

**SEISMIC HAZARD EVALUATION OF JAMMU
REGION AND RISK ASSESSMENT OF TUNNELS
IN THE HIMALAYAS**

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IN THE HIMALAYAS**

by

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Submitted

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

to the



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Dedicated
To
Ammi, Abbu, Musfera
and
Prof. K. Seshagiri Rao

CERTIFICATE

This is to certify that thesis entitled “**SEISMIC HAZARD EVALUATION OF JAMMU REGION AND RISK ASSESSMENT OF TUNNELS IN THE HIMALAYAS**” being submitted by **MR. ANSARI ABDULLAH MOMIN MOHAMMED AMEEN** to the Indian Institute of Technology Delhi, is a record of the Bonafide research work carried out by him under our supervision and guidance. This thesis work, in our opinion, has reached the requisite standard, fulfilling the requirement for **DOCTOR OF PHILOSOPHY** degree.

The thesis or any part thereof has not been presented or submitted, in part or full, to any other University or Institute, for any degree or diploma.

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ABSTRACT

Jammu Region (JR) in Jammu and Kashmir is located in the northwestern part of the Himalayas, frequently triggered due to both near-field as well as far-field earthquakes. This area strongly affected during the 2005 Muzaffarabad earthquake ($M_w = 7.6$) in Kashmir Valley (KV), with devastation of infrastructure projects such as roads, bridges, dams and retaining walls. Recent moderate earthquakes in this region include the 2013 Kishtwar earthquake ($M_w = 5.7$) and the 2019 Mirpur earthquake ($M_w = 5.6$).

The first part of the present study involves the defining seismic environment and logic tree based hazard analysis using both deterministic and probabilistic approaches for JR. It also includes the development of an updated earthquake catalogue and seismotectonic of map study area. Total 242 site locations selected, and geophysical testing carried out to measure the resonance frequency and shear wave velocity for understanding the regional site characterisation. The data obtained is further used for seismic response analysis and liquefaction hazard assessment. Seismic microzonation map divided the JR into four zones based on Seismic Hazard Indexing (SHI). For each zone, the seismic performance and vulnerability of circular tunnel at various overburden depths are studied. Detailed tunnel data collected from the Udhampur Srinagar Baramulla Rail Link (USBRL) project and its employed to check the risk and post-seismic serviceability of transportation networks. Further, deep learning approach is used to develop the Seismic Tunnel Damage Prediction (STDP) Model. The STD multi-graph and seismic design guidelines for damage prediction and required mitigation steps also proposed.

Within a 350 km radius of the Jammu, all potential seismic sources were identified, and an updated earthquake catalogue was prepared, spanning the years 1520 AD to 2020 AD. In DSHA, a hybrid scenario is developed using two independent earthquake scenarios. Three

declustering algorithms with four GMPEs for active shallow crustal and Himalayan region clubbed to form a hybrid model for PSHA. Peak ground acceleration and peak spectral acceleration at 0.2 sec and 1.0 sec were estimated for 2% and 10% probability of exceedance in 50 and 100 years. For rock site conditions, the seismic hazard curves and uniform hazard response spectrum are presented for ten main cities of the Jammu region. This area shows the PGA variation between 0.08 g to 0.66 g with maximum hazard in the southwestern part comprising of districts of Poonch, Rajouri, Jammu, and parts of Reasi. The hazard maps along with the Hazard Curves (HC) and Uniform Hazard Response Spectrum (UHRS) employed effectively in the structural design and evaluation of new and existing structures which are part of ongoing infrastructure projects in the JR. They may also be used to determine the ground motion at the given location and to develop improved strategies for disaster risk reduction for engineers and planners which may eventually lead to fewer infrastructure damages.

The second part of the present work covers the extensive geophysical testing for site characterization, seismic response analysis and liquefaction hazard assessment. Microtremor Horizontal to Vertical Spectral Ratio (MHVSR) and Multichannel Simulation with One Receiver (MSOR) results indicate that the southern part of the JR has very low values of resonance frequency (f_0) and shear wave velocity (V_s) due to thick sedimentary and alluvial deposits. JR is classified into five zones (Z1, Z2, Z3, Z4, and Z5) based on the measured resonance frequency in the range of 0.1 to 10 Hz. Zone Z1 is reserved for sites with low resonance frequencies. More than 40% of the study area has resonance frequencies ranging from 4.0 to 7.0 Hz. The average shear wave velocity at 30 m depth (V_{s30}) for the JR varies from 182 to 934 m/s. Based on statistical parametric tests, this study also developed a subgrouping zonation strategy. A correlation between V_{s30} and resonance frequency is also developed.

Joint Fit Inversion Modelling (JFIM) is performed which gives shear wave velocity at deeper profiles needed for underground construction projects. These sites have extremely high

amplification and are prone to significant structural damage in the event of seismic activity. Complete overlapping of resonance frequency (f_0) of foundation soil with fundamental frequency (f_f) of Reinforced Concrete (RC) buildings was discovered for the maximum sites in southwestern towns of Jammu, Kathua, and Samba, indicating a significant danger of Double Resonance Effect (DRE).

This study provides a platform for designers working on future construction, development, and expansion projects to develop any prospective earthquake mitigation strategies. Nine different bedrock motions from the Himalayan region were considered and a one-dimensional seismic response analysis for the equivalent linear case has been done. For short periods, amplification is higher at sites with rock outcrops in the north and northwest, and lower at alluvium sites in the south. For long periods, the amplification is greater at Simbal and Jatah-like alluvium sites near the banks of the Rivers Tawi, Ravi, and Chenab. In Shareef Bagh, Banihal, and Bafilaiz, the $PGA_{surface}$ is more than 0.45 g.

An attempt has been made to develop the zonation map for liquefaction hazard in the JR based on liquefaction potential index (LPI) and probability of liquefaction (P_L). To achieve this, factor of safety against liquefaction was estimated using Standard Penetration Test (SPT) data collected from geotechnical consultancies and shear wave velocity measured during field testing, and an integrated liquefaction hazard map generated. The geotechnical parameters obtained from consultancies and V_s data obtained from geophysical field testing were integrated for the study region and a correlation for all types of soils developed using regression analysis.

The liquefaction features such as sand blows and ground rupture were found in Jatah (Samba district) and Simbal (Jammu district). According to the integrated hazard map, places near the bank of Tawi River and Ravi River in Jammu have young alluvium, making them particularly prone to liquefaction. Liquefaction does not occur in the eastern and western sections because of high shear wave velocities and rock at shallow depth, and it also does not occur in the central

area due to thick sand deposits. LPI values ranged from 0 to 27.45 having very low to very high liquefaction risk. P_L is greater than 0.75 for sites located on the southwestern side due to uniformly graded soil having extremely low SPT (N) and V_s values. This study will aid site planners in the construction of structures that consider liquefaction mitigation and well-defined liquefaction risk measures.

In the third and last part, the seismic vulnerability of circular tunnels using the fragility function under various seismic environments discussed. For all-hazard zones, an empirical relationship between tunnel damage state and PGA generated which further used to develop the zone specific fragility functions at various overburden depths. To achieve this, the seismic performance of tunnels with diversified typology and seismic scenario is quantified to understand the damage state for each hazard zones, as recommended by microzonation outcomes. For a given earthquake intensity, the fragility curves presented in this work illustrate the conditional probability of a circular tunnel reaching or exceeding a specified damage state. The probability of extensive damage is very high for tunnels at shallow depth in soft soil (Zone A), even at low seismic intensity. For tunnels with less than 30 m overburden depth, noteworthy deformation can be seen in both full and no slippage conditions. Due to flexible integrity, the amplification factor of input ground motion is larger in the deep tunnel than in the shallow tunnel. The distortion in the tunnel lining is declined by 50% in deeper tunnels when compared to shallow tunnels. This study can help designers to understand the seismic behaviour of circular tunnels at any depth having similar tectonic settings and structural typologies, while also considering additional damage models and other factors that influence seismic performance.

Semi-Quantitative Seismic Risk Assessment (SQ-SRA) approach has been used to evaluate the seismic risk and post-seismic serviceability of Udampur Srinagar Baramulla Rail Link (USBRL) project. Out of the three alignment phases, the first one is accessible, the center one

is accessible but requires repair, and the last one is inaccessible, according to the risk matrices. The majority of the tunnel sections in the last phase are situated near zones prone to landslides and large tectonic sources, and they also include extensively weathered rock mass, resulting in deformation, squeezing and cavity formation during the excavation process. The progressive effect of these issues increases the probability that these tunnels may get extensive damage, which would render the track segment inoperable under post-seismic conditions. The risk matrices and maps provided will serve as a valuable tool for increasing public awareness and directing track operations in the future event of major near-field or far-field earthquake events in Jammu and Kashmir.

Further, a mathematical formulation-based Seismic Tunnel Damage Prediction (STDP) model is proposed using the deep learning (DL) approach. The pertinency of the DL model is validated using tunnel damage data from historical earthquakes such as the 1999 Chi-Chi earthquake, the 2004 Mid-Niigata earthquake, and the 2008 Wenchuan earthquake. Peak ground acceleration (PGA), source to site distance (SSD), overburden depth (OD), lining thickness (t), tunnel diameter (Φ), and geological strength index (GSI) were employed as inputs to train Feedforward Neural Network (FNN) for damage state prediction. The performance evaluation results provided a clear indication for further use in a variety of risk assessment domains.

The final form of the Seismic Tunnel Damage Prediction (STDP) Model is given as:

$$\ln(DI) = \left[\frac{(SSD \times OD^{0.002}) + \left(\frac{PGA}{t}\right)^{4.2}}{GSI + \Phi^{4.2}} \right] + 1.15$$

When compared to models based on historical data, the proposed STDP model produces consistent results, demonstrating the robustness of the methodology used in this work. All models perform well during validation based on fitness metrics. The "STD multiple graphs" is

also proposed which provide information on damage indexing, damage pattern, and crack predictive specifications. This can be used as a ready toolbox to check the vulnerability in post-seismic scenarios. The seismic design guidelines for tunnelling projects are also proposed, which discuss the damage pattern and suggest mitigation measures. The proposed STDP model, STD multiple graphs, and seismic design guidance are applicable to any earthquake-prone tunnelling project anywhere in the world.

सारांश

जम्मू और कश्मीर में जम्मू क्षेत्र (JR) हिमालय के उत्तर-पश्चिमी भाग में स्थित है, जो अक्सर निकट-क्षेत्र और दूर-क्षेत्र भूकंप दोनों के कारण ट्रिगर होता है। कश्मीर घाटी (KV) में 2005 के मुजफ्फराबाद भूकंप ($M_w = 7.6$) के दौरान यह क्षेत्र सड़कों, पुलों, बांधों और रिटेनिंग दीवारों जैसी बुनियादी ढांचा परियोजनाओं के विनाश के साथ दृढ़ता से प्रभावित हुआ। इस क्षेत्र में हाल के मध्यम भूकंपों में 2013 किश्तवाड़ भूकंप ($M_w = 5.7$) और 2019 मीरपुर भूकंप ($M_w = 5.6$) शामिल हैं।

वर्तमान अध्ययन के पहले भाग में JR के लिए नियतात्मक और संभाव्य दोनों दृष्टिकोणों का उपयोग करके भूकंपीय वातावरण और तर्क वृक्ष आधारित जोखिम विश्लेषण को परिभाषित करना शामिल है। इसमें एक अद्यतन भूकंप सूची और मानचित्र अध्ययन क्षेत्र के सिस्मोटेक्टोनिक का विकास भी शामिल है। कुल 242 साइट स्थान का चयन किया गया, और क्षेत्रीय साइट लक्षण वर्णन को समझने के लिए अनुनाद आवृत्ति और कतरनी तरंग वेग को मापने के लिए भूभौतिकीय परीक्षण किया गया। प्राप्त आंकड़ों का उपयोग भूकंपीय प्रतिक्रिया विश्लेषण और द्रवीकरण खतरे के आकलन के लिए किया जाता है। भूकंपीय माइक्रोज़ोनेशन मानचित्र ने जेआर को भूकंपीय खतरा अनुक्रमण (SHA) के आधार पर चार क्षेत्रों में विभाजित किया। प्रत्येक क्षेत्र के लिए, भूकंपीय प्रदर्शन और विभिन्न ओवरबर्डन गहराई पर परिपत्र सुरंग की भेद्यता का अध्ययन किया जाता है। उधमपुर श्रीनगर बारामूला रेल लिंक (USBRL) परियोजना से एकत्र किए गए विस्तृत सुरंग डेटा और परिवहन नेटवर्क के जोखिम और भूकंप के बाद की सेवा क्षमता की जांच करने के लिए नियोजित किया गया है। इसके अलावा, भूकंपीय सुरंग क्षति पूर्वानुमान (STDP) मॉडल विकसित करने के लिए गहरी सीखने के दृष्टिकोण का उपयोग किया जाता है। क्षति की भविष्यवाणी और आवश्यक शमन कदमों के लिए STDP मल्टी-ग्राफ और भूकंपीय डिजाइन दिशानिर्देश भी प्रस्तावित किए गए हैं।

जम्मू के 350 किमी के दायरे में, सभी संभावित भूकंपीय स्रोतों की पहचान की गई थी, और एक अद्यतन भूकंप सूची तैयार की गई थी, जो 1520 ईस्वी से 2020 ईस्वी तक फैली हुई थी। DSHA में, दो स्वतंत्र

भूकंप परिदृश्यों का उपयोग करके एक हाइब्रिड परिदृश्य विकसित किया जाता है। सक्रिय उथले क्रस्टल और हिमालयी क्षेत्र के लिए चार GMPE के साथ तीन डिक्लस्टरिंग एल्गोरिदम को PSHA के लिए एक हाइब्रिड मॉडल बनाने के लिए क्लब किया गया। 0.2 सेकंड और 1.0 से सी पर पीईक ग्राउंड त्वरण और पीक वर्णक्रमीय त्वरण 50 और 100 वर्षों में 2% और 10% अधिकता की संभावना के लिए अनुमानित किया गया था। जम्मू क्षेत्र के दस मुख्य शहरों के लिए एफ या रॉक साइट की स्थिति, टी वह भूकंपीय खतरा घटता और एक समान खतरा प्रतिक्रिया स्पेक्ट्रम प्रस्तुत किया जाता है। यह क्षेत्र पुंछ, राजौरी, जम्मू जिलों और रियासी के कुछ हिस्सों वाले दक्षिण-पश्चिमी भाग में अधिकतम खतरे के साथ 0.08 ग्राम से 0.66 ग्राम के बीच पीजीए भिन्नता को दर्शाता है। खतरे के नक्शे के साथ-साथ हैजार्ड क्रॉस (HC) और यूनिफॉर्म एचअजार्ड आरएस्पोंसे एसपेक्ट्रम (UHRS) ने नई और मौजूदा संरचनाओं के संरचनात्मक डिजाइन और मूल्यांकन में प्रभावी ढंग से नियोजित किया जो JR में चल रही बुनियादी ढांचा परियोजनाओं का हिस्सा हैं। उनका उपयोग दिए गए स्थान पर जमीनी गति को निर्धारित करने और इंजीनियरों और योजनाकारों के लिए आपदा जोखिम में कमी के लिए बेहतर रणनीतियों को विकसित करने के लिए भी किया जा सकता है जो अंततः कम बुनियादी ढांचे के नुकसान का कारण बन सकता है।

वर्तमान कार्य के दूसरे भाग में साइट लक्षण वर्णन, भूकंपीय प्रतिक्रिया विश्लेषण और द्रवीकरण खतरे के आकलन के लिए ई एक्सटेंसिव जियोफिजिकल परीक्षण शामिल है। माइक्रोट्रेमर क्षैतिज से ऊर्ध्वाधर वर्णक्रमीय अनुपात (MHVSR) और एक रिसीवर (MSOR) परिणामों के साथ मल्टीचैनल सिमुलेशन से संकेत मिलता है कि जेआर के दक्षिणी भाग में मोटी तलछटी और जलोढ़ जमा के कारण अनुनाद आवृत्ति (f_0) और कतरनी तरंग वेग (V_s) के बहुत कम मूल्य हैं। जेआर को 0.1 से 10 Hz की सीमा में मापा अनुनाद आवृत्ति के आधार पर पांच क्षेत्रों (Z1, Z2, Z3, Z4, और Z5) में वर्गीकृत किया गया है। जोन Z1 कम अनुनाद आवृत्तियों वाली साइटों के लिए आरक्षित है। अध्ययन क्षेत्र के 40% से अधिक हाअनुनाद आवृत्तियों 4.0 से 7.0 Hz तक है। 30 मीटर गहराई पर औसत कतरनी तरंग वेग (V_{s30}) JR

के लिए 182 से 934 मीटर / सांख्यिकीय पैरामीट्रिक परीक्षणों के आधार पर, इस अध्ययन ने एक उपसमूह ज़ोनेशन रणनीति भी विकसित की। और अनुनाद आवृत्ति के बीच एक सहसंबंध भी विकसित V_{s30} किया गया है।

जेऑइंट एफयह मैएनवर्जन एमओडेलिंग (JFIM) किया जाता है जो भूमिगत निर्माण परियोजनाओं के लिए आवश्यक गहरी प्रोफाइल पर कतरनी तरंग वेग देता है। इन साइटों में अत्यधिक उच्च प्रवर्धन है और भूकंपीय गतिविधि की स्थिति में महत्वपूर्ण संरचनात्मक क्षति का खतरा है। जम्मू, कठुआ और सांबा के दक्षिण-पश्चिमी शहरों में अधिकतम स्थलों के लिए प्रबलित कंक्रीट (RC) इमारतों की मौलिक आवृत्ति (f_f) के साथ नींव मिट्टी की अनुनाद आवृत्ति (f_b) की पूर्ण ओवरलैपिंग की खोज की गई थी, जो डबल अनुनाद प्रभाव (DRE) के एक महत्वपूर्ण खतरे को दर्शाता है।

यह अध्ययन भविष्य के निर्माण, विकास और विस्तार परियोजनाओं पर काम करने वाले डिजाइनरों के लिए किसी भी संभावित भूकंप शमन रणनीतियों को विकसित करने के लिए एक मंच प्रदान करता है। हिमालयी क्षेत्र से नौ अलग-अलग आधार गतियों पर विचार किया गया था और समकक्ष रैखिक मामले के लिए एक आयामी भूकंपीय प्रतिक्रिया विश्लेषण किया गया है। छोटी अवधि के लिए, प्रवर्धन उत्तर और उत्तर-पश्चिम में रॉक आउटक्रॉप्स वाली साइटों पर अधिक होता है, और दक्षिण में जलोढ़ साइटों पर कम होता है। लंबे समय तक, तवी, रावी और चिनाब नदियों के किनारे सिंबल और जटाह जैसे जलोढ़ स्थलों पर प्रवर्धन अधिक है। शरीफ बाग, बनिहाल और बाफलाइज में, 0.45 ग्राम से अधिक $PGA_{surface}$ है।

द्रवीकरण संभावित सूचकांक (LPI) और द्रवीकरण की संभावना (PL) के आधार पर जेआर में द्रवीकरण खतरे के लिए ज़ोनेशन मानचित्र विकसित करने का प्रयास किया गया है। इसे प्राप्त करने के लिए, द्रवीकरण के खिलाफ सुरक्षा के कारक का अनुमान भू-तकनीकी परामर्श और क्षेत्र परीक्षण के दौरान मापा गया कतरनी तरंग वेग से एकत्र किए गए मानक प्रवेश परीक्षण (SPT) डेटा का उपयोग करके लगाया गया था, और एक एकीकृत द्रवीकरण खतरा मानचित्र उत्पन्न किया गया था। परामर्श से प्राप्त भू-तकनीकी मापदंडों और भूभौतिकीय क्षेत्र परीक्षण से प्राप्त डेटा को प्रतिगमन विश्लेषण का उपयोग

करके सभी प्रकार की मिट्टी के लिए सहसंबंध उत्पन्न करने के लिए अध्ययन क्षेत्र के लिए एकीकृत किया गया था।

जटाह (सांबा जिला) और सिंबल (जम्मू जिला) में रेत के वार और जमीन टूटने जैसी द्रवीकरण विशेषताएं पाई गईं। एकीकृत खतरे के नक्शे के अनुसार, जम्मू में तवी नदी और रावी नदी के तट के पास के स्थानों में युवा जलोढ़ हैं, जिससे उन्हें विशेष रूप से द्रवीकरण का खतरा होता है। उथले गहराई पर उच्च कतरनी तरंग वेग और चट्टान के कारण पूर्वी और पश्चिमी वर्गों में द्रवीकरण नहीं होता है, और यह मोटी रेत जमा के कारण केंद्रीय क्षेत्र में भी नहीं होता है। LPI मूल्य 0 से 27.45 तक बहुत कम से बहुत अधिक द्रवीकरण जोखिम वाले होते हैं। बेहद कम एसपीटी (N) और V_s मूल्यों वाली समान रूप से वर्गीकृत मिट्टी के कारण दक्षिण-पश्चिमी तरफ स्थित साइटों के लिए P_L 0.75 से अधिक है। यह अध्ययन साइट योजनाकारों को संरचनाओं के निर्माण में सहायता करेगा जो द्रवीकरण शमन और अच्छी तरह से परिभाषित द्रवीकरण जोखिम उपायों पर विचार करते हैं।

तीसरे और अंतिम भाग में, विभिन्न भूकंपीय वातावरण के तहत नाजुकता फ़ंक्शन का उपयोग करके परिपत्र सुरंगों की भूकंपीय भेद्यता पर चर्चा की गई। सभी खतरे वाले क्षेत्रों के लिए, सुरंग क्षति राज्य और PGA के बीच एक अनुभवजन्य संबंध उत्पन्न हुआ जो आगे विभिन्न ओवरबर्डन गहराई पर क्षेत्र विशिष्ट नाजुकता कार्यों को विकसित करने के लिए उपयोग किया जाता था। इसे प्राप्त करने के लिए, विविध टाइपोलॉजी और भूकंपीय परिदृश्य के साथ सुरंगों के भूकंपीय प्रदर्शन को प्रत्येक खतरे वाले क्षेत्रों के लिए क्षति की स्थिति को समझने के लिए निर्धारित किया जाता है, जैसा कि माइक्रोज़ोनेशन परिणामों द्वारा अनुशंसित है। किसी दिए गए भूकंप की तीव्रता के लिए, इस काम में प्रस्तुत नाजुकता घटना एक परिपत्र सुरंग के एक निर्दिष्ट क्षति राज्य तक पहुंचने या उससे अधिक होने की सशर्त संभावना को दर्शाता है। नरम मिट्टी (जोन A) में उथली गहराई पर सुरंगों के लिए व्यापक क्षति की संभावना बहुत अधिक है, यहां तक कि कम भूकंपीय तीव्रता पर भी। 30 मीटर से कम ओवरबर्डन गहराई वाली सुरंगों के लिए, उल्लेखनीय विरूपण पूर्ण और कोई फिसलन की स्थिति दोनों में देखा जा सकता है। लचीली अखंडता

के कारण, इनपुट ग्राउंड गति का प्रवर्धन कारक उथली सुरंग की तुलना में गहरी सुरंग में बड़ा है। उथली सुरंगों की तुलना में गहरी सुरंगों में सुरंग अस्तर में विरूपण में 50% की गिरावट आई है। यह अध्ययन डिजाइनरों को समान टेक्टोनिक सेटिंग्स और संरचनात्मक टाइपोलॉजी वाले किसी भी गहराई पर परिपत्र सुरंगों के भूकंपीय व्यवहार को समझने में मदद कर सकता है, जबकि अतिरिक्त क्षति मॉडल और भूकंपीय प्रदर्शन को प्रभावित करने वाले अन्य कारकों पर भी विचार कर सकता है।

उधमपुर श्रीनगर बारामूला रेल लिंक (USBRL) परियोजना के भूकंपीय जोखिम और भूकंप के बाद की सेवा क्षमता का मूल्यांकन करने के लिए एस ईएमआई-क्यू क्वांटिटेटिव एसईस्मिक आरआईएसके एससेशन (SQ-SRA) दृष्टिकोण का उपयोग किया गया है। तीन संरेखण चरणों में से, पहला एक सुलभ है, सेंटएक सुलभ है लेकिन मरम्मत की आवश्यकता है, और लासटी एक दुर्गम है, जोखिम के अनुसार एमएट्रिकईएस। अंतिम चरण में सुरंग खंडों में से अधिकांश भूस्खलन और बड़े टेक्टोनिक खट्टे से ग्रस्त क्षेत्रों के पास स्थित हैं, और उनमें बड़े पैमाने पर अपक्षयी रॉक द्रव्यमान भी शामिल है, जिसके परिणामस्वरूप उत्खनन प्रक्रिया के दौरान विरूपण, निचोड़ और गुहा का गठन होता है। इन मुद्दों के प्रगतिशील प्रभाव से इस बात की संभावना बढ़ जाती है कि इन सुरंगों को व्यापक क्षति हो सकती है, जो भूकंपीय परिस्थितियों में ट्रेक सेगमेंट को निष्क्रिय कर देगी। प्रदान किए गए जोखिम मैट्रिक्स और मानचित्र जे अम्मू और कश्मीर में प्रमुख निकट-क्षेत्र या दूर-क्षेत्र अर्थक्वाकई घटनाओं की भविष्य की घटना में सार्वजनिक जागरूकता बढ़ाने और ट्रेक ऑपरेशन को निर्देशित करने के लिए एक मूल्यवान उपकरण के रूप में काम करेंगे।

इसके अलावा, डीप लर्निंग (DL) दृष्टिकोण का उपयोग करके एक गणितीय सूत्रीकरण-आधारित भूकंपीय सुरंग क्षति पूर्वानुमान (STDP) मॉडल प्रस्तावित है। DL मॉडल की प्रासंगिकता को ऐतिहासिक भूकंपों जैसे 1999 के ची-ची भूकंप, 2004 के मध्य-निगाटा भूकंप और 2008 के वेनचुआन भूकंप से सुरंग क्षति डेटा का उपयोग करके मान्य किया गया है। पीईक ग्राउंड त्वरण (PGA), स्रोत से साइट दूरी (SSD), ओवरबर्डन गहराई (OD), अस्तर मोटाई (t), सुरंग व्यास (ϕ), और भूवैज्ञानिक शक्ति सूचकांक (GSI)

को क्षति राज्य की भविष्यवाणी के लिए फीडफॉरवर्ड न्यूरल नेटवर्क (FNN) को प्रशिक्षित करने के लिए इनपुट के रूप में नियोजित किया गया था। प्रदर्शन मूल्यांकन परिणामों ने विभिन्न प्रकार के जोखिम मूल्यांकन डोमेन में आगे उपयोग के लिए एक स्पष्ट संकेत प्रदान किया।

भूकंपीय सुरंग क्षति पूर्वानुमान (STDP) मॉडल का अंतिम रूप इस प्रकार दिया गया है:

$$\ln(DI) = \left[\frac{(SSD \times OD^{0.002}) + \left(\frac{PGA}{t}\right)^{4.2}}{GSI + \Phi^{4.2}} \right] + 1.15$$

ऐतिहासिक आंकड़ों के आधार पर मॉडल की तुलना में, प्रस्तावित STDP मॉडल लगातार परिणाम उत्पन्न करता है, जो इस काम में उपयोग की जाने वाली पद्धति की मजबूती का प्रदर्शन करता है। सभी मॉडल फिटनेस मैट्रिक्स के आधार पर सत्यापन के दौरान अच्छा प्रदर्शन करते हैं। "STD मल्टीपल ग्राफ़" भी प्रस्तावित है जो क्षति अनुक्रमण, क्षति पैटर्न और दरार भविष्य कहनेवाला विनिर्देशों पर जानकारी प्रदान करता है। इसका उपयोग पोस्ट-भूकंपीय परिदृश्यों में भेद्यता की जांच करने के लिए एक तैयार टूलबॉक्स के रूप में किया जा सकता है। सुरंग बनाने की परियोजनाओं के लिए भूकंपीय डिजाइन दिशानिर्देश भी प्रस्तावित हैं, जो क्षति पैटर्न पर चर्चा करते हैं और शमन उपायों का सुझाव देते हैं। प्रस्तावित STDP मॉडल, STD मल्टीपल ग्राफ़, और भूकंपीय डिजाइन मार्गदर्शन दुनिया में कहीं भी किसी भी भूकंप-प्रवण सुरंग परियोजना पर लागू होते हैं।

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