TESTING AND CONSTITUTIVE MODELLING OF THE STRAIN-SOFTENING BEHAVIOUR OF SOME ROCKS

by

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Rock engineering
Strain softening

Dedicated

to

My Family

CERTIFICATE

This is to certify that the thesis entitled "**TESTING AND CONSTITUTIVE MODELLING OF THE STRAIN-SOFTENING BEHAVIOUR OF SOME ROCKS**" being submitted by **Mr. Rakesh Kumar** to the Indian Institute of Technology Delhi is a record of bonafide research work carried out by him under our supervision and guidance. The thesis work, in our opinion, has reached the standard, fulfilling the requirements for **DOCTOR OF PHILOSOPHY** degree. The research report and results presented in this thesis have not been submitted, in part or full, to any University or Institute for the award of any degree or diploma.

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ABSTRACT

Many civil engineering projects like hydropower, irrigation, transportation and mining projects are under various stages of planning, design and construction in India. The structures for these projects which include dam foundations, slopes, underground openings including powerhouse caverns, traffic and transportation tunnels, storage spaces and mining tunnels are increasingly located in/on rocks and rock masses. Rocks are geological materials formed through very complex natural processes. Many rocks in the field generally exhibit the phenomenon of strain softening under loads. The strain softening is the most predominant factor at very low confining pressure. The rocks in the field conditions exist in combination of complex geological features such as joints, faults, foliations, discontinuities and shear zones which further influence the behaviour of rocks.

In normal practice, the stress-strain behaviour of rock is obtained up to peak, using conventional stress-controlled loading machines. The complete stress-strain behaviour including post-peak behaviour can be captured by using the strain controlled loading machines like stiff testing or closed-loop servo-controlled testing machines. The servo-controlled machines have better capabilities than the stiff testing machines. Since the strain softening results in significant loss of strength in the rocks, it is important to include it in the analysis of the structures constructed in/on rocks and rock masses. The analysis of these complex structures is often carried out using numerical techniques such as Finite Element Method (FEM), Finite Difference Method (FDM) and Distinct Element Method (DEM). The constitutive models are integral part of such numerical methods. The results obtained from the analysis are as realistic as the characterization (constitutive modelling) of the rock/rock mass used in the analysis.

Based on the above factors, the present research work has been undertaken with the following objectives:

(i) To investigate the complete stress-strain behaviour including the strain softening response of various rocks in India under triaxial loading in the laboratory.

(ii) To study the stress-strain behaviour including strain softening response of jointed rock with a few joints under triaxial loading.

(iii) To study the behaviour of joints under direct shear loading.

(iv) To model the behaviour of intact and jointed rock using Mohr-Coulomb strain softening constitutive model.

(v) To conduct analysis of a typical tunnel using the above constitutive model and to compare the results with the constitutive model without strain softening.

For the present research work, a number of rock samples of varying geological origin, viz., igneous, sedimentary and metamorphic rocks have been collected from a number of major projects, primarily hydroelectric projects, from various parts of India. A model rock (silica lime rock) has been used for studying the effect of joints on rock behaviour. For intact rock testing, 15 rocks and silica lime have been used. For testing jointed rock with the model rock, seven single joint inclinations and four double joints inclinations have been used.

A total 340 rock specimens of 54 mm diameter with L/D ratios of 0.5, 1 and 2 has been prepared for Brazilian, point load index and triaxial tests respectively. The Brazilian strength and point load index for each rock type have been determined. The specimens of

60 x 60 x 25 mm have prepared for direct shear tests on joints. The specimens have been prepared for all laboratory tests as per ISRM standards.

A total of 150 specimens for intact rocks and 90 specimens for jointed model rock have been prepared for triaxial testing. A series of uniaxial compression and triaxial compression tests have been conducted on the rock specimens and silica lime specimens without and with joints using a closed-loop servo-controlled testing machine of 1000 kN capacity. All the tests have been conducted at a constant axial strain rate of 9.259×10^{-6} /s. A specially designed high pressure triaxial cell has been used in the present study. The confining pressures in the range of 0 to 57 MPa have been used in the present study. The confining pressure has been applied through high confining pressure unit. The strain gauges pasted on the specimens and the locally designed extensometers have been used for the measurement of strains. The extensometers measure strains by sensing movement of two points in the specimens. The distinguishing feature of the extensometer is that its functioning, unlike pasted strain gauges, is not affected by the cracking of the specimens during loading and can be reused.

The following major conclusions have been drawn from the experimental study:

i) The specially designed and fabricated extensometers used in the present study have been found quite promising and have certain advantages over the strain gauges and hence they can be effectively used to measure the strains in the specimens especially after the peak.

ii) The peak axial strains have been found to be minimum for igneous rocks and maximum for sedimentary rocks. For silica lime (model rock), the maximum peak axial strain has been observed for silica lime with single joint at $\beta=30^\circ$ and minimum for silica lime intact.

iii) The effect of strain softening is maximum for igneous rocks and minimum for metamorphic rocks. For model rock, the effect of strain softening is maximum for silica lime intact and minimum for silica lime with single joint at $\beta=30^\circ$. The effect of strain softening reduces with weakening of the rock.

iv) The average softening rate (slope of decreasing portion of stress- axial strain curve), ω_1 varies from 1.44 to 1.75 for igneous rocks, 1.27 to 1.44 for sedimentary rocks and 1.10 to 1.78 for metamorphic rocks. The average softening rate (slope of decreasing portion of stress- lateral strain curve), ω_2 varies from 1.85 to 3.81 for igneous rocks, 1.59 to 2.11 for sedimentary rocks and 1.25 to 3.00 for metamorphic rocks. The average softening rate, ω_1 for silica lime without and with joints varies from 1.99 to 4.33 and average strain softening rate, ω_2 varies from 3.80 to 4.33. By using these parameters as a guide and Mohr-Coulomb failure criterion, the post-peak behaviour can be approximately characterized using peak parameters from conventional testing.

Various empirical relationships for brittle to ductile transition, relations between point load index (PLI) and uniaxial compressive strength (UCS), tensile strength and UCS, modulus of elasticity (E) and confining pressure, Poisson's ratio (v) and confining pressure have been proposed in the present study based on the present data and data available in literature. The proposed equations have been found to be very promising for practical engineering problems.

A strain softening model based on Mohr-Coulomb strength criterion has been used for constitutive modeling the behaviour of intact and jointed rocks. The software package FLAC has been used for the analysis. The modeling has been carried out using parameters determined from experimental results of intact rocks and composite jointed rock parameters obtained from experimental results for silica lime with all joint inclinations. The predictions for silica lime with single and double joints with $\beta = 90^{\circ}$ are also done by explicit representation of rock and joints using the parameters of intact silica lime for intact block and properties of joint interface for interface elements. The following conclusions are drawn from the results:

(i) The cohesion (c) and friction angle (ϕ) decreases with increase in shear softening/hardening parameter (e^{ps}). However decrease in cohesion is more than that of friction angle. The dilation angle decreases with increase in confining pressure.

(ii) The predictions in terms of stress-strain-volume change response are in good agreement with experimentally observed results for all types of intact rocks and jointed rocks.

(iii) The predictions for silica lime with single and double joints with $\beta = 90^{\circ}$ are found to be satisfactory using interface elements as well as using composite jointed rock parameters. The approach using interface elements is quite promising as with the properties of joint interface and intact rocks, the predictions can be made for jointed rock with any number of joints with suitable three-dimensional modelling.

(iv) The Mohr-Coulomb strain softening model appears very promising in capturing the strain softening behaviour of both intact and jointed rocks and can be employed for strain softening behaviour of rocks and rock masses.

A circular tunnel has been analysed using FLAC using Mohr-Coulomb model without and with strain softening effect for three in-situ stress ratios of K_o = 0.5, 1.0 and 2.0. From the analyses it is found that,

(i) The effect of strain softening is predominant around and nearby tunnel boundary, due to low confining pressure. There is significant difference in yielded zones, x-displacements, y-displacements, maximum principal stresses and minimum principal stresses for Mohr-Coulomb strain softening model than that of Mohr-Coulomb model without strain softening.

(ii) The effect of strain softening is more predominant for non-uniform loading than that for uniform loading. The strain softening is most predominant for K_o = 2.0.

In the limited study, the analysis showed that the strain softening behaviour has significant effect on the analysis and design of engineering structures founded in/on rocks and rock masses.

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