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The Jajarkot Earthquake: Revealed the Vulnerability of Load Bearing Structures in Western Nepal

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Abstract

The Jajarkot Earthquake, which occurred on 3rd November, 2023 of magnitude 5.7 (M_w) exposed Nepal's longstanding vulnerability to seismic activity. This paper presents damage assessments derived from both on-site field observations and secondary resources to evaluate the damages sustained by load bearing masonry structures. In the region, 95% of the building structures are based on masonry construction. The damage status of structures in Jajarkot and Rukum East highlighted that about 50% of the building structures were partially and complete damage. The evaluation encompassed various aspects, including the types, mechanisms, and underlying causes of the damage incurred by structures. The observed damage was categorized using an established catalogue originally developed for the identification of failure mechanisms and vulnerability assessment. The common types of damage encompassed features like cracks in the load bearing external walls and corners, diagonal cracks originating from door and window corners, vertical out-of-plane displacement of external walls, collapse of external walls, and partial collapse of load bearing internal walls, fracturing of window and door lintels and complete collapse of structure. Some special forms of damage which was of new nature and distinct from those observed in prior seismic events such as the Gorkha earthquake included ruptures in the outer surfaces of loadbearing external walls, partial roof structure collapses, out-of-plane fragmentation or disintegration as well as rupture. The causes underlying this general damage were attributed to irregular bonding systems, weak mortar, stone block formation, size of stone blocks, absence of tie beams, weakly connected corners, insufficient connections of wall-roof and wall-floor systems, and differing internal wall systems. The mechanisms of damage varied based on the number and specifics of these causative factors, as well as certain structural attributes.

Keywords: Jajarkot earthquake, field observation, load bearing structures, failure patterns, structural vulnerability

1. Introduction

Nepal faces significant earthquake risks due to the interactions between two major Earth's plate: The Indian Plate and the Eurasian Plate. The primary cause of earthquakes in Nepal is the subduction of the Indian plate beneath the Eurasian plate [1]. These plates undergo gradual movement, averaging about 25mm per year, resulting in accumulated pressure and stress that eventually leads to seismic activity [2]. Nepal has numerous fault lines and geological features such as the Higher Himalayan Zone, Dun Valley, and Siwalik Range, establishing its position as one of the most earthquake-prone regions globally [3]. Fig. 1 presents the location of Main Frontal Thrust (MFT), Main Central Thrust (MCT) and Main Boundary Thrust which would be the sources of future earthquake in Nepal [4].

Nepal's history, significant earthquakes occurred in 1255, 1408, 1681, 1810, 1823, and 1834 [5]. In 1934, a catastrophic earthquake with a magnitude of 8.1 (Mw) caused widespread damage. Subsequent years, including 1966, 1980, and 1988, witnessed earthquakes with varying magnitudes and casualties [6]. The most devastating event was the 2015 Gorkha Earthquake, measuring 7.8, with a subsequent 6.8 magnitude aftershock [7].

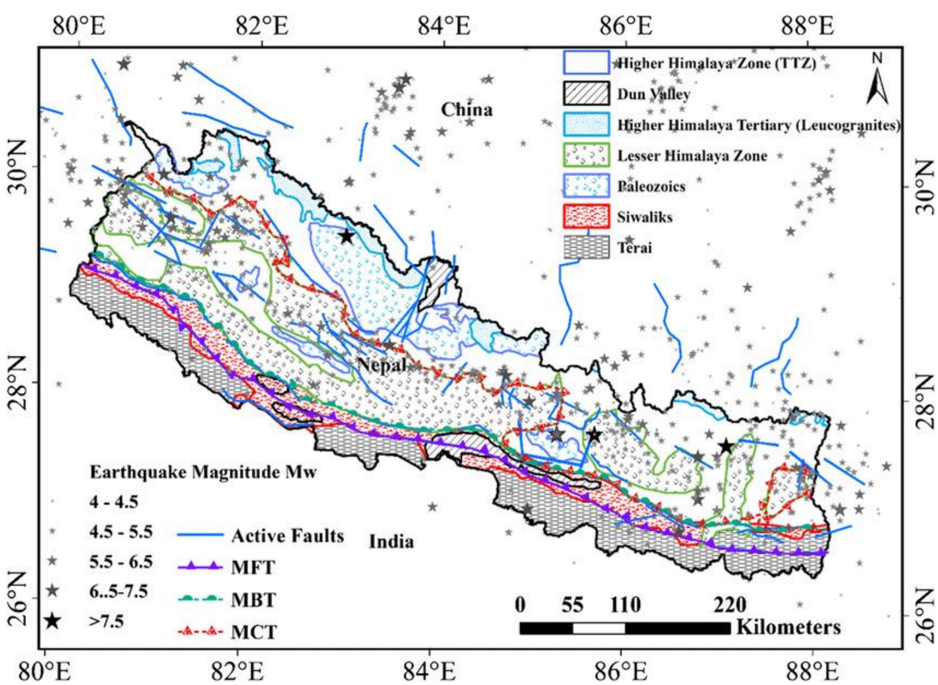


Figure 1: Major fault lines and Epi-center of past Earthquakes in Nepal [3]

Over the centuries, the country has witness series of devastating earthquakes. Even though Nepal has had many earthquakes in its history, the earthquake in 1934 is the first one that was properly recorded and studied by scientists using modern methods [8].Throughout analysis of historical seismic events in and around the Nepal Himalaya indicates frequent occurrences of earthquakes throughout the region. However, smaller earthquakes are more prevalent in the eastern, central, and far-western areas [9]. Researchers have been warning that a major earthquake is overdue in western Nepal, as there hasn't been a significant release of tectonic tension in over 600 years [10]. Recent earthquake in Jajarkot (M_w 5.7), Nepal which occurred on 3rd November, 2023 at around midnight 11:47 pm local time [11] supports the above statement. The 2015 earthquake, centered in Gorkha, did not affect the western half of Nepal because of which the region is at added risk due to potential for another major quake and inadequately constructed buildings [12].

Fig. 2 shows the movement recorded by sensors at the Bhimchula station during the main earthquake in Jajarkot, Nepal, in 2023. Bhimchula station is the closest one to where the earthquake happened. Nepal doesn't have many of these stations, but they're spread around the country. When we look at the data over time, we see that the strongest shaking during the main earthquake reached up to 70 centimeters per second squared. This is lower than what was expected based on calculations using a method called probabilistic seismic hazard analysis, which suggested a range of 295 to 340 centimeters per second squared over a 50-year period with a 10% chance of happening [13].

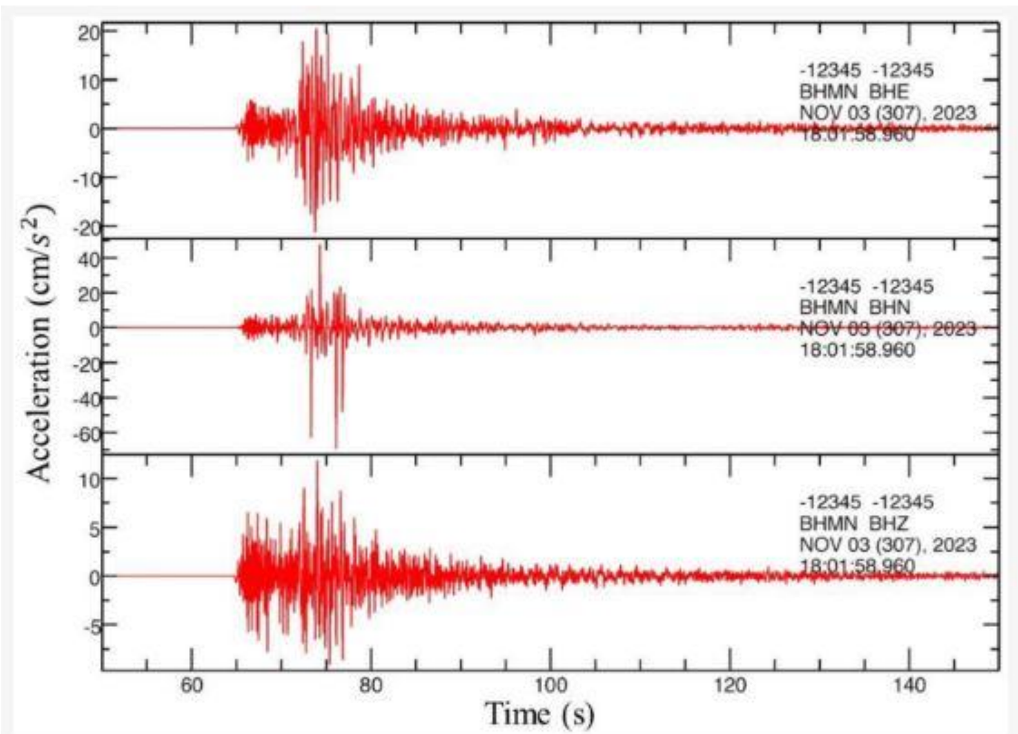


Figure 2 : Recorded accelerogram at Bhimchula station (28°39′20.88″ N, 81°42′51.84″ E) for the mainshock [13]

2. Damage and Casualties from Jajarkot Earthquake

The Jajarkot earthquake resulted in the collapse of many buildings, particularly those made of stone and mud mortar, causing significant casualties. Roads leading to the affected districts are obstructed by rock falls, and there are reports of substantial livestock losses. This earthquake, categorized as moderate and the maximum shaking intensity is estimated at around VIII on the MSK scale [14] caused more damage than expected, highlighting vulnerabilities in the region's structures. The severity of the earthquake in the Himalayan region was influenced by two critical factors: timing and infrastructure [15]. It's essential to recognize that it's not the earthquake itself that claims live, but rather the condition of the structures in place. As shown in *Fig. 3* and *Fig 4*, Jajarkot and Rukum (West) is the most affected areas among 12 districts affected by the earthquake. The official death toll in these affected areas had reached 153, with approx. more than 350 injured. 101 people have lost their lives in Jajarkot, the highest number among all affected areas and 52 people have died in Rukum West. Among the casualties, Rukum West has the highest with 200 people, while in Jajarkot, there are 145 reported casualties out of the total 363 as shown in Table 1.

Table 1: Number of death and serious casualties in Jajarkot Earthquake, 2023[16]

Affected Areas	Died	Seriously Injury
Rukum (West)	52	200
Jajarkot	101	145

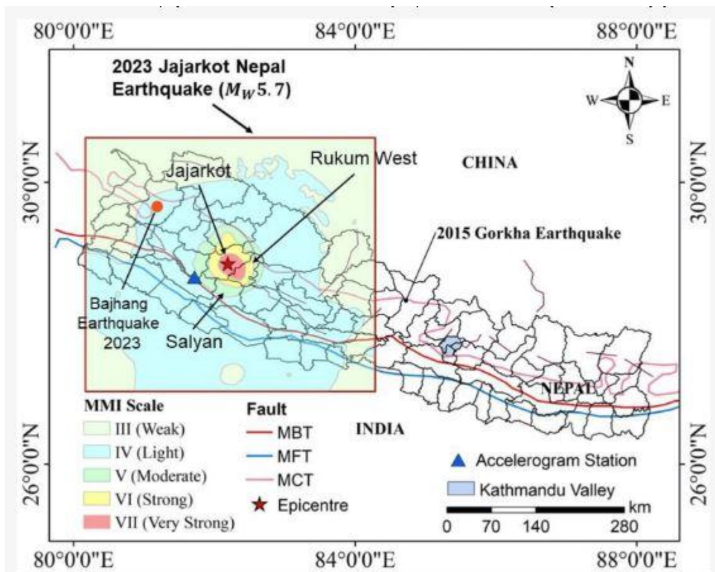
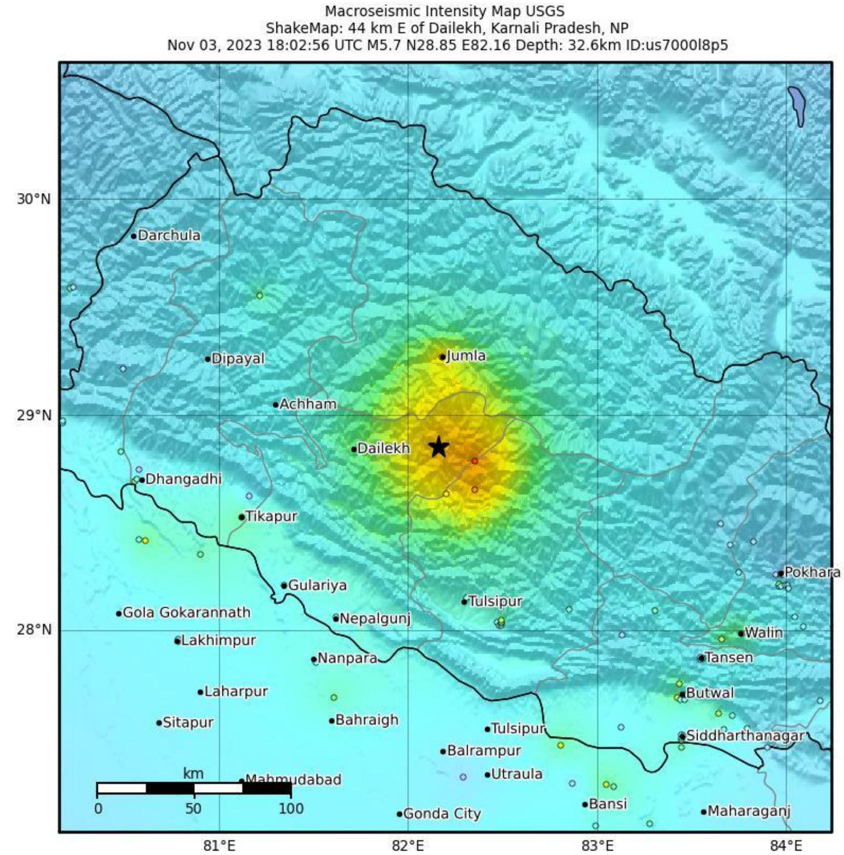


Figure 3: Location map of three mostly affected districts (Jajarkot, Rukum West, and Salyan) of Jajarkot Earthquake [14]



SHAKING	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
DAMAGE	None	None	None	Very light	Light	Moderate	Moderate/heavy	Heavy	Very heavy
PGA(%g)	<0.0464	0.297	2.76	6.2	11.5	21.5	40.1	74.7	>139
PGV(cm/s)	<0.0215	0.135	1.41	4.65	9.64	20	41.4	85.8	>178
INTENSITY	I	II-III	IV	V	VI	VII	VIII	IX	X+

Scale based on Worden et al. (2012) Version 9: Processed 2023-11-29T22:21:36Z
△ Seismic Instrument ○ Reported Intensity ★ Epicenter

Figure 4: Shake Map of Jajarkot seismic sequence and categorization of earthquake impact [14]

As visualized by the Table 2, Jajarkot's devastating earthquake in western Nepal resulted in significant destruction, affecting approximately 35,321 residences, both public and private. Mainly Jajarkot and Rukum West were the most affected districts by the earthquake. Among the affected dwellings, about 17,792 have suffered complete devastation, while an additional 17,529 have incurred partial damages. Specifically, in Rukum West alone 26,531 houses are fully or partially damaged among them 16,570 houses face complete destruction, with 9,961 others experiencing partial damages. Moreover, around 1,170 residences have sustained minor harm. Preliminary assessments estimate the overall district-wide damage to exceed Rs 1 billion. In Jajarkot, 1170 houses were entirely damaged, while 7,166 others faced partial destruction. Virtually no structure remained untouched by the quake, with nearly 90 percent requiring extensive reconstruction. Furthermore, the earthquake inflicted damage on roads and bridges.

Notably, three substantial landslides occurred along the Pasagad-Rimna section in the Bheri Corridor (Jajarkot-Dunai), resulting in road impairment and disruption of vehicular movement. Additionally, a significant landslide transpired at the Khalanga-Panchkatiya section. In

Jajarkot's Rimna area, a bridge also sustained minor damage, as reported by the local authorities [13].

Table 2: Number of houses Partial Collapse and Complete Collapse [16]

Affected area	Complete Collapse	Partial Damage
Rukum (West)	16570	9961
Jajarkot	1170	7166

Several researchers have reported the structural aspects of the earthquake, including building performance during different earthquakes in Nepal concentrating on different types of building structures [17-19]. Load-bearing masonry structures faced significant vulnerability due to their inherent construction characteristics [20]. These structures rely on walls constructed with bricks or stones to bear the vertical load of the building. In the event of an earthquake, the rigidity and ductility of masonry materials are often insufficient to absorb and dissipate the seismic energy, making them more susceptible to damage [21]. During ground shaking, load-bearing walls may experience torsion, shear, and flexural stresses, potentially leading to structural failure [22]. Additionally, inadequate bonding between bricks or stones, poor quality mortar, and insufficient reinforcement exacerbate the vulnerability of these structures. The seismic waves generated by the earthquake likely induced lateral forces that strained the load-bearing elements, potentially resulting in cracks, tilting, or partial collapse. The categorization of damage in houses experiencing varying degrees of structural deterioration was established through the examination of collected data and presented in this article [23].

3. Study Approach

This study employs standard approach to investigate the vulnerability of load-bearing masonry buildings in the aftermath of the Jajarkot Earthquake in 2023. The research initially focuses on the selection of the study area within the affected District, with an emphasis on choosing houses that reflect diverse structural characteristics and settlement patterns. The identification of sample houses is conducted through a combination of on-site surveys and information gathered from official government sources and national newspapers. Comprehensive on-site data collection is integral to this methodology. Visual inspections, interviews with residents, and consultations with local authorities are employed to gather detailed information on architectural, structural, and dimensional properties of the selected houses.

The analysis extends to seismic characteristics, where information on the Jajarkot earthquake's magnitude, depth, aftershock activity, acceleration values, and recorded waveforms is extracted from on-site measurements and official government seismic reports. This dual-source approach enables a thorough comparison against established seismic standards and codes.

The investigation also delves into the structural, architectural, and material properties of the affected houses. Data from official government reports and publications is cross-referenced with on-site assessments to ensure a comprehensive understanding. Material quality standards are assessed both on-site and by referencing guidelines set forth by relevant authorities. The damage sustained by the houses is then classified based on visual evidence and descriptions obtained from online resources. The categorization considers factors such as damage size, direction, and positions of structural components, as reported by official sources [24].

An in-depth analysis of the causes and mechanisms of damage follows, inferred from both on-site observations and official reports. This systematic approach draws upon established methodologies and cataloging systems used by experts in earthquake damage assessment, providing a nuanced understanding of contextual factors influencing the damage. In the final phase, the study synthesizes insights to derive valuable lessons and establish future directions. By analyzing the vulnerabilities and damage patterns observed in load-bearing masonry structures during the Jajarkot earthquake, the aim is to provide recommendations and guidelines for enhancing the seismic resilience of similar structures in earthquake-prone regions, ultimately contributing to more robust and disaster-resilient communities.

4. Building's distribution in earthquake affected areas

The Jajarkot earthquake had its most significant impact on the districts of Jajarkot and Rukum West. Among the affected districts, these two areas experienced the most pronounced devastation. As shown in *Fig. 5,* the distribution of households based on the type of foundation of housing units further highlights the vulnerability of these regions. In Rukum West, among a total of 37,290 houses surveyed, a staggering 33,886 were constructed using mud-bonded bricks or stone, with 1,939 employing cement-bonded bricks or stone. Additionally, 1,380 houses were built with reinforced cement concrete and pillars, while 59 relied on wooden pillars for support. Another 26 houses fell under the category of "others". Whereas in Jajarkot, among a total of 37,453 houses surveyed, a substantial 35,818 were constructed using mud-bonded bricks or stone, while 969 relied on cement-bonded bricks or stone. Additionally, 505 houses were built with reinforced cement concrete and pillars, while 133 utilized wooden pillars for support. Another 28 houses fell under the category of "others" This distribution underscores the prevalence of traditional construction methods in these regions, which have proven to be particularly vulnerable to seismic events. Mud and stone constructions, while common, lack the necessary reinforcement to withstand the force of an earthquake, making them susceptible to collapse or severe damage. Similarly, structures reliant on wooden pillars may not provide adequate stability in the face of significant seismic activity. The vulnerability of buildings in Jajarkot and Rukum West becomes even more apparent when considering factors such as construction quality and adherence to building codes. Many of the houses in these districts are constructed using traditional methods with little or no reinforcement. Mud-bonded or cement-bonded bricks and stones are commonly used, but these materials lack the structural integrity to withstand the intense shaking of an earthquake. Additionally, the absence of proper foundations and load-bearing structures further compromises the stability of these buildings. Moreover, due to limited resources and access to modern construction techniques, these communities often lack the means to implement earthquake-resistant measures. As a result, in the event of a seismic event, the risk of building collapse and subsequent loss of life and property is significantly heightened.

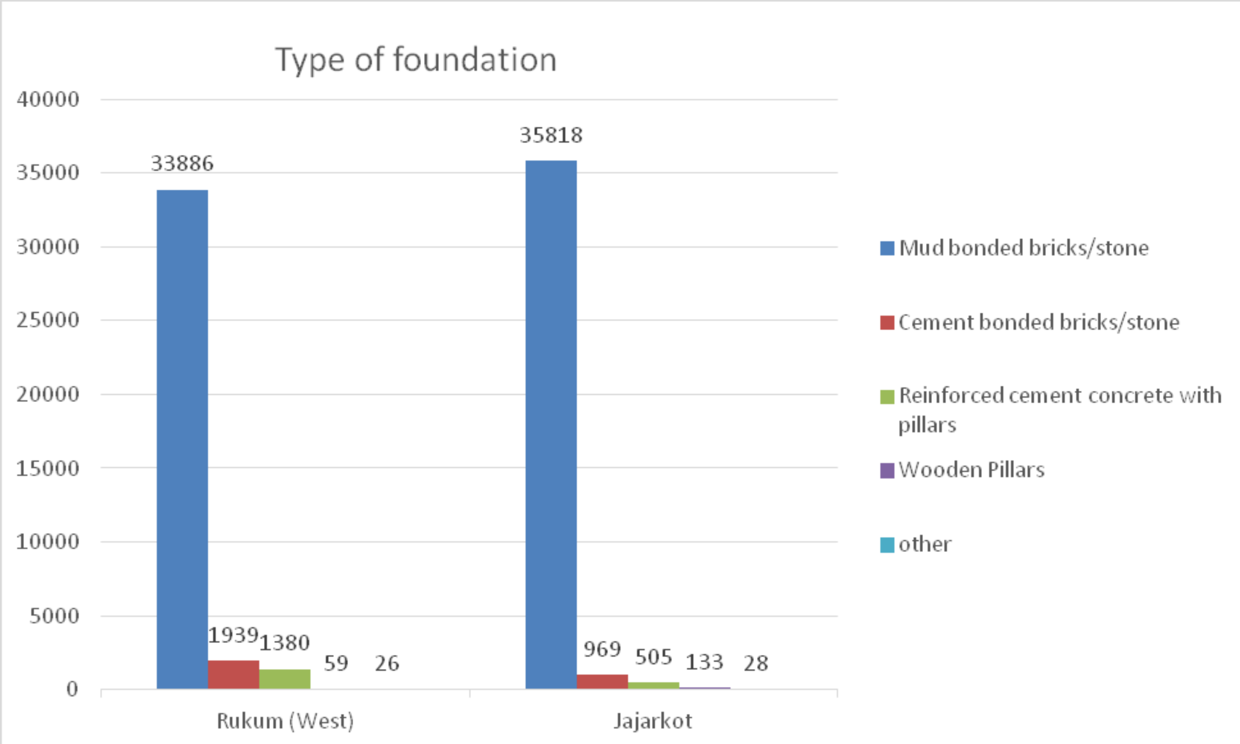


Figure 5: Distribution of Household having different Structure Foundation as per National Population and Housing Census, 2021as per National Population and Housing Census, 2021[25]

As *Fig. 6* clearly shows, in Rukum West, national census units reveal a significant reliance on traditional construction materials for outer walls. Among the total of 37,290 households assessed, a notable 31,963 were found to have outer walls constructed using mud-bonded bricks or stones, while 5,138 utilized cement-bonded bricks or stones. A smaller number, 47 households, relied on wood or planks, while 15 opted for bamboo. Additionally, 54 households employed unbaked bricks, while 62 used galvanized sheets. A mere 2 households chose prefabricated sheets, and 9 fell under the category of 'others'. Similarly, in Jajarkot, out of a total of 37,453 households surveyed, 34,854 featured outer walls made from mud-bonded bricks or stones, with 2,196 utilizing cement-bonded bricks or stones. A minority of households, 93 in number, had walls constructed from wood or planks, while 50 used bamboos. Furthermore, 167 households employed unbaked bricks, and 72 opted for galvanized sheets. A small fraction, 4 households, utilized prefabricated sheets, and 17 were categorized as 'others'. This distribution of construction materials highlights the prevalent use of traditional and locally available resources in these districts, underlining the importance of targeted interventions to enhance structural resilience in the face of potential seismic events.

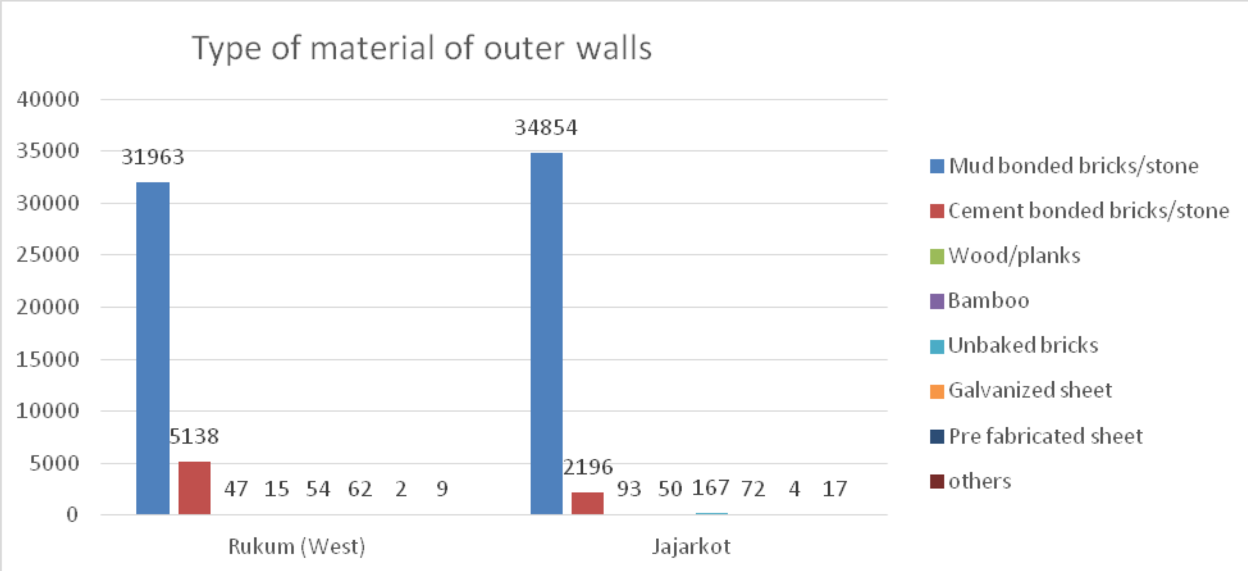


Figure 6: Distribution of Household with different type of material of outer walls as per National Population and Housing Census, 2021[25]

In *Fig. 7*, a detailed analysis of housing units in Rukum West and Jajarkot revealed varying types of roofing materials. In Rukum West, out of a total of 37,290 households surveyed, a significant 16,027 featured roofs made of galvanized sheets. Additionally, 2,704 households utilized reinforced cement concrete for their roofs, while 2,433 opted for thatch or straw. A smaller number, 50 households, had tile roofs, and 15,989 chose stone or slate. A minority of households, 18 in number, used wood or planks, and 49 relied on mud for roofing. A fraction, 20 households, fell under the category of 'others'. Similarly, in Jajarkot, among a total of 37,453 households assessed, 6,422 featured roofs made of galvanized sheets. Furthermore, 1,191 households utilized reinforced cement concrete, while 1,935 opted for thatch or straw. A smaller number, 58 households, had tile roofs, and 27,462 chose stone or slate. A minority of households, 74 in number, used wood or planks, and 273 relied on mud for roofing. A fraction, 38 households, fell under the category of 'others'. In rural communities, individuals often employ local masons to undertake construction projects. These masons, though skilled in their craft, have received no formal training and rely on personal judgment, field experience, and guidance from more seasoned colleagues. With no dedicated vocational schools for masonry in Nepal, the responsibility for many local construction endeavors falls on these craftsmen and their intuitive expertise.

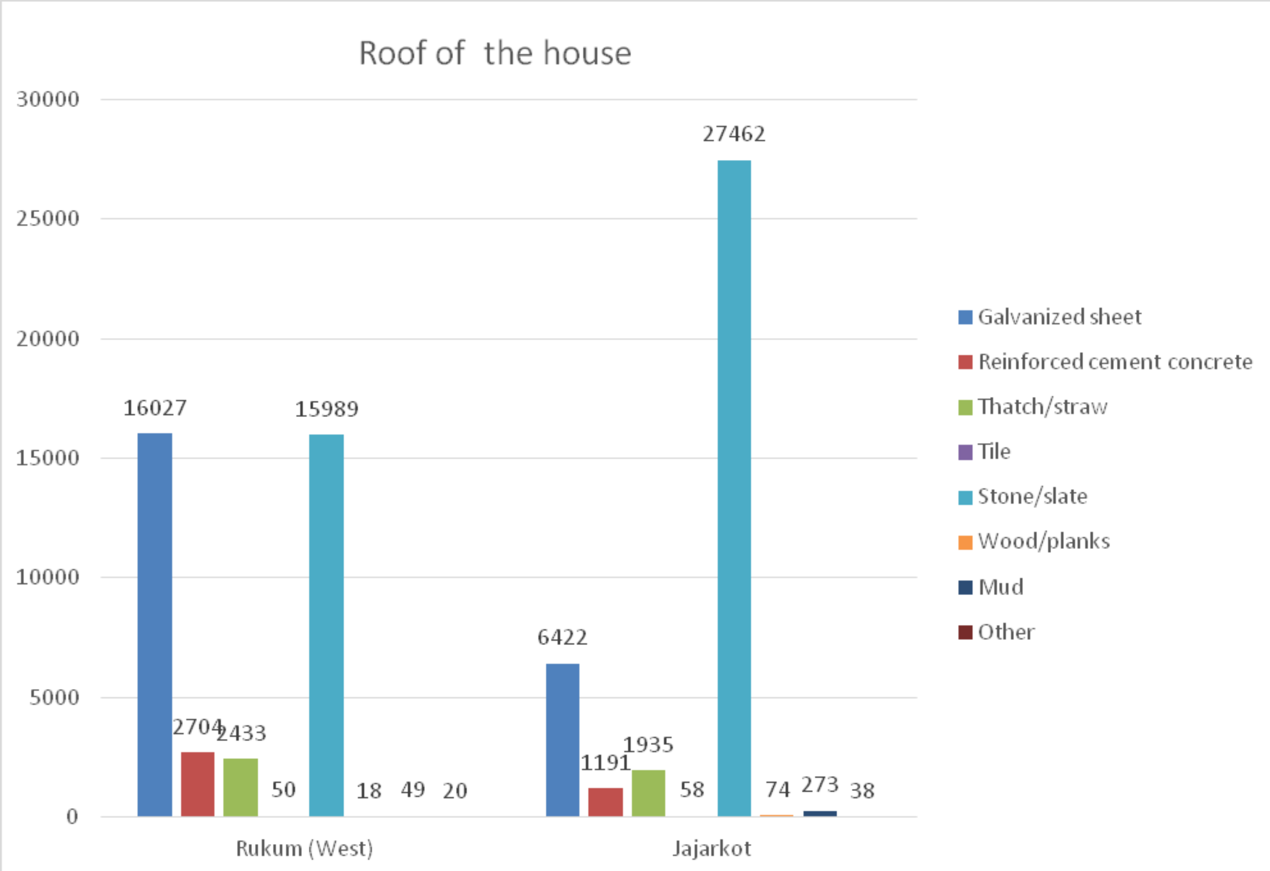


Figure 7: Distribution of Household with different type of roof of house as per National Population and Housing Census, 2021[25]

5. Observed Failure Mechanism of Load Bearing Structure

In this study, it looks at how load-bearing structures respond to different types of stress, strain, and outside forces mainly earthquake force. It involves finding and understanding weak points where buildings might break down partly or completely. Understanding these weaknesses helps in designing strong buildings, making old ones stronger, and protecting structures from earthquakes or other bad situations. This concept is important for making sure buildings stay strong and safe, and it gives useful information for engineers, risk evaluations, and improving how we build structures. Different Failure mechanism that were seen in masonry structures during the Jajarkot Earthquake are as follows:

5.1 Delamination of exterior walls

Delamination of exterior walls as shown in 8 refers to the separation or peeling off of layers in the masonry due to inadequate bonding between bricks or stones. This weakening of the wall structure of the buildings in the affected area were resulted from factors such as poor-quality mortar, insufficient curing, irregular bonding system, stone block formation, use of incompatible materials, exposure to freeze-thaw cycles, chemical reactions, aging, and seismic activity.

Figure 8: Delamination of the exterior walls

5.2 Complete collapse of the roof and gable wall

In the case of a Complete collapse of the roof and gable wall (*Fig* 5.2), it indicated a catastrophic failure where the entire roof structure, along with the gable wall, has given way. This type of failure was seen in the affected region due to inadequate bracing and improper construction techniques. It was also seen the use of slate stone, which is generally a heavier option for the roofing purpose, could be a reason of complete collapse of roof and gable wall.

Figure 9: Complete Collapse of Roof and Gable wall

5.3 Severe Cracking due to Inadequate Lintel Beam

Fig. 10, illustrates severe cracking, primarily caused by the absence of inadequacy of a lintel beam. A lintel beam provides crucial horizontal support above openings in load-bearing walls and divides the wall into smaller parts having more moment of inertia. In the figure it is clearly seen that the lintel was insufficient and just over the opening because of which the concentrated load from the wall above lead to extensive cracking at the corners of the building, weakening the overall structural integrity.

Figure 10: Severe Cracking due to Inadequate Lintel Beam.

5.4 Out of plane failure of exterior walls

Out of plane collapse as shown in figure 11, occurs when exterior walls fail in an outward direction, away from the building's center. The major causes for this type of failure in the building can be taken as lack of tensile reinforced resulting into weak structural integrity, deficient bond at corners continuous vertical joints and flexible floor diagram.

Figure 11: Out of plane failure of exterior walls

5.5 In-plane Failure of Exterior Walls

Fig.12 shows in-plane diagonal cracks, which form within the plane of the exterior walls as the lateral force acts parallel to the plane cause excessive shear forming diagonal cracks. These cracks indicated significant internal stress and deformation within the masonry. They resulted from the unequal distribution of seismic forces or inadequate reinforcement.

Figure 12: In-plane Failure of Exterior Walls

5.6 Diaphragm failure

Diaphragm failure as shown in fig.13 involves the inability of the horizontal diaphragm elements (such as floors or roofs) to effectively transfer loads to the vertical elements (walls and columns). It was seen in the building due to deficiency in tension anchoring, creating a cantilever effect at the base of the wall. This is caused by the diaphragm exerting pressure against the wall, resulting in a non-bending action.

Figure 13: Diaphragm failure

5.7 Torsional Failure

Torsional partial collapse as shown in fig. 14, occurs when torsional forces, which involve a twisting motion, lead to a partial failure of the structure. Torsional stresses were induced in the building due irregularities in the building's layout or improper distribution of loads, use of different material with in the same structure which showed different stiffness properties to the component of the building.

Figure 14: Torsional Failure.

5.8 Pounding Effects

Pounding effects as shown in fig.15 occur when adjacent structures collide during seismic events due to relative movement. As shown in figure it leads to additional damage and exacerbate the overall structural failure. Being situated in the one of the commercial area of that region, they attached two building without proper spacing and reinforcement which lead to the pounding effect and damaged the side gable wall of adjacent building.

Figure 15: Pounding Effect

5.9 Connection Failure Between Cross Wall

Connectivity failure as shown in fig.16, occurs when there is a breakdown in the connection between cross walls, which are essential for providing lateral stability to the structure. This type of failure was seen in the building because the use of longer tie stone was not provided in the connection and there was no use of any dowels, hooks or reinforcement to withstand concentrated loading at the corner.

Figure 16: Connection Failure

5.10 Failure due to Excessive Number of Openings

Fig 17 demonstrates the failure of openings in exterior walls, which occurred due to inadequate reinforcement around openings or poor construction practices. As seen in the figure the number of opening and their dimensions were not suitable as per the length of the exterior walls.

Figure 17: Failure due to excessive number of openings

5.11 Mixed Collapse

Mixed collapse as shown in fig.18, involves various structural elements exhibiting different forms of failure within the same structure. It was seen in the building due to inconsistency of mason during the construction of building, weaker connection in different places of the structure, irregular block pattern and haphazard placement of opening without proper planning can be the reason for the mix collapse in such areas.

Figure 18: Mixed Collapse

5.12 Complete Collapse

Complete collapse as shown in fig. 19, signified a catastrophic failure where the entire structure had given way, resulting in a total loss of structural integrity. This type of failure was a result of inadequate construction practices, weak materials, or insufficient structural support.

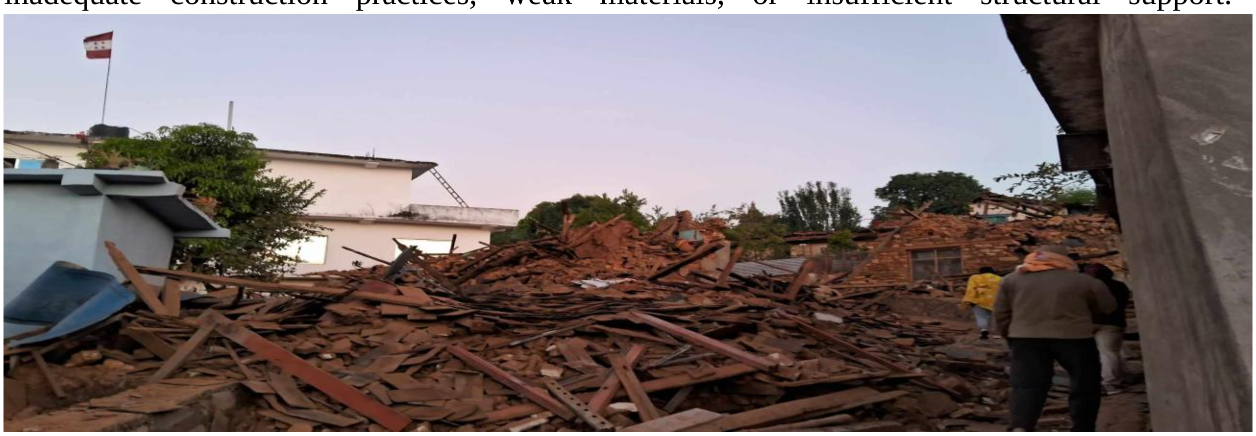


Figure 19: Complete Collapse

6. Causes, Lessons Learned and Future Direction

The seismic event, registering a magnitude (Mw) of 5.7, significantly impacted the regions of Jajarkot and Rukum (West). The predominantly rural houses constructed with local materials and made as load bearing structure in this area experienced extensive structural deterioration.

The observed types of damage included instances like delamination of exterior walls, full collapse of Roof and Gabble wall, severe cracks because of incomplete lintel beam, out of plane collapse of exterior walls, in-plane diagonal cracks on exterior walls, diaphragm Failure, complete Collapse, mixed Collapse, torsional Partial Collapse, connectivity failure between cross walls, opening failure on exterior walls, pounding effects.

Here, it is presented a concise summary of the findings regarding the factors contributing to these observed damages and some of the reasonable and practical approach to these problems.

- The structures were informally constructed with unskilled mason and did not adhere to the prescribed guidelines set forth by the Municipality or Rural Municipality. The primary deviation from standard practice was the insufficient reinforcement of the upper floors' connection to the vertical load-bearing exterior walls.

  To address informal construction practices, it is essential to prioritize professional oversight and training for builders. Strict enforcement of building codes, combined with community awareness and technical support, can ensure compliance. Additionally, offering incentives for adherence and imposing penalties for non-compliance will further encourage proper construction practices.
- The absence of tie beams on both the floor and roof levels of the load-bearing wall stands as the primary factor behind the extensive structural deterioration, which encompasses the outward collapse of external walls and partial failure of roof structures and the weight of the roofing and flooring was heavier to be supported by the weaker structural unit.

  To address this issue, implementing tie beams at both the floor and roof levels of load-bearing walls is crucial. These horizontal supports distribute the weight more effectively, providing essential reinforcement. Additionally, ensuring that roofing and flooring materials are appropriately selected and constructed to match the load-bearing capacity of the structural unit will help prevent overloading and subsequent deterioration. This approach ensures a balanced and resilient structural system.
- The load-bearing exterior walls exhibited a prevalent use of an uneven bonding system, often incorporating rubble stone components. Some buildings displayed these irregularities consistently along the entire wall. While these characteristics contributed to extensive structural harm, they also led to the fragmentation and disintegration of the outer surface of the external wall.

  To correct this problem, it is imperative to implement proper masonry techniques and bonding systems during construction. This includes ensuring a consistent and even distribution of masonry units and mortar to enhance structural integrity. Additionally, providing training and education for local builders and masons on correct masonry practices will help improve the quality of construction. Regular inspections and oversight during the construction process can also help identify and rectify any irregularities. Finally, using high-quality, durable materials that are suitable for load-bearing applications will contribute to the long-term stability and resilience of the exterior walls.
- The nature and causes of damage differ based on the number of factors contributing to the deterioration, the layout characteristics, and specific structural attributes. Notably, the extension of unsupported load-bearing walls within the layout led to the exacerbation of

more severe damage mechanisms. Additionally, the choice of materials, with wood employed in the internal wall system of upper floors and stone utilized in the lower levels, using of river aggregate without proper crushing etc, emerged as a critical determinant in elevating the extent of damage.

To ensure structural integrity, conduct a thorough assessment before construction and involve certified professionals for expert oversight. Utilize appropriate, high-quality materials and implement reinforcement measures like tie beams and braces. Adhere strictly to building codes, provide training for local builders, and conduct regular inspections to guarantee proper load-bearing support and prevent structural failure.

- The building lack proper connections between cross walls, leading to inadequate lateral stability.

  We should provide proper connections between cross walls, use suitable tie stones, and reinforce connections to withstand concentrated loads.
- There is deficiency in tension anchoring and inadequate load transfer from horizontal diaphragm elements to vertical elements in these buildings.

  It is necessary to strengthen tension anchoring and ensure effective load transfer mechanisms between horizontal and vertical elements.
- The problem is absence or inadequacy of a lintel beam, leading to concentrated loads and extensive cracking at building corners.

  The Solution is to install sufficient lintel beams above openings to evenly distribute loads and prevent excessive cracking.

7. Comparative structural performance analysis of Jajarkot Earthquake, 2023 with Gorkha Earthquake, 2023

The Gorkha Earthquake, Nepal which occurred in 2015 with a magnitude of 7.8, had some extensive devastation. Its impact was magnified by a subsequent 7.3-magnitude aftershock on May 12[18]. The toll was staggering, with 8,970 lives lost, 198 individuals reported missing, and 22,303 people sustaining injuries. The economic loss was found to be amounting to an estimated US$7 billion [5]. The structural damage was very high, causing nearly 95–99% of buildings in the hills and mountains of central Nepal to collapse [17, 25]. This left approximately eight million people affected, with hundreds of thousands homeless. The brunt of the destruction was felt in regions characterized by adobe brick and stone constructions, with 474,025 such buildings completely collapsing 19]. Landslides and avalanches, triggered by the seismic event, compounded the calamity. Various factors contributed to the structural damage, including construction deficiencies, substandard practices, poor binding materials, and the topographical effects of the region. Historic and monumental constructions suffered severe damage, and critical infrastructure, such as roads, bridges, hydropower plants, and water supply networks, sustained substantial harm [7].

In contrast, the Jajarkot Earthquake of 2023, with a magnitude of 6.4, brought attention to vulnerabilities in load-bearing masonry structures in western Nepal. Striking on November 3rd, it resulted in 363 reported casualties and economic losses surpassing Rs 1 billion. The most affected regions, particularly Jajarkot and Rukum West, witnessed significant damage to residences, impacting around 35,321 houses [16]. Load-bearing masonry structures faced vulnerability due to irregular bonding systems, weak mortar, and insufficient connections in building structures. Traditional construction methods, primarily employing mud-bonded bricks or stones, were prevalent in these regions, with 90.87% of affected households in Rukum West and 96.05% in Jajarkot constructed using these materials. The earthquake revealed specific damage patterns, including cracks in load-bearing external walls, vertical out-of-plane displacement, and partial collapse of internal walls. Despite its lower magnitude compared to the Gorkha Earthquake, the Jajarkot Earthquake underscored the importance of understanding regional construction practices and vulnerabilities to effectively mitigate seismic risks. Analyzing these seismic events, the Gorkha Earthquake of 2015 and the Jajarkot Earthquake of 2023 offer distinct case studies of seismic vulnerabilities in Nepal. They unveil weaknesses in construction practices, structural design, and adherence to building codes.

The Gorkha Earthquake exposed deficiencies in various building typologies, including soft-story collapses and brittle failures. Issues such as undersized columns, improper detailing, spalling of concrete, poor workmanship, and deficiencies in ductile detailing were observed in damaged residential constructions [17]. On the other hand, the Jajarkot Earthquake in 2023 revealed vulnerabilities in load-bearing structures, particularly in rural houses constructed with local materials. Failure mechanisms included delamination of exterior walls, complete collapse of roofs and gable walls, severe cracking due to inadequate lintel beams, and out-of-plane failures [13]. Both earthquakes underscore the critical role of material quality and construction practices.

In the Gorkha Earthquake, pancake destruction occurred due to undersized columns with large transverse rebar gaps. In the Jajarkot Earthquake, the absence of tie beams on both floor and roof levels contributed to extensive structural deterioration. Furthermore, the Jajarkot earthquake highlighted issues such as the use of heavy roofing materials like slate stone, leading to complete collapses and severe damage. Structural performance and seismic resilience were major concerns in both events. The Gorkha Earthquake revealed discrepancies in design and construction, particularly in apartments designed in India, leading to varying levels of damage. The Jajarkot Earthquake vividly exposed the vulnerability of load-bearing structures in rural areas, showcasing failure mechanisms such as diaphragm failure, torsional failure, pounding effects, connection failure between cross walls, and failure due to excessive openings.

In the aftermath of the Gorkha Earthquake, efforts were made to improve building code adherence and implement performance-based designs. Lessons learned included the importance of site-specific design considerations, the need for enhanced building codes, and seismic safety measures tailored for different housing types [7]. Similarly, the Jajarkot Earthquake emphasized the crucial role of professional oversight, the enforcement of building codes, and targeted interventions based on regional seismic risks [13].

8. Conclusions

The seismic event in Jajarkot and Rukum (West) highlighted significant structural issues in rural buildings, including delamination of exterior walls, complete collapse of roofs and gable walls, severe cracking due to inadequate lintel beams, out-of-plane and in-plane wall failures, diaphragm failure, torsional failure, pounding effects, connectivity failure between cross walls, failure due to excessive openings, mixed collapse, and complete collapse. Informal construction practices, lack of tie beams, uneven bonding systems, unsupported load-bearing walls, and material choices contributed to these failures. To address these issues, professional oversight, training for builders, strict enforcement of building codes, and use of appropriate materials are crucial. Implementing tie beams, reinforcing connections, strengthening tension anchoring, ensuring effective load transfer, and installing lintel beams above openings are necessary steps to improve structural resilience. The conclusion can be presented as in below topic.

Key Findings and Priorities: The Jajarkot Earthquake served as a reminder of the seismic vulnerability inherent in Western Nepal. With unique failure mechanisms and unique patterns of vulnerability the complexity of addressing seismic risks has increased. Comparative analysis with the Gorkha Earthquake showcased distinct weaknesses in rural load-bearing structures.

Roadmap for Future Directions: To deal with the faults, immediate priorities include training builders, enforcing building codes, implementing structural reinforcements, and promoting appropriate construction materials. The findings provide a clear guide to advancing civil engineering practices, emphasizing the importance of strategies for regional variations.

Collective Commitment: Understanding the diversity of regional construction practices is very necessary. Making strategies to specific regions ensures a more effective mitigation of seismic risks. The commitment to seismic resilience should be shared, involving communities, builders, policymakers, and engineers alike.

Lessons and A Safer Tomorrow: The lessons learned stress the importance of a complete, region-specific approach. By paying attentions to these lessons, implementing proactive measures, and promoting a collective commitment, Nepal can pave the way for a safer tomorrow. The synthesis of findings serves as a signal for advancing not only civil engineering practices but also a culture of preparedness and resilience in seismic-prone regions. In this collective effort, the journey towards a more secure built environment begins one step at a time.

References

1 Khattri, K. N. (1987). Great earthquakes, seismicity gaps and potential for earthquake disaster along the Himalaya plate boundary. Tectonophysics, 138(1), 79-92.

2 Bisht, H., Kotlia, B. S., Kumar, K., Dumka, R. K., Taloor, A. K., & Upadhyay, R. (2021). GPS derived crustal velocity, tectonic deformation and strain in the Indian Himalayan arc. Quaternary International, 575, 141-152.

3 Parajuli, H. R., Bhusal, B., & Paudel, S. (2021). Seismic zonation of Nepal using probabilistic seismic hazard analysis. Arabian Journal of Geosciences, 14, 1-14

4 Shanker, D., Paudyal, H., & Singh, H. N. (2011). Discourse on seismotectonics of Nepal Himalaya and vicinity: appraisal to earthquake hazard. Geosciences, 1(1), 1-15.

5 Chaulagain, H., Rodrigues, H., Silva, V., Spacone, E., & Varum, H. (2016). Earthquake loss estimation for the Kathmandu Valley. Bulletin of Earthquake Engineering, 14, 59-88.

6 Pandey, M. R., Tandukar, R. P., Avouac, J. P., Lave, J., & Massot, J. P. (1995). Interseismic strain accumulation on the Himalayan crustal ramp (Nepal). Geophysical Research Letters, 22(7), 751-754.

7 Gautam, D., & Chaulagain, H. (2016). Structural performance and associated lessons to be learned from world earthquakes in Nepal after 25 April 2015 (MW 7.8) Gorkha earthquake. Engineering Failure Analysis, 68, 222-243.

8 Acharya, I. P., Subedi, M., & KC, R. (2023). Liquefaction Hazard Assessment of Kathmandu Valley Using Deterministic and Probabilistic Approaches. Geo-Risk 2023 (pp. 307-317).

9 Pandey, M. R., Tandukar, R. P., Avouac, J. P., Vergne, J., & Heritier, T. (1999). Seismotectonics of the Nepal Himalaya from a local seismic network. Journal of Asian Earth Sciences, 17(5-6), 703-712.

10 Hossler, T., Bollinger, L., Sapkota, S. N., Lavé, J., Gupta, R. M., & Kandel, T. P. (2016). Surface ruptures of large Himalayan earthquakes in Western Nepal: Evidence along a reactivated strand of the Main Boundary Thrust. Earth and Planetary Science Letters, 434, 187-196.

11 National Earthquake Monitoring & Research Center. Available at: https://www.seismonepal.gov.np/ (Accessed: 10 November 2023).

12 Avouac, J. P., Meng, L., Wei, S., Wang, T., & Ampuero, J. P. (2015). Lower edge of locked Main Himalayan Thrust unzipped by the 2015 Gorkha earthquake. Nature Geoscience, 8(9), 708-711.

13 Subedi, M., KC, R., Sharma, K., Misra, J., & KC, A. (2024). Reconnaissance of the Effects of the M W5. 7 (M L6. 4) Jajarkot Nepal Earthquake of 3 November 2023, Post-Earthquake Responses, and Associated Lessons to Be Learned. Geosciences, 14(1), 20.

14 M 5.7-46 km E of Dailekh, Nepal. USGS, Earthquake Hazards Program. Available at: https://earthquake.usgs.gov/earthquakes/eventpage/us7000l8p5/shakemap/intensity (Accessed: 10 November 2023).

15 Malakar, S., & Rai, A. K. (2022). Earthquake vulnerability in the Himalaya by integrated multi-criteria decision models. Natural Hazards, 1-25.

16 National Emergency Operation Center (NEOC). Nepal Government, Ministry of Home Affairs. Available at: http://neoc.gov.np/en/ (Accessed: 10 November 2023).

17 Okamura, M., Bhandary, N. P., Mori, S., Marasini, N., & Hazarika, H. (2015). Report on a reconnaissance survey of damage in Kathmandu caused by the 2015 Gorkha Nepal earthquake. Soils and Foundations, 55(5), 1015-1029.

18 Rai, D. C., Singhal, V., Raj S, B., & Sagar, S. L. (2016). Reconnaissance of the effects of the M7. 8 Gorkha (Nepal) earthquake of April 25, 2015. Geomatics, Natural Hazards and Risk, 7(1), 1-17.

19 KC, A., Sharma, K., & Pokharel, B. (2019). Performance of heritage structures during the Nepal earthquake of April 25, 2015. Journal of Earthquake Engineering, 23(8), 1346-1384

20 De Santis, S. (2022). An expeditious tool for the vulnerability assessment of masonry structures in post-earthquake reconstruction. Bulletin of Earthquake Engineering, 20(15), 8445-8469.

21 Chourasia, A., Singhal, S. & Parashar, J. (2019). Experimental investigation of seismic strengthening technique for confined masonry buildings. Journal of Building Engineering, 25, p. 100834

22 Ingham, J., & Griffith, M. (2010). Performance of unreinforced masonry buildings during the 2010 Darfield (Christchurch, NZ) earthquake. Australian Journal of Structural Engineering, 11(3), 207-224.

23 Oliveira, C. S. (2003). Seismic vulnerability of historical constructions: a contribution. Bulletin of Earthquake Engineering, 1, 37-82.

24 D’ayala, D., & Speranza, E. (2002). An integrated procedure for the assessment of seismic vulnerability of historic buildings. In 12th European conference on earthquake engineering (p. 3).

25 Ghazoui, Z., Bertrand, S., Vanneste, K., Yokoyama, Y., Nomade, J., Gajurel, A. P., & van der Beek, P. A. (2019). Potentially large post-1505 AD earthquakes in western Nepal revealed by a lake sediment record. Nature communications, 10(1), 2258.

26 National Population and Housing Census 2021 (2021). National Statistics Office, Nepal. Available at: www.censusnepal.cbs.gov.np (Accessed: 10 November 2023).