ANALYSIS OF ABOVEGROUND AND UNDERGROUND STRUCTURES SUBJECTED TO BLAST LOADING AND BLAST-INDUCED VIBRATIONS

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SCHOOL OF INTERDISCIPLINARY RESEARCH
INDIAN INSTITUTE OF TECHNOLOGY DELHI
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by

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SCHOOL OF INTERDISCIPLINARY RESEARCH

submitted

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to the

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Dedicated to my beloved mother, husband, children, and friends for their endless affection, support, understanding, and inspiration.

CERTIFICATE

This is to certify that the Ph.D. thesis titled "**ANALYSIS OF ABOVEGROUND AND UNDERGROUND STRUCTURES SUBJECTED TO BLAST LOADING AND BLAST-INDUCED VIBRATIONS**" being submitted by **HARSHADA SHARMA** to the Indian Institute of Technology (IIT) Delhi for the award of the degree of **DOCTOR OF PHILOSOPHY** is a record of the bonafide research work carried out by her. She worked under our supervision to submit this Ph.D. thesis, which to our knowledge has reached the requisite standard demonstrated by excellent publications in international journals and conferences.

Further, the contents of her research work, in full or in part, have not been submitted to any other institute or university for the award of any degree or diploma to the best of our knowledge and belief.

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ABSTRACT

Underground and aboveground structures are subjected to rising threats from intended and accidental explosions. Understanding the structure's response to blast loading has become essential in ensuring the safety and resilience of buildings, important infrastructure, military installations, and mankind. Although the need to understand various types of blast loading, their effects, and the measures for blast resistance is essentially required, limited research is available in this field. The uncertainty involved in the occurrence of blast load demands blast-resistant design of structures and implementation of blast load mitigation strategies. Aboveground structures require sophisticated lightweight materials and design methodologies to ensure high-intensity confined or unconfined blast loads. However, underground structures must confront issues associated with shockwave propagation due to controlled or accidental blasts, soil-structure interaction, and confinement. Therefore, this study aims to provide blast load mitigation techniques to protect aboveground and underground structures from undue blast loads using computational analysis with finite element methods, thus, providing in-depth and visual insights into the complex phenomena occurring during the explosion.

The blast-induced shock wave propagation and the influence of varied geo-medium on the prediction of ground motion parameters for accidental underground blast scenarios is investigated in the study. The accurate estimation of BIGM facilitates to design the underground facilities for blast resistance. The performance of underground facilities exposed to an underground accidental explosion is investigated. An accidental explosion in the explosive storage structure (ESS), could affect the important structure, known as the equipment and personnel structure (EPS) containing personnel and equipment. The performance of the EPS structure subjected to blast-induced ground vibrations is investigated by installing a blast mitigation barrier between the ESS and EPS structure. Flat and curved barrier types are investigated to mitigate the blast waves, and their effectiveness is assessed on EPS structure. Moreover, the efficacy of a rooftop barrier positioned above the ESS structure is investigated and found effective in reducing the ground signatures. The ground signature formed due to underground blasts in the form of ground acceleration proves disastrous for the aboveground structures. The precise estimation of ground acceleration can offer better blast mitigation strategies to reduce the adverse effects of blasts. The empirical and numerical approach-based estimation of ground acceleration is used as base excitation to a multistory structure above the ground. The response of the structure is measured for both approach estimation of ground acceleration and a conservative method of estimation is proposed in the study.

Safety of personnel and heavy machinery is a key requirement in the case of aboveground industrial facilities under accidental blast events. Moreover, the selection of materials, structural systems, and construction practices for such infrastructure are required to support faster construction, without compromising safety. Therefore, a modular industrial control room made of steel and aluminum foam composites fabricated and assembled suitably, along with pertinent connection details to serve the functional requirements is proposed in the study. The structural assembly is exposed to confined and unconfined blast loading scenarios, as applicable to the scenario-specific accidental blast events in typical industrial setups. Furthermore, the structures featuring three distinct central core lightweight materials such as polyurethane (PU) foam, aluminum (Al) foam, and saffil® foam (S) are investigated for confined blast loads. The structures can effectively sustain blast loads according to their material strengths. However, the overall strength is further enhanced by converting the structure to a prestressed composite structure. Thus, these structures can be effectively used in emergency shelters, defense facilities, and industrial rooms. The modeling, analysis, design, and detailing strategies can be suitably adopted in designing facilities under the threat of blast-induced loading.

The confined blast-induced load becomes more critical when the explosives are enclosed in a casing. Steel is a commonly used explosive casing material and exhibits intricate and disastrous effects on the contained structure rupturing the casing material to develop fragments. The dynamic response of steel cubical structure and the influence of different lightweight explosive casing materials such as carbon fiber-reinforced polymer (CFRP), glass fiber-reinforced polymer (GFRP), and steel material on the response of the structure is assessed and compared. Furthermore, the response of the un-stiffened and stiffened cubical structure with different stiffener configurations i.e., cross, plus vertical, horizontal, and v-type is compared, and an effective configuration of the stiffener is proposed with the highest blast resistance of the structure. Thus, this doctoral research contributes to blast mitigation strategies and reliable composite structures with the use of lightweight materials.

सार

भूमिगत और उपरी संरचनाओं को जानबूझकर और आकस्मिक विस्फोटों से बढ़ते खतरों का सामना करना पड़ रहा है। इमारतों, महत्वपूर्ण बुनियादी ढांचे, सैन्य प्रतिष्ठानों और मानव जाति की सुरक्षा और लचीलापन सुनिश्चित करने के लिए विस्फोट भार के प्रति संरचना की प्रतिक्रिया को समझना आवश्यक हो गया है। हालाँकि विभिन्न प्रकार के विस्फोट भार, उनके प्रभावों और विस्फोट प्रतिरोध के उपायों को समझने की आवश्यकता अनिवार्य रूप से है, लेकिन इस क्षेत्र में सीमित शोध उपलब्ध है। विस्फोट भार की घटना में शामिल अनिश्चितता संरचनाओं के विस्फोट-प्रतिरोधी डिजाइन और विस्फोट भार शमन रणनीतियों के कार्यान्वयन की मांग करती है। उपरी संरचनाओं को उच्च तीव्रता वाले सीमित या बिना सीमित विस्फोट भार को सहन करने के लिए परिष्कृत हल्के पदार्थों और डिजाइन पद्धतियों की आवश्यकता होती है। हालाँकि, भूमिगत इमारतों को नियंत्रित या आकस्मिक विस्फोटों, मिट्टी-संरचना संपर्क और परिरोध के कारण शॉकवेव प्रसार से जुड़े मुद्दों का सामना करना पड़ता है। इसलिए, इस अध्ययन का उद्देश्य परिमित तत्व विधियों के साथ कम्प्यूटेशनल विश्लेषण का उपयोग करके उपरी और भूमिगत संरचनाओं को अनुचित विस्फोट भार से बचाने के लिए विस्फोट भार शमन तकनीक प्रदान करना है, इस प्रकार, विस्फोट के दौरान होने वाली जटिल घटनाओं में गहन और दृश्य अंतर्दृष्टि प्रदान करना है।

अध्ययन में विस्फोट से प्रेरित आघात तरंग प्रसार और आकस्मिक भूमिगत विस्फोट परिदृश्य के लिए भू-गति मापदंडों की भविष्यवाणी पर विभिन्न भू-माध्यमों के प्रभाव की जांच की गई है। BIGM का सटीक अनुमान विस्फोट प्रतिरोध के लिए भूमिगत सुविधाओं को डिजाइन करने में सुविधा प्रदान करता है। भूमिगत आकस्मिक विस्फोट के संपर्क में आने वाली भूमिगत सुविधाओं के प्रदर्शन की जांच की गई है। विस्फोटक भंडारण संरचना (ESS) में एक आकस्मिक विस्फोट, महत्वपूर्ण संरचना को प्रभावित कर सकता है, जिसे उपकरण और कार्मिक संरचना (EPS) के रूप में जाना जाता है जिसमें कार्मिक और उपकरण होते हैं। विस्फोट से प्रेरित भू-कंपन के अधीन EPS संरचना के प्रदर्शन की जांच ESS और EPS संरचना के बीच विस्फोट शमन अवरोध स्थापित करके की जाती है। विस्फोट तरंगों को कम करने के लिए सपाट और घुमावदार अवरोध प्रकारों की जांच की जाती है, और EPS संरचना पर उनकी प्रभावशीलता का आकलन किया जाता है। इसके अलावा, ESS संरचना के ऊपर स्थित छत अवरोध की प्रभावकारिता की जांच की गई और पाया गया कि यह भू-हस्ताक्षरों को कम करने में प्रभावी है। भू-त्वरण के रूप में भूमिगत विस्फोटों के कारण बनने वाले भू-हस्ताक्षर ऊपर की

संरचनाओं के लिए विनाशकारी साबित होते हैं। भू-त्वरण का सटीक अनुमान विस्फोटों के प्रतिकूल प्रभावों को कम करने के लिए बेहतर विस्फोट शमन रणनीतियों की पेशकश कर सकता है। भू-त्वरण के अनुभवजन्य और संख्यात्मक दृष्टिकोण-आधारित अनुमान का उपयोग जमीन के ऊपर एक बहुमंजिला संरचना के लिए आधार उत्तेजना के रूप में किया जाता है। भू-त्वरण के दृष्टिकोण अनुमान और अध्ययन में अनुमान की एक रूढ़िवादी विधि दोनों के लिए संरचना की प्रतिक्रिया को मापा जाता है।

आकस्मिक विस्फोट की घटनाओं के तहत जमीन के ऊपर औद्योगिक सुविधाओं के मामले में कर्मियों और भारी मशीनरी की सुरक्षा एक प्रमुख आवश्यकता है। इसके अलावा, सुरक्षा से समझौता किए बिना, तेजी से निर्माण का समर्थन करने के लिए ऐसी अवसंरचना के लिए सामग्री, संरचनात्मक प्रणालियों और निर्माण प्रथाओं का चयन आवश्यक है। इसलिए, अध्ययन में कार्यात्मक आवश्यकताओं को पूरा करने के लिए प्रासंगिक कनेक्शन विवरणों के साथ-साथ स्टील और एल्यूमीनियम फोम कंपोजिट से बना एक मॉड्यूलर औद्योगिक नियंत्रण कक्ष प्रस्तावित किया गया है, जिसे उपयुक्त रूप से निर्मित और इकट्ठा किया गया है। संरचनात्मक असेंबली सीमित और असीमित विस्फोट लोडिंग परिदृश्यों के संपर्क में है, जैसा कि विशिष्ट औद्योगिक सेटअप में परिदृश्य-विशिष्ट आकस्मिक विस्फोट घटनाओं के लिए लागू होता है। इसके अलावा, पॉलीयूरेथेन (पीयू) फोम, एल्यूमीनियम (अल) फोम और सैफ़िल फोम (एस) जैसी तीन अलग-अलग केंद्रीय कोर हल्की सामग्री वाली संरचनाओं की सीमित विस्फोट भार के लिए जांच की जाती है। संरचनाएं अपनी सामग्री की ताकत के अनुसार विस्फोट भार को प्रभावी ढंग से सहन कर सकती हैं। हालांकि, संरचना को प्रीस्ट्रेस्ड कंपोजिट संरचना में परिवर्तित करके समग्र ताकत को और बढ़ाया जाता है। इस प्रकार, इन संरचनाओं का आपातकालीन आश्रयों, रक्षा सुविधाओं और औद्योगिक कमरों में प्रभावी ढंग से उपयोग किया जा सकता है। विस्फोट-प्रेरित लोडिंग के खतरे के तहत सुविधाओं को डिजाइन करने में मॉडलिंग, विश्लेषण, डिजाइन और विवरण रणनीतियों को उपयुक्त रूप से अपनाया जा सकता है।

जब विस्फोटक आवरण में बंद होते हैं तो सीमित विस्फोट-प्रेरित भार अधिक महत्वपूर्ण हो जाता है। स्टील एक आम तौर पर इस्तेमाल की जाने वाली विस्फोटक आवरण सामग्री है और आवरण सामग्री को तोड़कर टुकड़े बनाने के लिए निहित संरचना पर जटिल और विनाशकारी प्रभाव प्रदर्शित करती है। स्टील क्यूबिकल संरचना की गतिशील प्रतिक्रिया कार्बन फाइबर-प्रबलित बहुलक (CFRP), ग्लास फाइबर-प्रबलित बहुलक (GFRP), और संरचना की प्रतिक्रिया पर स्टील सामग्री जैसे विभिन्न हल्के विस्फोटक आवरण सामग्री के प्रभाव का आकलन और तुलना की जाती है। इसके अलावा, विभिन्न

सार

स्टिफ़नर विन्यासों यानी क्रॉस, प्लस वर्टिकल, हॉरिजॉन्टल और वी-टाइप के साथ बिना कठोर और कठोर क्यूबिकल संरचना की प्रतिक्रिया की तुलना की जाती है, और संरचना के उच्चतम विस्फोट प्रतिरोध के साथ स्टिफ़नर का एक प्रभावी विन्यास प्रस्तावित किया जाता है। इस प्रकार, यह डॉक्टरेट अनुसंधान हल्के पदार्थों के उपयोग के साथ विस्फोट शमन रणनीतियों और विश्वसनीय समग्र संरचनाओं में योगदान देता है।

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ABBREVIATIONS

1D	One dimensional
2D	Two dimensional
3D	Three-dimensional
ACI	American Concrete Institute
ACSF	Aluminum cenosphere syntactic foam
Al	Aluminium
ALE	Arbitrary Lagrangian Eulerian
ANFO	Ammonium Nitrate/Fuel Oil
ANN	Artificial neural network
AO	Axis orientation of charge shape
BBO	Biogeography-based Optimization
BD	Buried depth
BIGA	Blast-induced ground acceleration
BIGM	Blast-induced ground motions
C	Channel
CDTI	Central difference time integration
c	Seismic velocity
C_{R}	Seismic velocity of *R* wave
C_{S}	Seismic velocity of *S* wave
C_{P}	Seismic velocity of P wave
CEL	Coupled Eulerian-Lagrangian
CFRP	Carbon fiber-reinforced polymer
CS	Cross stiffener
DOF	Degree of freedom

DS	Dense soil
E	Modulus of elasticity
EOS	Equation of state
ESS	Explosive storage structure
EPS	Equipment and personnel structure
FE	Finite element
FFT	Fast Fourier transform
FRP	Fiber reinforced polymer
GFRP	Glass fiber-reinforced polymer
GSI	Geological strength index
HE	High explosives
HS	Horizontal stiffener
HHO	Harris hawks optimizer
IS	Indian standard
JWL	Jones-Wilkinson-Lee
LS	Loose soil
MM-ALE	Multi-Material Arbitrary Lagrangian and Eulerian
MDOF	Multi-degree of freedom
PF	Principle frequency
PGA	Peak ground acceleration
PGD	Peak ground displacement
PPV	Peak particle velocity
PS	Plus stiffener
PU	Polyurethane
Q	Quality factor
RC	Reinforced concrete
RCC	Reinforced cement concrete

RF	Random forest
RQD	Rock quality designation
S	Saffil®
SC	Saturated clay
SDOF	Single degree of freedom
SS	Saturated soil
S-A-S	Steel- aluminium-steel
S-S-S	Steel-saffil-steel
S-P-S	Steel-polyurethane-steel
SPH	Smooth particle hydrodynamics
TNT	Trinitrotoluene
UFC	Unified facilities criteria
VS	Vertical stiffener
VTS	V type stiffener
v-m	Von Mises
WS	Without stiffener

MATHEMATICAL NOTATIONS

a_i	Actual output
A	Yield strength
A_v	Vertical acceleration
A_h	Horizontal acceleration
b	Decay constant
b_j	Net output
B	Hardening modulus
C	Seismic velocity
C_D	Drag coefficient
c_s	Damping of structure
d_i	Desired output
D	Displacement
D_v	Vertical displacement
D_h	Horizontal displacement
E	Elastic modulus of the soil
E_t	Tangent modulus
e_{int}	Specific internal energy at atmospheric pressure
f_l	Decoupling factor
f_c	Coupling factor
F	Frequency
g	Gravitational constant
G	Shear modulus of the soil or rock mass
I_1	First invariant of the stress tensor
J_2	Second invariant of the stress deviator

k	Site constant
k_{s}	Stiffness of structure
k_{v}	Velocity decay coefficient
K	Reference temperature
K_{2}	Constant for geo-medium
L	Total length of explosive
L_{i}	Length of the explosive at the i^{th} layer
m_{s}	Lumped mass
n	Attenuation coefficient
P_{so}	Peak positive overpressure
P_{o}	Ambient air pressure
P_{j}	Output in intermediate layers
Q	Charge weight
R	Radial distance
R^{2}	Correlation coefficient
SD	Scaled distance
$S_{ij}^{\Delta^{n+1/2}}$	Deviatoric Cauchy's stress tensor
t_{a}	Arrival time of the blast wave
t^{+}_{d}	Positive duration
t^{-}_{d}	Negative duration
t_{0}	Time at peak positive overpressure
T_{s}	Natural time period of structure
U_{j}	Input layer
v_{d}	Velocity of detonation
v_{0}	Initial fragment velocity
v_{s}	Velocity of fragments

V	Volume of charge chamber
V_v	Velocity in vertical direction
V_h	Velocity in horizontal direction
W	Charge weight
W_c	Weight of metal casing
W_f	Weight of fragment
W_i	Part of the charge exploding in the i^{th} layer
W_{ij}	Interconnecting weights of layer i with layer j
∇W_{ji}	Instantaneous weight change
X_i	Input
Z	Scaled distance
ρ	Density
β	Soil constant
ε_0	Residual strain
ρ_0	Reference density
γ	Adiabatic exponent of air
δ	Error function
δ_t	Total error
ϕ	Plastic yield surface function
σ_y	Uniaxial yield stress
$\dot{\varepsilon}_b$	Strain rate
ε_P	Effective plastic strain
σ_d	Dynamic yield stress
σ_i^{trial}	Trial stress
ω_f	Natural frequency
ξ	Damping ratio

μ	Poisson's ratio
$\overline{\varepsilon}^{p}$	Effective plastic strain
ε_f	Failure strain
σ_E	Quasi-static stress