

**SEISMIC HAZARD AND GEOTECHNICAL
VULNERABILITY ASSESSMENT OF THE SOILS IN THE
KASHMIR REGION, JAMMU AND KASHMIR**

FALAK ZAHOOR



**DEPARTMENT OF CIVIL ENGINEERING
INDIAN INSTITUTE OF TECHNOLOGY DELHI
HAUZ KHAS, NEW DELHI – 110016
INDIA**

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by

FALAK ZAHOOR

DEPARTMENT OF CIVIL ENGINEERING

submitted

in fulfilment of the requirements of the degree of

DOCTOR OF PHILOSOPHY

to the



**DEPARTMENT OF CIVIL ENGINEERING
INDIAN INSTITUTE OF TECHNOLOGY DELHI
HAUZ KHAS, NEW DELHI -110016**

APRIL 2023

Dedicated

to

My Parents, Husband, Family, and Teachers

CERTIFICATE

This is to certify that the thesis entitled, ‘**Seismic Hazard and Geotechnical Vulnerability Assessment of the Soils in the Kashmir Region, Jammu and Kashmir**’ submitted by **Ms. Falak Zahoor (2015CEZ8487)** 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. Ms. Falak Zahoor 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.

Prof. Neelima Satyam

Professor
IIT Indore

Prof. K. Seshagiri Rao

Professor
IIT Delhi

**Department of Civil Engineering
Indian Institute of Technology Delhi
Hauz Khas, New Delhi – 110016
INDIA**

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ABSTRACT

The Kashmir Nappe Zone is an asymmetrical synclinorium flanked by the Panjal Thrust and the Zaskar thrust, with the oldest stratigraphic basement floor composed of the Precambrian Salkhala series and the Dogra slates (Wadia, 1931). The sedimentary sequence is formed by the Panjal Volcanics (Panjal trap and Agglomeratic slates) and Triassic limestone. The sediments covering the synclinal basement of Kashmir are mainly of two types, namely, Plio-Pleistocene Karewas and the Holocene/Recent Alluvium (Wadia, 1931). The Alluvial plains/lowlands along with the Karewa highlands/terraces form an interesting combination of geological formations within the Kashmir valley. The surrounding hills, mountain ranges, the presence of wetlands, reclaimed swamps, and rivers contribute to the variability of soils within the region.

IS Code (IS 1893: 2016) designates seismic zones IV and V to the areas in the Kashmir valley. The region has suffered huge damages owing to devastating earthquakes in the past, the most significant being the M_w 7.6 2005 Kashmir earthquake. Landslides, flooding of rivers, ground fissures and cracks, huge ground movements, damage to built structures, and loss of life have been reported in previous earthquakes in Kashmir (Iyengar et al., 1999; Ahmad and Shafi, 2014). Moreover, liquefaction has occurred in many regions of Jammu and Kashmir both in the recent and the historic past during earthquakes (Bhat et al., 2005; Sahoo et al., 2007; Hough et al., 2009; Sana and Nath, 2016).

In view of the distinctive characteristics of the Kashmir region, the primary purpose of this study is to understand the behaviour of the deposits in the Kashmir Region and develop simplified recommendations aimed at guiding the selection of suitable foundation levels and/or ground improvement levels for future constructions within the area. The proposed guidelines are intended to assist planners and designers in taking appropriate decisions for the urbanisation and future town planning endeavours in the region. This study involves geotechnical and geological characterization of the region, assessment of seismic hazards, estimation of dynamic parameters of the deposits using geophysical tests, seismic site characterization and ground response analysis, liquefaction hazard assessment, bearing capacity assessment, and ultimately the determination of vulnerability zones.

Extensive geotechnical data for about 700 locations within the Kashmir valley was used to characterize the geotechnical properties of the soils in this region. The variation of the geotechnical properties within the geological units especially Karewa highlands and Alluvial

floodplains has been studied in detail. Maps for the various soil properties have been created to understand their spatial distribution within the region. The geotechnical database was combined with the geological information for the region to create seven transverse and five longitudinal comprehensive 2D cross-sections for the basin.

Seismic hazard assessment for the Kashmir region, using deterministic as well as probabilistic approaches has been performed. An earthquake catalogue has been prepared and subsequently, seismicity parameters (a , b -value, λ , M_C , and m_{max}) have been estimated for the complete Kashmir region. Spatial distributions for the peak ground acceleration (PGA) and peak spectral acceleration (PSA) at 0.2s and 1s have been presented in the form of contour maps at bedrock. Seismic zonation of the Kashmir region was carried out based on the distribution of PGA within the region. The Kashmir region has been divided into five zones ZA-ZE representing high to low seismicity zones. The mean PGA values derived from PSHA at 2475-year return period for the five zones are 0.514g, 0.456g, 0.379g, 0.258g, and 0.175g. The southern, northwestern and northernmost parts of the region including the districts of Pulwama, Shopian, Kulgam, and Budgam fall under high seismicity zones. In contrast, the central parts including the districts of Bandipora and Ganderbal fall under low seismicity zones. Seismic hazard curves, uniform hazard response spectra (UHRS) and disaggregation results have been presented for each of the ten districts as well as for each seismic zone

An extensive geophysical testing program was carried out which included tests at ~192 sites to determine dynamic soil parameters within the complete Kashmir region. Multichannel Analysis of Surface Waves (MASW) was performed to estimate shear wave velocity (V_s) and microtremor records were obtained to estimate the frequency response of the soil deposits. The V_{S30} (average shear wave velocity over 3m depth) varies from as low as 150-200m/s in the alluvial floodplains to as high as 350-500m/s in the Karewa highlands. On the other hand, the hilly regions show much higher values of ~500-900m/s indicating a close relationship of V_{S30} with geology. The horizontal-to-vertical-spectral ratio (HVSr) response of the soils is varied, with fundamental frequency (f_0) ranging from as low as 0.2Hz in the deep sedimentary deposits to as high as 20 Hz in the shallow region. Different groups of HVSr curves – clear, broad, and flat peaks were observed in the Kashmir region.

With regards to the exceptional nature of the physiography as well as topography of the region, the results obtained through geophysical tests suggest high variability. Fractured zones in fault lines have been detected in this study showing very high amplification due to the low velocity characteristics. Such zones may contribute to concentrated increased hazard

when subjected to favorable earthquake ground motions and must also be considered during the urban planning and construction processes. Joint inversion analysis of the dispersion and HVSR curves has been conducted to estimate the depth of the bedrock depth in the region. It is concluded that the Karewa deposits and Alluvial plains are deep sedimentary deposits with depths as large as 900-1300m. The shear wave velocity of the bedrock below the soft sediments is estimated to be ~1100-1900m/s. The depth of bedrock is shallow in the hills and mountains.

Although the conventional single-proxy approach for seismic site characterization has the advantage of being simple and based on a readily available parameter (V_{S30}), it neglects various key elements of site response (Castellaro and Mulargia, 2014). The results of the field testing in Kashmir reveal glaring anomalies in the behaviour of the deposits in the region pointing out the insufficiency of the parameter V_{S30} . V_{S30} completely lacks information pertaining to the actual variation of V_s with depth, the frequency dependence of response, and the influence of soil below 30m depth which can be critical in deep sedimentary deposits (Regnier et al., 2014). Consequently, a site classification scheme has been proposed in this study for the Kashmir region by modifying specific parameter ranges in Di Alessandro et al. (2012) classification which is based on the predominant frequency of the site, the HVSR shape, and V_{S30} .

1D nonlinear ground response analysis has been conducted for the 192 sites in the Kashmir region. The ground response analysis of the soils conducted in this study considers the actual depth of geological bedrock determined from the joint inversion analysis as the depth of input motion. The nonlinear behaviour has been captured by conducting a parametric study utilizing input motions of varied intensity (PGA) grouped into five intensity groups (M1-M5). Amplification factors have been recommended for each intensity group and each geological unit. The response spectra at the surface reveal that the deep deposits amplify the long-period (low-frequency) motions and deamplify the short-period (high-frequency) motions. This result is crucial since the impact may be particularly detrimental to tall buildings having longer fundamental periods due to the double resonance phenomenon in the soft soil deposits subjected to low-frequency earthquakes.

The expanded Srinagar Metropolitan Region – Greater Srinagar – in the Master Plan-2035 by the Town Planning Organization of Srinagar was selected for further detailed analysis including liquefaction hazard analysis and bearing capacity assessment. The liquefaction hazard assessment has been conducted considering the PGA_{bedrock} corresponding to 2475

years return period (10% probability of exceedance in 50 years). Both pseudo-probabilistic (PP), as well as simplified performance-based methods (sPBEE), have been used and the results from both methods have been compared. Simplified performance-based liquefaction triggering procedure allows engineers to adopt a risk-targeted strategy by utilizing the return period of liquefaction in place of the ground motion. Reference loading parameter maps at seven selected return periods (108, 225, 475, 1033, 2475, 4950, and 20000 years) were developed. Liquefaction hazard index (LHI) was estimated using three parameters, namely settlement (S), liquefaction potential index (LPI), and liquefaction severity number (LSN). Finally, LHI based zonation was conducted for the study area. It was concluded that young Holocene alluvial sediments deposited in low-energy fluvial environments are the most susceptible to liquefaction having the lowest factor of safety (<1) and the highest potential of liquefaction (~ 0.99). The sPBEE method in general overestimates the hazard in terms of settlement in moderate to high seismicity areas.

The bearing capacity of the soils at each site in the Greater Srinagar region has been assessed both under static as well as seismic loading conditions. The ultimate bearing capacity is in general less than 300kPa in the Jhelum floodplains indicating the low strength of the soils. The Karewa highlands and hills show much higher capacity (>300 kPa). The seismic bearing capacity ratio (SBCR) computed using Richards et al. (1993) and Choudhury and Subba Rao (2005) methods are lower (<0.86) in the Karewa deposits suggesting the critical nature of these deposits under seismic loads. Consequently, the bearing capacity hazard index (BCHI) has been determined at each location.

Finally, vulnerability zones (VZ-A to VZ-D) have been defined based on the integrated hazard index (IHI) computed by combining LHI and BCHI through the analytical hierarchy process (AHP). The Jhelum floodplains fall within the most critical category of VZ-D with the highest hazard of liquefaction and low bearing capacity. Deep foundations (e.g., piles) and deep ground improvement is imperative in the plains to prevent excessive settlements and bearing capacity failures in structures. Site-specific issues of lateral spread need to be assessed on land near the banks of rivers.

The Karewa highlands fall in categories VZ-B and VZ-C showing lower potential for liquefaction and good static bearing capacity yet significant chances of significant bearing capacity reduction during earthquakes. Integrated use of shallow foundations and ground improvement may be effective solution in such areas. There is an added hazard of landslides

and slope stability issues in the highlands which needs to be duly considered in foundation design.

The deep sedimentary deposits (Karewas and Jhelum floodplains) in general, can have a significant influence on the performance of structures existing on the ground in several aspects. Low-frequency amplification is critical for the multi-storeyed buildings on these deposits and a Mexico City-like disaster may be in waiting in event of a future earthquake of bolstering characteristics. Large ground deformations associated with the top 20-30m of the soft soils may lead to significant damage to structures if not incorporated adequately in design. The softened layers further filter out the high-frequency waves, amplifying the low-frequency components. In this respect, the characteristics of the soils like thickness, stratification, geotechnical properties, and stiffness play an important role in the response towards seismic waves. Proper damping measures must be provided in the construction of tall buildings on these deep sedimentary deposits.

The hills and mountains are designated VZ-A category suggesting that liquefaction is highly unlikely and static bearing capacity is quite significant. Shallow foundations may be sufficient in these areas, although extra provisions for slope stability issues and high-frequency amplifications need to be suitably made.

The vulnerability zones delineated in the Greater Srinagar region are intended to provide basic information about the geotechnical as well as seismic hazards in the region. In this study, we recommend certain measures to mitigate seismic hazard effects in the different vulnerability zones including ground improvement techniques and the selection of appropriate types of foundations with a proper reinforcement design.

सारांश

कश्मीर नेप्पे जोन एक विषम सिंकलिनोरियम है जो पंजाल थ्रस्ट और ज़ांस्कर थ्रस्ट से घिरा हुआ है, जिसमें सबसे पुराना स्ट्रेटिग्राफिक बेसमेंट फ्लोर है जो प्रीकैम्ब्रियन सलखला श्रृंखला और डोगरा स्लेट (वाडिया, 1931) से बना है। तलछटी अनुक्रम पंजाल ज्वालामुखी (पंजाल जाल और एग्लोमेरेटिक स्लेट) और ट्रायसिक चूना पत्थर द्वारा बनाया गया है। कश्मीर के समकालिक तहखाने को कवर करने वाले तलछट मुख्य रूप से दो प्रकार के होते हैं, अर्थात्, प्लियो-प्लेइस्तोसीन करेवास और होलोसीन / हालिया जलोढ़ (वाडिया, 1931)। कारेवा हाइलैंड्स/छतों के साथ जलोढ़ मैदान/तराई कश्मीर घाटी के भीतर भूवैज्ञानिक संरचनाओं का एक दिलचस्प संयोजन बनाते हैं। आसपास की पहाड़ियां, पर्वत श्रृंखलाएं, आर्द्रभूमि की उपस्थिति, पुनः प्राप्त दलदल और नदियाँ इस क्षेत्र के भीतर मिट्टी की परिवर्तनशीलता में योगदान करती हैं।

आईएस कोड (आईएस 1893: 2016) कश्मीर घाटी के क्षेत्रों में भूकंपीय क्षेत्र IV और V को नामित करता है। इस क्षेत्र को अतीत में विनाशकारी भूकंपों के कारण भारी नुकसान का सामना करना पड़ा है, सबसे महत्वपूर्ण एमडब्ल्यू 7.6 2005 कश्मीर भूकंप था। कश्मीर में पिछले भूकंपों में भूस्खलन, नदियों की बाढ़, जमीन की दरारें और दरारें, विशाल जमीन की आवाजाही, निर्मित संरचनाओं को नुकसान और जीवन के नुकसान की सूचना मिली है (अयंगर एट अल। अहमद और शफी, 2014)। इसके अलावा, भूकंप के दौरान हाल के और ऐतिहासिक अतीत दोनों में जम्मू और कश्मीर के कई क्षेत्रों में द्रवीकरण हुआ है (भट एट अल। साहू और अन्य, 2007; होफ एट अल, 2009; सना और नाथ, 2016)।

कश्मीर क्षेत्र की विशिष्ट विशेषताओं को ध्यान में रखते हुए, इस अध्ययन का प्राथमिक उद्देश्य कश्मीर क्षेत्र में जमा राशियों के व्यवहार को समझना और क्षेत्र के भीतर भविष्य के निर्माणों के लिए उपयुक्त नींव स्तरों और / या जमीनी सुधार स्तरों के चयन का मार्गदर्शन करने के उद्देश्य से सरलीकृत सिफारिशें विकसित करना है। प्रस्तावित दिशानिर्देशों का उद्देश्य योजनाकारों और डिजाइनरों को क्षेत्र में शहरीकरण और भविष्य के नगर नियोजन प्रयासों के लिए उचित निर्णय लेने में सहायता करना है। इस अध्ययन में क्षेत्र के भू-तकनीकी और भूवैज्ञानिक लक्षण वर्णन, भूकंपीय खतरों का आकलन, भूभौतिकीय परीक्षणों का उपयोग करके जमा के गतिशील मापदंडों का आकलन, भूकंपीय साइट लक्षण वर्णन और जमीनी प्रतिक्रिया विश्लेषण, द्रवीकरण जोखिम मूल्यांकन, असर क्षमता मूल्यांकन और अंततः भेद्यता क्षेत्रों का निर्धारण शामिल है।

कश्मीर घाटी के भीतर लगभग 700 स्थानों के लिए व्यापक भू-तकनीकी डेटा का उपयोग इस क्षेत्र में मिट्टी के भू-तकनीकी गुणों को चिह्नित करने के लिए किया गया था। भूवैज्ञानिक इकाइयों विशेष रूप से

करेवा हाइलैंड्स और जलोढ़ बाढ़ के मैदानों के भीतर भू-तकनीकी गुणों की भिन्नता का विस्तार से अध्ययन किया गया है। क्षेत्र के भीतर उनके स्थानिक वितरण को समझने के लिए विभिन्न मिट्टी के गुणों के लिए मानचित्र बनाए गए हैं। बेसिन के लिए सात अनुप्रस्थ और पांच अनुदैर्घ्य व्यापक 2 डी क्रॉस-सेक्शन बनाने के लिए भू-तकनीकी डेटाबेस को क्षेत्र के लिए भूवैज्ञानिक जानकारी के साथ जोड़ा गया था।

नियतात्मक और संभाव्य दृष्टिकोणों का उपयोग करके कश्मीर क्षेत्र के लिए भूकंपीय खतरे का आकलन किया गया है। एक भूकंप सूची तैयार की गई है और बाद में, पूरे कश्मीर क्षेत्र के लिए भूकंपीय मापदंडों (ए, बी-वैल्यू, ए, एमसी, और एमकेक्स) का अनुमान लगाया गया है। पीक ग्राउंड एक्सेलरेशन (पीजीए) और पीक स्पेक्ट्रल एक्सेलरेशन (पीएसए) के लिए 0.2 एस और 1 पर स्थानिक वितरण को आधार पर समोच्च मानचित्रों के रूप में प्रस्तुत किया गया है। कश्मीर क्षेत्र का भूकंपीय क्षेत्र क्षेत्र के भीतर पीजीए के वितरण के आधार पर किया गया था। कश्मीर क्षेत्र को पांच क्षेत्रों जेडए-जेडई में विभाजित किया गया है जो उच्च से निम्न भूकंपीय क्षेत्रों का प्रतिनिधित्व करते हैं। पांच क्षेत्रों के लिए 2475 साल की रिटर्न अवधि में पीएसएचए से प्राप्त औसत पीजीए मान 0.514 ग्राम, 0.456 ग्राम, 0.379 ग्राम, 0.258 ग्राम और 0.175 ग्राम हैं। पुलवामा, शोपियां, कुलगाम और बडगाम जिलों सहित क्षेत्र के दक्षिणी, उत्तर-पश्चिमी और उत्तरी हिस्से उच्च भूकंपीय क्षेत्रों में आते हैं। इसके विपरीत, बांदीपुरा और गांदरबल जिलों सहित मध्य भाग कम भूकंपीय क्षेत्रों में आते हैं। दस जिलों में से प्रत्येक के साथ-साथ प्रत्येक भूकंपीय क्षेत्र के लिए भूकंपीय जोखिम वक्र, समान जोखिम प्रतिक्रिया स्पेक्ट्रा (यूएचआरएस) और विघटन परिणाम प्रस्तुत किए गए हैं

एक व्यापक भूभौतिकीय परीक्षण कार्यक्रम किया गया था जिसमें पूर्ण कश्मीर क्षेत्र के भीतर गतिशील मिट्टी के मापदंडों को निर्धारित करने के लिए ~ 192 साइटों पर परीक्षण शामिल थे। सतह तरंगों का मल्टीचैनल विश्लेषण (एमएसडब्ल्यू) कतरनी तरंग वेग (वीएस) का अनुमान लगाने के लिए किया गया था और मिट्टी के जमा की आवृत्ति प्रतिक्रिया का अनुमान लगाने के लिए माइक्रोट्रेमर रिकॉर्ड प्राप्त किए गए थे। वीएस₃₀ (3 मीटर गहराई पर औसत कतरनी तरंग वेग) जलोढ़ बाढ़ के मैदान में 150-200 मीटर / सेकंड से लेकर करेवा हाइलैंड्स में 350-500 मीटर / सेकंड तक भिन्न होता है। दूसरी ओर, पहाड़ी क्षेत्र ~ 500-900 मीटर / सेकंड के बहुत अधिक मूल्य दिखाते हैं जो भूविज्ञान के साथ वीएस₃₀ के घनिष्ठ संबंध को दर्शाता है। मिट्टी की क्षैतिज-से-ऊर्ध्वाधर-वर्णक्रमीय अनुपात (एचवीएसआर) प्रतिक्रिया विविध है, जिसमें मौलिक आवृत्ति (एफ₀) गहरी तलछटी जमा में 0.2 हर्ट्ज से लेकर उथले क्षेत्र में 20 हर्ट्ज तक

होती है। एचवीएसआर मोड़ों के विभिन्न समूह - स्पष्ट, चौड़ी और सपाट चोटियां कश्मीर क्षेत्र में देखी गईं।

फिजियोग्राफी की असाधारण प्रकृति के साथ-साथ क्षेत्र की स्थलाकृति के संबंध में, भूभौतिकीय परीक्षणों के माध्यम से प्राप्त परिणाम उच्च परिवर्तनशीलता का सुझाव देते हैं। इस अध्ययन में फॉल्ट लाइनों में खंडित क्षेत्रों का पता लगाया गया है जो कम वेग विशेषताओं के कारण बहुत अधिक प्रवर्धन दिखाते हैं। अनुकूल भूकंप ग्राउंड गतियों के अधीन होने पर ऐसे क्षेत्र केंद्रित बढ़े हुए खतरे में योगदान कर सकते हैं और शहरी नियोजन और निर्माण प्रक्रियाओं के दौरान भी विचार किया जाना चाहिए। क्षेत्र में चट्टान की गहराई की गहराई का अनुमान लगाने के लिए फैलाव और एचवीएसआर वक्रों का संयुक्त व्युत्क्रम विश्लेषण किया गया है। यह निष्कर्ष निकाला गया है कि करेवा निक्षेप और जलोढ़ मैदान गहरे तलछटी निक्षेप हैं जिनकी गहराई 900-1300 मीटर तक है। नरम तलछट के नीचे चट्टान की कतरनी तरंग वेग ~ 1100-1900 मीटर / सेकंड होने का अनुमान है। पहाड़ियों और पहाड़ों में चट्टान की गहराई उथली है।

यद्यपि भूकंपीय साइट लक्षण वर्णन के लिए पारंपरिक एकल-प्रॉक्सी दृष्टिकोण सरल और आसानी से उपलब्ध पैरामीटर (वीएस 30) पर आधारित होने का लाभ है, यह साइट प्रतिक्रिया के विभिन्न प्रमुख तत्वों की उपेक्षा करता है (कैस्टेलारो और मुलरगिया, 2014)। कश्मीर में फील्ड परीक्षण के परिणामों से क्षेत्र में जमा के व्यवहार में स्पष्ट विसंगतियों का पता चलता है जो पैरामीटर वी एस 30 की अपर्याप्तता को इंगित करता है। वीएस 30 में गहराई के साथ वी एस की वास्तविक भिन्नता, प्रतिक्रिया की आवृत्ति निर्भरता और 30 मीटर गहराई से नीचे मिट्टी के प्रभाव से संबंधित जानकारी का पूरी तरह से अभाव है जो गहरी तलछटी जमा (रेगनियर एट अल। नतीजतन, इस अध्ययन में डी एलेसेंड्रो एट अल (2012) वर्गीकरण में विशिष्ट पैरामीटर श्रेणियों को संशोधित करके कश्मीर क्षेत्र के लिए एक साइट वर्गीकरण योजना प्रस्तावित की गई है जो साइट की प्रमुख आवृत्ति, एचवीएसआर आकार और वीएस 30 पर आधारित है।

कश्मीर क्षेत्र में 192 साइटों के लिए 1 डी नॉनलाइनियर ग्राउंड रिस्पांस विश्लेषण किया गया है। इस अध्ययन में किए गए मिट्टी के जमीनी प्रतिक्रिया विश्लेषण में संयुक्त व्युत्क्रम विश्लेषण से निर्धारित भूवैज्ञानिक आधार की वास्तविक गहराई को इनपुट गति की गहराई के रूप में माना जाता है। नॉनलाइनियर व्यवहार को पांच तीव्रता समूहों (एम 1-एम 5) में समूहीकृत विभिन्न तीव्रता (पीजीए) की इनपुट गतियों का उपयोग करके एक पैरामीट्रिक अध्ययन करके कैप्चर किया गया है। प्रत्येक तीव्रता समूह और प्रत्येक भूवैज्ञानिक इकाई के लिए प्रवर्धन कारकों की सिफारिश की गई है। सतह पर प्रतिक्रिया स्पेक्ट्रा से पता चलता है कि गहरी जमा लंबी अवधि (कम आवृत्ति) गति को बढ़ाती है और

छोटी अवधि (उच्च आवृत्ति) गतियों को कम करती है। यह परिणाम महत्वपूर्ण है क्योंकि कम आवृत्ति वाले भूकंपों के अधीन नरम मिट्टी जमा में दोहरी अनुनाद घटना के कारण प्रभाव लंबी मौलिक अवधि वाली ऊंची इमारतों के लिए विशेष रूप से हानिकारक हो सकता है।

श्रीनगर के नगर नियोजन संगठन द्वारा मास्टर प्लान-2035 में विस्तारित श्रीनगर महानगर क्षेत्र - ग्रेटर श्रीनगर - को द्रवीकरण जोखिम विश्लेषण और वहन क्षमता मूल्यांकन सहित आगे के विस्तृत विश्लेषण के लिए चुना गया था। 2475 वर्ष की वापसी अवधि (50 वर्षों में अधिक होने की 10% संभावना) के अनुरूप पीजीए आधार पर विचार करते हुए द्रवीकरण जोखिम मूल्यांकन आयोजित किया गया है। छद्म-संभाव्य (पीपी), साथ ही सरलीकृत प्रदर्शन-आधारित विधियों (एसपीबीईई) दोनों का उपयोग किया गया है और दोनों विधियों के परिणामों की तुलना की गई है। सरलीकृत प्रदर्शन-आधारित द्रवीकरण ट्रिगरिंग प्रक्रिया इंजीनियरों को जमीनी गति के स्थान पर द्रवीकरण की वापसी अवधि का उपयोग करके जोखिम-लक्षित रणनीति अपनाने की अनुमति देती है। सात चयनित रिटर्न अवधियों (108, 225, 475, 1033, 2475, 4950 और 20000 वर्ष) पर आर एफरेंस लोडिंग पैरामीटर मानचित्र विकसित किए गए थे। द्रवीकरण जोखिम सूचकांक (एलएचआई) का अनुमान तीन मापदंडों का उपयोग करके लगाया गया था, अर्थात् निपटान (एस), द्रवीकरण क्षमता सूचकांक (एलपीआई), और द्रवीकरण गंभीरता संख्या (एलएसएन)। अंत में, अध्ययन क्षेत्र के लिए एलएचआई आधारित जोनेशन आयोजित किया गया था। यह निष्कर्ष निकाला गया कि कम ऊर्जा वाले फ्लुवियल वातावरण में जमा युवा होलोसीन जलोढ़ तलछट द्रवीकरण के लिए अतिसंवेदनशील होते हैं जिनमें सुरक्षा का सबसे कम कारक (<1) और द्रवीकरण की उच्चतम क्षमता (~ 0.99) होती है। सामान्य रूप से एसपीबीईई विधि मध्यम से उच्च भूकंपीय क्षेत्रों में निपटान के संदर्भ में खतरे को अधिक महत्व देती है।

ग्रेटर श्रीनगर क्षेत्र में प्रत्येक स्थल पर मिट्टी की वहन क्षमता का आकलन स्थिर और भूकंपीय लोडिंग स्थितियों दोनों के तहत किया गया है। झेलम के बाढ़ क्षेत्र में अंतिम असर क्षमता सामान्य रूप से 300 केपीए से कम है जो मिट्टी की कम ताकत को दर्शाता है। करेवा हाइलैंड्स और पहाड़ियां बहुत अधिक क्षमता (>300 केपीए) दिखाती हैं। रिचर्ड्स एट अल (1993) और चौधरी और सुब्बा राव (2005) विधियों का उपयोग करके गणना की गई भूकंपीय असर क्षमता अनुपात (एसबीसीआर) करेवा जमा में कम (<0.86) है जो भूकंपीय भार के तहत इन जमाओं की महत्वपूर्ण प्रकृति का सुझाव देता है। नतीजतन, प्रत्येक स्थान पर असर क्षमता जोखिम सूचकांक (बीसीएचआई) निर्धारित किया गया है।

अंत में, विश्लेषणात्मक पदानुक्रम प्रक्रिया (एचपी) के माध्यम से एलएचआई और बीसीएचआई को मिलाकर गणना किए गए एकीकृत जोखिम सूचकांक (आईएचआई) के आधार पर भेद्यता क्षेत्रों (वीजेड-

ए से वीजेड-डी) को परिभाषित किया गया है। झेलम बाढ़ क्षेत्र वीजेड-डी की सबसे महत्वपूर्ण श्रेणी में आता है, जिसमें द्रवीकरण का सबसे अधिक खतरा और कम असर क्षमता है। संरचनाओं में अत्यधिक बस्तियों और वहन क्षमता विफलताओं को रोकने के लिए मैदानी इलाकों में गहरी नींव (जैसे, ढेर) और गहरी जमीन में सुधार अनिवार्य है। नदियों के किनारों के पास की भूमि पर पार्श्व फैलाव के स्थल-विशिष्ट मुद्दों का आकलन करने की आवश्यकता है।

करेवा हाइलैंड्स वीजेड-बी और वीजेड-सी श्रेणियों में आते हैं, जो द्रवीकरण और अच्छी स्थिर असर क्षमता के लिए कम क्षमता दिखाते हैं, फिर भी भूकंप के दौरान महत्वपूर्ण असर क्षमता में कमी की महत्वपूर्ण संभावना रखते हैं। उथली नींव का एकीकृत उपयोग और जमीनी सुधार ऐसे क्षेत्रों में प्रभावी समाधान हो सकता है। हाइलैंड्स में भूस्खलन और ढलान स्थिरता के मुद्दों का एक अतिरिक्त खतरा है जिसे नींव डिजाइन में विधिवत विचार करने की आवश्यकता है।

सामान्य रूप से गहरी तलछटी जमा (करेवास और झेलम बाढ़ क्षेत्र) कई पहलुओं में जमीन पर मौजूद संरचनाओं के प्रदर्शन पर महत्वपूर्ण प्रभाव डाल सकते हैं। इन निक्षेपों पर बहुमंजिला इमारतों के लिए कम आवृत्ति प्रवर्धन महत्वपूर्ण है और भविष्य में मजबूत विशेषताओं के भूकंप की स्थिति में मेक्सिको सिटी जैसी आपदा की प्रतीक्षा की जा सकती है। नरम मिट्टी के शीर्ष 20-30 मीटर से जुड़े बड़े जमीन विरूपण से संरचनाओं को महत्वपूर्ण नुकसान हो सकता है यदि डिजाइन में पर्याप्त रूप से शामिल नहीं किया जाता है। नरम परतें उच्च आवृत्ति तरंगों को फ़िल्टर करती हैं, कम आवृत्ति वाले घटकों को बढ़ाती हैं। इस संबंध में, मिट्टी की विशेषताएं जैसे मोटाई, स्तरीकरण, भू-तकनीकी गुण और कठोरता भूकंपीय तरंगों की प्रतिक्रिया में महत्वपूर्ण भूमिका निभाते हैं। इन गहरी तलछटी निक्षेपों पर ऊंची इमारतों के निर्माण में उचित उदासीनता उपाय प्रदान किए जाने चाहिए।

पहाड़ियों और पहाड़ों को वीजेड-ए श्रेणी नामित किया गया है जो यह सुझाव देता है कि द्रवीकरण की संभावना बहुत कम है और स्थिर असर क्षमता काफी महत्वपूर्ण है। इन क्षेत्रों में उथली नींव पर्याप्त हो सकती है, हालांकि ढलान स्थिरता के मुद्दों और उच्च आवृत्ति प्रवर्धन के लिए अतिरिक्त प्रावधान उपयुक्त रूप से किए जाने की आवश्यकता है।

ग्रेटर श्रीनगर क्षेत्र में चित्रित भेद्यता क्षेत्रों का उद्देश्य क्षेत्र में भू-तकनीकी के साथ-साथ भूकंपीय खतरों के बारे में बुनियादी जानकारी प्रदान करना है। इस अध्ययन में, हम विभिन्न भेद्यता क्षेत्रों में भूकंपीय खतरे के प्रभावों को कम करने के लिए कुछ उपायों की सिफारिश करते हैं, जिसमें जमीन सुधार तकनीक और उचित सुदृढीकरण डिजाइन के साथ उचित प्रकार की नींव का चयन शामिल है।

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