

**NUCLEAR EXPLOSION DEFORMS THE GROUND:
*HOW MUCH & HOW SURE?***

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NUCLEAR EXPLOSION DEFORMS THE GROUND:
HOW MUCH & HOW SURE?

by

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*Dedicated to my parents
who are my source of inspiration*

CERTIFICATE

It is to certify that the thesis titled **Nuclear Explosion Deforms the Ground: How Much & How Sure?** Submitted by Mr. **Shashank Pathak** to the Indian Institute of Technology, Delhi, for the award of the degree of **Doctor of Philosophy** is a record of the original bonafide research work carried out by him under my supervision and guidance. The thesis has reached the standards fulfilling the requirements of the regulations relating the degree.

The results contained in this thesis have not been submitted in part or full to any other University or Institute for the award of any degree or diploma.

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(Shashank Pathak)

ABSTRACT

The design of underground critical facilities for anticipated effects of nuclear-air-blast is becoming a challenge. Moving air-shock waves on the earth surface generated due to above-ground nuclear-explosions induce ground displacements. An accurate estimate of nuclear-air-blast-induced free-field ground displacement is crucial for the design of such protective structures. This thesis provides a computationally efficient and reliable estimate of ground displacements considering nuclear-air-overpressure, stress-strain characteristics of geomaterials, and associated uncertainties.

Of several blast load models available in literature, the ASCE manual No.-42 model captures the mean trend of the decay portion of the air-overpressure time-history reasonably well. This model predicts nuclear-air-overpressure time-history in terms of distance from ground-zero (R), height-of-burst (HOB), and yield of the explosion (W). The ASCE model is further modified to account for the uncertainties associated with (i) the ASCE model, (ii) occurrence of an explosion, and (iii) inherent variability of nuclear-attack parameters (R , W , and HOB) by (i) comparing the field data with model estimates, (ii) developing a probabilistic threat scenario model, and (iii) assigning appropriate probability distributions to the nuclear-attack parameters, respectively. The incorporation of these uncertainties into the ASCE model leads to the probabilistic characterization of nuclear-blast loads. For the direct use in design, two simple correlations are proposed for peak overpressure and positive phase duration in terms of their respective probability of exceedance along with another equation that represents a normalized air-overpressure time-history.

An appropriate description of stress-strain relationship of geomaterials subjected to blast loading is the next important step. Previous experimental and theoretical research efforts indicated that the constitutive behaviour of geomaterials under blast loading depends upon strain

rate, stress level, and interaction among the three phases (solid, liquid, and gases) and various advanced constitutive models are available to model such a stress-strain behavior of geomaterials. However, these models are based on large number of material parameters which needs to be calibrated through different experimental studies and numerical computations. Furthermore, the inherent variability of geomaterials, uncertainties of the nuclear-air-blast overpressures, epistemic uncertainties of the constitutive model itself would add significantly to the cost of computation of ground displacements. Therefore, as an alternative to advanced constitutive models, new functional forms, based on three parameters, namely, weight factor, initial modulus ratio, and strain recovery ratio, are proposed to capture the loading and unloading branches of experimentally determined or numerically simulated stress-strain curve of geomaterials subjected to blast loads. The three parameters are determined for an exhaustive data set of experimental stress-strain curves of different types of geomaterials (sands, silts, and clays) under different types of conditions (dry, saturated, partially saturated, confined, and unconfined) subjected to various loads (dynamic loads, blast loads, impact loads, and static loads) and a catalogue of the parameters is prepared for direct use by practitioners. It is observed that the functional forms reasonably capture the mean trend of the stress-strain data corresponding to not only blast loads and high strain rates but also to static and dynamic loads. The functions were also able to capture the stress-strain behaviour simulated from advanced constitutive models. The dependence of model parameters on strain-rate, lateral confinement, degree of saturation, initial compaction, and locking-initiation stress is also analyzed and some simple models or thumb-rules are proposed for reasonable estimation of the three parameters.

In the last step, to estimate the nuclear-air-blast-induced free-field vertical ground displacement a model is proposed in terms of air-overpressure time-history and depth-dependent geotechnical parameters (stress wave velocity, stress attenuation, and stress-strain model). The

estimated displacement time-histories are compared with the nuclear as well as non-nuclear test data and a reasonable agreement is found between the recorded and estimated displacements. It is observed that the model significantly overestimates the displacements at greater depths and at larger distances from ground-zero (GZ). The displacement model is utilized further to study the effect of loading and geotechnical parameters on peak ground displacement through parametric variations and sensitivity analysis. The analysis indicates that the peak ground displacement is highly sensitive to R , HOB , and constrained modulus.

The field data is utilized further to characterize the epistemic uncertainties associated with the displacement model. Since the quantification of model uncertainties is computationally tedious if model parameters are also uncertain, an approximate approach is proposed for model uncertainty characterization that is based on Taylor's series approximation and accounts for deterministic as well as uncertain input parameters. The proposed approach is compared with the computationally rigorous Bayesian approach and is observed to be in close agreement for prediction of mean model factors. Based on the proposed model uncertainty characterization approach, it is found that the mean model uncertainty factor (corresponding to peak displacement) varies between 0.78 and 0.99 for coefficients of variation of input parameters in the range of 0-20%. Since all the mean model uncertainty factors are less than unity, it indicates that the proposed model provides, on an average, conservative estimate of peak ground displacement.

Thus, using the proposed (i) probabilistic nuclear-blast load model, (ii) stress-strain function of geomaterials, (iii) displacement model, and (iv) model uncertainty factors, a reliable and computationally efficient estimate of nuclear-air-blast-induced ground displacements can be arrived at.

सार

परमाणु-वायु-विस्फोट के प्रत्याशित प्रभावों के लिए भूमिगत महत्वपूर्ण सुविधाओं का डिजाइन एक चुनौती है। परमाणु-विस्फोट के कारण उत्पन्न तीव्र हवा का दबाव जमीन के विस्थापन को प्रेरित करते हैं जिसका की सटीक अनुमान लगाना सुरक्षात्मक डिजाइन के लिए अति महत्वपूर्ण है। यह निबंध परमाणु-वायु-विस्फोट के कारण जमीन के विस्थापन का गणितीय आधार पर कुशलता और विश्वसनीयता के साथ अनुमान लगाने की विधि पर आधारित है।

एएससीई मैनुअल नंबर बयालीस में दिया गया मॉडल यथोचित रूप से परमाणु-विस्फोट-जनित हवा के दबाव में समय के साथ होने वाले बदलाव की ग्राउंड-जीरो से दूरी, विस्फोट की ऊंचाई, और विस्फोट की ऊर्जा के आधार पर औसत प्रवृत्ति का अनुमान लगाता है। इस निबंध में एएससीई मॉडल में मॉडल सम्बंधित, विस्फोट सम्बंधित, तथा परमाणु हमले के मापदंडों से सम्बंधित अनिश्चितताओं को सम्मिलित करके और अधिक बेहतर बनाने का प्रयास किया गया है। इसके लिए मॉडल के द्वारा लगाए गए अनुमानों की फील्ड डेटा के साथ तुलना की गयी है तथा संभाव्य परमाणु खतरे का अनुमान लगाने के लिए एक परिदृश्य विकसित किया गया है। डिजाइन में प्रत्यक्ष उपयोग के लिए, पीक ओवरप्रेसर और पॉजिटिव फेज का अनुमान लगाने के लिए दो सरल गणितीय समीकरण प्रस्तावित किये गए हैं। इस के आलावा एक और समीकरण एयरओवरप्रेसर हिस्ट्री के अनुमान के लिए प्रस्तावित किया गया है।

भू-विस्थापन के अनुमान के लिए, भू-अवयवों में विस्फोट के कारण उत्पन्न स्ट्रेस-स्ट्रेन का उपयुक्त विवरण एक महत्वपूर्ण पद है। पिछले प्रयोगात्मक और सैद्धांतिक अनुसंधानों के प्रयास ने यह संकेत दिया कि ब्लास्ट लोडिंग के तहत भू-अवयवों का व्यवहार विस्फोट कारण उत्पन्न दबाव, दबाव की दर तथा मृदा के तीन अवयवों (ठोस, तरल और गैसों) के आपसी सम्बन्ध पर निर्भर करता है तथा भू-अवयवों के व्यवहार को मॉडल करने के लिए उन्नत मॉडल भी उपलब्ध हैं। ये उन्नत मॉडल बहुत सारे भौतिक मापदंडों पर आधारित होते हैं,

जिनको कि अलग-अलग प्रायोगिक अध्ययनों और संख्यात्मक अभिकलनों के माध्यम से कैलिब्रेट करना पड़ता है। इसके अलावा, जियोमैटेरियल्स की अंतर्निहित परिवर्तनशीलता, परमाणु-वायु-विस्फोट-जनित ओवरप्रेसर की अनिश्चितता, तथा स्ट्रेस-स्ट्रेन मॉडल की अनिश्चितताओं के कारण जमीनी विस्थापन की गणना की लागत में और अधिक वृद्धि होगी। इसलिए, उन्नत मॉडल के विकल्प के रूप में, नया कार्यात्मक रूप जो की मात्र तीन मापदंडों: वेट फैक्टर, प्रारंभिक मापांक अनुपात, और स्ट्रेन रिकवरी अनुपात पर आधारित है, को इस निबंध में प्रस्तावित किया गया है। इन तीन मापदंडों के लिए एक चार्ट प्रस्तावित किया गया है जो की प्रायोगिक रूप से निर्धारित या संख्यात्मक रूप से सिमुलेटेड स्ट्रेस-स्ट्रेन डेटा सेट का इस्तेमाल करके कैलिब्रेट किया गया है। इस्तेमाल किये गए डाटा सेट में विभिन्न प्रकार के मृदा (रेत, सिल्ट और क्ले) जो की विभिन्न प्रकार की परिस्थितियों (सूखा, संतृप्त, आंशिक रूप से संतृप्त) के अधीन थीं तथा विभिन्न प्रकार के भार (गतिशील भार, ब्लास्ट लोड, और स्थिर भार) से दबायी गयीं थी उनको लिया गया है। प्रस्तावित चार्ट को इंजीनियर प्रत्यक्ष रूप से उपयोग में ला सकते हैं। यह देखा गया है कि प्रस्तावित कार्यात्मक रूप, न केवल ब्लास्ट लोड के लिए बल्कि स्थिर और अन्य गतिशील भार के लिए भी औसत रूप से स्वीकरणीय परिणाम देता है। इन मापदंडों की तनाव-दर, लेटरल कन्फ़ाइनमेंट, संतृप्ति की डिग्री, प्रारंभिक संघनन तथा लॉकिंग इनिसिएशन स्ट्रेस पर निर्भरता का विश्लेषण किया गया है और इन तीन मापदंडों का उचित अनुमान लगाने हेतु कुछ सरल मॉडल भी प्रस्तावित किए गए हैं।

इस निबंध के अंतिम चरण में, परमाणु-वायु-विस्फोट-प्रेरित जमीन के विस्थापन का अनुमान लगाने हेतु एक मॉडल, जो की एयरओवरप्रेसर हिस्ट्री और गहराई के साथ बदलने वाले भू-तकनीकी मापदंडों (तनाव तरंग वेग, तनाव क्षीणन और स्ट्रेस-स्ट्रेन मॉडल) पर आधारित है, प्रस्तावित किया गया है। अनुमानित विस्थापन की तुलना परमाणु तथा गैर-परमाणु परीक्षणों से प्राप्त परिणामों से की गयी है और उनके बीच एक उचित मिलान पाया गया है। यह देखा गया है कि प्रस्तावित मॉडल अधिक गहराई और ग्राउंड-जीरो से अधिक दूरी

पर विस्थापन का वास्तविकता से काफी अधिक अनुमान लगाता है। धरती पर परमाणु विस्फोट द्वारा लगाए गए दबाव तथा भू-तकनीकी गुणों का विस्थापन के ऊपर पड़ने वाले प्रभाव का अध्ययन करने के लिए भी प्रस्तावित मॉडल उपयोग किया गया है। इसके लिए पैरामीट्रिक अध्ययन तथा संवेदनशीलता विश्लेषण किया गया है। यह विश्लेषण इंगित करता है कि जमीन का विस्थापन सबसे अधिक ग्राउंड जीरो से दूरी, विस्फोट की ऊंचाई, और भू-अवयवों के विरूपण मापांक के प्रति संवेदनशील होता है।

परमाणु परीक्षणों द्वारा एकत्रित डेटा को प्रस्तावित विस्थापन मॉडल संबंधी अनिश्चितताओं को चिह्नित करने के लिए भी उपयोग में लाया गया है। चूंकि मॉडल पैरामीटर भी अनिश्चित हैं, इसलिए मॉडल अनिश्चितताओं की मात्रा का अनुमान लगाना गणितीय रूप से अत्यधिक कठिन और समय लेने वाला प्रक्रम है। इसलिए अनिश्चितताओं की मात्रा का अनुमान लगाने के लिए एक नया सन्निकट दृष्टिकोण प्रस्तावित किया गया है जो की टेलर की श्रृंखला के सन्निकटन पर आधारित है। प्रस्तावित दृष्टिकोण की तुलना एक उन्नत बायेसियन दृष्टिकोण पर आधारित परिणामों से की गयी है तथा यह पाया गया की प्रस्तावित मॉडल सन्निकट माध्य मॉडल कारकों की भविष्यवाणी बड़ी ही सरलता से कर लेता है। प्रस्तावित अनिश्चितता लक्षण वर्णन मॉडल के आधार पर यह पाया गया कि यदि प्रस्तावित विस्थापन मॉडल के मापदंड 0-20% की सीमा में अनिश्चित रूप से बदलें तो माध्य मॉडल अनिश्चितता कारक 0.78 से 0.99 के बीच में रहता है। चूंकि सभी माध्य मॉडल अनिश्चितता कारक 1 से कम हैं, यह इंगित करता है की प्रस्तावित विस्थापन मॉडल औसतन एक ऐसा अनुमान प्रदान करता है जो की वास्तविकता से थोड़ा अधिक होगा।

इस प्रकार (i) प्रस्तावित संभाव्य परमाणु-विस्फोट लोड मॉडल, (ii) प्रस्तावित स्ट्रेस-स्ट्रेन कार्यात्मक रूप, (iii) प्रस्तावित विस्थापन मॉडल, और (iv) प्रस्तावित मॉडल अनिश्चितता कारक का उपयोग करके परमाणु-वायु-विस्फोट-प्रेरित जमीन विस्थापन का गणितीय कुशलता के साथ एक विश्वसनीय अनुमान लगाया जा सकता है।

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