

**DYNAMIC RESPONSE OF AN ANISOTROPIC ROCK
AND ITS APPLICATION TO A BLAST LOADING
PROBLEM**

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**DEPARTMENT OF CIVIL ENGINEERING
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by

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DEPARTMENT OF CIVIL ENGINEERING

Submitted

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

to the



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JUNE 2023

Dedicated to my parents and my wife

Certificate

This is to certify that the thesis entitled “**DYNAMIC RESPONSE OF AN ANISOTROPIC ROCK AND ITS APPLICATION TO A BLAST LOADING PROBLEM**” submitted by **Mr. Venkatesh Madhukar Deshpande (2017CEZ8071)** 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 him. He worked under my supervision for the submission of the thesis, which to my knowledge, has reached the requisite standard as demonstrated by excellent international publications in journals and conferences.

To the best of my knowledge and belief, the contents of his research work have not been submitted in full or in part to any other university or institute to confer a degree or diploma.

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Abstract

The present work investigates the dynamic mechanical behavior of an anisotropic rock, namely Jhiri shale, at five anisotropy angles (0° , 30° , 45° , 60° , and 90°) using a large diameter (76 mm) split Hopkinson pressure bar. Jhiri shale is a transversely isotropic rock. Initially, the dimensions of a copper pulse shaper glued on the incident bar face are optimized. It is found that as the diameter or thickness increases, the incident rise time improves. A pulse shaper of diameter 15 or 20 mm and thickness 2.5 mm is recommended as it facilitates dynamic force equilibrium and constant strain rate loading in the rock specimens. For diameters 25 and 30 mm, the oscillations observed in the incident wave are attributed to inertia-induced pressure.

From the dynamic tests on Jhiri shale, it is found that the dynamic strength is rate-dependent, and it increases with a rise in the strain rate. At high strain rates, the strength varies in a U-type fashion. The anisotropy ratio lessens from 3.50 to 3.37 when the strain rate changes from quasi-static to $\sim 320/\text{s}$. All the samples are pervasively fragmented. As the strain rate increases, the degree of fragmentation intensifies. Samples with intermediate anisotropy angles (30° , 45° , 60°) are subjected to a higher degree of fragmentation than those with 0° and 90° . The rock fragments exhibit fractal distribution, which can be described using a power-law relationship.

The dynamic experiments are numerically simulated using the discrete element method. The rock grains are generated as randomly sized and distributed polygonal blocks using Voronoi tessellation. The micro-parameters are calibrated using the dynamic stress responses deduced experimentally. The initiation and propagation of micro-cracks and failure mechanisms are explored via numerical simulations. It is found that samples mainly undergo shear failure dynamically. As the strain rate increases, the number of cracks increases. For samples with

intermediate anisotropy angles, shear cracks begin along the bedding planes and then spread internally. At any given strain rate, they have a higher number of cracks than 0° and 90° samples, indicating a higher degree of fragmentation, as noted experimentally.

Finally, using the calibrated microparameters, the dynamic response of a tunnel subjected to blast loading is assessed. The tunnel is placed in Jhiri shale rock. The influence of bedding plane anisotropy, joint spacing, Voronoi polygon size, cover depth, and lateral earth pressure coefficient on tunnel stability are studied. It is found that it is vital to discretize rock grains as Voronoi blocks for studying tunnel stability. Voronoi blocks increase the tunnel stability for angles 30° and 60° , whereas they reduce the stability for angles 0° and 90° .

सार

वर्तमान कार्य एक अनिसोट्रोपिक शिला के गतिशील यांत्रिक व्यवहार की जांच करता है। इस शिला का नाम झिरी शेल है। झिरी शेल के गतिशील यांत्रिक व्यवहार की जांच पांच अनिसोट्रोपी कोणों (0° , 30° , 45° , 60° , और 90°) पर एक बड़े व्यास (७६ मिलीमीटर) स्प्लिट हॉपकिंसन प्रेशर बार (एस एच पी बी) का उपयोग करके की गयी है। झिरी शेल एक अनुप्रस्थ आइसोट्रोपिक शिला है। संशोदन के प्रथम भाग में तांबे के पल्स शेपर के आयामों को अनुकूलित किया है। पल्स शेपर इंसिडेंट बार के स्ट्राइकर बार के निकट छोर पर लगाया जाता है। यह पाया गया है कि जैसे-जैसे पल्स शेपर का व्यास अथवा मोटाई बढ़ती है, इंसिडेंट तरंग के समय में सुधर आता है। व्यास १५ अथवा २० मिलीमीटर और मोटाई २.५ मिलीमीटर के पल्स शेपर का अनुमोदन किया जाता है क्योंकि वे शिला नमूनों में गतिशील बल संतुलन और निरंतर तनाव दर लोडिंग की सुविधा प्रदान करते हैं। व्यास २५ और ३० मिलीमीटर के पल्स शेपरो द्वारा उत्पत्तित इंसिडेंट तरंग में देखे गए दोलनों का कारण जड़ता-प्रेरित दबाव है।

झिरी शेल पर गतिशील परीक्षणों से, यह पाया गया है कि गतिशील शक्ति स्ट्रेन रेट पर निर्भर है, और यह स्ट्रेन रेट में वृद्धि के साथ बढ़ती है। उच्च स्ट्रेन रेट पर, गतिशील शक्ति अनिसोट्रोपी कोणों के बदलाव के साथ यू-आकर में पायी गयी है। अनिसोट्रोपी अनुपात ३.५० से ३.३७ घट जाता है जब स्ट्रेन रेट अर्ध-स्थैतिक से $\sim 320/s$ बढ़ता है। सभी नमूने व्यापक रूप से खंडित होते हैं। जैसे-जैसे स्ट्रेन रेट बढ़ता है, विखंडन की डिग्री तेज होती जाती है। मध्यवर्ती अनिसोट्रोपी कोण (30° , 45° , 60°) वाले नमूनों में 0° और 90° वाले नमूनों की तुलना में विखंडन ज्यादा होता है। शिला के खंडित टुकड़े फ्रैक्टल वितरण प्रदर्शित करते हैं, जिसे पावर-लॉ संबंध का उपयोग करके वर्णित किया जा सकता है।

गतिशील प्रयोगों का न्यूमेरिकल सिमुलेशन डिस्क्रीट एलिमेंट पद्धति द्वारा किया गया है। रॉक ग्रेन को वोरोनोई टेसलेशन का उपयोग करके बेतरतीब ढंग से आकार और वितरित बहुभुज ब्लॉक के रूप में उत्पन्न किया गया है। प्रयोगों से निकाले गए गतिशील तनाव-समय रेखाचित्रों का उपयोग करके माइक्रो-पैरामीटरों को कैलिब्रेट किया गया है। न्यूमेरिकल सिमुलेशन के माध्यम से सूक्ष्म दरारों और विफलता तंत्र की शुरुआत और प्रसार का पता लगाया गया है। यह पाया गया है कि नमूने मुख्य रूप से शियर विफलता से गुजरते हैं। जैसे-जैसे स्ट्रेन रेट बढ़ता है, दरारों की संख्या बढ़ती है। मध्यवर्ती अनिसोट्रॉपी कोण वाले नमूनों के लिए, शियर दरारें बेडिंग प्लान्स पर शुरू होती हैं और फिर आंतरिक रूप से फैलती हैं। किसी भी स्ट्रेन रेट पर मध्यवर्ती अनिसोट्रॉपी कोण वाले नमूनों में दरारों की संख्या 0° और 90° नमूनों की तुलना में अधिक हैं, जो विखंडन की उच्च डिग्री का संकेत देती हैं, जो प्रयोगों द्वारा भी पता चला है।

अंत में, कैलिब्रेटेड माइक्रो-पैरामीटरों का उपयोग करके, सुरंग की गतिशील प्रतिक्रिया का आंकलन किया गया है जिस पर ब्लास्ट लोडिंग लगायी गयी है। सुरंग झिरी शेल रॉक में स्थित है। सुरंग की स्थिरता पर बेडिंग प्लेन अनिसोट्रॉपी, जॉइंट स्पेसिंग, वोरोनोई पॉलीगॉन साइज, कवर डेप्थ और लेटरल अर्थ प्रेशर कोफिशिएंट के प्रभाव का अध्ययन किया गया है। यह पाया गया है कि सुरंग की स्थिरता का अध्ययन करने के लिए वोरोनोई ब्लॉक के रूप में रॉक ग्रेन को बनाना महत्वपूर्ण है। वोरोनोई ब्लॉक 30° और 60° के कोणों के लिए सुरंग की स्थिरता को बढ़ाते हैं, जबकि वे 0° और 90° के कोणों के लिए स्थिरता को कम करते हैं।

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