APPLICATION OF PIEZO SENSORS IN CONDITION MONITORING OF UNDERGROUND STRUCTURES

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by

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Submitted

in fulfilment of the requirements of the degree of DOCTOR OF PHILOSOPHY

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Dedicated to my family, teachers and friends,

for their support and guidance

CERTIFICATE

This is to certify that the thesis titled "**APPLICATION OF PIEZO SENSORS IN CONDITION MONITORING OF UNDERGROUND STRUCTURES**" which is being submitted by **Mr. PRATEEK NEGI** for the fulfilment of the requirements for the award of the degree of Doctor of Philosophy, is a record of the student's own work carried out at the **Indian Institute of Technology (IIT) Delhi** under my supervision and guidance. The matter embodied in this thesis has not been submitted elsewhere for the award of any other degree or diploma.

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ABSTRACT

The underground structures built in rocks are complex in design and require continuous inspection for their maintenance. However, some of the underground areas are inaccessible for the inspection team or might warrant special clearing arrangement, leaving the structure out of service. The complexity of their design, construction and the conditions encountered during service life necessitate the deployment of a dedicated structural health monitoring (SHM) system. It is very crucial to identify the damage in the surrounding rocks in its incipient stage to prevent its further propagation and safeguard the structure built over it. The damage detection in rocks requires an efficient SHM system to monitor the rocks on a regular basis.

At times the stress ratio in the rock due to overburden stress and tectonic activities may reach high value exceeding the threshold, which may lead to rock bursts and subsequent failure of the structure. Besides the static and the quasi-static stresses, cyclic loads acting upon the rocks due to natural or artificial sources lead to deterioration of strength slowly and may result in its fatigue failure. The SHM technique becomes important for underground infrastructure to enable timely detection of the damage caused by any anticipated or unanticipated loads.

In the present study, lead zirconium titanate (PZT) patches are used to monitor the condition of rocks under various forms of loadings using electro-mechanical impedance (EMI) technique. The vibrations generated by the actuation of PZT patch are sensed by the same PZT patch and recorded in the form of conductance and susceptance signatures. The signatures have been quantified using the root mean square deviation (RMSD) method. The study clearly establishes the potential of the EMI technique in detecting and quantifying load induced damages in rocks surrounding the underground structures, opening avenues for applications in real-life situations.

Besides the EMI technique, the same smart sensors are checked for their potential to be used for acoustic emission (AE) monitoring of rocks. The study presents a new simple and cost-effective low-frequency AE technique for monitoring damages in the rocks. The AE technique is demonstrated for monitoring acoustic events happening within the rock specimens under uniaxial compressive loading. Also, the same sensors are used at different orientation positions to monitor the hydration of concrete which is used in the construction of underground structures.

सार

चट्टानों में निर्मित भूमिगत ढांचे डिजाइन में जटिल होते हैं और उनके रखरखाव के लिए निरंतर निरीक्षण की आवश्यकता पड़ती है। हालांकि, कुछ भूमिगत क्षेत्र निरीक्षण टीम के लिए पहुँचने योग्य नहीं होते जिस कारन जांच के समय वो सेवा से बाहर हो सकते हैं। अपने कार्य काल के दौरान उनके डिजाइन, निर्माण और परिस्थितियों में जटिलता को समर्पित संरचनात्मक स्वास्थ्य निगरानी (एसएचएम) प्रणाली की तैनाती की आवश्यकता होती है। अपने प्रारंभिक चरण में आस-पास के चट्टानों में होने वाली क्षति की पहचान करना बहुत महत्वपूर्ण है ताकि इसके आगे के प्रचार को रोकने और उस पर बनाए गए ढांचे की रक्षा की जा सके। चट्टानों में क्षति का पता लगाने के लिए, एक नियमित आधार पर चट्टानों की निगरानी करने के लिए एक कुशल एसएचएम प्रणाली की आवश्यकता होती है। कभी-कभी अतिरंजित तनाव और टेक्टोनिक गतिविधियों के कारण चट्टान में तनाव अनुपात थ्रेसहोल्ड से अधिक मूल्य तक पहुंच सकता है, जिससे चट्टानों के विस्फोट और संरचना की विफलता हो सकती है। स्थिर और अर्ध-स्थैतिक तनाव के अलावा, प्राकृतिक या कृत्रिम स्रोतों के कारण चट्टानों पर चलने वाले चक्रीय भार धीरे-धीरे ताकत में गिरावट का कारण बनते हैं और इसके परिणामस्वरूप स्ट्रक्चर को शती पोहोच सकती है। किसी भी अनुमानित या अप्रत्याशित भार के कारण होने वाली क्षति के समय पर पता लगाने के लिए भूमिगत आधारभूत संरचना के लिए एसएचएम तकनीक महत्वपूर्ण हो जाती है।

वर्तमान अध्ययन में, लीड ज़िकोनियम टाइटेनैट (पीजेडटी) पैच का उपयोग इलेक्ट्रो मैकेनिकल प्रतिबाधा (ईएमआई) तकनीक का उपयोग करके लोडिंग के विभिन्न रूपों के तहत चट्टानों की स्थिति की निगरानी के लिए किया जाता है। पीजेडटी पैच के क्रियान्वयन से उत्पन्न कंपन को एक ही पीजेडटी पैच द्वारा महसूस किया जाता है और आचरण और संवेदना हस्ताक्षर के रूप में दर्ज किया जाता है। हस्ताक्षर को रूट माध्य स्क्वायर विचलन (आरएमएसडी) विधि का उपयोग करके मात्राबद्ध किया गया है। अध्ययन स्पष्ट रूप से भूमिगत संरचनाओं के आसपास चट्टानों में लोड प्रेरित क्षति का पता लगाने और मापने में वास्तविक ईएमआई तकनीक की क्षमता को स्थापित करता है, वास्तविक जीवन स्थितियों में अनुप्रयोगों के लिए मार्ग खोलता है।

ईएमआई तकनीक के अलावा, चट्टानों की ध्वनिक उत्सर्जन (एई) निगरानी के लिए उपयोग की जाने वाली संभावित क्षमता के लिए एक ही स्मार्ट सेंसर की जांच की जाती है। अध्ययन चट्टानों में क्षति की निगरानी के लिए एक नई सरल और लागत प्रभावी कम आवृत्ति एई तकनीक प्रस्तुत करता है। एई तकनीक का प्रदर्शन अनियमित संपीड़न लोडिंग के तहत चट्टानों के नमूने के भीतर होने वाली ध्वनिक घटनाओं की निगरानी के लिए किया गया है। साथ ही, भूमिगत संरचनाओं के निर्माण में उपयोग की जाने वाली कंक्रीट की हाइड्रेशन की निगरानी के लिए अलग-अलग अभिविन्यास स्थितियों पर एक ही सेंसर का उपयोग किया गया है।

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LIST OF SYMBOLS

A	Force required to produce a unit velocity in the PZT patch
B	Susceptance
C_p	Capacitance of the sensor
C_0	Static capacitance for a square PZT patch of size l
D	Electric displacement
$[D_m]$	Electric displacement vector
$[d_{jm}]$	Third order piezoelectric strain coefficient tensors for direct piezoelectric effects
$[d_{mj}]$	Third order piezoelectric strain coefficient tensors for converse piezoelectric effects
d_{31}	Piezoelectric strain coefficient
d_{ij}, e_{ij}, $g_{ij,}$ h_{ij}	Constants for describing piezoelectricity
dA_1, dA_2, dA_3	Area of electrodes in the 2-3, 1-3 and 1-2 planes respectively
E	External field/ Electric field
$[E]$	Applied external electric field
E_{dry}	Dry elastic modulus of rock
F	Force
f_{ck}	Characteristic strength of concrete
G	Conductance
G_j^1	Post-damage conductance at the j^{th} frequency point
G_j^0	Conductance value pertaining to the pristine state at the j^{th} frequency point
G_s	Specific gravity of rock
j	Unit imaginary number
k	Electro-mechanical coupling factor
k_n, κ	Wave number
L/D	Length to diameter ratio
l_s	Half-length of sensor
m	Mass per unit length
P_r	Remanent polarization
P	Polarization
q	Charge
S	Strain
S_1	Strain in direction-1 (x)
$[s_{ji}^E]$	Fourth order elastic compliance tensor under constant electric field
$[S_j]$	Second order strain tensor
s_{km}^E	Elastic compliance
T	Mechanical stress

$[T]$	Stress tensor
T_1	Axial stress in direction-1 (x)
t_s	Thickness of sensor
t_r	Time of rise
t	Time
$\tan\delta$	Dielectric loss factor of the PZT material
$\dot{u}$	Velocity response
u	Displacement in the piezo patch in direction-1 (x) at time t
V	Voltage
V_s	Developed voltage
w_s	Width of sensor
$\overline{Y}$	Electromechanical admittance
Y_s	Young's modulus of the piezoelectric material
$\overline{Y^E}$	Complex Young's modulus of elasticity of the PZT patch
Z_E	Electrical impedance
Z_T, Z_a	Mechanical impedance of the piezoelectric patch
Z_S, Z	Mechanical impedance of the host structure
β	Damping ratio
ε	Dielectric constant
ε_0	Permittivity of free space equal to 8.854×10^{-12} F/m
ε_T	Permittivity for free condition
ε_S	Permittivity for fixed condition
ε_{km}^E	Dielectric permittivity
ω	Angular frequency
$\overline{\varepsilon_{33}^T}$	Complex electric permittivity in direction-3 (z) of the piezo material at constant stress
η	Mechanical loss factor of the PZT material
ρ	Density of the patch
ρ_{dry}	Dry density of rock
ρ_{sat}	Saturated density of rock
σ_c	Unconfined compressive strength of rock
μ_{dry}	Dry Poisson's ratio of rock
ϕ_{true}	True porosity

LIST OF ACRONYMS

AE	Acoustic Emission
CCD	Correlation Coefficient Deviation
CTM	Compression Testing Machine
EMI	Electro Mechanical Impedance
ESG	Electrical Strain Gauges
FFT	Fast Fourier Transformation
FBG	Fiber Bragg Grating
FE	Finite Element
H-N	Hsu-Neilson
LCR	Inductance Capacitance Resistance
LR	Load Ratio
LEFM	Linear Elastic Fracture Mechanics
MAPD	Mean Absolute Percentage Deviation
MIT	Mechatronic Impedance Transducer
NDT	Non-Destructive Testing
NDE	Non-Destructive Evaluation
PC	Personal Computer
PLB	Pencil-Lead Breakage
PZT	Lead Zirconate Titanate
RMSD	Root Mean Square Deviation
RC	Reinforced Concrete
RD	Relative Deviation
SNR	Signal to Noise Ratio
SHM	Structural Health Monitoring
S-RMSD	Sub-Root Mean Square Deviation
UCS	Unconfined Compressive Strength