STATIC AND CYCLIC BEHAVIOUR OF HIMALAYAN ROCKS

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TO MY BETTER HALF

CERTIFICATE

This is to certify that the thesis entitled, “STATIC AND CYCLIC BEHAVIOUR OF HIMALAYAN ROCKS” being submitted by Mr. Mainak Ghosh Roy 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. Mainak Ghosh Roy has worked under my guidance for the submission of this thesis which to my knowledge has reached the requisite standard.

The thesis or any part thereof has not been submitted to any other University or Institution for the award of any degree or diploma.

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ABSTRACT

Weakening of rock under cyclic loading is termed as “rock fatigue”. One of the earliest researchers to address the topic was Wöhler, who in 1870 gave the general law which may be stated as:

“Rupture may be caused, not only by a steady load which exceeds the carrying strength, but also by repeated application of stresses, none of which are equal to this carrying strength.”

The phenomenon of premature failure due to cyclic or repetitive loading leaves a significant scope for research in the field of rock mechanics due to growing evidence that such strength weakening is found in underground excavation as well as in dam reservoir, bridge abutments, dam foundations, open cut benches and structures subjected to earthquake. Thus consideration of time dependence in the form of static and cyclic behaviour of rock is essential for judicious design of surface and subsurface engineering structures in the mountainous terrain like Himalaya.

From literature review, it was observed that although number of intuitive and constitutive models describe deformation behaviour of rock under constant loading like creep, very few models have been proposed to describe the deformation behaviour of rock under both cyclic damage and cyclic hardening experiments. Irreversible axial strain method is one of the most reliable damage variable because it has a distinct physical meaning and can describe the initial fatigue damage and degradation process of rock subjected to fatigue loading.

Keeping in view the above considerations, the fundamental aim of the present research was to study the effect of cyclic loading on strength and mechanical properties of Siwalik and Tertiary Himalayan sandstones to identify damage mechanisms induced by fatigue in the rock and propose a strain based fatigue damage model. A systematic laboratory investigation was planned to study (i) nature and index properties of the rock (ii) influence of major cyclic parameters like peak stress, amplitude, frequency and number of cycles under uniaxial and triaxial conditions (iii) mechanisms of fatigue damage evolution (iv) cyclic hardening behaviour (v) static and cyclic properties relationship (vi) microstructural analysis (vii) deformation analysis for proposal of a new fatigue damage model and (viii) numerical analysis simulating a prototype situation. The rock selected comprises of three sandstones collected from Katra, Disang and Barail formations of Himalaya which are isotropic in nature and having contrasting strength values.

To understand the nature of rock, petrographic analysis, scanning electron microscopy and X-ray diffraction studies were carried out. The physical and strength properties were tested in the laboratory on the core samples following ISRM and Indian Standards (IS) test procedures. The results show that Barail sandstone consisting predominantly of quartz with strong intergranular bonding has the highest compressive strength and modulus of elasticity while Katra sandstone consisting predominantly of loosely binded quartz in argillaceous cement has the lowest strength and modulus of elasticity.

Following the strength characterization of the three sandstones, two types of cyclic loading experiments – Cyclic damage test and Cyclic hardening test were carried out at amplitude controlled, stress controlled, frequency controlled and cycle controlled mode under both uniaxial and triaxial conditions to determine strength and deformation behaviour of the selected rocks. The result of cyclic damage test shows that while increase in frequency enhances the fatigue strength of the rock, peak stress and amplitude drastically reduces the fatigue strength. Increase in cycle leads to progressive degradation of rock strength. A good correlation was found to exist between fatigue life and amplitude, peak stress and frequency.

Cyclic mechanical properties which are the direct manifestation of the progressive damage behaviour induced in the rock in microscale, were derived from the resultant stress-strain curve through MATLAB programming to analyse and interpret mechanism of damage evolution under cyclic loading. Degradation of elastic behaviour is represented by inverted Z-shaped non-linear curves illustrating the three stage fatigue damage behavior-primary or transient phase, secondary or steady state phase and tertiary or accelerating phase while increase in plastic deformation is represented by inverted S-shaped non-linear curves. Damage behaviour of the rock has shown a sharp drop in their elastic parameters at failure with increase in amplitude and peak stress and increase in deformation parameters like irreversible axial/ diametral strain and Poisson's ratio. Influence of frequency has shown a contrasting behaviour enhancing the strength of the rock at higher values.

Cyclic hardening tests were carried out which involves deciphering the static strength of the fatigued rock subjected to predetermined number of cycles of loading and unloading under triaxial compression for actual assessment of in-built damages induced in the same rock due to cyclic loading. The result shows that below a threshold value of amplitude and number of cycles, static strength increases upto 36% and 49% with amplitude and upto 24.5 % and 29% with number of cycles for Barail and Disang sandstones respectively.

Deep seated tunnels located in mountainous terrain during excavation are both under the influence of static stress as well as stress generated by cyclic loading. Thus relationship between static and cyclic mechanical properties has been derived from the experiments under frequency, amplitude and stress controlled mode to relate the damaging influence of static and cyclic compression . The result shows that static and cyclic Young's modulus can be related with normalized amplitude and frequency by power law and they show a linear relationship with normalized stress whereas static and cyclic Poisson's ratio can be related with normalized amplitude and frequency by an exponential relationship under cyclic damage tests.

Based on the experimental results, two predictive strain based constitutive models and one model describing the elastic modulus degradation with increasing number of cycles, has been proposed through non-linear regression analysis modifying generalized Voigt-Kelvin and Lomnitz model which were proposed to predict behavior of rock under constant loading conditions known as Creep. The proposed models are applicable to all the three stages of deformation behaviour during cyclic loading:

Deformation Model I: $$\varepsilon_{irr} = \frac{\sigma_{\max}}{E_1} + \frac{\sigma_{\max}}{E_2}\left(1 - \exp^{-\frac{E_2}{\eta}N}\right)$$

Deformation Model II: $$\varepsilon_{irr} = A + B\log(n) + C(n)^2 + D(n)^3$$

Modulus Degradation Model: $E_t = aN^b + c^2$

Deformation model-I explains the deformation evolution of rock in the primary and secondary stages under cyclic hardening tests while Deformation model-II explains deformation evolution in all the three stages-primary, secondary and tertiary leading to failure of the rock under cyclic damage tests. The proposed models were validated with cyclic experimental results carried out by different researchers under similar conditions and compared with the constitutive creep based deformation models available in the literature.

A deformation analysis through finite element model ABAQUS/CAE was carried out to simulate ground borne vibration due to noise generated by high speed moving train or heavy traffic in a rail or road tunnel. The model analysis shows that deformation increases with amplitude irrespective of nature of bedrock.

Present research may act as future impetus for deriving a suitable fatigue damage mechanism applicable to both isotropic and anisotropic Himalayan rocks subjected to varied range of stress and deformation regime owing to its unique geological setting.

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LIST OF SYMBOLS

Static Nomenclature

ρ_{dry}	Dry density
ρ_{sat}	Saturated density
n	Porosity
MR	Modulus ratio
P_d	Packing density
P_p	Packing proximity
σ_c	Uniaxial compressive strength (UCS)
V_p	P-wave velocity
V_b	Bulk volume
V_m	Volume of the matrix
E_d	Dynamic elastic modulus
G	Shear modulus
V_L	Longitudinal infinite medium velocity
V_S	Shear wave velocity
σ_t	Brazilian tensile strength
I_s	Point load strength index
Δt	Interval transit time
c	Cohesion
Φ	Internal angle of friction
E	Static Young's modulus
ν	Poisson's ratio
γ_d	Density
e	Void ratio
ε_a	Static axial strain
ε_d	Static diametral strain
ε_v	Static volumetric strain
σ_H	Horizontal in situ stress
σ_V	Vertical in situ stress
P_z	Principal insitu stress parallel to the longitudinal axis of the opening
σ_θ	Tangential stress
σ_r	Radial stress
η	Viscocity
σ_1	Major principal stress under quasi-static loading
AE	Acoustic emission
σ_f	Failure stress

σ_i	Stress at initiation of microcrack
σ_{cc}	Stress at crack closure
σ_d	Stress at dilatancy
σ_3	Minor principal stress
$\dot{\varepsilon}$	Strain rate
T	Temperature
Q	Activation energy
σ_n	Normal stress
τ	Shear stress
E_{avs}	Average static Young's modulus

Cyclic Nomenclature

σ_{max}	Maximum stress at a fraction of static strength
σ_{mon}	Monotonic/static strength
σ_{stat}	Static strength of fatigued rock
N	Number of cycles
P.L.	Peak load
K	Stress intensity
R_s	Stress ratio
a	Crack length
σ_a	Load/Stress amplitude
f	Frequency
$\varepsilon_{v,re}$	Residual volumetric strain
ε_a	Cyclic strain
E_s	Secant modulus
E_u	Unloading modulus
E_t	Young's modulus
U	Hysteresis energy
$\varepsilon_{a,irr}$	Irreversible axial strain
$\varepsilon_{d,irr}$	Irreversible diametral strain
ν	Poisson's ratio
A_s	Axial stiffness
C	Damping coefficient
λ	Damping ratio
σ_p	Peak stress
σ_{min}	Valley stress
$\Delta\sigma$	Differential stress
$\Delta\varepsilon$	Differential strain
τ_{stat}	Static triaxial compressive strength

A_R	Area of hysteresis loop
A_S	Area of the triangle
X	Response amplitude
Ω	Circular frequency of loading-unloading
W_e	Stress energy
ε_l	Lateral strain
σ_{cd}	Cyclic uniaxial compressive strength
E_{avd}	Average cyclic Young's modulus
σ_m	Mean load
τ_{oct}	Octahedral shear stress
γ_c	Shear strain
Amp.	Amplitude
S_u	Cyclic stress (% of UCS) under uniaxial compression
S_t	Cyclic stress (% of UCS) under triaxial compression
L	Fatigue life
D	Cyclic dilatancy
ε_{vd}	Cyclic volumetric strain at failure
ε_{vs}	Static volumetric strain at failure
σ_{cyc}	Fatigue strength
D_{amp}	Amplitude controlled damage
D_{cyc}	Cycle controlled damage
R_{amp}	Amplitude controlled hardening
R_{cyc}	Cycle controlled hardening
ε_c	Creep strain
β	Velocity level measured in decibel
I	Intensity of sound