ANALYSIS OF UNDERGROUND STRUCTURES UNDER SQUEEZING ROCK CONDITIONS

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ANALYSIS OF UNDERGROUND STRUCTURES UNDER SQUEEZING ROCK CONDITIONS

by

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I dedicate this thesis to my parents, ***Om Prakash Jain and Sharda Jain*** *and my wife* ***Dr. Iti Gupta*** *for their rationale inspiration and unconditional and absolute support. This thesis is also devoted to my guide,* ***Prof. K. S. Rao*** *who encouraged me to build and maintain my motivation towards this research.*

Certificate

This is to certify that the thesis entitled, "**Analysis of Underground Structures under Squeezing Rock Conditions**" submitted by Mr. Ashwani Jain to the Department of Civil Engineering, 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. Ashwani Jain has worked under my supervision for the submission of this thesis, which to my knowledge has reached the requisite standard.

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

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ABSTRACT

The Himalaya has undergone various tectonic activities which resulted in variant geology in the region. Complex geology and weak geological structures along with ingress of water give rise to a high degree of fragility and instability in the whole mountain system. Moreover, the high mountainous topography causes high overburden pressure in the underground structures causing squeezing and other stability problems.

During excavation of underground structures, in such areas when overburden stress exceeds the rock mass strength it will lead to tunnel instability, which causes squeezing phenomenon along with development of plastic zone around the tunnel leading to excessive tunnel deformation which can cause man and equipment safety hazard and tremendous financial loss during construction. Thus the massive tunneling can only be materialized using professional and scientific approaches.

The main objectives of this thesis are to review and check the validity of available approaches through squeezing prediction assessment, tunnel stability and support pressure estimation. Relevant laboratory tests were carried out to determine rock mass parameters. In addition, numerical modelling was done to compare the interpreted results and thereafter new correlations were developed for squeezing prediction using comparative and parametric study.

In this thesis Rohtang tunnel, located in Kullu district, India, has been taken as the case study. Several tunnel sections while passing through phyllitic quartzite, quartzitic phyllite, migmatitic gneiss and biotite mica schist type rocks encountered squeezing condition. The rock mass quality in these squeezed sections is extremely poor to exceptionally poor.

A comprehensive study has been undertaken for determining physico-mechanical behavior of these rocks through laboratory tests and its impact during

tunnel excavation. Along with this the squeezing assessment has been done using empirical, semi-analytical, analytical and numerical approaches.

It was observed that the mechanical properties of metamorphic rocks change with change in petrographic characteristics and physical properties. The petrographic and petrofabric analysis was done through scanning electron microscope (SEM), X-ray powder diffraction (XRD) and thin sections, whereas the other physical and geotechnical properties are determined through laboratory testing. Various relations have been developed between porosity, density and mineral compositions of rocks with the help of SEM, XRD and physical properties. Strength and deformation behaviour of the rocks were also defined and compared with various physical properties. The failure pattern under uniaxial compressive strength, Brazilian tensile strength and triaxial strength tests were discussed.

Numerous studies have been done to study the various aspects of squeezing and tunnel stability. In this thesis, four main approaches empirical (Jethwa, 1984; Singh et al., 1992 and Goel, 1994), semi-analytical (Kovari, 1998 and Hoek and Marinos, 2000), analytical (Duncan-Fama, 1993 and Carranza-Torres and Fairhurst, 2000) and numerical program Phase^2 have been used for evaluation of squeezing phenomenon. In addition, analysis is carried out through convergence confinement method with Hoek-Brown criteria. Numerical modeling is of utmost importance to understand rock behavior and deformation mechanisms leading to failure in varying conditions of stability.

Above approaches were compared and possible reasons for variation in results by different approaches have been documented in this study and an attempt has been made to develop new correlations for squeezing predictions through comparative and parametric study and compared with the existing correlation.

In comparative study 172 tunnel sections from case histories and 64 tunnel sections of Rohtang tunnel with squeezing and non-squeezing condition have been collected from numerous published case histories and compared to develop new linear classifications for overburden height up to 1900m using parameters rock mass quality index (Q), rock mass number (N) and overburden height (H) for squeezing prediction. These linear classification equations obtained for Q and N are

$$\text{For squeezing } H > 390Q^{0.29}$$

$$\text{For squeezing } H > 253N^{0.32}$$

The parametric study was carried out using 122 tunnel sections (including 65 tunnel sections of Rohtang tunnel) published in literatures and new correlations were developed using parameters Q, N, ratio of horizontal stress (σ_h) to vertical stress (σ_v) i.e. K_0, support stiffness (K), vertical stress (σ_v), joint factor (J_f), tunnel radius (a). The correlation equations are

$$\frac{U_p}{a} = \frac{1x10^{-12}\sigma_v J_f^{4.01} K_0^{1.5}}{K + 2.2} + 0.005$$

$$\frac{U_p}{a} = \frac{0.011\sigma_v Q^{-0.3} K_0^{1.25}}{K + 4} + 0.005$$

$$\frac{U_p}{a} = \frac{0.023\sigma_v N^{-0.3} K_0^{1.2}}{K + 5.2} + 0.005$$

These equations can be used for prediction of squeezing in tunnels excavated through drill and blast method in Himalayan region.

सारांश

हिमालय विभिन्न विवर्तनिक गतिविधियों से गुज़रा है, जिसके परिणामस्वरूप इस क्षेत्र में भिन्न भूविज्ञान पाया जाता है। पानी के प्रवेश के साथ जटिल भूविज्ञान और कमजोर भूगर्भीय संरचनाएं पूरे पर्वतीय प्रणाली में उच्च स्तर की नाजुकता और अस्थिरता को जन्म देती हैं। इसके अलावा, उच्च पर्वतीय स्थलाकृति भूमिगत संरचनाओं में उच्च अधिभार दबाव का कारण बनता है जिससे सुरंग में निचोड़ और अन्य सुरंग की स्थिरता की समस्याएं होती हैं।

इस प्रकार के क्षेत्र में भूमिगत संरचनाओं की खुदाई के दौरान जब ओवरबर्डन तनाव रॉक मास की ताकत से अधिक हो जाता है तो यह सुरंग अस्थिरता को जन्म देता है। यह अस्थिरता सुरंग क्षेत्र के चारों ओर प्लास्टिक जोन के विकास के साथ-साथ अत्यधिक सुरंग विरूपण के कारण निचोड़ने वाली घटना का कारण बनती है जिससे निर्माण के दौरान मनुष्य और उपकरण की सुरक्षा और जबरदस्त वित्तीय नुकसान का खतरा पैदा होते हैं। अतः इस प्रकार बड़े पैमाने पर सुरंगन को केवल पेशेवर और वैज्ञानिक दृष्टिकोण का उपयोग करके ही किया जा सकता है।

इस शोध का मुख्य उद्देश्य निचोड़ भविष्यवाणी आकलन, सुरंग स्थिरता और समर्थन अनुमान आकलन के माध्यम से उपलब्ध दृष्टिकोण की वैधता की समीक्षा और जांच करना है। रॉक मास मापदंडों को निर्धारित करने के लिए प्रासंगिक प्रयोगशाला परीक्षण किया गया। इसके अलावा संख्यात्मक परिणामों की व्याख्या परिणामों की तुलना करने के लिए की गई थी और उसके बाद तुलनात्मक और पैरामीट्रिक अध्ययन का उपयोग कर निचोड़ने की भविष्यवाणी करने के लिए नए सहसंबंध विकसित किए गए ।

इस शोध में, भारत के कुल्लू जिले में स्थित रोहतांग सुरंग को अध्ययन के रूप में लिया गया है। सुरंग संरेखण के दौरा फ़ीलिटिक क्वार्टजाइट, क्वार्टजिटिक फ़ीइलाइट, माइग्मिटिटिक शैल और बायोटाइट माइका शीस्ट प्रकार की चट्टानों में भारी निचोड़ की समस्या का सामना करना पड़ा । निचोड़ वाले खंडों में चट्टानों की रॉक मास गुणवत्ता असाधारण रूप से खराब है।

रोहतांग सुरंग की खुदाई के दौरान प्राप्त रूपांतरित चट्टानों पर प्रयोगशाला परीक्षण के माध्यम से रॉक मास के भौतिक-यांत्रिक व्यवहार का निर्धारण करने और सुरंग खुदाई के दौरान इसके प्रभाव को जानने के लिए एक व्यापक अध्ययन किया गया है। इसके साथ ही अनुभवजन्य, अर्ध-विश्लेषणात्मक, विश्लेषणात्मक और संख्यात्मक दृष्टिकोणों का उपयोग करके निचोड़ मूल्यांकन किया गया है।

यह देखा गया कि चट्टानों के यांत्रिक गुण पेट्रोग्राफिक विशेषताओं और रूपांतरित चट्टानों के भौतिक गुणों में परिवर्तन के साथ बदलते हैं। पेट्रोग्राफिक और पेट्रोफैब्रिक विश्लेषण स्कैनिंग इलेक्ट्रॉन माइक्रोस्कोप (एसईएम), एक्स-रे पाउडर विवर्तन (एक्सआरडी) और पतले वर्गों के माध्यम से किया गया था, जबकि अन्य भौतिक और भू-तकनीकी गुणों को प्रयोगशाला परीक्षण के माध्यम से निर्धारित किया गया है। एसईएम, एक्सआरडी और भौतिक गुणों की मदद से चट्टानों के छिद्र, घनत्व और खनिज रचनाओं के बीच विभिन्न संबंध विकसित किए गए हैं। विभिन्न शारीरिक गुणों के साथ चट्टानों की शक्ति और विरूपण व्यवहार को भी परिभाषित किया गया था। अनियंत्रित संपीडन शक्ति, ब्रेज़ीलियन तन्यता शक्ति और त्रिअक्षीय शक्ति परीक्षण के तहत विफलता पैटर्न पर भी चर्चा की गयी है।

निचोड़ और सुरंग स्थिरता के विभिन्न पहलुओं का अध्ययन करने के लिए कई दृष्टिकोण दिए गए हैं। इस शोध में, चार मुख्य दृष्टिकोण अनुभवजन्य (जेठवा, 1984; सिंह एवं अन्य, 1992 और गोयल, 1994), अर्ध-विश्लेषणात्मक (कोवरी, 1998 और होक एंड मैरिनो, 2000), विश्लेषणात्मक (डंकन-फामा, 1993 और कैरंज्जा-टॉरेस एवं फेयरहर्स्ट, 2000) और संख्यात्मक मॉडल फेज 2 का उपयोग निचोड़ की घटना के मूल्यांकन करने के लिए किया गया है। इसके अलावा होएक-ब्राउन मानदंडों के साथ अभिसरण संधि विधि के माध्यम से भी विश्लेषण किया गया है। स्थिरता की बदलती परिस्थितियों में चट्टानों का व्यवहार और विरूपण तंत्र की विफलता को समझने के लिए संख्यात्मक मॉडलिंग अत्यंत महत्वपूर्ण है।

उपरोक्त दृष्टिकोणों की तुलना की गई और इस अध्ययन में विभिन्न दृष्टिकोणों के परिणामों में भिन्नता के संभावित कारणों का दस्तावेजीकरण भी किया गया है। तुलनात्मक और पैरामीट्रिक अध्ययन के माध्यम से चट्टान निचोड़ने की भविष्यवाणियों को करने के लिए नए सहसंबंधों को विकसित करना एवं मौजूदा सहसंबंध के साथ तुलना करने का प्रयास भी इस शोध में किया गया है।

तुलनात्मक अध्ययन में निचोड़ और गैर-निचोड़ वाली स्थिति के साथ 172 सुरंग वर्गों (रोहतांग सुरंग के 64 सुरंग खंडों सहित) के मामले जो की इतिहास में प्रकाशित है को एकत्र किया गया है। 1900 मीटर तक की ओवरबर्डन ऊंचाई के लिए रॉक मास क्वालिटी इंडेक्स(Q), रॉक मास संख्या (N) और ओवरबर्डन ऊंचाई (H) जैसे मापदंडों का उपयोग करते हुए निचोड़ भविष्यवाणी करने के लिए एक नए रैखिक वर्गीकरण को विकसित करने का प्रयाष इस शोध में किया गया है।

चट्टान निचोड़ने के लिए $H > 390Q^{0.29}$

चट्टान निचोड़ने के लिए $H > 253N^{0.32}$

साहित्य में प्रकाशित 122 सुरंग वर्गों (रोहतांग सुरंग के 65 सुरंग खंडों सहित) का उपयोग करते हुए पैरामीट्रिक अध्ययन किया गया है। इस अध्ययन में मापदंडों Q, N, क्षैतिज तनाव (σ_h) एवं ऊर्ध्वाधर तनाव (σ_v) का अनुपात यानी K_0, ऊर्ध्वाधर तनाव (σ_v), संयुक्त कारक (J_f), सुरंग त्रिज्या (a) का उपयोग करके नए सहसंबंध विकसित किए गए। ये विकसित सहसंबंध है

$$\frac{U_p}{a} = \frac{1x10^{-12}\sigma_v J_f^{4.01} K_0^{1.5}}{K + 2.2} + 0.005$$

$$\frac{U_p}{a} = \frac{0.011\sigma_v Q^{-0.3} K_0^{1.25}}{K + 4} + 0.005$$

$$\frac{U_p}{a} = \frac{0.023\sigma_v N^{-0.3} K_0^{1.2}}{K + 5.2} + 0.005$$

इन समीकरणों का उपयोग हिमालयी क्षेत्र में ड्रिल और ब्लास्ट विधि के माध्यम से खोदी गई सुरंगों में निचोड़ने की भविष्यवाणी के लिए किया जा सकता है।

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List of Abbreviations

The following list defines the principle Abbreviations and their definitions as used in the thesis. Abbreviations not listed here are defined as they appear in the text.

IS	Indian Standards
ASTM	American Society for Testing and Materials
ISRM	International Society for Rock Mechanics
CPS	Counts per Second
ICDD	International Centre for Diffraction Data
COD	Crystallography Open Database
XRD	X-Ray Powder diffraction
PDF	Powder Diffraction File
SEM	Scanning Electron Microscopy
SDI	Slake Durability Index
PQ	Phyllitic Quartzite
QP	Quartzitic Phyllite
MG	Migmatitic Gneiss
BMS	Biotite Mica Schist
P	Phyllite
SQ	Sheared Quartzite
L/D	Length/Diameter
UCS	Uniaxial Compressive Strength
RQD	Rock Quality Index
RMR	Rock Mass Rating

SRF	Stress Reduction Factor
GSI	Geological Strength Index
OB	Overburden
UG	Underground
HRT	Head Race Tunnel
F	Fresh
SW	Slightly Weathered
MW	Moderately Weathered
HW	Highly Weathered
CW	Completely Weathered
SI	Squeezing Index
NS	No Squeezing
S	Squeezing
LS	Light Squeezing
FS	Fair Squeezing
VMS	Very Mild Squeezing
MS	Mild/Minor Squeezing
Mod S	Moderate Squeezing
HS	High Squeezing
SS	Severe Squeezing
VHS	Very High Squeezing
VSS	Very Severe Squeezing
CCM	Convergence Confinement Method

LDP	Longitudinal Displacement Profile
GRC	Ground Reaction Curve
SCC	Support Characteristic Curve
HB	Hoek-Brown Criteria
MC	Mohr-Coulomb Criteria
CTF	Carranza-Torres and Fairhurst
ISMB	Indian Standard Medium Weight Beam
ISHB	Indian Standard Heavy Beams
NW-SE	Northwest Southeast
NATM	New Australian Tunneling Method
FEM	Finite Element Method
FDM	Finite Difference Method
BEM	Boundary Element Method
DEM	Distinct Element Method
DDA	Discontinuous Displacement Analysis
SF	Strength Factor
RPZ	Radius of Plastic Zone
MPS	Major Principal Stress
COA	Coefficient of Accordance

List of Notations

The following list defines the principle symbols and their brief definition as used in the thesis. Symbols not listed here are defined as they appear in the text.

θ	Angle in radians
μm	Distance in micrometers
^{0}C	Degree celcius (temperature unit)
α	Wavelength
β	Beta particle emission
Å	Angstrom
mm; cm; m	Length S.I. units as millimeters, centimeters and meters
mA	Milliamperes (current unit)
kV	Kilovolts (voltage unit)
Kg; g	Weight S.I. units as kilograms and grams
hr; min; s	Time S.I unit as hours, minutes and seconds
MPa; KPa	Pressure S.I. unit as megapascals and kilopascals
psi	Pressure imperial unit as pound per second
Υ_{dry}	Dry unit weight
Υ_{sat}	Saturated unit weight
M_D	Dry mass
M_S	Saturated mass
ρ_{dry}	Dry density
ρ_{sat}	Saturated density
η	Porosity

V_v	Volume of voids
σ_t	Ultimate tensile strength
$\sigma_{t(dry)}$	Dry tensile strength
$\sigma_{t(sat)}$	Saturated tensile strength
Ω	Ohms (resistance unit)
ν	Poisson's ratio
E_{T50}	Tangent Young's modulus at 50% ultimate strength
σ_1	Major principal stress
σ_2	Intermediate principal stress
σ_3	Minor principal stress
m	Gradient or slope
b	Intercept on y-axis
τ	Shear stress
σ_n	Normal stress
k	Coefficient of hydraulic conductivity or permeability
Jv	Volumetric joint count
m^3	Volume in cubic meter
A	Area of cross section
Vp	Sound wave velocity
L	Length of the specimen
t	Time taken in seconds (s)
Q	Rock mass quality index
N	Rock mass number

γ	Unit weight of rock mass
J_n	Joint set number/joint frequency i.e. number of joints per meter in the direction of loading
J_r	Joint roughness number
f	Correction factor for tunnel closure
J_f	Joint factor
n	Joint inclination parameter
r	Joint strength parameter
β	90-θ (degree)
θ	Dip angle of joint
PR or S	Joint spacing
H	Overburden height
f	Correction factor for tunnel closure
m_i	A constant that is defined by the frictional characteristics of the component materials in these rock elements
GSI	A constant that relates the properties of the intact rock elements to those of the overall rock mass
a	Radius of tunnel
b	Radius of concentric broken zone
R	External radius of the support (taken to be the same as the radius of the tunnel)
R_p	Radius of the plastic zone
R_{pp}	Radius of perfect plastic region
R_{pb}	Radius of residual plastic region
D	Diameter or span of the tunnel

B	Tunnel width
d_o	Original tunnel diameter
d_p	Plastic zone diameter
x	Distance to the opening face
σ_v	Vertical insitu stress (0.027H)
σ_h	Horizontal insitu stress
K_0	Ratio between horizontal and vertical stress
P_o	In situ stress along the tunnel axis,
P_s	Ultimate support pressure
P_i	Support pressure
p_o	Hydrostatic pressure or in situ stress = depth * unit weight
p_i	Internal support pressure
σ_{ci}	Uniaxial compressive strength of intact rock
σ_{cm}	Uniaxial compressive strength of rock mass
σ_{cc}	Unconfined compressive strength of the shotcrete or concrete
φ	Angle of internal friction or angle of shear resistance
φ_r	Friction angle of intact rock mass
φ_f	Friction angle of failed rock
c	Cohesion
C_p	Peak cohesion of intact rock
C_r	Residual cohesion of failed rock
ψ	Dilation angle
ν_c	Poisson's ratio for the shotcrete or concrete (dimensionless)

ε_{cr}	Critical strain
f	Ratio of radial to axial strain, (ν) for perfect plastic part
d	Radial tunnel deformation in %
U	Radial deformation of tunnel
U_{ao}	Initial radial tunnel closure before support
u_a	Tunnel closure
δ_i	Tunnel sidewall deformation
U_p	Predicted tunnel deformation
U_{est}	Estimated tunnel deformation
U_{obs}	Observed tunnel deformation
K	Support stiffness
K_s	Stiffness of steel ribs
K_b	Stiffness of backfill
E	Modulus of elasticity
E_s	Modulus of elasticity of steel
E_b	Modulus of elasticity of backfill
E_c	Young's modulus for the shotcrete or concrete
E_s	Young's modulus for the steel
E_B	Young's modulus for the block material
E_s	Young's modulus for the bolt or cable
A_s	Cross sectional area of steel
σ_{ys}	Yield strength of the steel
S	Spacing between ribs or steel sets

t_c	Thickness of the ring
t_b	Thickness of backfill
t_B	Thickness of the block
As	Cross sectional area of the section
Is	Moment of inertia of the section
d	Overbreak thickness filled with shotcrete
d_b	Bolt or cable diameter
l	Free length of the bolt or cable
T_{bf}	Ultimate load obtained from a pull-out test
s_c	Circumferential bolt spacing
s_l	Longitudinal bolt spacing