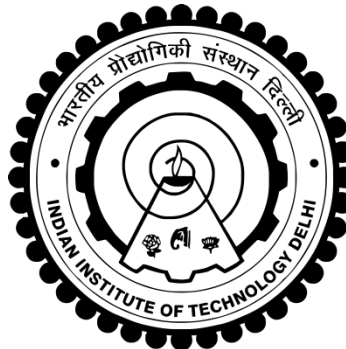


**CHARACTERIZATION OF HIGH STRAIN RATE
RESPONSE OF ROCK AND ITS APPLICATION IN
BLAST ANALYSIS OF TUNNELS**

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INDIAN INSTITUTE OF TECHNOLOGY DELHI
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BLAST ANALYSIS OF TUNNELS

by

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Department of Civil Engineering

Submitted

in fulfilment of the requirements of the degree of Doctor of Philosophy

to the



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*Dedicated to my family
For their endless love, support and encouragement*

CERTIFICATE

This is to certify that the thesis entitled, “**CHARACTERIZATION OF HIGH STRAIN RATE RESPONSE OF ROCK AND ITS APPLICATION IN BLAST ANALYSIS OF TUNNELS**” which is being submitted by **Ms. Sunita Mishra (2014CEZ8162)** to the Indian Institute of Technology (IIT) Delhi for the award of the degree of **DOCTOR OF PHILOSOPHY** is a record of the student’s bonafide research work carried out by her. She worked under our supervision for the submission of thesis, which to our knowledge has reached the requisite standard as demonstrated by excellent international publications in journals and conferences.

Further, the contents of her research work, in full or in parts, 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

In the twentieth century, manmade disasters, e.g. bomb blast, projectile attack, mine blast have created headlines in the news due to blast in London and Paris underground metro tunnels, projectile attack in Gaza, landmine blast in Kashmir. The disastrous events like blast or projectile attack, when happens underground, create ground shock that gives rise to a high rate of loading in soil and rock in the surroundings. The strain rate generated in rock when subjected to blast loading may go as high as $10^2/s$ to $10^4/s$. The stress-strain response of rock, its peak stress and stiffness are significantly affected when subjected to such high rate of loading.

The present thesis aims to understand the stress-strain response of ten different types of rocks under high loading rate through detailed experimental and numerical analyses. The high strain rate characterisation of these ten rocks are done for two different diameters, and five different slenderness ratios of the rock specimens using a 76 mm diameter split Hopkinson pressure bar (SHPB) device to understand the standard specimen dimension for the rocks in SHPB test exhibiting highest sensitivity to loading rates. The stress-strain response of the rock specimens is studied by varying the length of the striker bars and the gas gun pressure values systematically. Petrological and static characterisation of the ten different types of rocks are also carried out to assess the response of the rock specimens. Based on the test results, a methodology is proposed to characterize the rock specimens under high loading rate. Further, numerical validation of SHPB test on these ten different types of rocks are performed using strain rate dependent Johnson-Holmquist (JH-2) model in the finite element software, LS-DYNA and the parameters are determined. The parameters obtained are then used in blast analysis of a tunnel subjected to 20 kg trinitrotoluene (TNT) explosion.

The major findings of this thesis comprise of modification of a 76 mm SHPB device design to characterize heterogeneous materials like rock, concrete and ceramics. The physical, petrological and mechanical properties of the rock create a database for designing of underground structures.

The appropriate specimen dimension for characterising ten different types of rock by using SHPB device are determined and recommended based on two approaches, e.g., the highest sensitivity of DIF with respect to loading rate and highest sensitivity of energy absorption with respect to volume of the specimen. A strain rate dependent JH-2 constitutive model is calibrated using the experimental stress-strain response of the appropriate specimen size. The determined JH-2 parameters are used in blast analysis of tunnels in each rock type. The response obtained are studied and final design propositions are made. Moreover, parametric studies on blast analysis in tunnel has been conducted for one rock type from each formation category, e.g., granite (igneous rock), limestone (sedimentary rock) and phyllite (metamorphic rock). The results obtained from the parametric studies support the recommendation made on the selection of appropriate specimen dimension from the experimental results. Lastly, a classification system based on the dynamic characterisation is proposed based on the compressive strength and dynamic modulus of the rocks.

सार

बीसवीं शताब्दी में, मानव निर्मित आपदाएँ, उदा। बम विस्फोट, प्रक्षेप्य हमला, खनन विस्फोट ने लंदन और पेरिस की भूमिगत मेट्रो सुरंगों, गाजा में प्रक्षेप्य हमले, कश्मीर में बारूदी सुरंग विस्फोट के कारण खबरों में सुर्खियां बनाई हैं। ब्लास्ट या प्रोजेक्टाइल अटैक जैसी विनाशकारी घटनाएं, जब भूमिगत होती हैं, तो ग्राउंड शॉक बनाते हैं जो आसपास की मिट्टी और चट्टान में लोडिंग की उच्च दर को जन्म देता है। ब्लास्ट लोडिंग के अधीन होने पर चट्टान में उत्पन्न तनाव दर $10^2/s$ से $10^4/s$ तक जा सकती है। जब लोडिंग की इतनी उच्च दर के अधीन, रॉक का तनाव-तनाव प्रतिक्रिया, इसका चरम तनाव और कठोरता काफी प्रभावित होती है।

वर्तमान थीसिस का उद्देश्य विस्तृत प्रयोगात्मक और संख्यात्मक विश्लेषण के माध्यम से उच्च लोडिंग दर के तहत दस विभिन्न प्रकार की चट्टानों के तनाव-तनाव प्रतिक्रिया को समझना है। इन दस चट्टानों का उच्च तनाव दर लक्षण वर्णन दो अलग-अलग व्यास के लिए किया जाता है, और रॉक नमूनों के पांच अलग-अलग पतला अनुपात में एक 76 मिमी व्यास विभाजन हॉपकिंसन दबाव बार (SHPB) डिवाइस का उपयोग करके SHPB परीक्षण में चट्टानों के लिए मानक आयाम आयाम को समझने के लिए किया जाता है, जो लोडिंग दरों के प्रति उच्चतम संवेदनशीलता प्रदर्शित करते हैं। रॉक नमूनों के तनाव-तनाव प्रतिक्रिया का अध्ययन स्ट्राइकर बार की लंबाई और गैस बंदूक दबाव मूल्यों को व्यवस्थित रूप से अलग-अलग करके किया जाता है। रॉक नमूनों की प्रतिक्रिया का आकलन करने के लिए दस विभिन्न प्रकार की चट्टानों के पेटोलॉजिकल और स्थैतिक लक्षण वर्णन भी किया जाता है। परीक्षण के परिणामों के आधार पर, उच्च लोडिंग दर के तहत रॉक नमूनों को चिह्नित करने के लिए एक कार्यप्रणाली प्रस्तावित की जाती है। इसके अलावा, इन दस अलग-अलग प्रकार की चट्टानों पर SHPB परीक्षण की संख्यात्मक मान्यता, परिमित तत्व सॉफ्टवेयर, LS-DYNA में तनाव दर निर्भर जॉनसन-होल्मक्विस्ट (JH-2) मॉडल का उपयोग करके की जाती है और मापदंडों का निर्धारण किया जाता है। इसके बाद प्राप्त

मापदंडों का उपयोग 20 किलोग्राम ट्रिनिट्रोटोलुइन (टीएनटी) विस्फोट के अधीन एक सुरंग के विस्फोट विश्लेषण में किया जाता है।

इस थीसिस के प्रमुख निष्कर्षों में रॉक, कंक्रीट और सिरेमिक जैसी विषम सामग्रियों को चिह्नित करने के लिए 76 मिमी SHPB डिवाइस डिज़ाइन का संशोधन शामिल है। चट्टान के भौतिक, पेटोलॉजिकल और यांत्रिक गुण भूमिगत संरचनाओं के डिज़ाइन के लिए एक डेटाबेस बनाते हैं।

SHPB डिवाइस का उपयोग करके दस विभिन्न प्रकार की चट्टान को चिह्नित करने के लिए उपयुक्त नमूना आयाम दो दृष्टिकोणों के आधार पर निर्धारित और अनुशंसित हैं, उदाहरण के लिए, लोडिंग दर के संबंध में डीआईएफ की उच्चतम संवेदनशीलता और नमूना की मात्रा के संबंध में ऊर्जा अवशोषण की उच्चतम संवेदनशीलता। एक तनाव दर निर्भर जेएच -2 संवैधानिक मॉडल उपयुक्त नमूना आकार के प्रयोगात्मक तनाव-तनाव प्रतिक्रिया का उपयोग करके कैलिब्रेट किया जाता है। प्रत्येक रॉक प्रकार में सुरंगों के विस्फोट विश्लेषण में निर्धारित JH-2 मापदंडों का उपयोग किया जाता है। प्राप्त प्रतिक्रिया का अध्ययन किया जाता है और अंतिम डिज़ाइन प्रस्ताव बनाए जाते हैं। इसके अलावा, सुरंग में ब्लास्ट विश्लेषण पर पैरामीट्रिक अध्ययन प्रत्येक गठन श्रेणी से एक रॉक प्रकार के लिए आयोजित किया गया है, जैसे, ग्रेनाइट (आग्नेय चट्टान), चूना पत्थर (तलछटी चट्टान) और फिलाइट (रूपांतरित चट्टान)। पैरामीट्रिक अध्ययन से प्राप्त परिणाम प्रयोगात्मक परिणामों से उपयुक्त नमूना आयाम के चयन पर की गई सिफारिश का समर्थन करते हैं। अन्त में, गतिशील वर्णक्रम के आधार पर एक वर्गीकरण प्रणाली का प्रस्ताव किया जाता है जो चट्टानों की संपीड़ित शक्ति और गतिशील मापांक पर आधारित होता है।

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