

**SEISMIC HAZARD AND STRUCTURAL STABILITY ON HILL SLOPES  
OF NORTH EAST INDIA**

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OF NORTH EAST INDIA**

by

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Submitted

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

to the



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Dedicated to My Sister and My Father

Hope you are fine up there in heaven

## CERTIFICATE

This is to certify that the thesis entitled, ‘**Seismic Hazard and Structural Stability on Hill Slopes of North East India**’ submitted by **Rebecca Ramhmachhuani** to the Indian Institute of Technology Delhi for the award of the degree of **DOCTOR OF PHILOSOPHY** is a record of the bonafide research work carried out by her. Rebecca Ramhmachhuani has worked under our supervision for the submission of this thesis, which to our knowledge has reached the requisite standard.

The thesis or any part of it has not been presented or submitted to any other University or Institute for any degree or diploma.

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## ABSTRACT

The region surrounding North East India is one of the most seismically active regions of the world, with several devastating earthquakes in the past including the Great Assam earthquakes of 1897, 1934 and 1950 which exceeded a moment magnitude  $M_w$  of 8.0. It lies in the foothills of the Himalayas which is believed to be formed as a result of collision of Indian and Asian plates some 50 million years ago.

The thesis covers seven (7) main objectives which include updating of earthquake catalogue for northeast India, delineating seismic sources in and around the region and establishing the seismological activities based on past earthquakes; generation of ground motion prediction equation and preparation of seismic hazard using deterministic and probabilistic approach; Estimation of shear wave velocity and predominant frequency in the region using geophysical investigations, static and dynamic stability and behavior of slopes and structures resting on slopes with different foundation system.

In short, the present study involves determining the seismic hazard of 43 cities/towns of North-East India's region deterministically as well as probabilistically. It also includes preparing earthquake catalog for each of these cities and towns. Further, to understand the behavior of hillslopes and the structures constructed on them in case of seismic load, one of the cities of the region, is selected for further study. The city chosen for detailed study is Aizawl, capital of Mizoram, where geophysical site characterization is carried out to find the shear wave velocity and the predominant frequency of the soil. The data obtained is further used in ground response study, the results of which are used as the dynamic loads in structural and slope stability analyses.

Seismotectonic map of the study area is prepared by considering 360 km radius around each city/town, which consists of seismogenic sources, past earthquake data collected from

various sources, the completeness of the data evaluated using decade based and yearly based methods. The data is then analyzed statistically, and the recurrence relationships for each is obtained using G-R method (Gutenberg and Richter 1994).

Two hundred and forty-three datasets are collected from 36 earthquakes which are used for generation of attenuation relationship for the region. The attenuation relationship generated is used in the deterministic and probabilistic seismic hazard study of North-East India for estimating the bedrock level PGA. The probabilistic approach is used for determining the PGA models at bedrock level corresponding to return periods of 475, 950, 975, 1950, 2475 and 4950 years respectively. The PGA maps at various return periods are then prepared.

Multi spectral analysis of surface wave (MASW) is used for measuring the shear wave velocity ( $V_s$ ) at forty-two (42) locations within Aizawl city using a 48-channel seismograph. Using the analysis result, the average shear wave velocity up to a depth of 30m ( $V_{S30}$ ) is also calculated which range from 230 to 880 m/s within the city. The sites are classified based on NEHRP site classification where the city is divided into three zones. Further, the local site conditions are assessed for local site effects using microtremor studies. Local site effects are often expressed regarding the resonance or fundamental frequency, its spectral amplification, and vulnerability index (Nakamura 1996, 1997) which depends on soil condition and bedrock depth. The test is performed on the same 42 locations in Aizawl, and a classification is also proposed. The proposed classification is based on the shape of H/V spectra, its predominant frequency, and its vulnerability index. A correlation between  $V_{S30}$  and predominant frequency is also developed for Aizawl area as

$$V_{S30} = 357.87 f^{0.42}$$

This correlation will be useful in estimating the  $V_{S30}$  for the locations in and around Aizawl. Ground response of the city is determine using various input parameter, and the

amplification map of the city is prepared. Further, the entire city lies on a hill slopes with the hills trending longitudinally in a series of north-south plunging anticlines and synclines with slope angle ranging between 10° and 70°. The building configurations are different than in plain areas and the slopes are constantly excavated for construction. The present study analyzed these slopes considering three most common configurations, categorize as bench slope, slope-bench and slope-bench-slope. These slopes are analyzed using Phase2D software which is FEM based for different densities and shear strengths range of combinations found in the region. Further, the building loads found in the region are imposed on these slopes. These slopes are exerted by different earthquake force generated using the ground response analysis to find the change in the factor of safety of the slope and the possible displacement. The results obtained are used for generation of permanent displacement model as given below.

$$\log D = 0.185 + \log \left[ \left( 1 - \frac{a_c}{a_{max}} \right)^{2.631} \left( \frac{a_c}{a_{max}} \right)^{-1.262} \right]$$

where, D is the displacement in cm,  $a_c$  is the critical angle of the slope where  $a_c = (FS-1)g \sin \alpha$ ,  $\alpha$  is the slope angle.  $a_{max}$  is the maximum acceleration .

Further, the study compares the behavior of a step-back configuration building for different soil conditions and dynamic forces. Four different conditions were adopted, namely, rigid based, soft soil sites, medium soil sites and hard rock sites based on the site classification proposed. It is observed that rigid based and hard rock sites behave similarly so as soft and medium soil sites. The interstorey drift, its hinge formation pattern, etc. are studied. It is observed that maximum hinge formations are observed on the soft soil site and the minimum on the medium soil sites. These observations are in accordance with ASCE-08 and hence are further analyzed for non-linear time history analysis using the ground motion

generated from the ground response studies normalized to PGA of 0.10, 0.20, 0.30, 0.36, 0.40, 0.50, 0.60 g respectively.

The results of this is used for determining the probability of exceeding a certain level of ductility at each floor. The acceptance of ductility for a normal reinforced building in accordance to IS13290 is 3.0-7.0. The results found that on medium and soft soil sites, the ductility demand may exceed the allowable demand in the top 2,3-storeys, where as in rigid and hard rock foundation level, the ductility demand increases between the 3<sup>rd</sup> and 5<sup>th</sup> storey, i.e. the middle floors, hence, future developers depending upon the foundation level have to take care of either the top floor or middle floor to take care of the ductility demand of the building.

## सार

पूर्वोत्तर भारत के आस-पास का क्षेत्र दुनिया के सबसे अधिक भूकंपीय सक्रिय क्षेत्रों में से एक है, जिसमें पूर्व में 1897, 1934 और 1950 के ग्रेट असम भूकंप सहित कई विनाशकारी भूकंप शामिल हैं, जो कि 8.0 के एक क्षण की सीमा से अधिक है। यह हिमालय की तलहटी में स्थित है, जो कि 50 मिलियन वर्ष पूर्व भारतीय और एशियाई प्लेटों के टकराव के कारण बनने का अनुमान है।

थीसिस सात (7) मुख्य उद्देश्यों को शामिल करता है जिसमें पूर्वोत्तर भारत के लिए भूकंप सूची को अद्यतन करना शामिल है, इस क्षेत्र में और आस-पास भूकंपीय स्रोतों को चित्रित करना और पिछले भूकंपों के आधार पर भूकंप संबंधी गतिविधियों की स्थापना करना; नियतनिष्कृत और संभाव्य दृष्टिकोण के आधार पर भू-गति भविष्यवाणी समीकरण और भूकंपीय खतरे की तैयारी; भूभौतिकीय जांच, स्थैतिक और गतिशील स्थिरता और ढलानों और ढांचे के व्यवहार का उपयोग करके क्षेत्र में कतरनी लहर वेग और प्रमुख आवृत्ति का आकलन, विभिन्न ढांचे प्रणाली के साथ ढलानों पर आराम।

संक्षेप में, वर्तमान अध्ययन में पूर्वोत्तर भारत के 43 शहरों / कस्बों के भूकंपीय खतरे के निर्धारण के साथ-साथ संभाव्य रूप से संभाव्य रूप से संभाव्य रूप से भी शामिल है। इसमें इन शहरों और कस्बों में से प्रत्येक के लिए भूकंप सूची तैयार करना भी शामिल है। इसके अलावा, पहाड़ियों के व्यवहार और भूकंपीय भार के मामले में उन पर निर्मित संरचनाओं को समझने के लिए, इस क्षेत्र के शहरों में से एक को आगे के अध्ययन के लिए चुना गया है। विस्तृत अध्ययन के लिए चुना गया शहर ऐज़ावल, मिजोरम की राजधानी है, जहां भूगर्भीय साइट का लक्षण वर्णन किया जाता है ताकि कतरनी लहर वेग और मिट्टी की प्रमुख आवृत्ति मिल सके। प्राप्त आंकड़ों का उपयोग ग्राउंड रिजविक अध्ययन में किया जाता है, जिसके परिणामस्वरूप संरचनात्मक और ढलान स्थिरता विश्लेषण में गतिशील भार के रूप में उपयोग किया जाता है।

प्रत्येक क्षेत्र / शहर के आसपास 360 किमी त्रिज्या पर विचार करके तैयार किया जाता है, जिसमें सीज़ोजेनिक स्रोत होते हैं, विभिन्न स्रोतों से एकत्र हुए पिछले भूकंप के आंकड़े, दशकों आधारित और वार्षिक आधारित तरीकों का उपयोग करके मूल्यांकन आंकड़ों की पूर्णता। डेटा को तब सांख्यिकीय रूप से विश्लेषण किया जाता है, और प्रत्येक के लिए पुनरावृत्ति संबंध जी-आर विधि (गुटेनबर्ग और रिक्टर 1994) के द्वारा प्राप्त किया जाता है।

36 भूकंपों से दो सौ और चालीस-तीन डेटासेट एकत्र किए जाते हैं जो क्षेत्र के लिए क्षीणन रिश्ते बनाने के लिए उपयोग किया जाता है। उत्पन्न होने वाली क्षीणन संबंधी संबंधों को आधारभूत पीजीए के आकलन के लिए उत्तर-पूर्व भारत के नियतात्मक और संभाव्य भूकंपी खतरे के अध्ययन में उपयोग किया जाता है। संभाव्य दृष्टिकोण का उपयोग क्रमशः 475, 950, 975, 1950, 2475 और 4950 वर्ष की वापसी अवधि के अनुरूप पीजीए मॉडल को निर्धारित करने के लिए किया जाता है। विभिन्न रिटर्न अवधि पर पीजीए मानचित्र तब तैयार होते हैं। सतह लहर (MASW) का मल्टी स्पेक्ट्रल विश्लेषण का उपयोग ऐजोल शहर के 48-चैनल सीस्मोग्राफ के उपयोग के बीच 42-दिवसीय (42) स्थानों पर कतरनी लहर वेग ( $V_s$ ) को मापने के लिए किया जाता है। विश्लेषण परिणाम का उपयोग करते हुए, औसत कतरनी लहर वेग 30 मीटर की गहराई तक ( $V_{s30}$ ) भी गणना की जाती है जो शहर के भीतर 230 से 880 मीटर / एस तक फैली हुई है। साइटों को एनईएचआरपी साइट वर्गीकरण के आधार पर वर्गीकृत किया गया है जहां शहर को तीन क्षेत्रों में विभाजित किया गया है। इसके अलावा, स्थानीय साइट शर्तों को स्थानीय साइट प्रभावों के लिए माइक्रोट्रैमरेमोर अध्ययनों का उपयोग करके मूल्यांकन किया जाता है। साइटों को एनईएचआरपी साइट वर्गीकरण के आधार पर वर्गीकृत किया गया है जहां शहर को तीन क्षेत्रों में विभाजित किया गया है। इसके अलावा, स्थानीय साइट शर्तों को स्थानीय साइट प्रभावों के लिए माइक्रोट्रैमरेमोर अध्ययनों का उपयोग करके मूल्यांकन किया जाता है। स्थानीय साइट प्रभाव अक्सर अनुनाद या मौलिक आवृत्ति, इसकी वर्णक्रमीय प्रवर्धन और भेद्यता सूचकांक (नाकामुरा 1996, 1997)

के बारे में व्यक्त किया जाता है जो मिट्टी की स्थिति और आधारभूत गहराई पर निर्भर करता है। परीक्षा में आइजोल के 42 स्थानों पर प्रदर्शन किया जाता है, और एक वर्गीकरण भी प्रस्तावित होता है। प्रस्तावित वर्गीकरण H/V स्पेक्ट्रा, इसकी प्रमुख आवृत्ति, और इसकी भेद्यता सूचकांक के आकार पर आधारित है। ऐजोल क्षेत्र के लिए  $V_{S30}$  और प्रमुख आवृत्ति के बीच एक संबंध भी विकसित किया गया है

$$V_{S30} = 357.87 f^{0.42}$$

ऐजावल में और आस-पास की जगहों के लिए  $V_{S30}$  का आकलन करने में यह सहसंबंध उपयोगी होगा। शहर के ग्राउंड प्रतिक्रिया विभिन्न इनपुट पैरामीटर का उपयोग करके निर्धारित किया जाता है, और शहर का प्रवर्धन नक्शा तैयार है। इसके अलावा, पूरे शहर एक पहाड़ी ढलानों पर स्थित है, जिसमें उत्तर-दक्षिण की एक श्रृंखला में लंबे समय तक चलने वाली पहाड़ियों के साथ पहाड़ियों पर चढ़ाई हुई है और 10° और 70° के बीच ढलान के कोण के साथ समेकित होते हैं। इमारत विन्यास सादे क्षेत्रों की तुलना में अलग हैं और ढलानों को लगातार निर्माण के लिए उत्खनन किया जाता है। वर्तमान अध्ययन में इन ढलानों का विश्लेषण किया गया है जो तीन सबसे सामान्य कॉन्फिगरेशनों पर विचार कर रहे हैं, बेंच स्लोप, ढाल-बेंच और ढाल-बेंच-ढाल के रूप में वर्गीकृत करें। इन ढलानों का विश्लेषण Phase2D सॉफ्टवेयर का उपयोग करके किया जाता है जो कि क्षेत्र में पाए जाने वाले संयोजनों की विभिन्न घनत्व और कतरनी शक्ति सीमाओं के आधार पर एफईएम है। इसके अलावा, इन ढलानों पर क्षेत्र में पाए जाने वाले भवन भार को लगाया जाता है। इन ढलानों को ढलान की सुरक्षा के कारक और संभव विस्थापन में परिवर्तन को खोजने के लिए ग्राउंड रिस्पॉस विश्लेषण के उपयोग से उत्पन्न विभिन्न भूकंप बल द्वारा उपयोग किया जाता है। प्राप्त परिणाम स्थायी विस्थापन मॉडल के निर्माण के लिए नीचे दिए गए हैं।

$$\log D = 0.185 + \log \left[ \left( 1 - \frac{a_c}{a_{max}} \right)^{2.631} \left( \frac{a_c}{a_{max}} \right)^{-1.262} \right]$$

इसके अलावा, अध्ययन विभिन्न मिट्टी की स्थितियों और गतिशील ताकत के लिए एक कदम-बैक कॉन्फ़िगरेशन बिल्डिंग के व्यवहार की तुलना करता है। साइट वर्गीकरण के आधार पर प्रस्तावित चार अलग-अलग स्थितियों को अपनाया गया, अर्थात् कठोर आधारित, मुलायम मिट्टी की जगहें, मध्यम मिट्टी साइटें और हार्ड रॉक साइटें। यह देखा गया है कि कठोर आधारित और हार्ड रॉक साइटें इसी तरह से व्यवहार करती हैं ताकि नरम और मध्यम मिट्टी की साइटें हो सकें। इंटरस्टॉरी ड्रिफ्ट, इसका काज रचना पैटर्न आदि का अध्ययन किया जाता है। यह देखा गया है कि मृदा मृदा साइट पर अधिकतम हंसी संरचनाएं देखी जाती हैं और मध्यम मिट्टी साइट पर न्यूनतम। इन टिप्पणियों को एससीई -08 के अनुसार किया गया है और इसलिए इसके आधार पर गैर-रैखिक समय के इतिहास के विश्लेषण के लिए विश्लेषण किया जाता है, जो ग्राउंड रिजॉल्यूशन के सामान्य अध्ययन से उत्पन्न ग्राउंड गति का उपयोग करते हैं, जो क्रमशः 0.10, 0.20, 0.30, 0.36, 0.40, 0.50, 0.60 ग्राम पीजीए में होता है।

इसका परिणाम प्रत्येक मंजिल पर लचीलापन के एक निश्चित स्तर से अधिक होने की संभावना का निर्धारण करने के लिए किया जाता है। IS13290 के अनुसार एक सामान्य प्रबलित इमारत के लिए लचीलापन की स्वीकृति 3.0-7.0 है। परिणामस्वरूप पाया गया कि मध्यम और नरम मिट्टी की जगहों पर, लचीलापन की मांग शीर्ष 2 और 3 मंजिला में स्वीकार्य मांग से अधिक हो सकती है, जहां कठोर और हार्ड रॉक नींव स्तर के रूप में, लंचता की मांग तीसरी और पांचवीं मंजिल के बीच बढ़ जाती है, अर्थात् मध्य फर्श, इसलिए, भविष्य के डेवलपर्स को नींव स्तर के आधार पर भवन की लचीलापन की मांग का ख्याल रखने के लिए या तो शीर्ष मंजिल या मध्य मंजिल का ख्याल रखना होगा।

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## LIST OF NOTATIONS

The following list defines the principle symbols and abbreviations used in the thesis. Symbols not given here are defined as they appear in the test.

$\phi$	angle of internal friction
$\tau_{\sigma}$	shear resistance
$\sigma\Delta$	stress parameter
$\sigma_e$	effective vertical stress of the soil
$\Delta$	displacement
$(G/G_{\max})$	shear modulus ratio
$\gamma_{\text{sat}}$	saturated density
$\Delta d$	distance between the receivers
$a_c$	critical acceleration
AHSA	average horizontal spectral amplification
$a_{\max}$	maximum ground surface acceleration
$A_r^{\text{NHV}}$	H/V ratio rock site
$A_s$	horizontal to vertical ratio
$c$	cohesion intercept
$D_H$	horizontal displacement
DSHA	deterministic seismic hazard analysis
$E$	Young's modulus
$f$	predominant frequency
$f_c$	corner frequency
FFT	fast Fourier transform
FS	factor of safety
$g$	specific gravity
$G$	shear modulus
$G_{\max}$	maximum shear modulus
$I_{\text{MM}}$	modified Mercalli scale
JMA	Japan Metrological Agency
$k$	bulk modulus

K	stiffness
$K_g$	vulnerability index
L	dynamic load
MASW	multichannel analysis of surface waves
mb	body wave magnitude
$M_d$	duration magnitude
$M_k$	Kawasumi magnitude
$M_L$	Local magnitude
MMI	modified Mercalli intensity
$M_s$	surface wave magnitude
$M_w$	seismic moment magnitude
PGA	peak ground acceleration
PHA	peak horizontal acceleration
PSHA	probabilistic seismic hazard analysis
PVA	peak vertical acceleration
R	hypocentral distance
RA	relative amplification
$R_{JB}$	Joyner and Boore distance
$S_a$	spectral acceleration
SAF	soil amplification factor
T	time period
$T_p$	predominant period
$V_b$	S wave velocity of the basement layer
$V_s$	shear wave velocity
$V_{s30}$	average shear wave velocity up to 30 m
Z	zone factor
$\varepsilon$	standard error
$\mu$	shear modulus / ductility
$\sigma$	Poisson's ratio
$\phi$	phase difference / slope angle
$\tau$	shear stress on the soil element
$\omega_g$	ground frequency
$\xi_g$	ground damping