EXPERIMENTAL CHARACTERIZATION OF ROCK SALT FOR UNDERGROUND STRUCTURES

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by

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in fulfillment of the requirements of the degree of Doctor of Philosophy

to the

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Dedicated to my Parents

and

To my loving wife Pratibha Gupta &

my adorable kids Charvi and Aarav

CERTIFICATE

This is to certify that the thesis entitled **"EXPERIMENTAL CHARACTERIZATION OF ROCK SALT FOR UNDERGROUND STRUCTURES"** submitted by **Mr. Chandan Kumar** to the Indian Institute of Technology Delhi is a record of the bonafide research work carried out by him under my supervision and guidance. This thesis work, in my opinion, has reached the standard, fulfilling the requirements for **Doctor of Philosophy** degree.

The research report and the results presented in this thesis have not been submitted, in part or full, to any other university or institute, for the award of any degree or diploma.

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At the end, I feel sorry that I don't have enough wisdom to comprehend many aspects of this research subject. Many questions were answered, and many remained unanswered. I wish I could have given more time and understanding to them. My guide puts a very high level of expectation from each researcher, and rightly so, as it has yielded many outstanding pieces of research which have been highly appreciated and recognized by the technical fraternity across the world. I feel sorry if I have not reached to that level. I feel sorry to my wife and kids as they keep waiting for me for long to return for IIT and spend quality time with them. I feel sorry for my mistakes if found in my technical understating to this vast salt cavern technology.

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Chandan Kumar

ABSTRACT

Over 600 Million Years ago, a thick-bedded formation resulted from the halogenic deposits on the South Western Asiatic Plates, produced a beautiful translucent red earthy material called "ROCK SALT" which is geologically stable, free from flowing water and practically impermeable. These deep-seated natural rock salt formations spread over the surface area of more than 50,000 Sq. Km which covers much of northwestern Rajasthan, India, offers an ideal medium to safeguard our country's continuous energy demand by storage of hydrocarbon in underground salt caverns as well as protect our future and environment by providing a safe place to permanently dispose the nuclear wastes that would remain radioactive for thousands of years.

In this context, the present study is an attempt to characterize the thermo-mechanical behaviour of rock salt of this region through a set of laboratory testing and observe their geomechanical response in the deep underground caverns.

The research thesis is broadly divided into two parts. The first part discusses the detailed experimental investigation program, the results of which are covered in Chapters 3, 4, 5, and 6. The second part of the thesis discusses the detailed design and geo-mechanical analyses of salt caverns based on the results of experimental investigation taken as a basic input in Chapters 7 and 8.

The experimental investigation includes the collection of samples, specimen preparation, and determination of physical, mechanical, rheological, and thermal properties. The stress-strain behaviour and mechanical properties of rock salt were investigated through uniaxial and triaxial compression at varying strain rates and confining pressures. The results show that the rock salt is found to have higher critical stress expressed in terms of the felicity ratio (FR) of around 0.9 during the entire unloading and reloading excursion cycle up to

failure. With this critical stress, the stress-strain response of rock salt up to failure, including the zone of cyclic unloading and reloading can be expressed by a proposed constitutive model. The governing equation for strain in uniaxial compression test is given as:

$$\varepsilon(t_n) = \left(\frac{\sigma_0(t_n)}{E}\right) + \sum \frac{\sigma_0(t_{n-1})}{\eta}(t_n - t_{n-1}) + \left(\frac{\sigma_0(t_n)+\sigma_0(t_{n-1})}{2\eta}\right)(t_n - t_{n-1})\ if\ [\frac{d\sigma_o}{dt} \geq 0\ ;\ \sigma_0 \geq \sigma_{cri}]\ \text{and}$$

$$\varepsilon(t_n) = \varepsilon(t_{n-1}) + \frac{\sigma_0(t_n)-\sigma_0(t_{n-1})}{E}\quad if\ [\frac{d\sigma_0}{dt} < 0\ ;\ \sigma_0 < \sigma_{cri}\ and\ \frac{d\sigma_o}{dt} > 0\ ;\ \sigma_0 < \sigma_{cri}]$$

The creep parameters of rock salt are estimated from the UCS testing in terms of viscosity η and strain rate $\dot{\varepsilon}$ through a nonlinear regression analysis and are expressed as:

$$\eta = 37\ /\dot{\varepsilon}^{0.96}$$

Viscosity obtained from the proposed relationship based on UCS testing is found to be in good agreement with the measured values from the creep test.

The time-dependent viscoelastic behaviour of rock salt was captured by performing single and multi-step constant load creep test in uniaxial condition with a newly designed and manufactured cantilever type creep testing machine. The result shows that the steady-state creep rate increases with an increase in deviatoric stress and are approximated by a power function by the following expression:

$$\dot{\varepsilon}^{cr} = A\ x\ \sigma^n$$

where, a pre-factor *A* and stress component, *n* is estimated as 7 x 10^{-7} MPa^{-n} d^{-1} and 1.41 from the nonlinear regression analysis. The creep behaviour of rock salt as described by the proposed constitutive model approximated by power function can satisfactorily describe the creep strain measured over the operational period of a salt cavity.

Uniaxial compression strength (UCS) tests carried out at various temperatures between 25 and 250°C with a new temperature-controlled testing device has revealed a distinct variation of the influence of temperature on the mechanical characteristics of rock salt. An overall decrease of around 20% in strength for the entire range of testing temperature is observed. The decrease, however, is more pronounced at temperatures greater than 100°C. The stiffness (Young's modulus) of salt decrease at a rate of around 0.025 GPa/K as temperature increases.

A set of geo-mechanical analyses of salt caverns created through solution mining were performed using ABAQUS FEA (Finite element analysis) software to assess the quantitative effects of different design parameters that would be expected in an oil storage cavern sited within rock salt formation. The parametric study examined the overall performance of salt caverns by evaluating the displacement field, stress field, creep displacement, volume shrinkage, ground subsidence, and damage zone surrounding the cavern. Two commonly used cavern shapes such as cylindrical and spherical of varying dimensions are considered for this research pursuit. Plots for estimating displacement and stress during the construction period of a salt cavern of varying shape and size are proposed.

The research pursuit also attempts two case studies. The first case study discusses the solution-mined salt caverns as a storage alternative for the strategic petroleum reserve (SPRs) program of India and the second case study entails the feasibility of long-term nuclear waste disposal repositories. The case study considered the geological setting of the proposed site location, loading, and geomaterial condition. The results show that the vast expanse of the bedded salt formation near Bikaner, Rajasthan, offers the possibility of creating a large inventory of crude oil and nuclear waste repository in underground storage caverns. A moderate displacement and stress state field with some minor damage and a maximum volumetric loss of around 10.08% after an operational run of 25 years is expected in a salt cavern made for oil storage. Nuclear repository room with waste placed inside observed complete closure in 50-60 years. Disturbed rock zone (DRZ) is limited to the extent of around 2m near the waste disposal and as the stress drives towards equilibrium, the waste is expected to be entombed in the rock salt forever.

सार

600 मिलियन साल पहले, दक्षिण-पश्चिमी एशियाई प्लेटों पर हैलोजेनिक निक्षेप के परिणामस्वरूप एक मोटी-परत का गठन हुआ, जिससे " सेंधा नमक" ("रॉक नमक") नामक एक सुंदर पारभासी लाल लवण चट्टान का उत्पादन हुआ, जो कि भूगर्भीय रूप से स्थिर है, जो बहते पानी से मुक्त है और व्यावहारिक रूप से अभेद्य है। ये गहरे बैठे प्राकृतिक सेंधा नमक संरचनाएं 50,000 वर्गमीटर से अधिक के सतह क्षेत्र में फैली हुई हैं जो उत्तर-पश्चिमी राजस्थान, भारत के हिस्से में आता है। भूमिगत सेंधा नमक, हाइड्रोकार्बन के भंडारण द्वारा हमारे देश की निरंतर ऊर्जा मांग को सुरक्षित रखने का एक आदर्श माध्यम प्रदान करता है और साथ ही परमाणु अपशिष्ट जो हजारों साल के लिए रेडियोधर्मी बने रहते हैं को स्थायी रूप से निपटाने के लिए एक सुरक्षित स्थान प्रदान करके हमारे भविष्य और पर्यावरण की रक्षा करता है।

इस संदर्भ में, वर्तमान अध्ययन, प्रयोगशाला परीक्षण के माध्यम से इस क्षेत्र के सेंधा नमक के ताप-यांत्रिक व्यवहार को चिह्नित करने का प्रयास है और गहरी भूमिगत कंदरो में उनके भूयांत्रिक प्रतिक्रिया का निरीक्षण करता है।

शोध को मोटे तौर पर दो भागों में विभाजित किया गया है। पहला भाग विस्तृत प्रयोगात्मक कार्यक्रम पर चर्चा करता है, जिसके परिणाम अध्याय 3, 4, 5 और 6 में शामिल किए गए हैं। शोध के दूसरे भाग में नमक कंदरो के विस्तृत डिजाइन और भू-यांत्रिक विश्लेषणों की चर्चा अध्याय 7 और 8 में की गई है, जो प्रायोगिक जाँच परिणामों के आधार पर किए गए हैं।

प्रयोगात्मक जांच में नमूनों का संग्रह, नमूना तैयार करना, और उसके भौतिक, यांत्रिक, श्यानता और ताप गुणों का निर्धारण शामिल है। प्रतिबल-विकृति व्यवहार और सेंधा नमक के यांत्रिक गुणों की जांच अलग-अलग विकृति दरों और सीमित दबावों में एकाक्षीय संपीड़न परीक्षण (यूसीएस) और त्रिअक्षीय संपीड़न के माध्यम से की गई थी। परिणामों से पता चलता है कि पूरे अनलोडिंग और पुन: लोडिंग भ्रमण चक्र के दौरान रॉक नमक में उच्च क्रिटिकल प्रतिबल लगभग 0.9, जिसे फेलिसिटी अनुपात (एफआर) के संदर्भ में व्यक्त किए गए है, पाया जाता है। इस क्रिटिकल प्रतिबल

के साथ, चक्रीय अनलोडिंग और फिर से लोडिंग के क्षेत्र सहित रॉक नमक की विफलता के प्रतिबल-विकृति व्यवहार की प्रतिक्रिया एक प्रस्तावित संवैधानिक मॉडल द्वारा व्यक्त की जा सकती है। यूसीएस परीक्षण में विकृति के लिए अधिनियंत्रक समीकरण निम्नानुसार है:

$\varepsilon(t_n) = \left(\frac{\sigma_0(t_n)}{E}\right) + \sum \frac{\sigma_0(t_{n-1})}{\eta}(t_n - t_{n-1}) + \left(\frac{\sigma_0(t_n)+\sigma_0(t_{n-1})}{2\eta}\right)(t_n - t_{n-1})\ if\ [\frac{d\sigma_o}{dt} \geq 0\ ;\ \sigma_0 \geq \sigma_{cri}]$ और

$\varepsilon(t_n) = \varepsilon(t_{n-1}) + \frac{\sigma_0(t_n)-\sigma_0(t_{n-1})}{E}\ \ if\ [\frac{d\sigma_0}{dt} < 0\ ;\ \sigma_0 < \sigma_{cri}\ and\ \frac{d\sigma_0}{dt} > 0\ ;\ \sigma_0 < \sigma_{cri}]$

यूसीएस परीक्षण से अनुमानित किया रॉक नमक के विसर्पण के मापदंडों को श्यानता (η) और विकृति की दर ($\dot{\varepsilon}$) के रूप में एक अरैखिक प्रतिगमन विश्लेषण के माध्यम से निम्न रूप में व्यक्त किए गए है:

$\eta\ =\ 37\ /\dot{\varepsilon}^{0.96}$

यूसीएस परीक्षण के आधार पर प्रस्तावित संबंधों से प्राप्त श्यानता, विसर्पण परीक्षण से माप मूल्यों के साथ अच्छे समझौते में पाए गए है।

रॉक नमक के समय-निर्भर श्यान-मापांक व्यवहार को एक नए डिजाइन और निर्मित कैंटिलीवर प्रकार विसर्पण परीक्षण मशीन के साथ एकल और बहु-चरणीय निरंतर भार एकाक्षीय संपीड़न में प्रग्रहण किया गया है। परिणाम से पता चलता है कि स्थायी अवस्था विसर्पण दर, विवातक प्रतिबल में वृद्धि के साथ बढ़ता है और एक शक्ति फलन द्वारा निम्नलिखित अभिव्यक्ति से अनुमानित किया जाता है:

$\dot{\varepsilon}^{cr} = A\ x\ \sigma^n$

जहां, एक पूर्व-कारक "A" और संपीड़न घटक, "n" को अरैखिक प्रतिगमन विश्लेषण से $7\ x\ 10^{-7}$ $MPa^{-n}\ d^{-1}$ और 1.41 के रूप में अनुमानित किया गया है।

शक्ति फलन से प्रस्तावित संरचक मॉडल द्वारा वर्णित रॉक नमक का श्यानता व्यवहार संतोषजनक रूप से एक नमक कंदरा के परिचालन अवधि में मापा विसर्पण का वर्णन कर सकता है।

25 से 250 डिग्री सेल्सियस के बीच विभिन्न तापमानों पर किए गए एक नए तापमान-नियंत्रित परीक्षण उपकरण के साथ एकाक्षीय संपीड़न परीक्षण (यूसीएस) परीक्षणों में सेंधा नमक की यांत्रिक

विशेषताओं पर तापमान के प्रभाव की एक भिन्नता का पता चला है। परीक्षण तापमान की पूरी श्रृंखला के लिए लगभग 20% की ताकत में समग्र कमी देखी गई है। हालांकि, कमी 100 ° C से अधिक तापमान पर अधिक स्पष्ट है। तापमान बढ़ने पर नमक की कठोरता (यंग मापांक) लगभग 0.025 GPa / K की दर से घट जाती है।

विलयन खनन के माध्यम से बनाई गई नमक कंदरो के भू-यांत्रिक विश्लेषण का एक सेट विभिन्न नमक मापदंडों के मात्रात्मक प्रभावों का आकलन करने के लिए अबाक्यूस एफईए (परिमित तत्व विश्लेषण) सॉफ्टवेयर का उपयोग करके प्रदर्शन किया गया है। प्राचलिक अध्ययन ने विस्थापन क्षेत्र, तनाव क्षेत्र, विसर्पण विस्थापन, आयतन संकोचन, भू-अवमंदन और गुफा के आसपास के क्षति क्षेत्र का मूल्यांकन करके नमक कंदरो के समग्र प्रदर्शन की जांच की। आमतौर पर इस्तेमाल की जाने वाली दो कंदरो की आकृतियाँ जैसे कि अलग-अलग आयामों की बेलनाकार और गोलाकार होती हैं, इस शोध के लिए मानी गयी हैं। अलग-अलग आकार के नमक कंदरो के निर्माण की अवधि के दौरान विस्थापन और संपीड़न का आकलन करने के लिए विभिन्न चार्ट प्रस्तावित हैं।

अनुसंधान खोज दो मामले (केस स्टडी) के अध्ययन का प्रयास भी करता है। पहला केस अध्ययन भारत के रणनीतिक पेट्रोलियम रिजर्व (SPRs) कार्यक्रम के लिए भंडारण विकल्प के रूप में विलयन खनन नमक कंदरो पर चर्चा करता है और दूसरा केस अध्ययन लंबी अवधि के परमाणु अपशिष्ट निपटान रिपॉजिटरी की व्यवहार्यता को दर्शाता है। केस स्टडी ने प्रस्तावित स्थान की भूवैज्ञानिक विन्यास, भारण और भूभौतिकीय दशा पर विचार किया। परिणामों से पता चलता है कि राजस्थान के बीकानेर के पास सेंधा नमक के निर्माण का विशाल विस्तार, भूमिगत भंडारण कंदरो में कच्चे तेल और परमाणु अपशिष्ट भंडार की बनाने की संभावना प्रदान करता है। तेल के भंडारण के लिए बनाए गए नमक के कंदरो में 25 साल के परिचालन के बाद कुछ मामूली क्षति और लगभग 10.08% की अधिकतम मात्रा में आयतन संकोचन नुकसान के साथ एक मध्यम विस्थापन और संपीड़न की संभावना है। अंदर रखे परमाणु अपशिष्ट के साथ परमाणु भंडार कक्ष 50-60 वर्षों में पूरी तरह से बंद हो जाएगा। विक्षत शैल क्षेत्र (DRZ) अपशिष्ट भंडार कक्ष के पास लगभग 2 मीटर की सीमा तक सीमित है और जैसे ही संपीड़न संतुलन की ओर बढ़ता है, अपशिष्ट को हमेशा के लिए सेंधा नमक में सुरक्षित बंद हो जाने की उम्मीद है।

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σ_1	Major Principal Stress
σ_2	Intermediate Principal Stress
σ_3	Minor Principal Stress
σ_c	Unconfined Compressive Strength
σ_r	Radial Stress
σ_θ	Tangential Stress
c	Intercept of Cohesion
$\emptyset$	Friction Angle
υ	Poisson's Ratio
E	Elastic Modulus
u	Radial Deformation
u_e	Radial Deformation at Elastic-Plastic Interface
u_c	Radial Deformation at Circular Opening
ϵ_{ze}	Elastic Strain in z-Direction
ϵ_{re}	Elastic Strain in Radial Direction
$\epsilon_{\theta e}$	Elastic Strain in Tangential Direction
ϵ_{zp}	Plastic Strain in z-Direction
ϵ_{rp}	Plastic Strain in Radial Direction
$\epsilon_{\theta p}$	Plastic Strain in Tangential Direction
$a,$	Mogi-Coulomb Strength Parameter in Plastic Zone/ Residual
a_e	Mogi-Coulomb Strength Parameter in Elastic Zone/ Peak
P_o	In-situ Pressure
q	Out-of Plane In-situ Stress
t	Time

η	Maxwell Viscosity
P_i	Internal Pressure in Tunnel Opening
Ψ	Dilation Angle
B_{d}	Dilation Parameter
τ_{oct}	Octahedral Shear Stress
$\sigma_{m,2}$	Mean Normal Stress
UCS	Uniaxial Compression Strength
FEA	Finite Element Analysis