ENGINEERING BEHAVIOUR OF JOINTED MODEL MATERIALS

by

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Dedicated

to

My Parents

CERTIFICATE

This is to certify that the thesis entitled, "**Engineering Behaviour of Jointed Model Materials**" being submitted by **Mr. Mahendra Singh** to the Indian Institute of Technology, Delhi for the award of the degree of **DOCTOR OF PHILOSOPHY** is a record of the bonafide research work carried out by him. Mr. Singh has worked under our guidance for the submission of this thesis, which to our knowledge has reached the requisite standard.

The thesis or any part thereof has not been presented or submitted to any other University or Institute for any degree or diploma.

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ABSTRACT

The discontinuities in general and joints in particular are the inevitable part of rock mass encountered in almost all Civil and Mining Engineering projects. Under very low confining pressure or unconfined stress condition, they dictate a major influence on strength and deformational behaviour of the jointed rock mass. The uncertainty in predicting the behaviour of a jointed mass under uniaxial stress condition is essentially due to scale effect and unpredictable nature of the mode of failure of the mass. In nature several combinations of modes of failure are possible and without assessing the probable mode, the reliable prediction of strength and deformability of the mass is not possible. Several studies have been conducted on strength and deformational aspects but most of them are directed towards explaining the behaviour of the mass under confined state. Moreover, no study is available which links the strength and modulus of deformation of a scale free jointed mass to that of intact rock through configuration of joints and failure modes. In the present work, an attempt has been made to link the strength, tangent modulus, modulus ratio and failure strain of jointed block mass to intact rock through failure mode which is governed by configuration of joints.

Tests have been conducted on specimens of jointed block mass under uniaxial stress conditions. A suitable model material with average uniaxial compressive strength of 17.13 MPa has been used. The tangent modulus of the material is 5344 MPa and the material is classified as 'EB' on Deere-Miller classification chart. The specimens are assembled, out of blocks of model material and a specimen consists of more than 260 blocks for the majority of the experiments. The scale free nature of the mass is thus ensured. Various combinations of four types of the geometries of blocks, eight number of joint orientations and 8 number of staggering conditions were used to simulate the most probable configurations of joints in the field.

Four distinct modes of failure under unconfined state have been observed during the present study namely: splitting, shearing, rotation and sliding. The modes of failure

lie in specific regions defined by the orientation of joints and the interlocking conditions controlled by their staggering. The guidelines have been suggested to assess the probable mode of failure in the field depending on the orientation of joints and interlocking condition of the mass. The strength, tangent modulus, modulus ratio and failure strain are found to be dependent on these modes of failure. The geometry of the block forming the specimen is also observed to be affecting the strength and modulus values of the jointed mass. The mass is found to behave anisotropically in strength and deformational response. The anisotropy curves for strength and tangent modulus are different from usually reported V-shape in the literature whereas for modulus ratio nearer to V-shape of the anisotropy is observed. The interlocking conditions systematically affect the anisotropy of strength and tangent modulus but have no such effect on anisotropy in modulus ratio.

A reliable assessment of the strength of the jointed rock mass in the field can be done by using the concept of joint factor, J_f. The joint factor is a weakness coefficient and represents the effect of joint configuration through mode of failure. The methods for computing J_f for various modes of failure have been established. The value of the J_f is computed for each metre depth as:

$$J_f = J_n / (n.r)$$

where J_n = number of potential failure surfaces per meter depth computed by the method suggested, n= joint inclination parameter, and r= joint strength parameter along the sliding joint.

The effect of Joint Factor on the strength and tangent modulus of the jointed mass has been studied. The data for other studies available from literature has also been analysed. Based on the configuration of joints and assigned mode of failure (as suggested in guidelines), one can compute the Joint Factor for the mass and compute the strength under uniaxial state as:

i. splitting $\sigma_{cj} = \sigma_{ci} \exp(-0.0123\ J_f)$

ii. shearing $\sigma_{cj} = \sigma_{ci} \exp(-0.0122\ J_f)$

iii. rotation $\sigma_{cj} = \sigma_{ci} \exp(-0.0250\ J_f)$

iv. sliding $\sigma_{cj} = \sigma_{ci} \exp(-0.0400\ J_f)$

where, σ_{cj} and σ_{ci} are the uniaxial compressive strengths of the mass and the intact rock respectively and J_f is the Joint Factor.

The tangent modulus of the jointed mass for different modes of failure can be assessed as:

i. splitting $E_j = E_i \exp(-0.020\ J_f)$

ii. shearing $E_j = E_i \exp(-0.020\ J_f)$

iii. rotation $E_j = E_i \exp(-0.040\ J_f)$

iv. sliding $E_j = E_i \exp(-0.060\ J_f)$

where, E_j and E_i are the tangent moduli for rock mass and intact rock respectively.

The above mentioned expressions for strength and tangent modulus have been suggested for a mass with more than one sets of joints. The lower and upper bound curves have also been suggested and can be used depending on the confidence of the investigations in the field. The above expressions give lower bound values. It is interesting to note that splitting and shearing modes develop similar values of strength and modulus of deformation.

The value of modulus ratio can be computed by dividing E_j by σ_{cj}. The failure strain in axial direction for all the modes of failure can be assessed as:

$$\epsilon_{aj} = 84.8\ (M_{rj})^{-0.86}$$

where, ϵ_{aj} is failure strain in % and M_{rj} is modulus ratio.

The stress-strain curve upto the peak load can be approximated by using following equation:

$$y = \frac{A}{1 + C(\rho)^x}$$

where x is axial strain in %, y is stress in MPa and A, C and ρ are the parameters of the equation given by

$$A = 1.06\,\sigma_{cj} - 0.037 \approx 1.06\,\sigma_{cj}$$

$$\rho = \exp\left[-2\,\frac{E_j}{\sigma_{cj}}\,\frac{1}{(1 - \frac{\sigma_{cj}}{2A})}\right]$$

$$C = \frac{1}{(\rho)^x}\left[\frac{A}{\sigma_{cj}} - 1\right]$$

where, E_j is predicted tangent modulus divided by 100.

The strength, tangent modulus and failure strain thus computed for the jointed mass can be used to classify the rocks similar to Deere - Miller approach. One can use strength and modulus ratio classification or as an alternate approach, the strength and failure strain.

The strength and modulus ratio classification can be used to provide rough check on reliability of the predicted strength and tangent modulus. A line from the point representing the intact rock on the classification chart can be drawn with specific gradient, representing the locus of points indicating the positions of jointed rock with increasing degree of jointing. The gradient for different modes of failure has been suggested. For all the modes an average gradient of 1.60 can be adopted.

Few case studies from published reports are also discussed. The application of the methodologies developed under the present study to field situations is demonstrated. The results predicted by other approaches are also discussed. The comparison of results shows, that the J_f concept is most reliable technique to predict the strength and deformational behaviour of the jointed rock mass.

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