PETRO-PHYSICO AND MECHANICAL BEHAVIOR OF RESERVOIR ROCKS UNDER STATIC AND DYNAMIC CONDITIONS

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SEPTEMBER 2019

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by

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Submitted

In fulfillment of the requirement of the degree of Doctor of Philosophy

to the

INDIAN INSTITUTE OF TECHNOLOGY DELHI

SEPTEMBER 2019

Dedicated to my parents, husband, sister and brothers for their support and belief

This humble work is a sign of my love to you

To the memory of my brother, Masoud, who always believed in my ability to be successful in the academic arena. You are gone but your belief in me has made this journey possible.

CERTIFICATE

This is to certify that the thesis entitled"**Petro-Physico and Mechanical Behavior of Reservoir Rocks under Static and Dynamic Conditions**", being submitted by **Mahin Esmaeil Zaei** to the Indian Institute of Technology Delhi, for the award of **Doctor of Philosophy** is a record of the bonafide research work carried out by her under my supervision of this thesis, which to the best of my knowledge has reached the requisite standard. The material contained in this thesis has not been submitted in part or fully to any other university or institute for the award of any degree or diploma.

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ACKNOWLEDGMENTS

First and foremost I offer my sincerest gratitude to my supervisor, Prof. K.S.Rao, who has supported me throughout my thesis with his patience and knowledge whilst allowing me the room to work in my own way. I attribute the level of my Ph.D. degree to his encouragement and effort and without him this thesis, too, would not have been completed or written. One simply could not wish for a better or friendlier supervisor.

I am grateful to many colleagues in the GRG group of Rock Mechanics laboratory for their help and support, Mr. Alok Kumar who assisted me in the lab work. My sincere thanks to Ankesh, Swapnil, Rebecca, Aditya, Tarun, Falaq, Nirbhay and my other colleagues in GRG group for making the facilities available during the research work and friendly support. I would also like to acknowledge Prof, R. Ayothiraman for his assistance. During the course of my work, I had the pleasure of working with several people from Coal India Ltd, ONGC, DGH and Schamberger company. Their assistance during the present work is gratefully acknowledged. The Department of Civil Engineering has provided the support and equipment I needed to produce and complete my thesis.

Finally, I thank my parents, husband, brothers and sister for supporting me throughout all my studies at the institute to complete my Ph.D.

Date:27/09/2019 Mahin Esmaeil Zaei

Entry no.2014CEZ8237

ABSTRACT

Some of the large petroleum reserves in the world located in highly seismic and tectonically active regions. In conventional and unconventional petroleum reservoir rocks, wellbore stability is a challenge to drill a horizontal, vertical or inclined wellbore, especially in a high-risk basin. The geological features such as discontinuities and the anisotropy effect drilling event and mud weight pressure. Also, the water injection induces minor earthquakes along with drilling vibrations to cause a dynamic effect on productivity and stability of hydrocarbon basin. Therefore, the understanding of petrology, permeability, physical and mechanical properties of reservoir rocks under static and dynamic conditions are very important to design safe mud weight for drilling a stable wellbore. The Tipam sandstone from Upper Assam oil basin is considered for the present work. To understand the anisotropic behaviour, temperature and water content effect, various experiments were performed on Tipam sandstone samples after thermal treatment with varying temperatures between 100° and 800° C. The investigation related that the physical properties are influenced by the temperature and anisotropic nature of rock.

The petro-fabric study from XRD, SEM and thin section analyses of Tipam sandstone shows the presence of feldspar (F), quartz (Q), carbonates (C), illite (I), mica (M), kaolinite (K), pyrite (P), magnetite, strained quartz and clay minerals. Quantitatively, it is observed that quartz, kaolinite, mica, illite, feldspar and carbonate were present in 45%, 5.42%, 2%, 0.1%, 0.12%, 2.8% respectively. It is observed from the XRD pattern that there is a transaction of mineral's peak height and location for 400°C to higher temperature and dehydration, weight loss take place. Thin section analysis of theses rocks shows micro-level pores, laminated structure of micron thickness and overgrowth of quartz. Also, it is observed that the oxidation magnetite (Fe_3O_4) at 400°C crystallized into hematite (Fe_2O_3, ferrihydrite) at 600°C. The SEM analysis shows the quartz overgrowth, minor authigenic quartz, locally fragmented pore throats and cracks, increased due to increasing temperature.

Mechanical properties of Tipam sandstone were investigated by considering strength anisotropy. The specimens were prepared at anisotropy angle, $\beta = 0°$, 30°, 45°, 60° and 90°. The influence of loading direction with foliation on tensile strength of Tipam sandstone is studied and the tensile strength was found to be maximum at $\beta = 90°$. It is found that the tensile strength increases with increase in β. Further, point load test results show that the diametrical point load value decreased with increase in loading angle. The

maximum and minimum values of point load strength of Tipam sandstone were found to be 9.97 MPa (dry) and 1.14 (saturated) MPa respectively.

Investigations related to the permeability of Tipam sandstone showed that the coefficient of permeability (k) of the -8th order. Usually, rock permeability parallel to the bedding is more significant than that of perpendicular to it. A decrease in the coefficient of permeability values was observed with increase in confining pressure from 50psi (0.34 MPa) to 1200psi (8.27 MPa). It was observed that the coefficient of permeability value decreases from $\beta = 0°$ to 90° due to lamination effect. With an increase in head, hydraulic conductivity decreased because the pores of the rock close at higher confining pressure. Increase in temperature shows a decrease in the dynamic viscosity of the fluid.

The uniaxial and triaxial tests were conducted on thermal treated at 100°C, 400°C, 600°C and 800°C Tipam sandstone for both dry and saturated conditions. It is observed that the compressive strength at $\beta = 90°$ was highest and lowest at β= 45°. Failure occurs along two conjugate shear planes located symmetrically reduces the axial direction.

It is also observed that the modulus of elasticity does not show considerable variation with the increase in the water content. Young's modulus is decreasing with increase in the anisotropy angle from $\beta = 0°$ to 90°. The static triaxial tests were conducted at confining pressure 0, 5, 10 and 15 MPa. It is observed that strength anisotropy reduces with increase in confining pressure. Moreover, unconfined compressive strength is found to be maximum in at $\beta = 90°$ with minimum value at $\beta = 0°$. The Tipam sandstone shows the 'shoulder-type anisotropy' and it is because of the presence of weak bedding planes. The cyclic triaxial tests conducted on anisotropic specimen with the confinement of 0, 5, 7, 10 MPa at 1, 2 and 3 hertz frequency, varying relative UCS percentage, base load and amplitude. The strength increased with increase in the confinement pressure from 0 to 10 MPa. The failure strength shows decrease with decreasing frequency, increase in the fatigue life at lower UCS percentage with minimum values at β = 30° and highest at 3 Hz frequency. With the increase in numbers of cycles and applied stress, the UCS percentage is decreasing. The S-N curve is plotted for all anisotropy angles in dry and saturated conditions.

1D Mechanical Earth Model was designed using conventional logs and laboratory static and cyclic test data by Techlog software. The conventional logs of two wellbores of Tipam sandstone are selected up to 2400m from Digboi oil field. Shear strength is attempted on both static and dynamic conditions. 50% to 90% peak strength of UCS in static condition was used for cyclic loading to design the wellbore stability (WBS) under the dynamic condition with different β. It is found that the calibration of strength is less conservative by the Modified Lade failure criteria. The result indicates accuracy and applicability of suitable failure criteria for safe mud window. The stress map in different β is generated from the 3D MEM by Petrel software. Using cyclic test data for WBS is a new approach of the study to predict basin problem under long term vibration. It is investigated the stress maps counter values are maximum at $\beta = 90°$ and minimum at $\beta =$ 30° to 45°. It observed that the values of the counters are much higher in absence of hydrocarbons. The results of the modeling will be of immense value to locate a safe wellbore in the Digboi oil field.

सार

दुनिया के कुछ बड़े पेट्रोलियम भंडार अत्यधिक भूकंपीय और विवर्तनिक रूप से सक्रिय क्षेत्रों में स्थित हैं। पारंपरिक और अपरंपरागत पेट्रोलियम जलाशय चट्टानों में, वेलबोर स्थिरता एक क्षैतिज, ऊर्ध्वाधर या इच्छुक वेलबोर को ड्रिल करने के लिए एक चुनौती है, खासकर उच्च जोखिम वाले बेसिन में। भूवैज्ञानिक विशेषताएं जैसे कि विच्छेदन और अनिसोट्रॉपी प्रभाव ड्रिलिंग और कीचड़ वजन दबाव घटना । इसके अलावा, जल इंजेक्शन ड्रिलिंग कंपन के साथ-साथ हाइड्रोकार्बन बेसिन की उत्पादकता और स्थिरता पर एक गतिशील प्रभाव पैदा करने के लिए छोटे भूकंपों को प्रेरित करता है। इसलिए, स्थिर और गतिशील परिस्थितियों में जलाशय चट्टानों की पेट्रोलाजी, पारगम्यता, भौतिक और यांत्रिक गुणों की समझ एक स्थिर वेलबोर ड्रिलिंग के लिए सुरक्षित मिट्टी के वजन को डिजाइन करने के लिए बहुत महत्वपूर्ण है। ऊपरी असम तेल बेसिन से टिपम बलुआ पत्थर को वर्तमान कार्य के लिए माना जाता है। अनिसोट्रोपिक व्यवहार, तापमान और पानी की सामग्री के प्रभाव को समझने के लिए, 100° और 800° C के बीच अलग-अलग तापमान के साथ थर्मल उपचार के बाद टिपम बलुआ पत्थर के नमूनों पर विभिन्न प्रयोग किए गए थे। यह जांच संबंधित थी कि भौतिक गुण तापमान और अनिसोप्रोपिक प्रकृति से प्रभावित हैं। चट्टान।

एक्सआरडी, एसईएम और पेटम सैंडस्टोन के पतले खंड विश्लेषण से पेट्रो-फैब्रिक अध्ययन में फेल्डस्पार (एफ), क्वार्ट्ज (क्यू), कार्बोनेट्स (सी), इलाइट (आई), माइका (एम), काओलाइट (के) की उपस्थिति से पता चलता है। पाइराइट (P), मैग्नेटाइट, तने हुए क्वार्ट्ज और मिट्टी के खनिज। मात्रात्मक रूप से, यह देखा गया है कि क्वार्ट्ज, काओलाइट, माइका, इलाइट, फेल्डस्पर और कार्बोनेट क्रमशः 45%, 5.42%, 2%, 0.1%, 0.12%, 2.8% में मौजूद थे।यह एक्सआरडी पैटर्न से देखा गया है कि 400 C से उच्च तापमान और निर्जलीकरण के लिए खनिज की चरम ऊंचाई और स्थान का लेनदेन होता है, वजन कम होता है। थिस चट्टानों का पतला खंड विश्लेषण सूक्ष्म स्तर के छिद्रों, माइक्रोन मोटाई के टुकड़े टुकड़े में संरचना और क्वार्ट्ज के अतिवृद्धि को दर्शाता है।इसके अलावा, यह देखा गया है कि 400 C सघन पर ऑक्सीकरण मैग्नेटाइट (Fe_3O_4) 600°C में हेमेटाइट (Fe_2O_3, फेरिहाइड्राइट) में क्रिस्टलीकृत हो जाता है।एसईएम विश्लेषण क्वार्ट्ज अतिवृद्धि, मामूली ऑर्टिजेनिक क्वार्ट्ज, स्थानीय रूप से खंडित गले और दरारें दिखाता है, जो बढ़ते तापमान के कारण बढ़ जाता है।

टिपम बलुआ पत्थर के यांत्रिक गुणों की जांच ताकत अनिसोट्रॉपी पर विचार करके की गई थी।नमूनों को अनिसोट्रॉपी कोण, $\beta = 0°$, 30, 45°, 60° और 90° में तैयार किया गया था। टिपम बलुआ पत्थर की तन्य शक्ति पर फ़ोलिएशन के साथ लोडिंग दिशा के प्रभाव का अध्ययन किया जाता है और तन्य शक्ति $\beta = 90°$ पर अधिकतम पाई गई।यह पाया जाता है कि तन्यता ताकत β वृद्धि के साथ बढ़ती है। इसके अलावा, बिंदु भार परीक्षण के परिणाम बताते हैं कि लोडिंग कोण में वृद्धि के साथ व्यास बिंदु लोड मूल्य में कमी आई है। तिपम बलुआ पत्थर की बिंदु भार शक्ति के अधिकतम और न्यूनतम मूल्यों को क्रमशः 9.97 एमपीए (सूखा) और 1.14 (संतृप्त) एमपीए पाया गया।

तिपम बलुआ पत्थर की पारगम्यता से संबंधित जांच से पता चला है कि -8 आदेश की पारगम्यता (के) का गुणांक है।आमतौर पर, बिस्तर के समानांतर रॉक पारगम्यता इसके लिए लंबवत की तुलना में अधिक महत्वपूर्ण है।50psi (0.34 MPa) से 1200psi (8.27 MPa) तक सीमित दबाव में वृद्धि के साथ पारगम्यता मूल्यों के गुणांक में कमी देखी गई।यह देखा गया कि फाड़ना प्रभाव के कारण पारगम्यता मूल्य का गुणांक $\beta = 0°$ से 90° तक घट जाता है।सिर में वृद्धि के साथ, हाइड्रोलिक चालकता कम हो गई क्योंकि चट्टान के

छिद्र उच्च दबाव वाले दबाव में बंद हो गए। तापमान में वृद्धि तरल पदार्थ की गतिशील चिपचिपाहट में कमी दर्शाती है।

शुष्क और संतृप्त दोनों स्थितियों के लिए 100°C , 400 °C, 600°C और 800 °C टिपम बलुआ पत्थर के थर्मल ट्रीटमेंट पर एकपक्षीय और त्रिअक्षीय परीक्षण किए गए थे।यह देखा गया है कि $\beta = 90°$ पर संपीड़ित शक्ति $\beta= 45°$ पर उच्चतम और निम्नतम थी।दो संयुग्मित कतरनी विमानों के साथ सममित रूप से स्थित विफलता अक्षीय दिशा को कम करती है।

यह भी देखा गया है कि लोच के मापांक पानी की सामग्री में वृद्धि के साथ काफी भिन्नता नहीं दिखाते हैं। यंग का मापांक $\beta = 0°$ से 90° तक अनिसोट्रॉपी कोण में वृद्धि के साथ घट रहा है। स्थिर त्रिअक्षीय परीक्षण 0, 5, 10 और 15 एमपीए के दबाव में किए गए थे। यह देखा गया है कि ताकत अनिसोट्रॉपी दबाव को कम करने के साथ बढ़ती है। इसके अलावा, अपरिभाषित संपीड़ित शक्ति ज्यादा से ज्यादा
$\beta = 90°$ से अधिकतम $\beta = 0°$ पर न्यूनतम मूल्य के साथ पाई जाती है। टिपम बलुआ पत्थर 'कंधे-प्रकार के अनिसोट्रॉपी' को दर्शाता है और इसका कारण कमजोर बिस्तर विमानों की उपस्थिति है। 0, 5, 7, 10 MPa की 1, 2 और 3 हर्ट्ज आवृत्ति, रिश्तेदार UCS प्रतिशत, आधार भार और आयाम अलग-अलग होने के साथ अनिसोट्रोपिक नमूने पर किए गए चक्रीय त्रिअक्षीय परीक्षण। 0 से 10 एमपीए तक की सीमा के दबाव में वृद्धि के साथ ताकत बढ़ी। विफलता की ताकत घटती आवृत्ति के साथ कम हो जाती है, कम यूसीएस प्रतिशत पर थकान जीवन में वृद्धि, न्यूनतम मूल्यों के साथ $\beta = 30°$ और उच्चतम 3 हर्ट्ज आवृत्ति पर। चक्रों और लागू तनाव की संख्या में वृद्धि के साथ, यूसीएस प्रतिशत कम हो रहा है। एस-एन वक्र शुष्क और संतृप्त स्थितियों में सभी ऐसोट्रॉपी कोणों के लिए प्लॉट किया जाता है।
1 डी मैकेनिकल अर्थ मॉडल टेक्नोलॉग सॉफ्टवेयर द्वारा पारंपरिक लॉग और प्रयोगशाला स्थैतिक और चक्रीय परीक्षण डेटा का उपयोग करके बनाया गया था। डिगबोई तेल क्षेत्र से टीपैम बलुआ पत्थर के दो वेलबोर के पारंपरिक लॉग 2400 मीटर तक चुने गए हैं। कतरनी शक्ति का प्रयास स्थिर और गतिशील दोनों स्थितियों पर किया जाता है। स्थिर स्थिति में यूसीएस की 50% से 90% चोटी की ताकत का उपयोग चक्रीय लोडिंग के लिए किया गया था ताकि विभिन्न परिस्थितियों के साथ गतिशील β स्थिति के तहत वेलबोर स्थिरता (WBS) को डिजाइन किया जा सके। यह पाया गया है कि संशोधित लैड विफलता मानदंडों द्वारा ताकत का अंशांकन कम रूढ़िवादी है। परिणाम सुरक्षित मिट्टी की खिड़की के लिए उपयुक्त विफलता मानदंड की सटीकता और प्रयोज्यता को इंगित करता है। अलग-अलग β में तनाव का नक्शा पेट्रेल सॉफ्टवेयर द्वारा 3 डी मेम से बनाया गया है। WBS के लिए चक्रीय परीक्षण डेटा का उपयोग दीर्घकालिक कंपन के तहत बेसिन समस्या का अनुमान लगाने के लिए अध्ययन का एक नया दृष्टिकोण है। यह जांच की जाती है कि तनाव मानचित्र काउंटर मान अधिकतम $\beta = 90°$ हैं और न्यूनतम $\beta = 30°$ से 45° । यह देखा कि हाइड्रोकार्बन की अनुपस्थिति में काउंटरों का मूल्य बहुत अधिक है। डिगबोई तेल क्षेत्र में एक सुरक्षित वेलबोर का पता लगाने के लिए मॉडलिंग के परिणाम बहुत अधिक होंगे।

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LIST OF NOTATIONS

k	Permeability
EDX	Energy Dispersive X-ray Microanalysis
SEM	Scanning Electron Microscope
V_P	Sonic Wave Velocity
XRD	X-Ray Diffraction
β	Anisotropy Angle
σ_1	Maximum Failure Stress (Major principal stress)
σ_t	Brazilian Strength
τ	Shear stress
ρ	Density
ν	Poisons ratio
ϕ	Porosity
σ_3	Confinement Stress (Minor Principal Stress)
σ_v	Vertical or Overburden Stress
σ_H	Maximum Horizontal Stress
σ_h	Minimum Horizontal Stress
σ_θ	Major Principal Stress
σ_z	Longitudinal Stress
σ_r	Radial Stress
UCS	Unconfined Compressive Strength
Pp	Pore Pressure
Φ	Friction Angle
MEM	Mechanical Earth Model
σ_v	Overburden Stress
C	Centigrade

MPa	Megapascal
Psi	Pound-force per square inch
Hz	Hertz
QC	Quality Check
WBS	Wellbore Stability Analysis
PSDM	Prestack Depth Migration
PSTM	prestack Time Migrated
GR	Gamma Ray
DT	Sonic Travel Time Data, Compressional Slowness
RHOZ	Density Log
PHIE	Porosity Log Data
PHIT-D	Total Porosity
PHIE-D	Effective Porosity
TVD	True Vertical Depth
ρ_b	Bulk Density
PPRS	Pore Pressure Log
SVERTICAL_EXT	Vertical stress computed by the Extrapolation module
OBMW_EXT	Overburden Stress
PPG	Pore Pressure Gradient
G	Shear Modulus
E	Young’s Shear
PPRS_NORM	Normal Pore Pressure
Mpsi	Megapound-Force/Square Inch
G_{dyn}	Shear Modulus (Dynamic)
K_{dyn}	Bulk Modulus (Dynamic)
ρ_b	Bulk Density of The Formation
R_{sp}	Ratio of Shear and Compressional Slowness
Es	Static Young's Modulus
Ed	Dynamic Young's Modulus
PR_STA	Poisson’s Ratio (Static)
FANG	Friction Angle
FPRS_EATON	Fracture Pressure for Eaton

Breakdown Pressure	CMW_MAX
Shear Failure	CMW_MIN