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Earthquake hazard: A silent crisis in Kashmir valley, NW Himalaya

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ABSTRACT

Kashmir Valley, an intermontane Himalayan basin has always been vulnerable to earthquakes due to the ongoing tectonic activities between Indian and Eurasian plates. Earthquakes have remained a silent crisis in the region and has caused devastating damage in the past. This study focus on understanding the likelihood of earthquake consequences in Kashmir Valley using seismological, geophysical and engineering datasets. The Valley has witnessed larger magnitude earthquakes in the past including M_W 7.6 in 1555, M_W 7 in 1669, M_W 7.5 in 1779, M_W 7.5 in 1885 etc. with devastating effects. Total magnetic intensity (TMI) surveys at the strike of typical Balapur fault in Kashmir Valley suggest subsurface magnetic constrains and minima's which are likely due to the ongoing fault activities. Extreme value theory, the magnitude–frequency relationship regression coefficients of earthquake events $> M_W$ 5 was estimated with the negative slope of 0.09294 and the positive intercept of 4.7528. Using dynamic response analysis with simulations to earthquake excitations, the lateral loads are evident in residential as well as institutional buildings. The study highlights the earthquake vulnerability in Kashmir Valley and urgent need for risk based design decisions.

1. Introduction

Every year, around 60,000 people die in natural disasters, and the deaths are mostly caused by building collapses even though engineering solutions exist and can almost eliminate the risk of such deaths (Kenny, C. 2009). The 2005 *Mw* 7.6 Kashmir earthquake was the deadliest earthquake in the region, with more than 80,000 fatalities and nearly 200,000 injuries (EERI, 2005, 2006). According to the reports, 19,000 children died, mostly due to the building collapses, and 3.5 million were rendered homeless (EERI, 2005). Also, ~250,000 farm animals died, and more than 500,000 animals required immediate shelter from the harsh winters. The earthquake hazard has caused the worst damage in the past than any other natural hazard and has massively impacted civil infrastructure across the globe. It is always inappropriate to overlook the possible occurrence of destructive earthquakes considering the earthquake vulnerability of the past. Also, the gap between the engineers and seismologists can obstruct the development of policies related to earthquake-resistant design decisions. The geology and historic study reveal that the Himalaya will witness much larger earthquake events than the 2005 event that have stuck recently (Hough et al., 2009; Bilham R, 2019; Ayaz and Bukhari, 2020). The scientists claim, based on the massive scale of faults in the Himalayan arc and enormous forces, the large magnitude earthquakes can inevitably strike (Bilham, R. 2019; Michel, S. et al., 2021). Based on the historical and seismological data, the experts believe that the death toll from a future nocturnal earthquake in the Himalaya could possibly exceed 100,000 due to increased populations and the vulnerability of present-day construction methods (Bilham, 2019). Bilham (2019) has evaluated the slip potential for 15 Himalayan segments and has suggested that 10 of these 15 segments are currently mature to host a greater magnitude of $M_w \geq 8$.

In recent past, several studies have suggested the increasing seismic vulnerability for the Kashmir valley (Bilham and Ambraseys, 2005; Avouac et al., 2006; Parsons et al., 2006; Malik and Mohanty, 2007; Ali et al., 2009; Shah, 2013; Schiffman, 2013; Ahmad et al., 2015a, 2015b). The data obtained from the United States Geological Survey (USGS) show that the region neighboring to Kashmir basin has already witnessed two large earthquakes in the recent past, the April 1905 Kangra earthquake and the October 2005 Kashmir earthquake. The region has witnessed devastating earthquakes in the past too and many of them are highlighted in (Table 1). In Kashmir valley, the September 1555 earthquake of Mw > 7.6, has been described the largest earthquake in (Bilham, 2019). The earthquake occurred at around midnight, collapsed many houses in Srinagar and toppling some into the river, and was accompanied by fissuring and ground cracks (Bilham, 2019). This study attempts to understand the possibility of high magnitude earthquake and risk based design decisions in Kashmir Basin using integrated approaches.

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Table 1
Significant earthquakes in and around Kashmir valley.

Date (Year)	Latitude (°N)	Longitude (°E)	Magnitude (approx.)	Location & Source
1123	34	74.8	7.5	Srinagar, Jammu & Kashmir. (Stein, 1892; Bilham and Bali, 2013)
1501	34	74.8	7	Srinagar, Jammu &Kashmir. (Bilham and Bali, 2013)
1505	34	71	7.9	Kabul, Afghanistan. (Ambraseys and Bilham, 2003a)
1519	35	71.5	7.5	Bajaur, Afghanistan. (Ambraseys and Bilham, 2003a)
1555	34.25	74.8	8	Jammu & Kashmir. (Iyengar and Sharma, 1996; Iyengar et al., 1999; Ambraseys and Jackson, 2003; Bashir et al., 2009; Bilham and Bali, 2013)
1669	34	74.8	7	Srinagar, Jammu & Kashmir. (Bashir et al., 2009; Bilham and Bali, 2013)
1678	34	74.8	6.8	Srinagar, Jammu & Kashmir. (Bashir et al., 2009; Bilham and Bali, 2013; Bilham, 2019)
1683	34	74.8	6.8	Srinagar, Jammu & Kashmir. (Bashir et al., 2009; Bilham and Bali, 2013)
1736	34	74.8	7	Srinagar, Jammu & Kashmir. (Bashir et al., 2009)
1779	34	74.8	7.5	Srinagar, Jammu & Kashmir. (Bashir et al., 2009; Oldham, 1883)
1784	34	74.8	7.5	Srinagar, Jammu & Kashmir. (Oldham, 1883)
1803	31.5	79	7.9	Gangotri, Srinagar (Gharwal), Almora (Ambraseys and Jackson, 2003; Rajendran et al., 2013, 2015)
1828	34	74.5	7.5	Srinagar, Jammu & Kashmir. (Vigne, 1844; Bashir et al., 2009)
1863	34	74.5	6	Srinagar, Jammu & Kashmir. (Bashir et al., 2009; Lawrence, 1895)
1878	34.48	72.18	7.4	Hazara, Pakistan (Szeliga et al., 2010)
1885	34.54	74.68	7.5	Baramulla, Jammu & Kashmir (Jones, 1885; Bashir et al., 2009; Szeliga et al., 2010)
1905	32.63	76.78		Kangra, India (Szeliga et al., 2010; Szeliga and Bilham, 2017)
2005	34.45	73.64	7.6	Muzaffarabad (Durrani et al., 2005; Hussain, 2005)

2. Geology and tectonic setting

Geologically, Himalaya serves an excellent model of continent-continent collision which has formed as a result of the northward drift of the Indian plate and southward drift of the Eurasian plate, subduction of intervening oceanic crust of neo-Tethys over 200 to 50 million years. The rise of the Himalaya has given birth to numerous intermontane basins throughout the plate boundary between Eurasian and Indian Plates. The Kashmir valley is one among the intermontane basins developed along the Kashmir Seismic Gap, one of the most tectonically significant yet historically under-ruptured regions of the Himalayan arc (Bilham, 2019). Basin is filled with thick Quaternary lacustrine and fluvio-deltaic sediments, the Karewa Group, overlying older Siwalik and Lesser Himalayan sequences (Bhat et al., 2019). The Kashmir basin is surrounded by numerous thrust faults like Himalayan Frontal Thrust (HFT), Main Boundary Thrust (MBT), Main Central Thrust (MCT), Main Mantle Thrust (MMT), Kishtwar Fault as well as many other lesser distribution faults (Fig. 1). The HFT is considered as one of the greatest fault systems with seismological characteristics of large historical earthquakes and strong ground motions (Nakata, 1972, 1989; Yeats and Lillie, 1991; Yeats et al., 1992; Ambraseys and Bilham, 2000; Ambraseys and Douglas, 2004; Wallace et al., 2005). The Himalayan frontal thrust, passing by the western side of the Kashmir basin, is primarily the active structure, were moderate to the large earthquake rupture the surface (Lave and Avouac, 2000; Malik et al., 2010). The MBT and MCT are two mega lineaments of western Himalaya. The Jammu thrust in the western Himalaya is considered to be a footwall structure of the main boundary thrust (Heim and Gansser, 1939; Yin, 2006). The MCT or locally known as Panjal thrust, shields the Kashmir valley from the western side and therefore remains closest to the valley and is one of the principal tectonic scars in the region. The Panjal thrust dips steeply (45°–55°) towards the northeast and seems a superficial phenomenon of orogenic movements. On the western side, the valley is shielded by the Zanskar mountain range, which is a part of Tethys Himalaya formed by strongly folded sedimentary series. In recent past, the scientists have put forward various suggestions related to tectonic structure ranging from out-of-sequence-thrusting to strike-slip motion (Shah, 2015a,b; Ahmad et al., 2015b). Ahmad et al. (2015b) suggest that the Kashmir basin has evolved as a dextral pull-apart quaternary sediment depression, and the steep slopes have initially developed as a result of strike-slip displacement. The authors estimate that the local basement structure had played a key role in shaping the basin, which they suggest has evolved as a result of strike-slip motion along the Central Kashmir fault (CKF). Shah (2016) suggest that the dextral strike-slip fault system is not possible, and the structure can't pass in the middle of the Kashmir. Further, Bilham (2019) suggests the absence of evidence for strike-slip faulting in the mountains beyond the ends of the valley. The arguments put forward by these authors have opened new window of uncertainties in understanding the regional stress and the fault mechanisms in the Kashmir valley. The present study focus by considering all the possibilities and the current seismic crisis.

2.1. Soil and groundwater conditions

The development of safe infrastructure relies on determining the suitable soil, which has stability through wetting and drying cycles, strength under pressure, and ability to capture precipitation. The loss of strength and stiffness in response to the stresses due to ground shaking by earthquakes can give challenges to infrastructural development. The 2001 Bhuj earthquake (Mw 7.7) caused severe ground deformation and widespread co-seismic liquefaction, with sand blows and lateral spreading reported even at distances up to 200 km from the epicenter (Youd et al., 2002; Tiwari et al., 2007). Kashmir valley has a high to very high liquefaction potential Sana and Nath (2016); Sana and Nath (2016) have determined the liquefaction potential index (LPI) based on standard penetration tests and suggested the soils of major civil infrastructural regions like Baramulla, Kupwara, and Srinagar have very high to high LPI values. The groundwater conditions play an important role in featuring seismic risk & hazard assessments and control the effective normal stresses during liquefaction (Kishida, 1970; Youd, 1973; Andrews and Martin, 2000). Being the oval-shaped basin, the Kashmir valley has a shallow water table and is directly controlled by the topography of the region. The average depth of the groundwater in the Kashmir valley ranges from 1.5 m to 4 m below ground level and 1.75–6 m below ground level during the month of summer and winter, respectively (Groundwater information Ground Water Information

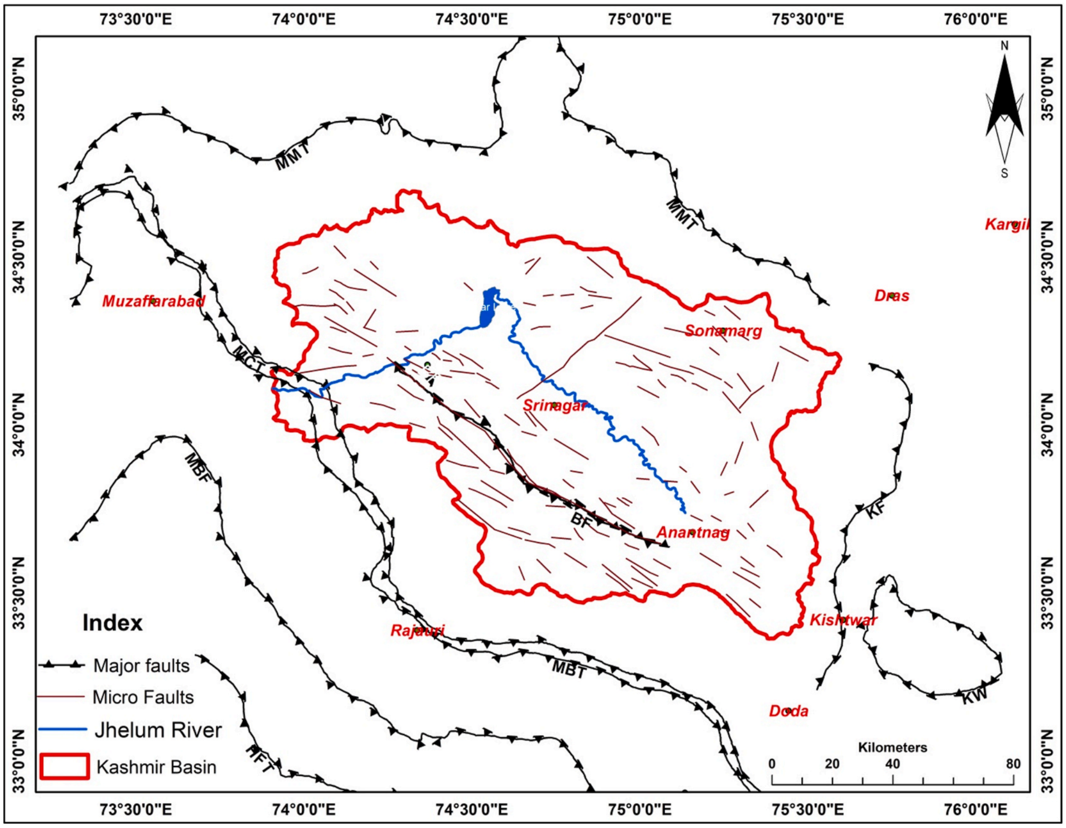

Fig. 1. Tectonic features in and around Kashmir Basin: Main Crystalline Thrust (MCT), Main Mantle Thrust (MMT), Main Boundary Thrust (MBT), Himalayan Frontal Thrust (HFT), Kishtwar Fault (KF), Balapur Fault (BF), and Kishtwar Window (KW). (Modified after Thakur and Rawat, 1992; Ayaz and Bukhari, 2020).

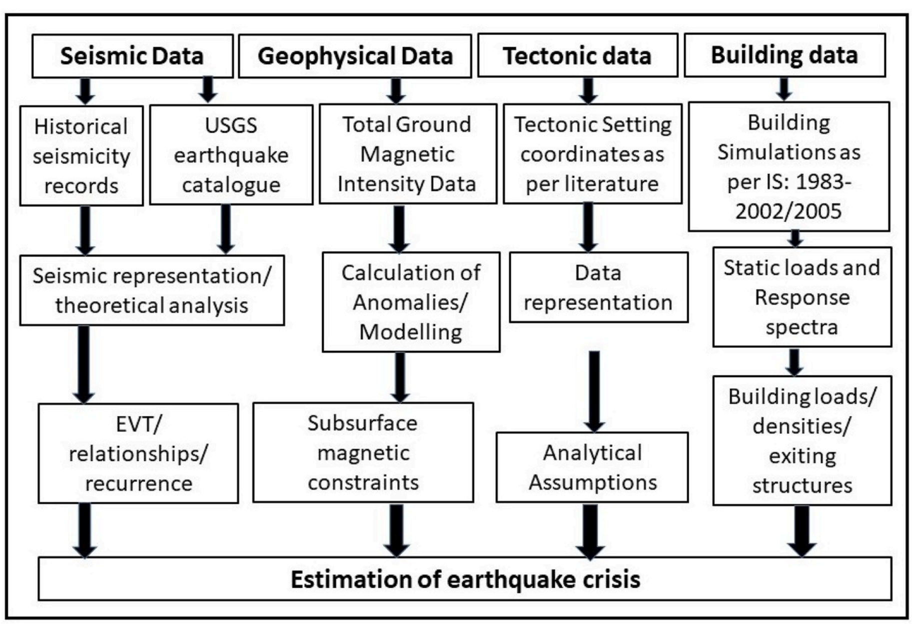

Fig. 2. Flow chart of Methodology.

Booklet, 2009, 2013). Further, the calamity related to floods is not unknown to the Kashmir valley. The region has witnessed various flood events in recent history, including the devastating 2014 flood, which killed hundreds and rendered thousands homeless. These events contribute to groundwater fluctuations and are considered as the agents for soil liquefaction and ground shaking amplification (Romshoo et al., 2018). The earthquake liquefaction studies in Kashmir valley are still not comprehensive. Estimating soil liquefaction potential is essential because liquefaction of saturated, loose alluvial and lacustrine deposits can produce large ground deformations that can severely damage foundations, even when peak ground accelerations are moderate.

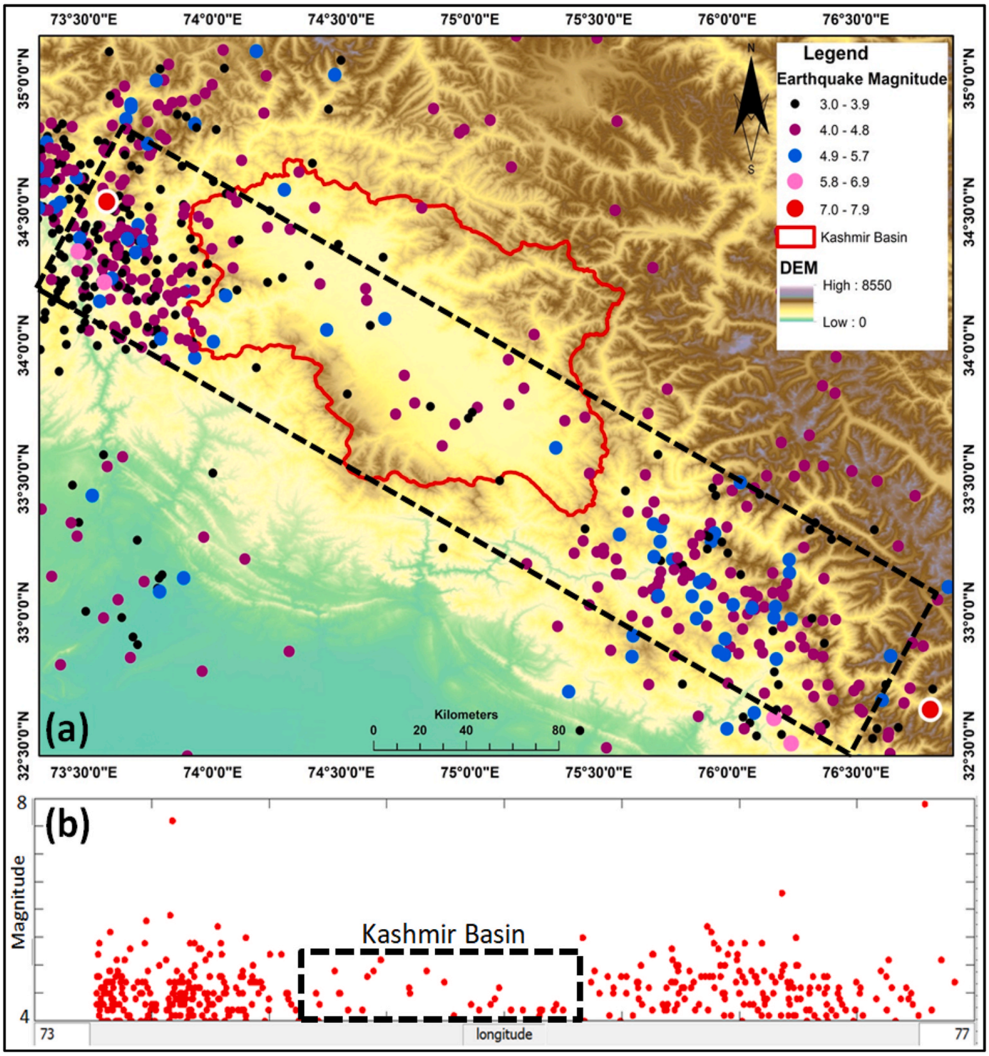

Fig. 3. Earthquake epicenter locations (a) earthquake locations on digital elevation model with 30 m image resolution; the black rectangle encompasses the earthquake clustering at the basin extensions, as well as a specific pattern of earthquake occurrences, (b) distance of earthquake epicenters; the rectangle represents the Kashmir basin which shows less distribution of earthquake locations comparative to its surroundings.

3. Data and methods

The study used seismological, geophysical and engineering datasets to accesses the likelihood of earthquake vulnerability in Kashmir Valley. The earthquake data was obtained from United States Geological Survey (USGS) database for the year 1900 onwards and the historical data was obtained from literature (Table 1). Ground magnetic surveys were carried out using proton procession magnetometers using linear array across the fault strike. The tectonic data was obtained using Georeferencing literature maps and represented using ArcGIS. The building simulations were performed using Staadpro fulfilling IS code: 1983–2002/2005.

The study used statistical approach of Extreme Value Theory (EVT) to analyze the recurrence intervals of significant earthquakes and magnitudes >5 were treated as extreme values within probability distributions. The study employed commonly used Guttenberg-Richter empirical relationship describing the relationship between the cumulative number of earthquakes and magnitude on a log scale. The probabilistic earthquake occurrence not exceeding the value more than M in one year is calculated using (Eq. (1)):

$$GM = e^{-\alpha^{**} - \beta M} \tag{1}$$

Where M represents the magnitude and α, β are regression coefficients.

Also, according to the Guttenberg-Richter law, the earthquake nucleating at any place, at any time will randomly grow to a magnitude $\geq M$ (Eq. (2))

$$Log\ (N) = a - bM \tag{2}$$

Further, the probability that any nucleating earthquake will grow to magnitude $\geq M$ (Eq. (3))

$$P(M) = 10^{6(Mmin - M)} \tag{3}$$

where M is number of earthquakes $\geq$ M, a & b are regression coefficients, and $Mmin$ is the minimum earthquake magnitude.

The correlation between coefficients of Type-I asymptotic equation and constants and Guttenberg-Richter law was calculated by (Eqs. (4)–(6))

$$\alpha = 10^{a}, a = \log\ (\alpha) \tag{4}$$

$$\beta = \frac{b}{\log(e)}, b = \beta \log\ (e) \tag{5}$$

$$N = ae^{(-\beta M)} = -\ln\ (G) \tag{6}$$

Further, the equivalent earthquakes (j) and relative frequencies (f)

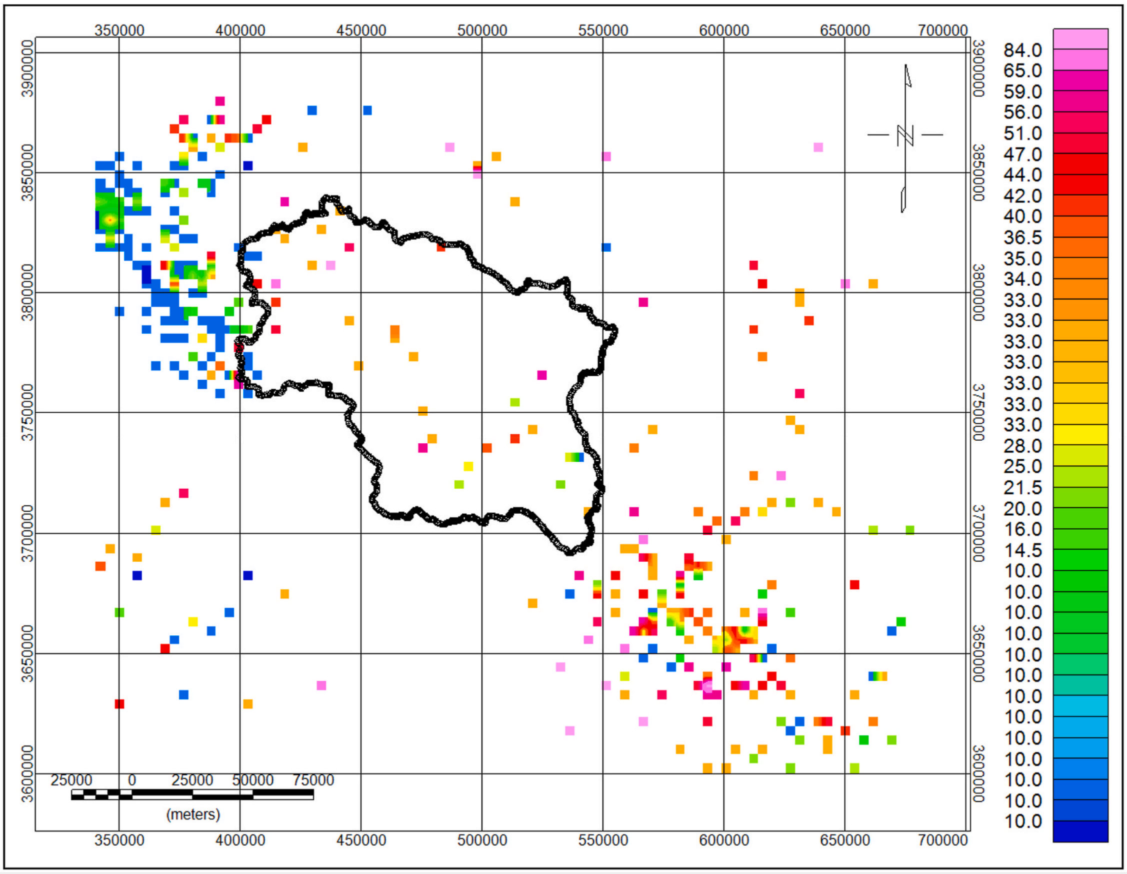

Fig. 4. Variation of earthquakes depths occurred from 1905 to 2022.

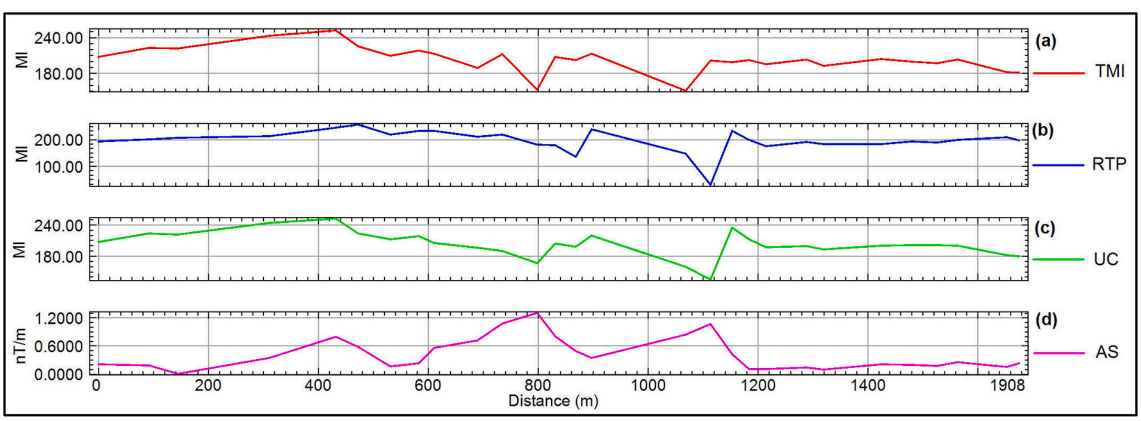

Fig. 5. Typical Example of anomalies at Balapur Fault (a)Total magnetic anomaly (b) Reduction to poles (c) Upward Continuation (d)Analytical signal.

were calculated by (Eq. (7))

$$f(n) = \frac{j}{n} + 1 \quad (7)$$

The study used two WCZ proton precession magnetometers with 0.1 nT resolution and accuracy of ±1 nT. The instrument has a measuring range of ≥100,000 nT and gradient permission up to ≥5,000 nT/m. The device is auto-tuned for zone detection and allows configuring the survey direction and data transfer for interpretations. One instrument was used for base station to measure the earth's magnetic field at a certain location frequently to analyze the diurnal magnetic variations. The Data for assessing the secular variations were obtained by the International Geomagnetic Reference Field model available at the International Association of Geomagnetism and Aeronomy (IAGA). Further, the topographical data were obtained by the Global Positioning System (GPS) for every magnetic station. The database was created by removing the model of the earth's normal magnetic field and diurnal variations to assess the detailed magnetic characteristics of subsurface faults and related susceptibilities (Eqs. (8) and (9)):

$$TMI = f_i - IGRF \quad (8)$$

$$f_i = Ip - Dv \quad (9)$$

Where f_i is the earth's magnetic field intensity, IGRF is the Magnetic reference model, Ip is the average magnetic intensity at a certain point, and DV is the diurnal variation for a particular station.

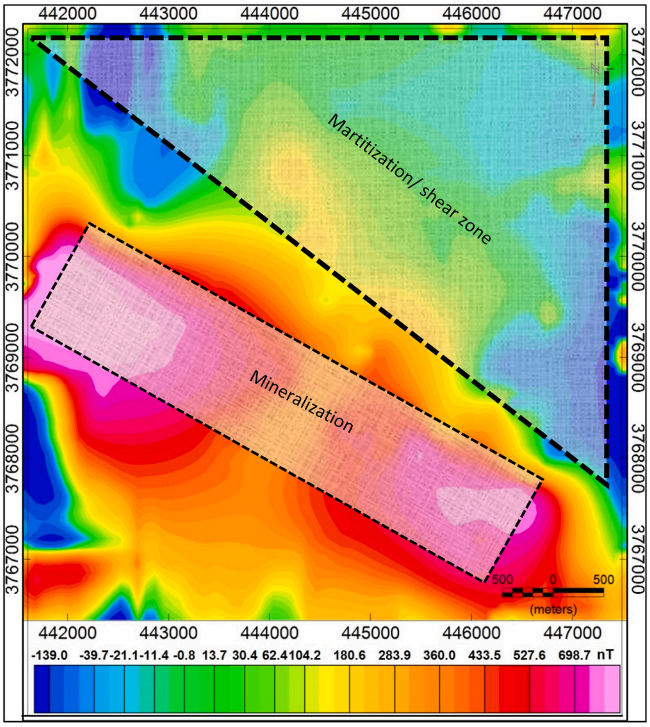

Fig. 6. Gridded database at strike of the Balapur Fault at central kashmir after TMI analysis. The high TMI represents mineralization at shear zone. The minama zone represents Martitization/shear zone.

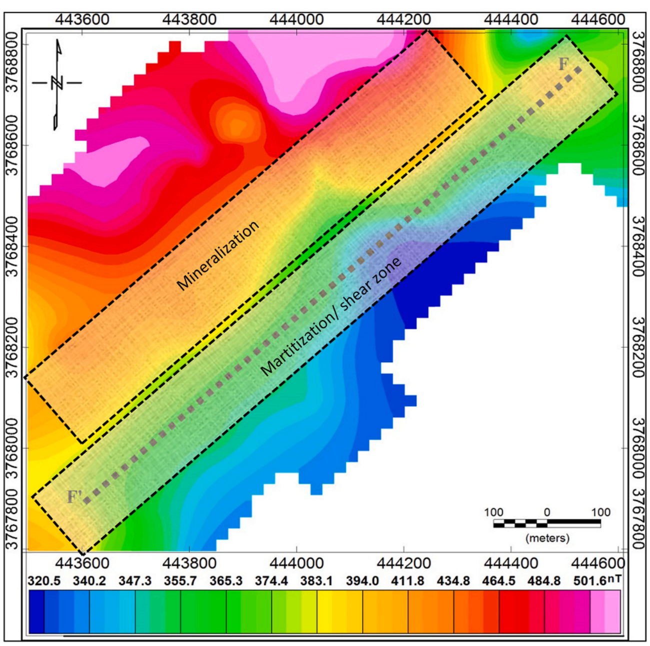

Fig. 7. TMI grid at northern part of Balapur fault representing low magnetic lineation. The high TMI represents mineralization at shear zone. The minama zone represents Martitization/shear zone.

The average magnetic field intensity at a point (*Ip)* and diurnal variations (*Dv*) were calculated as (Eqs. (10) and (11))

$$IP = mi_1 + mi_2 + mi_3/3 \quad (10)$$

$$Dv = m_b - m_i \quad (11)$$

Where, mi_1, $mi_{2,}$ and mi_3 represent the normal earth's field magnetic intensities at a certain point, m_b is the earth's magnetic intensity at a base station for a particular time, and I_i is the initial magnetic intensity recorded at the base station.

The data enhancements and filtering processes were carried out for the effective interpretations of the obtained total magnetic intensity database. Various convenient data interpretation techniques like Reduction to pole, Continuation methods, Analytical signals, and mathematical derivatives were used for precise subsurface analysis. The geophysical software like Geosoft Oasis montaj, Surfer, and Magmap were used for the study. Various interpretations were carried out to evaluate the presence of subsurface magnetic anomalies at the strike of the fault and to understand the subsurface constraints (Blakely, 1995; Ponce, 1996; Henkel and Guzmin, 1997; Verduzco et al., 2004; Hanafy et al., 2012; Andrean et al., 2017; Ayaz and Bukhari, 2020, 2023, 2025; Dar et al., 2023, 2024).

The study evaluated the performance-based designs with earthquake loading and to compare the results with the already existing structures in the Kashmir valley using equivalent static load method and Response spectrum analysis in Staadpro. The study used bay frame open structures including two stories common residential reinforced concrete buildings and three-story Institutional/commercial buildings. The building parameter for two-story residential buildings was taken as 12 m length, 6 m height and 12 m width for each bay whereas for three stories Institutional/commercial building parameters were 36.5 m length, 12 m height, and 18 m width for each bay. The seismic loads were defined according to IS 1893–2002/2005 for the seismic zone V (Kashmir valley) with Z factor of 0.36 for response reduction of spatial RC moment-resisting frame (SMRF) and damping ratio of 5 %. The floor weight of 3.75kN/m2 for the X range of 12 m and 36 m, the self-weight factor of 1, member weight 15 kN/m were used for seismic definitions whereas part 4 of IS:1893 code was included for the institutional/commercial buildings. The load cases for X and Z directions were performed as seismic loads. The flow chart of methodology is described in Fig. 2.

4. Results and discussions

The data obtained from USGS show that the Kashmir Valley and its near proximity has witnessed approximately 1000 earthquake events of >*Mw* 3 from 1905 onwards, in which approximately 150 earthquake events were found > *M*w 5. There is a spatial clustering of earthquake events located on the NNW and SSE extensions of the Kashmir basin (Fig. 3a). Also, a noticeable pattern displayed by the majority of these earthquake events in the region can be possibly due to specific tectonic mechanism. It is, however seen that there is less density of earthquake events inside the Kashmir basin, followed by the denser patches of earthquake events at the extensions of the Kashmir basin signifying the Kashmir seismic gap (Fig. 3b). Among 1000 earthquake events of Mw > 3 that have occurred in a close proximity of Kashmir Basin (9700 km^2) in 20 decades, the basin has witnessed only 43 earthquake events. The analysis shows that the high magnitude earthquake occurred inside the basin during this time was in October 2005 *Mw* 5.2, which can be linked to the 2005 Muzaffarabad aftershock, and the *Mw* 7.6 earthquake may have extended fractures towards the Kashmir basin. Further, there is a significant variation of earthquake depths between the clusters located at the extensions of the Kashmir basin. The shallow depth of earthquake events is prevailing at the NNW basin extension, whereas the earthquake depths at the SSW extension of the Kashmir basin are deep (Fig. 4). The average depth of earthquake events at the NNW extension of the Kashmir basin is ranging from 10 km to 20km, whereas the SSW extension shows the average depth in the range of 33 km–64km. This, however, procures more insights about the structural set up in the region and impending large magnitude earthquakes towards the NNW extension of the Kashmir basin.

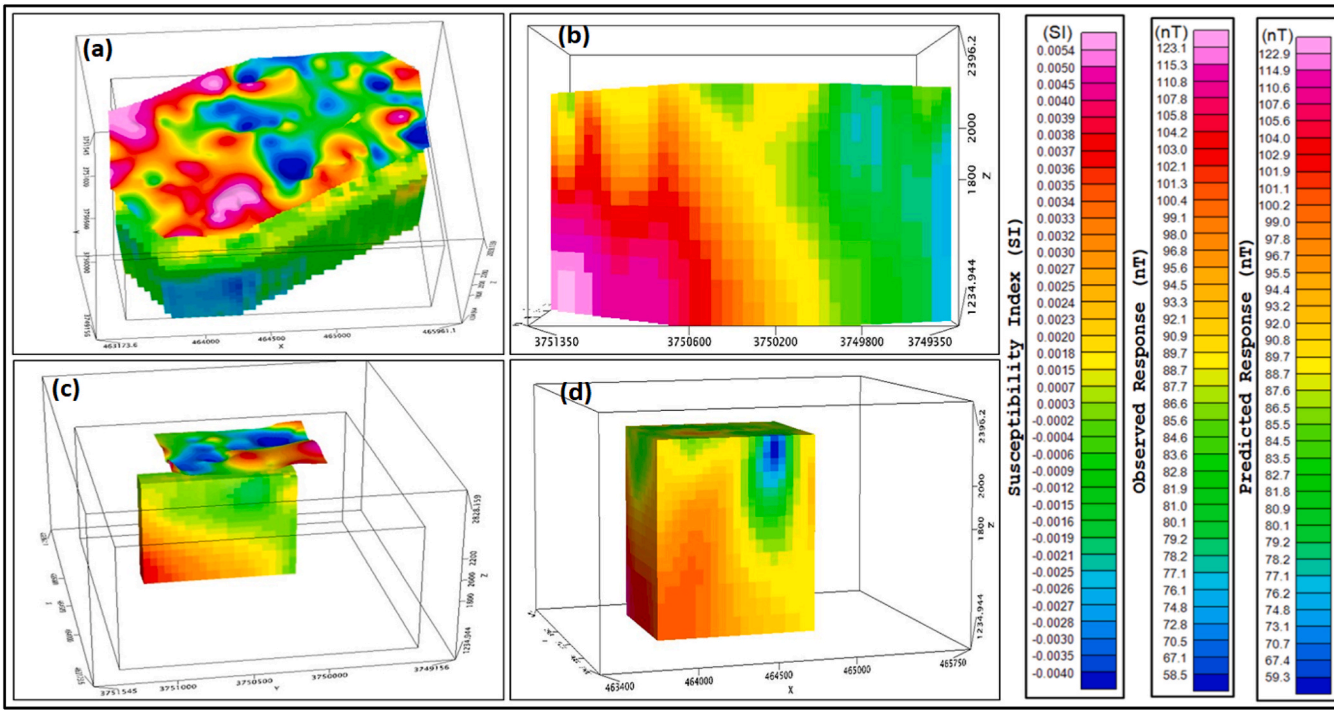

Fig. 8. The map represents the cross sections of material Susceptibility at northern segment of Balapur fault with matching color legends of observed and predicted responses (a) Sub-surface material susceptibility slab overlain by Predicted map (b) Sub-surface material susceptibility slab east view (c) Material susceptibility slap beneath Balapur fault at central region overlain by predicted map (d) Material susceptibility slap in vertical view.

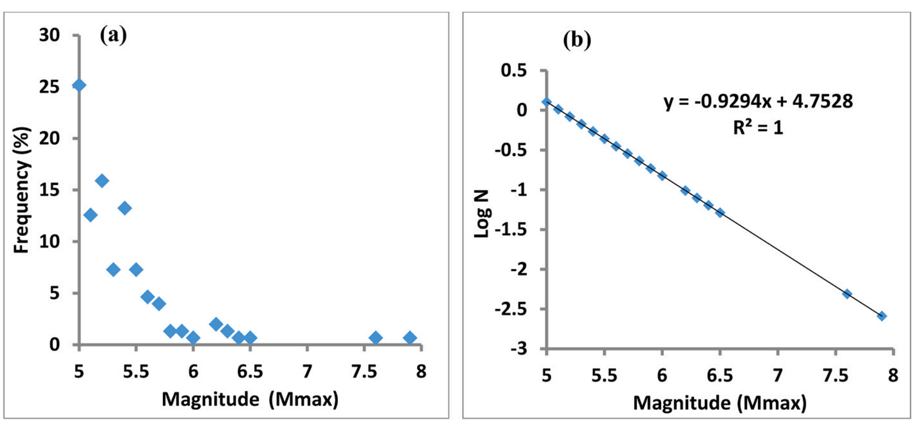

Fig. 9. (a) Frequency of seismic events, (b) magnitude–frequency relationship.

4.1. Geomagnetic analysis

The fault magnetization reflections were found associated with the magnetic minima's and the anomaly is considered as the product of hydraulic activities at fault planes. The oxidation and martitization processes are considered to have taken place at fault rupture zones and has reduced the iron grade from magnetite to hematite, thereby producing anomaly in linear profiles. The statistics of the typical example of Total magnetic Intensity database recorded 201 nT as mean with the standard deviation of 21.5 nT. The total magnetic intensity database was found ranging between the magnetic minima of 150.7 nT and magnetic maxima of 251.2 nT. The two corresponding magnetic minima's were recorded as152nT and 150 nT (Fig. 5).

The analysis of approximately 50 magnetic stations covering an area of 2 km^2 was found averaging at ~352 nT with the standard deviation of 238 nT. The total magnetic intensity database was found ranging between the minima and maxima of −139nT and 1741 nt respectively. The analysis of the gridded database reveals the presence of fault-related anomalies ranging from magnetic minima's between −139nT and 70 nT. The long, nearly linear magnetic transition, orienting southwest to northeast, is the reflection of magnetic lineation at the Balapur fault (Fig. 6).

The grid at northern part of Balapur fault, consisting of approximately 60 magnetic stations were found averaging at 421 nT with the minima and maxima are ranging between 326 nT and 515 nT. The analysis revealed the clear passage of magnetic minima's and therefore the presence of high martitiazation at the strike of the fault (Fig. 7).

The Balapur fault-related susceptibility index was estimated from −0.0035 to 0.0015 and the observed and predicted response values were found ranging between 67.1 nT to 87.7 nT and 67.4 nT–86.6 nT respectively. The observed and predicted response values of the higher magnetic characteristic channels were found ranging from 102 nT to 123 nT and 101 nT–122 nT respectively. Various other curvilinear magnetic transitions zones based on magnetization factors were also

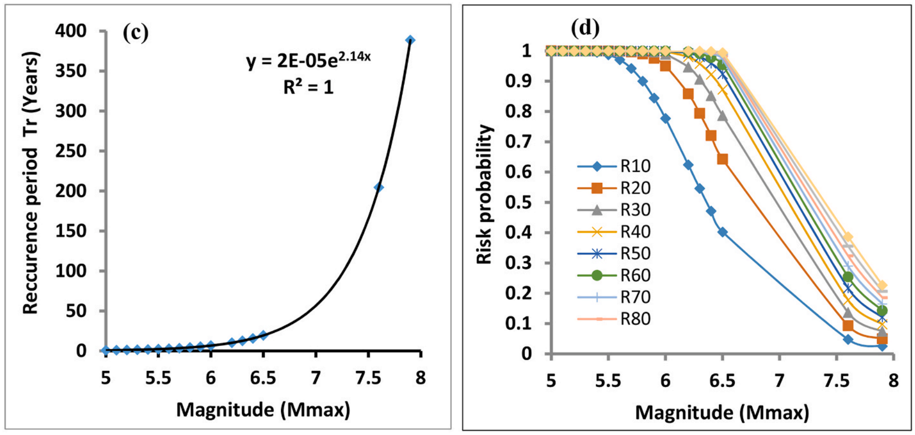

Fig. 10. (a) Earthquake recurrence pattern, (b) Risk probability.

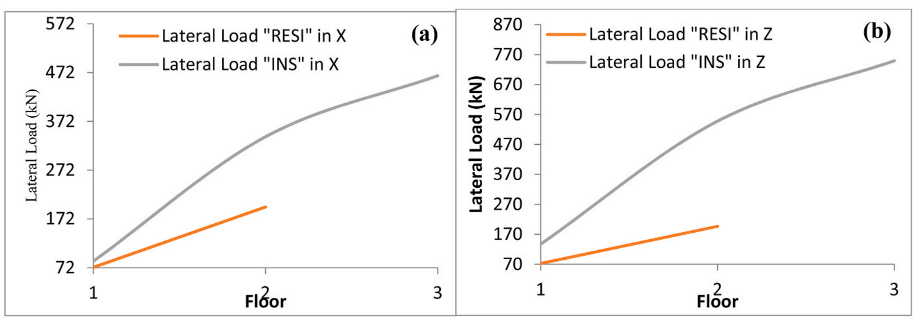

Fig. 11. Seismic lateral load in X and Z directions for Residential and Institutional/commercial buildings.

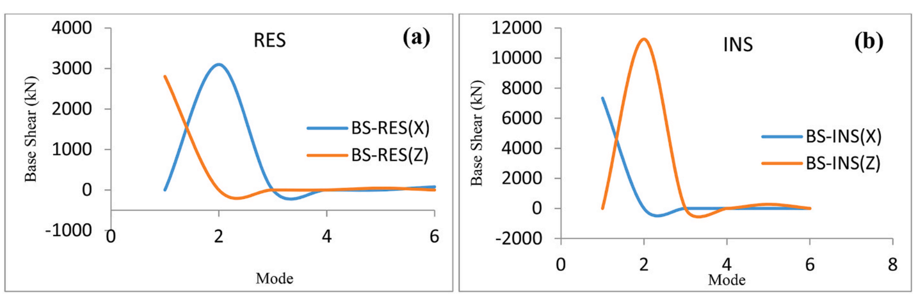

Fig. 12. Base shear at each mode in X and Z directions (a) Residential buildings (b) Institutional/Commercial Buildings.

recorded and are considered as the difference in the nuclear magnetic strains, however higher than fault zones. Further, the susceptibility slabs in 3D are also portraying the presence of linear low magnetic zones, therefore active fault-related anomalies (Fig. 8).

The reflection of magnetic minima's of total magnetic intensity data and seismological data portray that the Balapur fault is vulnerable to earthquakes Also, the Balapur fault in the northern region has produced fault branching/step faulting around Ferozpur nalla.

4.2. Magnitude-frequency relationship

The relationship adopted via Guttenberg-Richter for the seismic events of M $\geq$ 5 was adopted via (Eq. (12))

$$log_{10}\, N = 4.7528 - 0.9294M \quad (12)$$

The frequency of magnitude M 5–5.5 is 82 % among all earthquakes of $M \geq 5$ that have occurred in the region. The assumption carried out by curve fitting method and log (N) resemble downslope linear trend which indicate the decrease in earthquakes and increase in their magnitudes (Fig. 9). The study analyzed R^2 as 1 and therefore, the linear trend indicates that the regression predictions perfectly fit the data and the magnitude is increasing at a steady rate.

4.3. Risk probability

The risk probability of earthquakes from different periods (T_r) was calculated by (Eqs. (13)–(16))

$$N(M) = ae^{(-\beta M)} \quad (13)$$

Where *N(M)*: The number of earthquakes with a magnitude greater than or equal to M. a: A constant related to the frequency of earthquakes. β: A regression coefficient related to the distribution of earthquake magnitudes. *M*: The magnitude of the earthquake. *exp*: the exponential function

$$T_r = 1/N(M) \quad (14)$$

Where T_r: Risk probability or time interval. *N(M)*: Expected number of

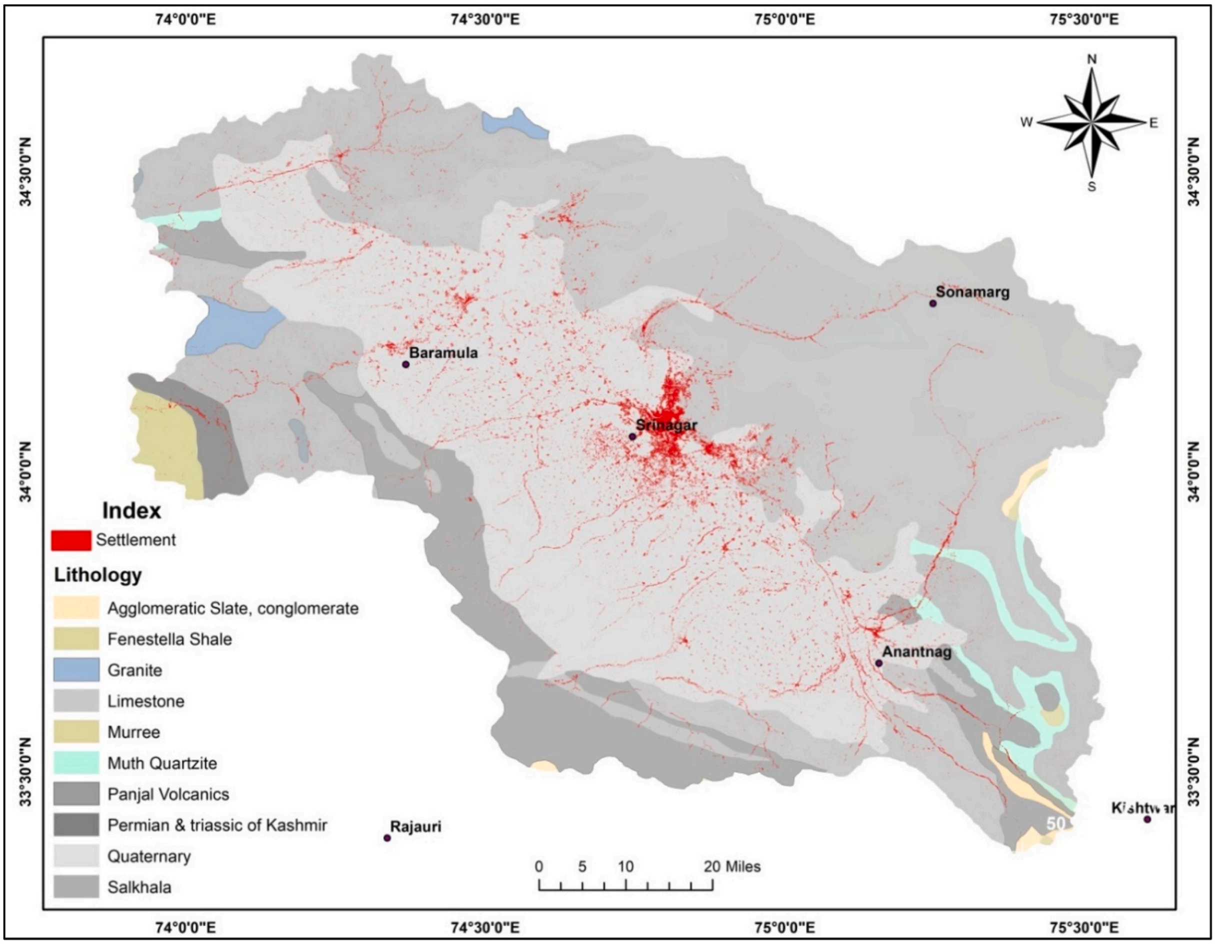

Fig. 13. Settlement map of the Kashmir basin.

earthquakes with magnitude greater than M.

$$R1(M) = 1 - e^{-N(M)} \tag{15}$$

Where *R1(M)*: Represents the probability that at least one earthquake with magnitude *M* will occur within a specific time period. *N(M)*: Represents the expected number of earthquakes with magnitude greater than M. *e*: The base of the natural logarithm (approximately equal to 2.71828).

$$RD(M) = 1 - e^{-DN(M)} \tag{16}$$

Where *RD(M)*: Represents the probability that at least one earthquake with magnitude M will occur during a reference time period. *D*: Represents a constant related to the time period, such as a duration factor. *N (M)*: Represents the expected number of earthquakes with magnitude greater than M.

The probabilities of earthquake events that have occurred in the region were calculated for magnitudes *Mw* 5–8. The probabilities were related as the magnitude for periods denoted as *N*, 10 *N*, 20 *N*, 30 *N* … … 100 *N* and the risk were calculated as *R1*, *R10*, *R20*, *R30* … … … … … *R100* with the gap of 10 years. The analysis shows that the probability of earthquake $M \geq 8$ once in ~380 years. Also, there is a probability of recurrence of *M* 7.6 once in ~200 years (Fig. 10a). However, the noticeable outputs are that the recurrence of earthquake events of $Mw \geq 6.5$ is 19 years and that of $Mw \geq 6$ is 6 years. The data shows that the probability of $Mw \leq 6.5$ in 20 years is 100 %. There are ~40 % chances to have an earthquake event of $Mw \geq 7.6$ in 100 years (Fig. 10b). The value of R^2 as perfectly linear in the exponential trend line resembles the line to be perfectly filling the data. It is therefore important to notice that the occurrence of high earthquake magnitude in future can't be ruled out.

4.4. Equivalent lateral load and response spectrum analysis

The lateral load in the X direction for residential buildings was found at 72.596 kN and 196.461 kN at the 1st and 2nd floors respectively whereas the lateral load in the same direction for the institutional/ commercial buildings were found at 85.099 kN, 340.396 kN, and 465.489 kN at 1st, 2nd and 3rd floors respectively. The lateral load in the Z direction for residential buildings was calculated as 72.596 kN and 196.461 kN for the 1st and 2nd floors whereas the load for institutional/ commercial buildings in the same direction was calculated as 136.968 kN, 547.872 kN and 749.2 kN for the 1st, 2nd and 3rd floors respectively (Fig. 11). The maximum lateral load in X direction was found at joint 14 on 1st floor and was recorded as 13.92 kN and 32 kN on the same floor. The maximum load in the Z direction was found same X-direction. The lateral load for Institutional/commercial buildings in X direction was found as 85.099 kN, 340.396 kN, and 465.489 kN at 1st, 2nd, and 3rd floors respectively whereas the load cases in Z direction were recorded as 136.968 kN, 547.872 kN and 749.20 kN at 1st, 2nd, and 3rd floors respectively. The maximum lateral load of 38.560 kN was found at joint 30, 31, 46, and 47 of the 3rd floor in X direction whereas the maximum load of 62.063 kN in Z direction was recorded at joint 30, 31, 46, and 47 of 3rd floor.

The modal base actions were calculated to estimate the forces acting on all modes in all directions to analyze the building moments. The peak moments in all the three directions in residential buildings were found starting at 1.3sec whereas for the institutional buildings were found at

Fig. 14. Building practices performed in the Kashmir valley. The traditional construction include (a) Dajji Dewar (b) Taq system, the present unsafe structures are depicted by (c) and (d), (e) and (f) shows the wood runners at floor level and connection of bracers, (g) represent the density of settlement at Srinagar city.

1.9sec. The maximum base shear of 3099 kN at mode 2 and 2082 kN at mode 1 was found in X and Z directions respectively for residential buildings (Fig. 12a). The total CQC shears of 3105 kN and 2805 kN in X and Z directions were recorded for residential buildings. The maximum base shear of 7334 kN at mode 1 and 11258 kN at mode 2 in X and Z directions respectively were recorded for institutional/commercial buildings (Fig. 12b). The total CQC shears of 7334 kN and 11272 kN in X and Z directions were recorded for institutional/commercial buildings.

4.5. Existing structures

The study shows the majority of the infrastructure in the Kashmir basin has been built on the quartanery alluvium (Fig. 13). The relationship between the amplification of seismic waves and the density and rigidity of sediments implies that this built-up is more vulnerable to damage due to the ground shaking by soft sediments at the time of the earthquake (Kanai, 1961). The field investigations show that most of the built-up in the Kashmir valley are constructed using concrete material with a shallow foundation. It has been seen that the platform of these structures directly reposes on the ground without proper foundation evaluations. The settlement built-up in the hilly regions and river terraces is highly vulnerable to earthquake vibrations due to their slope consequences and abandoned foundations. The present construction practices with load-bearing concrete wall structures may lack seismic strategies despite high seismic risk in the Kashmir valley. Further, the density of buildings in cities become more concerned about earthquake mitigations (Bukhari et al., 2018). The rare but safe construction practices called Dajji Dewar and Taq systems have been also witnessed in the valley (Fig. 14). These systems replicate the risk reduction to earthquake threats through the use of bearing masonry piers and infill walls (Bashir et al., 2016). The structures contain braced timber frames with masonry infill, backed brick masonry with mud and concrete mortar, wood runners at each floor level, the connection of bracers and possesses tremendous resilience against lateral forces. The overall behavior of Dajji Dewar and Taq systems imply that the lateral load capacity mainly depends on the competence of the timber framework. However, the endorsement of these structural systems seems lacking whereas the risk based concrete structures with indecorous seismic guidelines continue to shape the earthquake-related revulsion in the Kashmir valley.

4.6. Limitations

The study integrates seismological, magnetic geophysical, and structural simulations, however, spatial resolution of magnetic and seismic data is constrained by field accessibility and instrument sensitivity, which may impact the results, if not carefully addressed. The collection of the ground magnetic data can have the noise effects and therefore normalizing noise and improper filtering can impact the results as well. Also simulations are based on idealized material properties and boundary conditions. Therefore this study may not fully represent in-situ heterogeneities. The future studies integrating continuous seismic monitoring, higher-resolution geophysical imaging, and 3D structural modeling can further improve the understanding about the seismic vulnerability, induced disaster consequences and soil-structure interactions in Kashmir Valley.

5. Conclusions

Based on the nature of the statistical results and the evident subsurface magnetic constraints, the study suggest that the occurrence of a large magnitude earthquake can't be ruled out in Kashmir Valley. In these scenarios, the study is expecting enough lateral loads and building moments during the earthquake shaking considering the topography and tectonic setting of the basin. The response spectrum of the buildings based on a complete quadratic combination equation (CQC) estimated the shear of 3105 kN and 3805 kN for residential buildings and 7334 kN and 11272 kN for institutional/commercial buildings. Even though the construction pattern along the Balapur fault is somehow different, but study suggest that these regions may be more vulnerable to seismic intensity considering the nature of the Balapur Fault. Kashmir Valley has witnessed huge growth in population during last few decades among other states of the Himalayan region, leading to tremendous increase in the built-up area expansion of the urban clusters. Although there are building codes (IS-4326 of 1993; IS-1893 of 2002 modified in 2007) and other regulations that are mandatory for all buildings in earthquake prone areas of India, however these codes and regulations may have been neglected to some extent. The earthquake activity in the Kashmir valley remain a silent crisis and therefore there is an urgent need for risk based design decisions and disaster mitigation policies.

Declaration of competing interest

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Data availability

Data will be made available on request.

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