Subsidence-Induced Damage Assessment of Buildings on Joshimath Hills

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ABSTRACT

In hilly areas due to seepage of water, soil erosion, weathering, earthquakes, undercutting by river current, overloading of the landmass cause creeping of land. The creeping leads to ground subsidence, landslides etc., thereby inflicting damage to buildings. In Joshimath on 2nd January 2023, an incidence of ground subsidence occurred which damaged many buildings and infrastructures. This study addresses the exploratory work on rapid visual damage assessment of buildings based on method developed by National Disaster Management Authority (NDMA) and European Macroseismic Scale (EMS) - 98. The building vulnerability was assessed using building attributes like typology, number of storeys, area, construction materials, occupancy, configuration, construction practice etc. The damage attributes considered are based on siting issues, soil and foundation conditions, architectural features and elements, structural aspects and components, material & construction details, crack monitoring etc. In the critical buildings, cracks were monitored using crack meters. This study concludes out of total 2364 building surveyed, 37%, 42%, 20%, 1% buildings fall under "Usable", "Further Assessment", "Unusable", "to be demolished" categories respectively.

Keyword:

Construction practice, Ground subsidence, Damage assessment, Crack Monitoring, Building vulnerability analysis.

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INTRODUCTION

Distress mapping of buildings in hilly regions which are subjected to ground subsidence, settlement etc. becomes essential as the it helps in planning effective response and recovery strategies. Field studies are crucial, as it provides relatively accurate data, and valuable experience about the building typologies, construction practices, nature of the hazard and its impact, and risk thereof. The field study aimed to develop a roadmap for risk-informed development planning and create an ecologically sensitive, culturally appropriate, and economy-driven recovery plan.

An incidence of ground subsidence occurred in Joshimath on 2nd January 2023[1,2], resulting in the development of ground fissures and cracks on civil structures, including residential buildings, roads, hotels, etc. Joshimath town (79°33'-79 ° 35'E, 30 ° 31'-30 ° 34'N) is situated on the northerly upper-middle slopes on the left flank of the Alakananda River in the Garhwal Himalaya at an elevation of 1890 m above MSL. The basal substrate of the hill lies in the Central Crystalline of the Higher Himalaya comprising streaky and banded gneiss and schist in the hanging wall of the Main Central Thrust[3]. The northerly dipping rocks constitute a dip slope and are covered with a thick pile of paleo-landslide deposit constituting mainly coarse-grained debris materials and massive boulders[4].

Based on previous report [5,6], it is evident that Joshimath town has been largely constructed on old landslide debris and lacks sufficient support from in-situ rock mass. Previous studies have reported that Joshimath is prone to landslide and subsidence due to complex geology and tectonic instability[7]. The town has also documented history of slope failures, which renders it susceptible to ground distress, deformations, and displacements. Geologically, Joshimath is situated on the vicinity of MCT and close to Munsiari Thrust line [8]. The Munsiari Thrust (MT) and Main Central Thrust (MCT) are both relatively flimsy lines. Thus, Joshimath is extremely prone to earth subsidence or sinking because it is situated on an active tectonic fault line.

Moreover, the region experienced a significant earthquake of magnitude 6.6 on 29th March 1999, and it regularly encounters low-magnitude seismic activity due to its location in Seismic Zone V[9]. Besides, these tectonic discontinuities[10], and burgeoning anthropogenic pressure, the debris-laden slope showed prolonged northerly movements[11,12] causing cracks and tilting of buildings in different pockets of the slope, as observed physically by the authors during the filed study. The incidence of excessive discharge of groundwater along with soil particles, land movements, and ground subsidence, has triggered sinking zones and reactivated many old landslides. The significant pointers of the ground settlement could be geological i.e., presence of weak, fissured, sensitive, and unconsolidated material; geomorphologic i.e., kinematically unstable slopes, fluvial and glacial erosion; hydrology – drainage; and anthropogenic activities. To gain deeper insights, the authors conducted reconnaissance survey and performed physical observations at the site. Their first-hand assessment allowed them to witness the aftermath of the subsidence and its impact on the affected structures. In these circumstances, a field study was conducted using a multidimensional approach to provide a comprehensive overview of the damages caused by the landslide and subsidence. The outcome of the study will help in mitigating the risk by ensuring effective deployment of emergency response teams, disaster resilient construction, and identifying topics for follow-up research activities in hazard estimation and measures adopted to reduce the vulnerabilities.

PRESENT STUDY

According to the Population Census of 2011, the total population was 16,709[13]. With a 27% decadal growth rate[14], the population in 2021 rose to 21,700. The district administration estimates[15] a further increase, projecting a population of 22,900 for the year 2023. This population growth is driven by various factors, including the town's location as a key transit hub for pilgrims heading to Badrinath and Hemkund Sahib, Auli. During the peak season, Joshimath experiences a staggering footfall. This influx of visitors exerts significant anthropogenic pressure on the town's resources, infrastructure, and natural environment, necessitating careful planning and sustainable management to ensure its ecological and social well-being in the face of such rapid development and urbanization. As per the data provided by local administration Joshimath town, is spread across a total area of 13.47 square kilometers, housing around 2364 buildings and is divided into 9 administrative zones *viz.* Gandhinagar, Marwari, Lower Bazar, Singdhar, Manoharbagh, Upper Bazar, Sunil, Parsari and Ravigram. The region has long been a priority sector for hydro-power projects and has received sizable public investments. The increasing intensities of hazards with growing risk have renewed the urgency in developing a deeper understanding of the buildings and their typology along with different attributes – number of storeys, area, siting, structural components, configuration, construction practice, material and construction details, condition/distress assessment and crack monitoring, if any, etc., and provide the way forward towards reducing vulnerability and/or risk. The present study was undertaken by conducting field visits to different administrative zones during the month of January 2023.

THE BUILDINGS

There are mainly four types of building construction typologies followed in the affected region, namely Vernacular- wooden post and beam with stone masonry infill; Stone / Brick Masonry; RC frame type with infill walls and Hybrid buildings. Generally, construction practices are adopted according to the availability of materials and economic aspects. The different building typologies are shown in Fig.1.a-e.

Vernacular Buildings

Most of the vernacular buildings represent Garhwal architecture, having two-storeyed built with 450mm thick undressed stone masonry walls, with regularly placed horizontal and vertical wooden elements in lime-sand mortar. The walls are placed with mud or lime-surkhi mortar on thick stone masonry. The wooden joist and secondary beams support wooden planks with lime-surkhi screed as flooring on the first floor. The lightweight sloping roof with Corrugated Galvanised Iron (CGI) sheet supported over wooden rafters and purlins. Generally, heavy sections of wooden door and window frames with limited (around 15%-20% of wall area) openings in the wall are provided. In spite of the non-engineered structure, such typology fulfils most of the seismic safety requirements viz. anchorage, bracings, and proper connections between different elements, as a result of ensuing integral box action[16-18] which led to no damage during the 1991 Uttarkashi and 1999 Chamoli earthquakes nor due to minor ground subsidence in most of such typology.

The damage noticed in various proportions in vernacular buildings are mainly due to (a) Houses that are connected to adjoining retaining walls wherein differential settlement of wall affecting the foundation of the house and tilting of the wall, thereof (b) Excessive long walls of stone masonry, without wooden reinforced elements of buttresses were susceptible to out-of-plane bending (c) Absence of 'through stones'; multiple irregular stones; low strength mortar; splitting of stone masonry wythes; bulging of walls, inadequate foundation width/depth etc.

Masonry Buildings

The majority of houses in Joshimath are Unreinforced Masonry (URM) load-bearing buildings ranging between 2 to 3 storied, with story height in the range of 2 to 2.7*m*. The masonry houses are primarily with brick/stone/ concrete block masonry as walling units with cement plaster and roof consisting of light-weight CGI sheets. Masonry units have been joined together using various types of mortars such as mud, lime, cement, surkhi, *etc*.

There are numerous variations to this housing typology over time, these include: (i) brick (230mm thick) or undressed stone (450mm thick) masonry walls in mud, cement mortar (ii)sill mud walls replaced by half-brick thick burnt clay brick unreinforced masonry walls, (iii) sill masonry walls or sill mud walls (iv) wood frame is replaced by a lightly reinforced RC frame, wood floor of two storey building with RC slab, and roof replaced with light gauge CGI. In general, the masonry strip footing, 600mm deep, 450-600mm wide, resting on loose strata are adopted, with the intention of one-storey construction, however, need-based vertical extensions were carried out up to 4 storeys, without any strengthening measures of the foundation of the lower storey.

The commonly observed salient undesirable features of the URM buildings are (a) the use of poor quality unburnt or sun-dried clay brick units; (b) adoption of multi-wythe construction of unreinforced stone masonry walls; (c) absence of connectivity between these wythes using through stones or wood runners; (d) in-sufficient connection between thick masonry walls and heavy timber floors; (e) use of masonry arches and columns; (f) tall storey heights; (g) part of building height is below road level (h) building connected to retaining walls or hill slope (i) re-entrant corners in plan (j) buildings on slope ground, (k) absence of bands and box action[16 - 18] of walls and (l) inadequate drainage around building causing foundation settlements.

The distress in the masonry buildings is primarily due to non-engineering practices (Fig.2.a-f) along with lack of maintenance and poor quality of construction. Diagonal cracks have been observed in the walls due to differential settlement of the foundation (Fig.2-a). Wythes separations in stone masonry occurred due to the unavailability of through stones (Fig.2-b). Diagonal shear cracks have been observed in the corners of the walls and doors of the masonry buildings (Fig.2-c). Fig.2-d shows the typical crack pattern in the wall of the masonry building due to land subsidence with crack width being maximum at the bottom and gradually decreasing with height due to local adjustment. Sliding shear failure is observed in most of the ground-story buildings due to low vertical load accompanied by poor-quality of mortar (Fig.2-e). Vertical shear cracks along the height of the building have been observed in mud masonry houses (Fig.2-f). The engineered buildings performed relatively well as compared to non-engineered buildings and were subjected to minor cracks.

Reinforced Concrete Frame Buildings

Most of the RC framed buildings are non-engineered, burnt clay or concrete block infills, up to 5-6 storied, planned on a rectangular grid of columns of smaller bays, founded on an isolated footing of size ranging between 1.2-1.5m. As the floor levels of lower stories are below the road level on the sloped ground connected to adjoining retaining walls, contributing to the significant vertical irregularity of the building. Moreover, the buildings are constructed with no gap between adjacent buildings of dissimilar storey heights. Besides these construction features, poor quality of construction material, workmanship, the smaller size of RC elements, inadequate reinforcement detailing, walls over cantilever, masonry walls over RC slab in upper floors etc. are common anomalies that are widely adopted in construction practice at Joshimath. When such typology is susceptible to ground subsidence, it suffered damages of some form or the other: the most common being the in-plane failure of weak infills and out-of-plane failure of slender walls, shear and/or flexure failure at column ends, failure of beam-column joints etc. Fig.3.a-g shows the typical failure of different RCC buildings when subjected to ground subsidence.

CAUSES OF DISTRESS

The damage in buildings when subjected to even minor ground subsidence could not resist the forces acting predominantly due to mud mortar as binding material and the absence of RC/wooden bands), excessive long walls having out-of-plane failure, dilation effect due to light roofing and weak binding mortar, opening in walls at the corner, subsidence of foundation due to excessive seepage, presence of steep slope, inadequate retaining structure close to the foundation, and vertical and plan irregularity of buildings.

Crack patterns in buildings due to ground subsidence have been broadly categorized as per the EMS[25] guidelines:

Type 1: A more or less vertical wall crack that starts (widest end) at either the top of a wall between roof beams or the base of a wall and in the case of masonry walls, extends stair-stepping through the mortar.

Type 2: A crack that starts (widest end) from a doorway or window, usually from one of the corners, and extends upward in a stepped fashion through the mortar between concrete blocks or in various orientations through masonry.

Type 3: Complex crack pattern in the floor slab and wall which originates (widest end) at the intersection of the floor slab crack with the wall and extends upward into the wall generally in a diagonal orientation. The wider crack at the bottom and reduced crack width at the top end of the walls are due to the floor movement horizontally rather than settling downward.

Type 4: A horizontal crack along masonry joints, generally between 4^{th} to 7^{th} courses usually at mid-wall in masonry walls. This type of crack is due to out-of-wall plane movement of the ground.

Type 5: In load-bearing buildings, a crack that starts (widest end) at top of the wall under a roof beam and extends downward, majorly due to inadequate bearing surface for roof beams on supporting walls or increased ground settlement resulting in stress concentration on the material under the beam beyond the material's strength.

Among the different types of cracks as mentioned above, the majority of cracks observed in damaged buildings at Joshimath region were predominantly in the Type 3 category and at a few locations under Types 1, 2, 4 and 5, category. This corroborates the main cause of cracks is due to land settlement/movement and partially due to excessive vibration in the ground for the building located and connected to the road. The typical cracks observed in buildings are shown in Fig. 2.a-f & Fig. 3.a-g.

DAMAGE ASSESSMENT

A scientifically sound methodology for assessing damage sustained by buildings during ground movement has been implemented[19-24]. A detailed study of prevailing construction material used, construction practises, building typology, and foundation system along with features acting negatively on building performance when subjected to lateral forces was captured. Subsequently, the installation of crack meters (Fig. 4) at appropriate locations followed by detailed crack measurements and monitoring was performed at frequent intervals. Crack meters were placed perpendicular to the crack to measure the displacement in two vertical planes of the wall. The crack displacement illuminates whether the cracks are growing or stable and provided information on vulnerability classification. Based on the progressive crack width measurements [25], the building vulnerability has been classified as Highly Vulnerable (crack width >5mm); Moderately Vulnerable (crack width between 2-5mm); Slightly Vulnerable (crack width up to 2mm). The anomalous increase in crack widths in most of the identified buildings is compelling evidence that ground subsidence/movement is the root cause of distress in buildings.

Structural damage classification in five different grades was adopted, as per EMS-1998 guidelines[25] for masonry and RCC buildings. The damage grades are classified as: Grade 1: Negligible to slight damage; Grade 2: Moderate damage; Grade 3: Substantial to heavy damage; Grade 4: Very heavy damage; Grade 5: Near Collapse. The above information has been assimilated for each building to decide the vulnerability class as Usable (Green Tag), Assess Further (Yellow Tag), and Unusable (Red Tag) and to be demolished (Black Tag) (Fig.5).

RESULTS & DISCUSSION

The buildings are the most affected infrastructure when subjected to ground subsidence in the mountainous region due to various attributes. Among many dominating attributes, a few are - siting (slope), configuration, number of stories, building typology, construction material and practice etc. Based on an extensive physical damage assessment survey of 2364 buildings, spread over 13.47 sq.km of hilly terrain, in 9 administrative zones, the data was analysed for assessing their building vulnerability. The analysis was performed on various parameters like buildings and their typology along with different attributes – number of storeys, area, siting, structural components, configuration, construction practice, material and construction details, condition/distress assessment and crack monitoring, if any, etc., were considered for the damage building classification and to draw risk map Joshimath.

The town has 44%, 42%, and 14% of masonry, RCC and other (traditional, hybrid) construction typologies, respectively, among which 99% are non-engineered i.e., not complying with the National Building Code of India 2016 provisions. The number of stories of a building is an important attribute which indicates that 38%, 43%, 14%, and 5% are comprised of 1, 2, 3 and more than 4-floor buildings respectively.

These features further stress the ground/foundation from overloading consideration, wherein building siting is of paramount importance. The analysis shows that 1%, 48%, 20%, and 31% of buildings have foundations on Flat up to 5^o, between $5\text{-}15^o$, between $15\text{-}30^o$, and more than 30^o sloped ground respectively. The siting aspect of buildings based on ground characteristics is shown in Fig. 6, indicating that the majority of the buildings in Manoharbagh is situated on a steep slope (> 30 °) at hill toe whereas the majority of the buildings in Ravigram is situated on flat *to* the mild slope (0-15°). Administrative Zones- Gandhinagar, Singhdhar, Manoharbagh where the percentage of buildings are more in the steep to medium category, the no. of buildings in the unusable and demolish categories show an upward trend. On the contrary zones such as Sunil, Parsari and Ravigram where the majority of buildings are in Flat to mild slope, has the least number of buildings in the unusable category.

When building configuration/shape is considered, it has been observed that Gandhinagar Zone which has a maximum percentage (around 5%) of irregular shape buildings is one with the most percentage of affected buildings falling under the unusable category second to Singhdhar zone. As shown in Fig.8, the average height of most buildings in the region is around 3.3 m of which the masonry building are the ones most affected. From Fig.7 it can be concluded that the majority of the buildings have rectangular configurations followed by L-shaped buildings. The building height classification and the number of stories in the buildings is shown in Fig.8 and Fig.9 respectively.

The various damaged states of the buildings as per various administrative zones are shown in Fig.11. Also, the administrative zone-wise distribution of the damaged state of the buildings is presented in Fig.12, highlighting about 37% of the total buildings are under ‘Usable’, 42% of the total building’s needs “Further Assessment”, 20% of the total buildings are “Unusable” and 1% of the total building’s needs “To be demolished”.

As a whole, these aspects are closely influencing the vulnerability of buildings in the region and point towards the construction practices implemented in the region. During the survey of the region, the authors have observed around 40 fissures having widths up to 300 mm and 3-4m deep, which the local administration informed, that have formed in January 2023, wherein most of the surrounding buildings were damaged. Based on the analysis and building vulnerability classification, the spatial distribution of all the buildings under different classes have been shown in Fig.13, which clearly indicates the high concentration of vulnerable buildings around the fissures-formed region.

While the issue is reviewed from a relief and rehabilitation point of view with respect to covered area demand. The analysis data indicates approximately Joshimath has 389110 sqm.

of covered area amongst which 1%, 53%, 34%, 9%, and 2.7% are constructed in Lower Ground, 1, 2, 3, and >4 floors of the buildings, respectively. (Fig.10)

CONCLUSIONS

The buildings situated over Joshimath hills reported extensive cracks. The paper highlights the building construction typology and construction practices adopted in the region. The exploratory work on damage assessment of existing buildings subjected to settlements/subsidence was accomplished in a rapid, simple, economical and efficient manner using a scientifically driven methodology.

Based on an extensive physical damage assessment survey of 2364 buildings, spread over 13.47 sq.km hilly terrain, in 9 administrative zones of Joshimath, building vulnerability was assessed using various parameters like buildings and their typology along with different attributes – the number of storeys, area, siting, structural components, configuration, construction practice, material and construction details, condition/distress assessment and crack monitoring, if any, etc., for building damage classification and to draw building vulnerability map. A number of key findings from the investigation are summarised as follows:

1. Joshimath town is situated on Vaikrita groups of rocks overlain by morainic deposits. These are composed of irregular boulders and clay of varying thicknesses. Such deposits are less cohesive and susceptible to slow ground subsidence.
2. There is a history of creeping and occasional subsidence in the region. The current episode is another such event.
3. A scientifically sound methodology, based on vulnerable building features, crack propagation has been implemented for assessing damage sustained by buildings during ground movement. The anomalous increase in crack widths in most of the identified

buildings is compelling evidence that ground subsidence/movement is the root cause of distress in buildings.

4. The dominating attributes for building damage in hilly regions are sitting (slope), configuration, number of stories, building typology, construction material and practice etc., coupled with the development of ground fissures.
5. In Joshimath township out of the 2364 buildings surveyed in this study, 37%, 42%, 20%, and 1%, respectively, fall into the "Usable," "Further Assessment," "Unusable," and "to be demolished" categories.
6. Singdhar, Gandhinagar administrative zones are largely affected by the incidence of ground subsidence and large number of buildings were found to be in distress conditions.
7. The plots of the spatial distribution of all the buildings under different classes corroborate the fact that a high concentration of vulnerable buildings is around the observed ground fissures formed in the region. The building vulnerability map developed may be superimposed over the geological, geo-morphological, geotechnical, seismological and hydro-geological map for a holistic risk map of the region. This will help administration, and policymakers to draw futuristic guidelines, strategies for the safety of buildings and people and their rehabilitation strategies.
8. There is a need for reviewing the principles of town planning for the development of towns in hilly regions with rigours stress on good construction typology, practices, material, regulatory mechanism, and awareness among the stakeholders based on geotechnical and geo-climatic conditions.
9. The database of this study can be utilised for the development and validation of robust methods of rapid damage assessment using advanced techniques viz. Digital surface model from LiDAR data, building shadow detection and extraction from imagery, and simulation of building shadows that can be attributed to building damage.

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Declaration of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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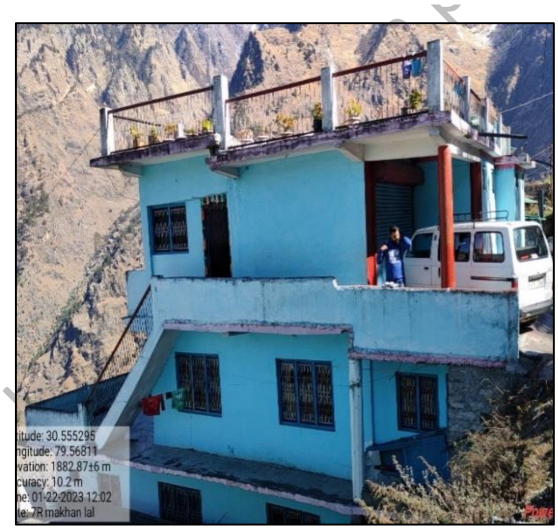
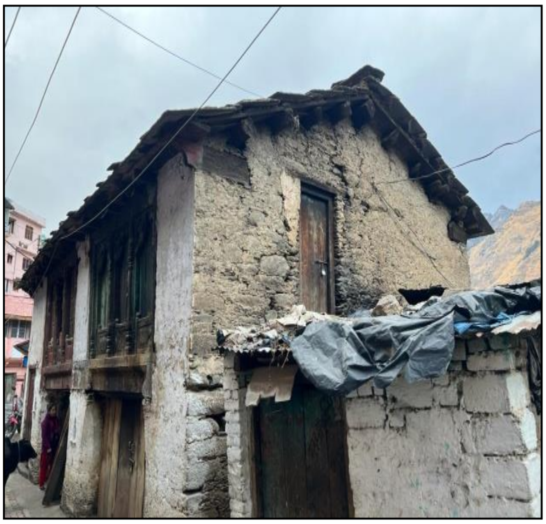
Figure Legend



a. Reinforced Cement Concrete

b. Brick Masonry



c.Stone Masonry

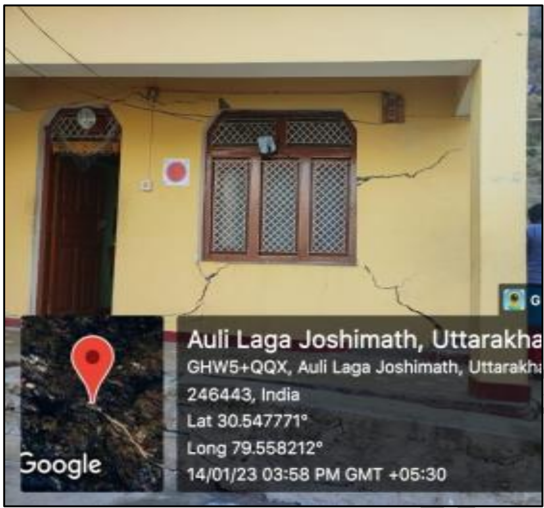
d.Mud and Wooden Masonry

e. Hybrid Construction

Fig. 1: Different Building typologies at Joshimath

a. Failure in Masonry building due to land subsidence

b. Failure of rubble masonry due to unavailability of firm ground and footing



c. Diagonal shear Failure of Masonry Infill

d. Failure of masonry infill due to land subsidence

e. Sliding Shear Failure of Masonry Building

f. Vertical shear crack along the wall

Fig. 2: Typical crack pattern in Masonry-damaged buildings

a. Excessive cantilever projection

b. Shear Failure at column footing junction

c. Bearing failure of the ground story

d. Roof sliding due to land subsidence

e. Damage due to lateral soil thrust

f. Rotation in RCC Column g. Shear failure in RC Beam

Fig. 3. Typical crack pattern in RCC damaged buildings

Fig.4: Installed crack meter over the wall

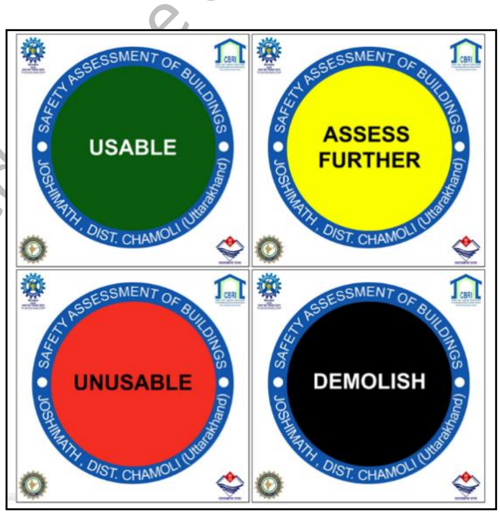


Fig.5: Classification of building vulnerability class

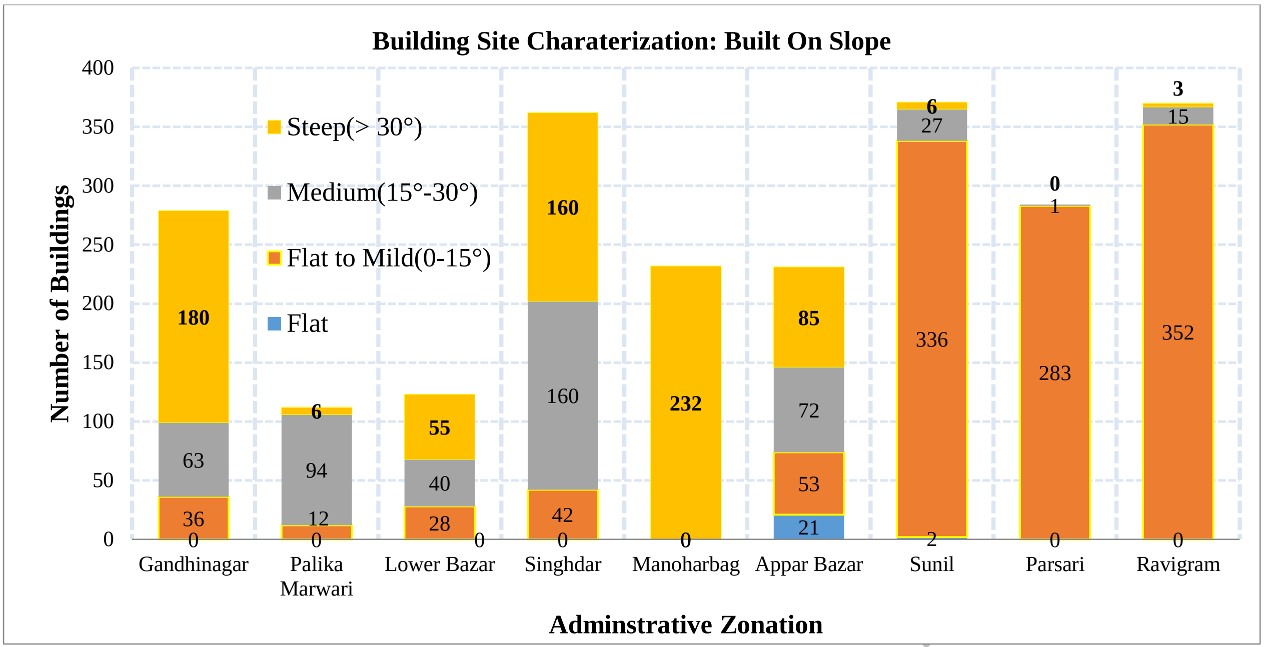


Fig. 6: Building site characterization

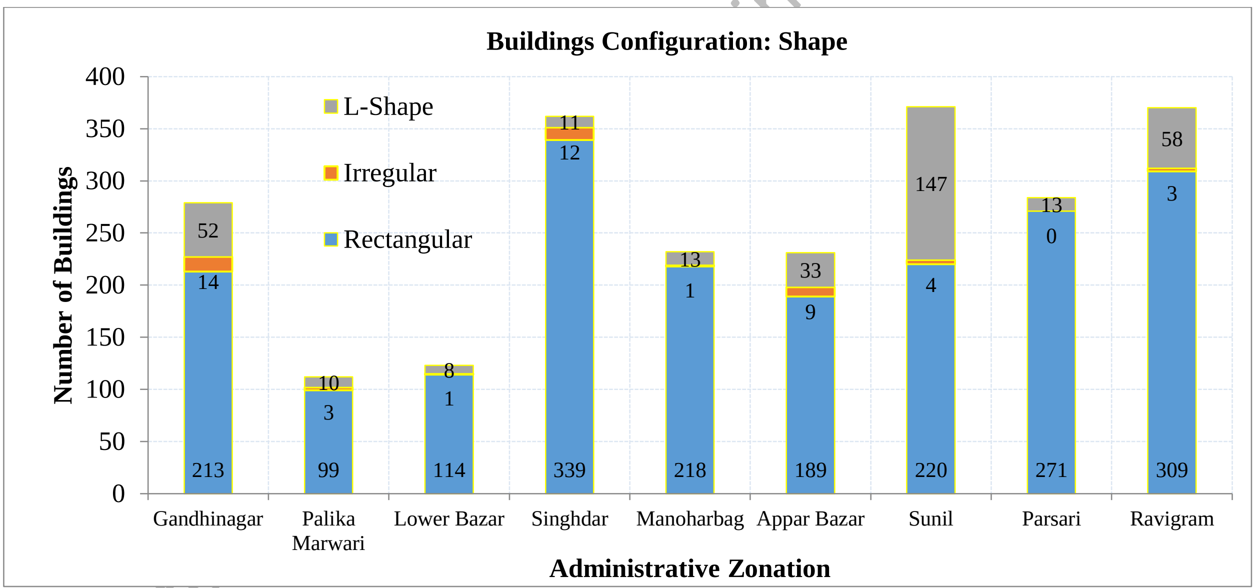


Fig. 7: Building Configuration (Shape)

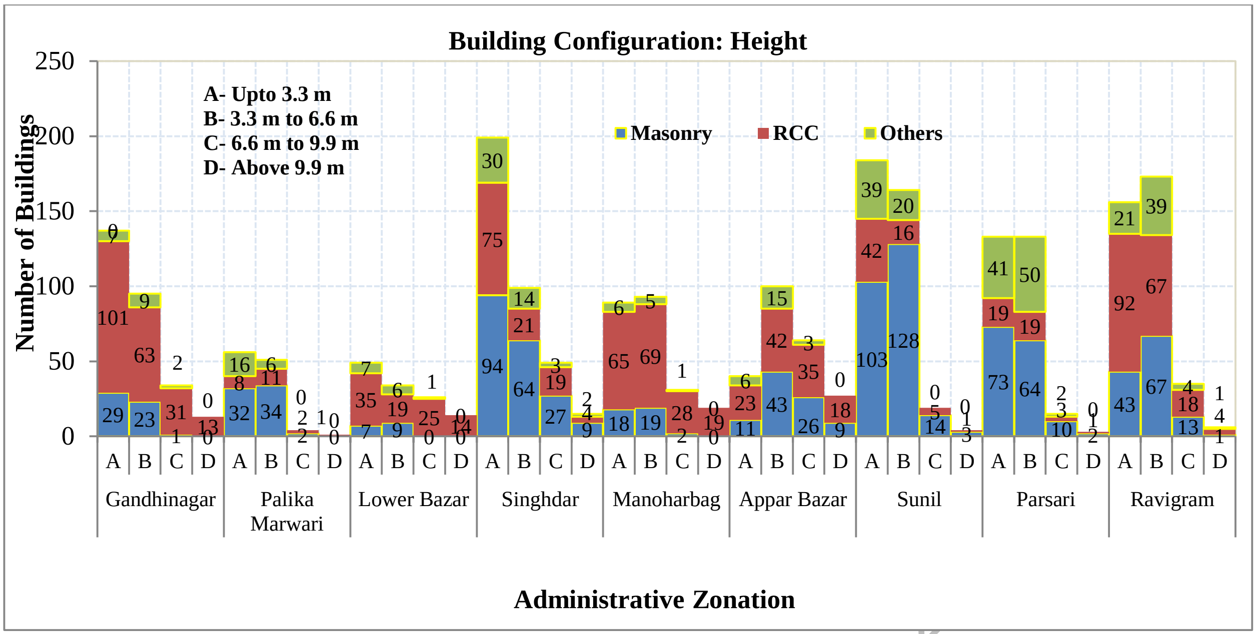


Fig. 8: Building Configuration (Height)

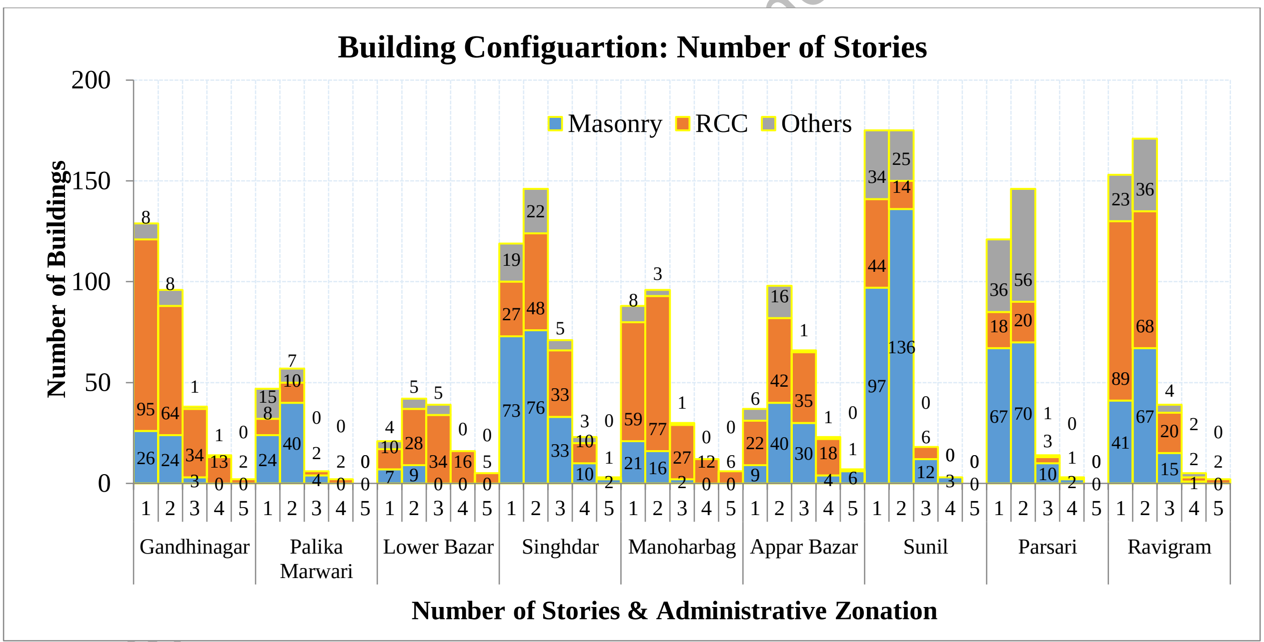


Fig. 9: Building Configuration (Number of Stories)

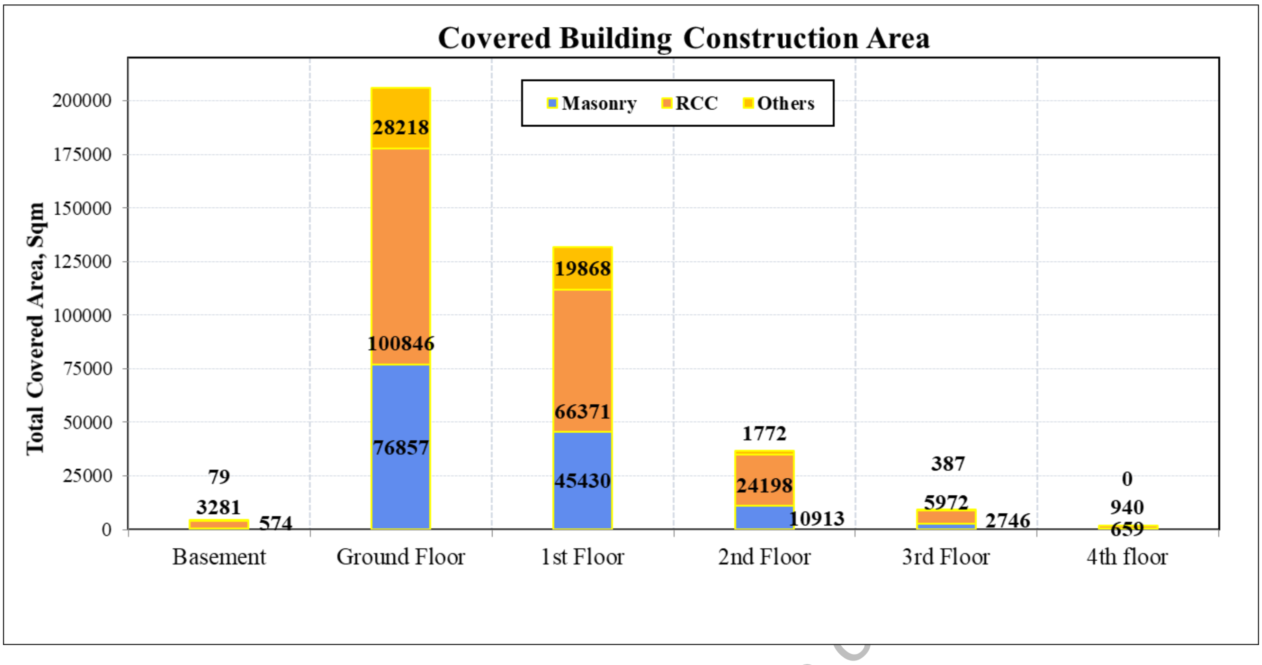


Fig. 10: Covered Building Construction Area

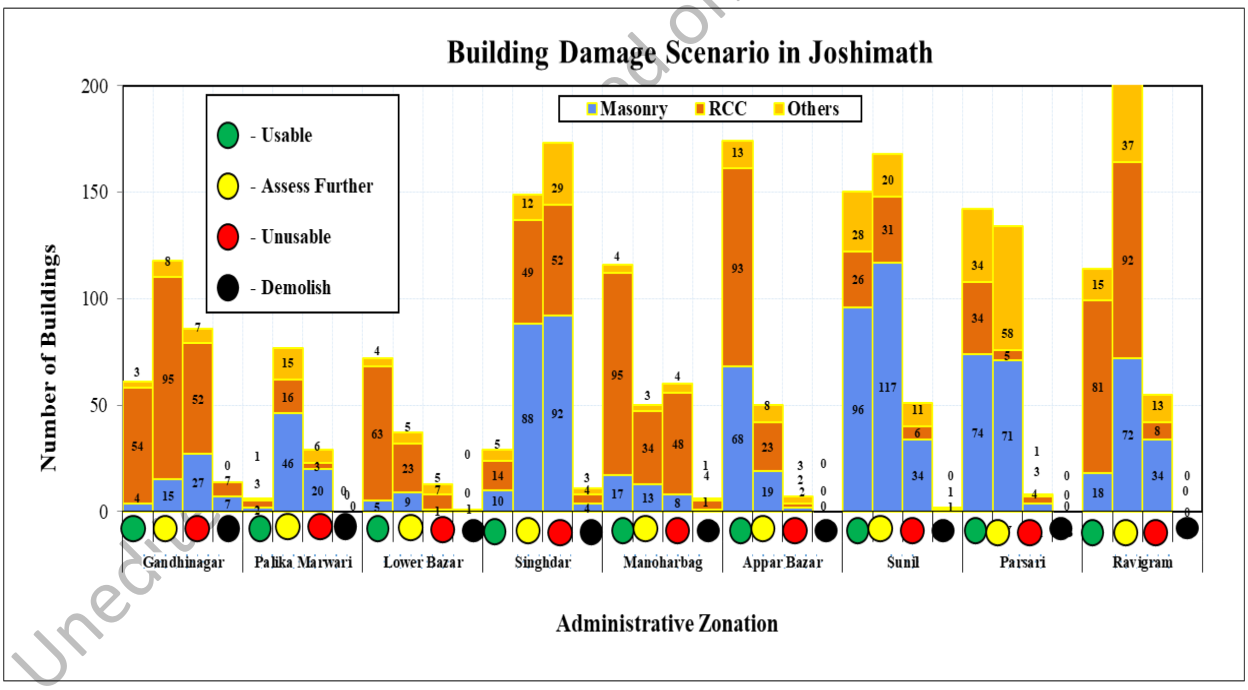


Fig. 11: Building Damage Scenario in Joshimath

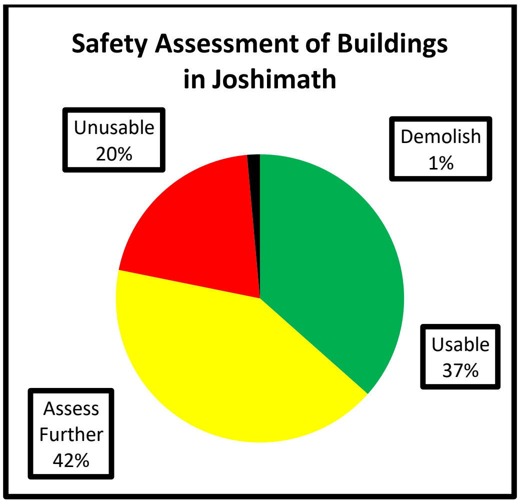


Fig. 12: Overall Damage state classification of buildings

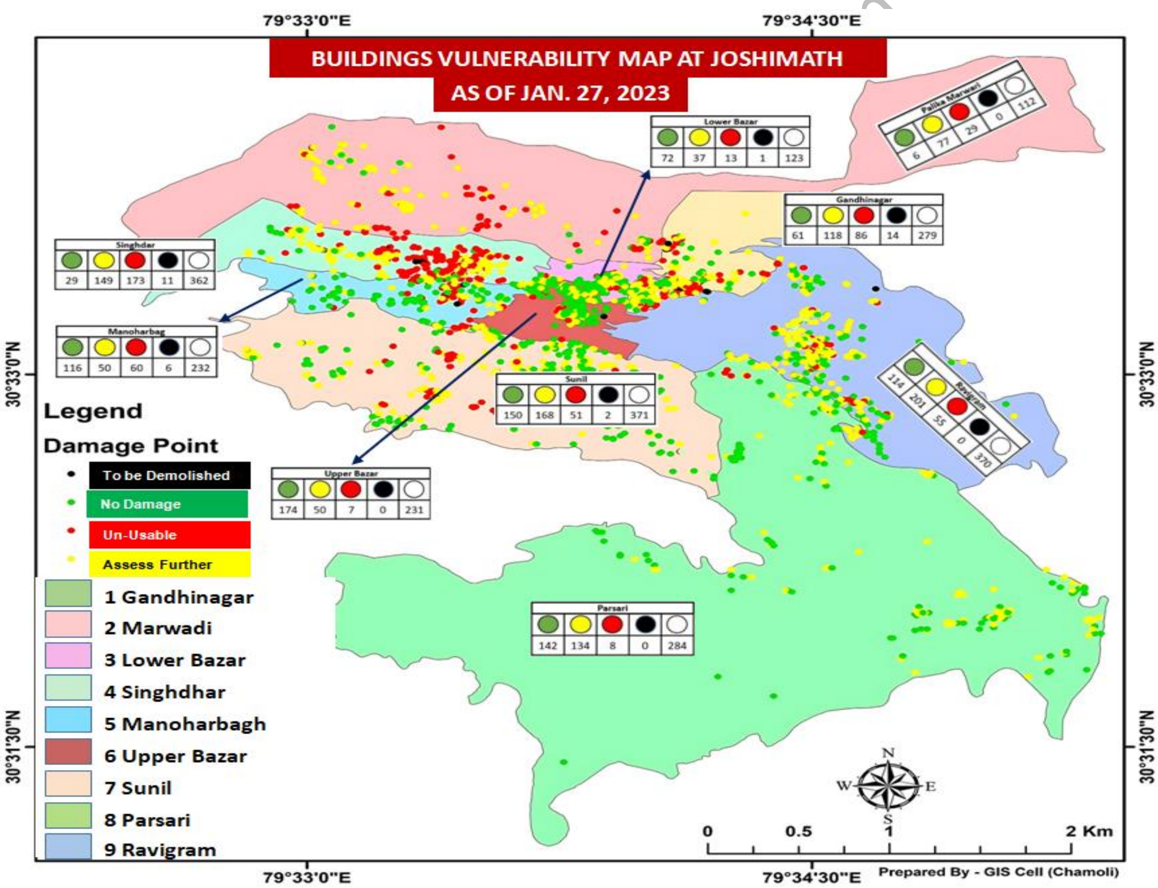


Fig. 13. Buildings Vulnerability Map for Joshimath