations, displacements at the model boundaries were under predicted in the case of horizontal displacements and over predicted in the case of vertical displacements by the equivalent continuum assumption of the laboratory test setup. The polarity of the error as shown in Figure 4, is to highlight the fact that displacements in horizontal and vertical directions are under and over predicted respectively.

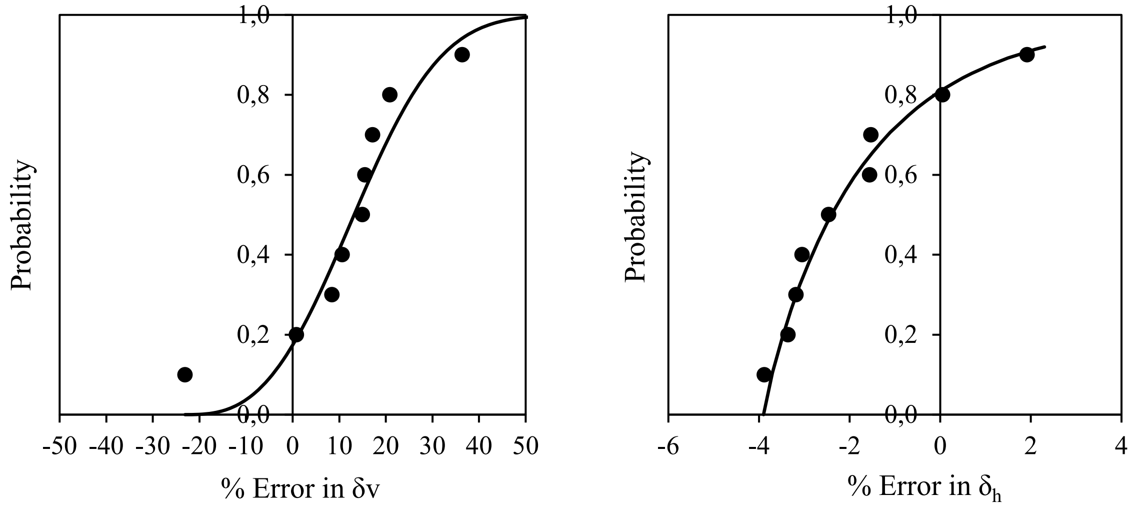

Figure 4. The cumulative probability of error in predicted (a) vertical displacements (b) horizontal displacements.

4 CONCLUDING REMARKS

A laboratory study was used to understand the effect of joint orientation and stress ratio on jointed rock modulus. A total number of nine tests were performed with varied joint orientations and in-situ stress levels. The test specimen is devised to have two joint sets to represent the anisotropic behaviour of jointed rock mass. A comparison of the rock mass modulus values obtained from tests on specimens of various sizes proved a striking effect of scale on decline of jointed modulus. A decreasing trend of jointed rock modulus value is also observed with an increasing stress ratio. In addition, the experimental findings are used to calibrate the finite element model by assuming equivalent continuum behaviour of rock mass.

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