Thesis Title: Seismic Hazard Evaluation of Jammu Region and Risk Assessment of Tunnels in the Himalayas

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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 Cruves (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. Th 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 Baflaiz, 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 Udhampur 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.

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