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Seismic vulnerability of lifeline buildings in Himalayan province of Uttarakhand in India

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ABSTRACT

Seismic vulnerability of around 67, 60, 36, 23 and 18% buildings of Fire and Emergency Service, Police, hospital, school and local administration respectively in the earthquake prone Uttarakhand province located in Indian Himalaya has been assessed using Rapid Visual Screening (RVS) methodology. The study suggests that 71.86% of the surveyed local administration buildings, 64.58% schools, 62.08% Police stations, 56.25% Fire and Emergency Service stations and 52.86% hospitals together with 61.68% buildings of other departments would be put to disuse immediately after an earthquake that would pose challenges of various sort in mobilising resources for search, rescue and emergency healthcare together with relief and restoration as the remaining facilities would be highly overburdened. The study highlights poor quality of construction, lack of maintenance and non-compliance of safety standards as the main reasons enhancing vulnerability of the surveyed buildings. It is therefore recommended to undertake prioritised, planned and prompt demolition and reconstruction of Grade 5 buildings and detailed assessment and retrofitting of Grade 4 and Grade 3 buildings besides introducing measures for routine maintenance of public infrastructure and ensuring seismic safety provisions in these.

1. Introduction

Attributed largely to ongoing northward drift of the Indian plate despite collision with the Eurasian plate around 55 Ma, earthquake is a major hazard in the Himalayan region that has witnessed six major seismic events in the previous 120 years; Mw ~ 8.0 Shillong 1897 [1,2], Mw ~ 7.8 Kangara 1905 [3,4], Mw ~ 8.2 Bihar–Nepal 1934 [5,6], Mw ~ 8.6 Assam now Arunachal 1950 [7,8], Mw ~ 7.6 Kashmir 2005 [9] and Mw ~ 7.8 Gorkha 2015 [10]. Some sectors of the Himalaya have however not ruptured for a long time and lying between the epicentres of 1905 and 1934 great earthquakes the province of Uttarakhand in India is located in one such sector that falls in Zone V and IV of Earthquake Zoning Map of India (Fig. 1; [11]).

Despite Mw ~ 6.7 Uttarkashi 1991 and Mw ~ 6.4 Chamoli 1999 earthquakes, Mw ~ 7.5 Garhwal 1803 earthquake is recognised as the most recent major seismic event in this area [12–15]. Besides massive losses in Garhwal Himalaya [16,17] this earthquake caused damage as far as Delhi, Aligarh and Mathura [18]. Intensity of IX-X is attributed to this earthquake around Srinagar and Devaprayag together with magnitude Mw ~ 7.7 ± 0.4 [14] that is close to Mw ~ 7.5 assessed by Ambraseys and Douglas [19].

High seismic vulnerability of built environment of the region, as assessed by a study of Mw ~ 7.8 Kangara 1905 event [20] and confirmed by Mw ~ 7.6 Kashmir 2005 earthquake [21], damage and destruction to lifeline infrastructure in an earthquake incidence and consequent disruption of post-disaster emergency operations is a major cause of concern as it is to significantly escalate loss of human lives together with trauma and misery of the affected population. It therefore becomes highly pertinent to evaluate seismic vulnerability of the lifeline infrastructure so as to plan and implement appropriate corrective measures.

Previous studies on this important issue have focused either on a

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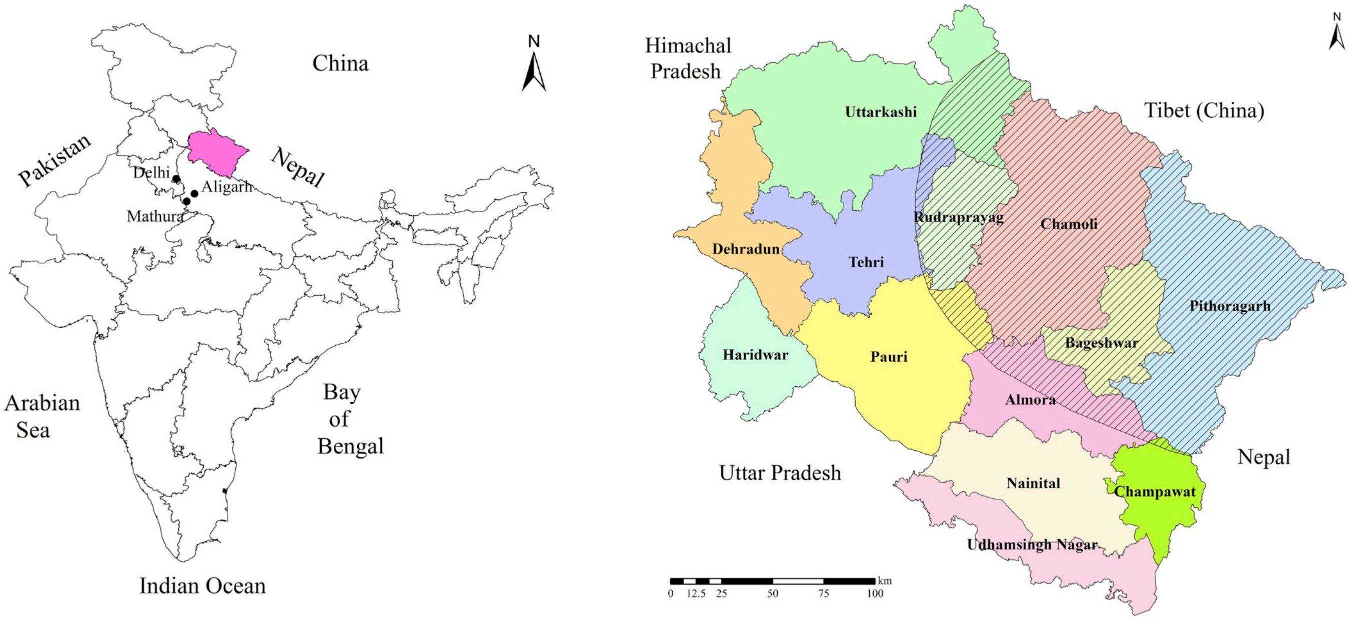

Fig. 1. Map of the province of Uttarakhand depicting district boundaries in different colours with hatched portion representing Zone V of Earthquake Zoning Map of India and unhatched portion depicting Zone IV [11].

small geographical area [22–25] or limited number of lifeline structures [26]. These at the same time neither provide structural details of the surveyed building nor the causes of vulnerability. Present study is the first attempt to holistically address the issue of seismic vulnerability of lifeline infrastructure in this region and covers significant proportion of the infrastructure of various important departments of the provincial government spread across a wide geographical area so as to (i) identify buildings that are seismically vulnerable, (ii) assess degree of seismic vulnerability, (iii) prioritise buildings for reconstruction, detailed assessment and retrofitting, and (iv) classify buildings based on various parameters such as building typology, construction material and the like.

This study is intended to help the concerned authorities in preparing phased plan for improving seismic performance of the buildings of the departments that are required to deliver important lifeline services on the aftermath of any disaster incidence.

2. Methodology

There exist several methodologies for vulnerability assessment and classification of existing buildings [27] of which Rapid Visual Screening (RVS) is recognised as being fast and economic technique of screening buildings for detailed investigation and corrective measures. RVS requires identification of primary structural lateral load-resisting system of the building together with building attributes that modify seismic performance expected for this system. The inspection, data collection and decision-making process typically occurs at the building site and screening is based on numerical seismic hazard and vulnerability scores that are probability functions consistent with the advanced assessment methods.

On the basis of identified building parameters Basic Structural Hazard (BSH) score and Performance Modification Factors (PMF) for the surveyed buildings are assessed and subsequently integrated to generate the final Structural Score (S). BSH reflects estimated likelihood of a typical building of that category sustaining major damage in the given seismic environment.

Based upon damage data of Mw ~ 6.2 Killari 1993, Mw ~ 5.8 Jabalpur 1997 and Mw ~ 7.6 Bhuj 2001 earthquakes Agrawal and Chourasia [28] have modified BSH scores suggested by ATC-21 [29] and ATC-21-1 [30] of FEMA to suit the Indian context and categorised individual buildings as (i) reinforced concrete (RCC) frame buildings with unreinforced masonry infill walls, and (ii) unreinforced masonry (URM) that are respectively assigned BSH scores of 3.0 and 2.5. PMF relate to deviation from normal structural practice or conditions and Agrawal and Chourasia [28] have considered (i) number of stories, (ii) minimum gap between adjacent buildings, (iii) building site location, (iv) soil type, (v) irregularity in elevation, (vi) soft storey, (vii) vertical irregularity, and (vii) cladding for allocating PMF scores that are based on damage surveys undertaken previously. Apart from these, parameters pertaining to (i) roofing material, (ii) parapet height, (iii) reentrant corner, (iv) heavy mass at the top, (v) construction quality, (vi) condition/maintenance, and (vii) overhang length have been included in the present study, so as to make the assessment suitable for the building stock in the region. Details of PMF values utilised for the present study are given in Table 1.

RVS is performed using a form prepared in android platform utilising Open Data Kit (ODK) framework through a team of trained engineers.

3. The built environment: key observations

18,835 units of 11,239 buildings spread across the province of Uttarakhand are surveyed under the present study (Table 2; Fig. 2) of which 10,496 units of 7172 buildings are located in Zone V of Seismic Zoning Map of India [11].

Table 1
Performance Modification Factors (PMF) score considered for the purpose of present study.

Sl. No.	Parameters	Specification/Boundary	Modification factor
1.	Number of stories	< 2	0
		2 to 5	−0.15
		> 5	−0.5
2.	Minimum gap between adjacent building	< 100 mm per storey	−0.2
		Otherwise	0
3.	Building site located at	Hill top	−0.2
		High slope of hill	−0.15
		Mild slope	−0.1
		Plain	0
4.	Building location	Isolated	0
		Internal	−0.1
		End	−0.15
		Corner	−0.2
5.	Soil type	Rock/Hard soil	0
		Medium soil	−0.1
		Soft soil	−0.25
		Reclaimed/Filled soil	−0.2
		Partially filled soil	−0.15
		Loose sand	−0.3
6.	Roofing material	RCC slab	−0.15
		Tiles	−0.2
		GI sheets	0
		Asbestos sheet	−0.1
		Wooden building	−0.25
7.	Parapet	Secured	0
		Not secured	−0.2
8.	Re-entrant corner	≤15%	0
		> 15%	−0.25
9.	Regularity/irregularity in elevation	Regular	0
		L – shaped	−0.3
		T – shaped	
		□ - shaped	
10.	Soft storey exist	Yes	−0.3
		No	0
11.	Heavy mass at top	Yes	−0.25
		No	0
12.	Construction type	Engineered	0
		Non-engineered	−0.2
13.	Building construction quality	High	0
		Medium	−0.1
		Low	−0.2
14.	Building condition/ maintenance	Excellent	0
		Good	0
		Damaged	−0.1
		Distressed	−0.2
15.	Overhang length; balcony (in m)	< 1.5	0
		> 1.5	−0.2
16.	Plan irregularity	Symmetric	0
		Asymmetric	−0.25

Table 2
District wise details of surveyed building units in the province of Uttarakhand.

Sl. No.	District	Type of construction				Total
		Masonry		RCC		
		Number	Percent	Number	Percent	
1.	Almora	791	75.98	250	24.02	1041
2.	Bageshwar	1237	83.08	252	16.92	1489
3.	Champawat	257	73.85	91	26.15	348
4.	Chamoli	2192	74.53	749	25.47	2941
5.	Dehradun	1074	82.11	234	17.89	1308
6.	Haridwar	364	92.15	31	7.85	395
7.	Nainital	472	83.25	95	16.75	567
8.	Pauri Garhwal	1914	81.34	439	18.66	2353
9.	Pithoragarh	1792	77.95	507	22.05	2299
10.	Rudraprayag	657	51.81	611	48.19	1268
11.	Tehri Garhwal	1233	82.15	268	17.85	1501
12.	Udhamsingh Nagar	798	96.61	28	3.39	826
13.	Uttarkashi	1967	78.71	532	21.29	2499
Total		**14,748**	**78.30**	**4087**	**21.70**	**18,835**

69.83, 8.38, 6.95, 1.58 and 0.17% of the surveyed building units respectively belong to education, local administration, health, Police and Fire and Emergency Service while the rest (3.09%) are those of other departments of the provincial government (Fig. 2). The survey thus accounts for approximately 67% Fire and Emergency Service stations, 60% Police stations, 36% hospitals, 23% schools and 18% local administration buildings in the province.

3.1. Building typology

Building type and construction material are important parameters for vulnerability assessment and the surveyed buildings are categorised as RCC and masonry (Table 2). 78.30% of the surveyed building units are masonry structures. RCC construction is observed to be more prevalent in the hilly terrain of the province and 48.19, 26.15, 25.47, 24.02, 22.05 and 21.29% of the surveyed building units in Rudraprayag, Champawat, Chamoli, Almora, Pithoragarh and Uttarkashi districts are RCC structures (Fig. 2). Large proportion of the RCC buildings are accounted for by the schools.

3.2. Number of stories

But for suitable engineering inputs, vulnerability of a structure increases with height and number of stories is a good indicator of its height; 9–10 feet per storey for residential and 12 feet per storey for commercial or office building [29]. 90.42, 9.49 and 0.08% masonry and 73.97, 24.52 and 1.42% RCC building units are respectively single, double and triple storeyed. Only one RCC unit is observed to be five storied while two masonry and three RCC units are four storeyed.

3.3. Age of the building

Time of construction is an important element of RVS procedure as (i) construction practices are generally tied to the prevalent building codes, (ii) deterioration in building strength is related to its age, and (iii) revision of building code over the passage of time often makes old buildings seismically deficient.

Classified according to changes in building code in India 3.66 and 2.80% masonry and RCC building units are respectively observed to be constructed before 1962 (Table 3), i.e. before the introduction of seismic code in India. Majority of the buildings units, 86.97 and 89.09% masonry and RCC respectively, are however constructed between 1984 and 2016.

3.4. Roofing material

Roofs of most building units (82.75%) are RCC slab while 16.79% have CGI sheets. Only a few buildings have tiles, wood and asbestos sheet as roofing material.

3.5. Walling material

Walls in a building are either load bearing or non-load bearing (partition). Masonry walls of the surveyed building units are observed to be built using dressed stone (Ashlar stone), brick, CC block and random rubble while cement, lime surkhi and mud are used as mortar (Table 4). Stones used in random rubble masonry walls are either undressed or roughly dressed while those in Ashlar masonry are observed to be finely dressed with courses of uniform height and all joints being regular, thin and of uniform thickness.

Despite stone and wood being traditional building materials of the region [31,32], walls of most building units (68.33%) are observed to be constructed using brick masonry in cement mortar. Even non load bearing walls of RCC building units are built using bricks.

24.51, 19.22, 16.16 and 14.84% of the surveyed buildings in Uttarkashi, Rudraprayag, Pithoragarh and Chamoli districts are

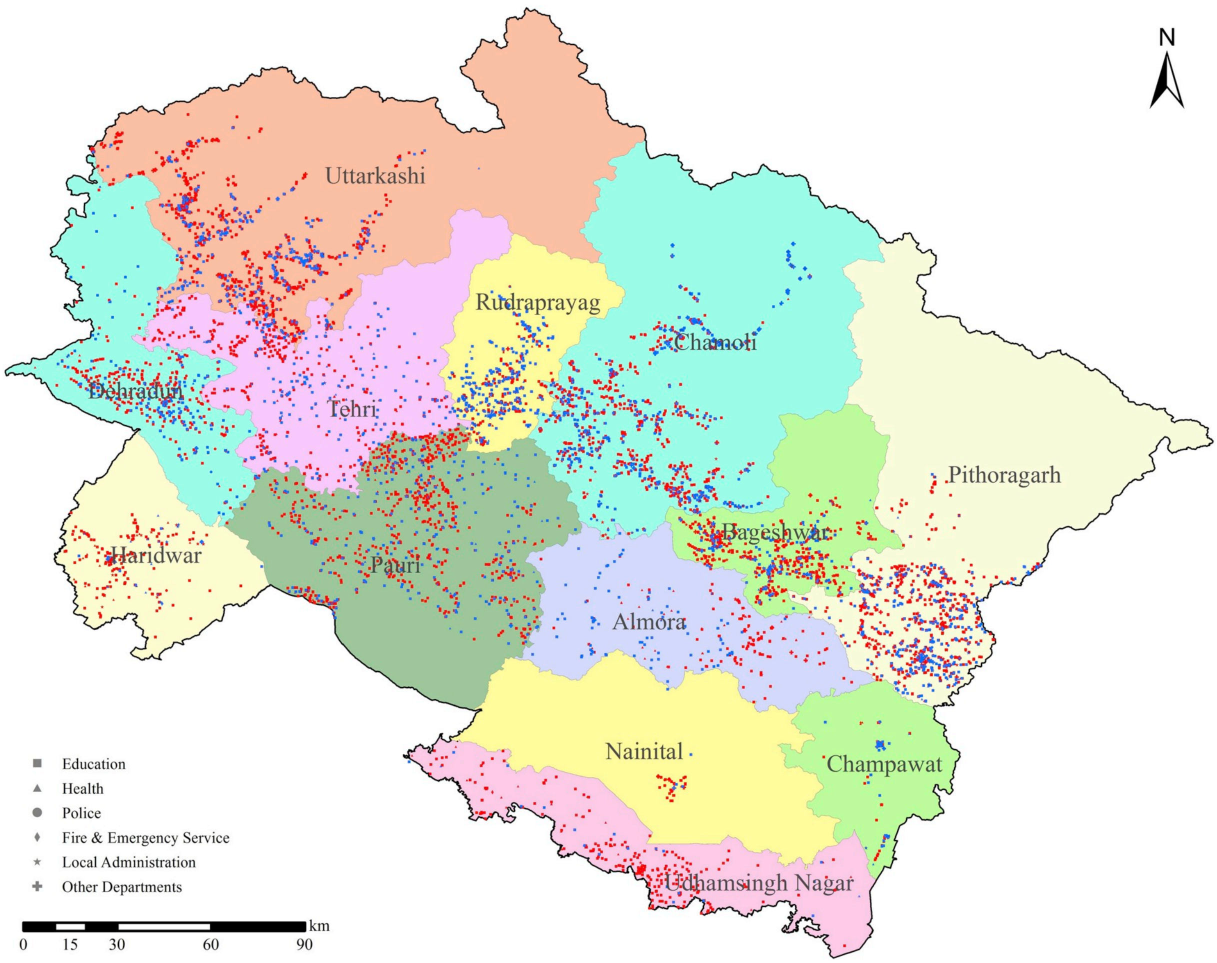

Fig. 2. Department wise spatial distribution of the surveyed building units in the province of Uttarakhand. Shown in red are masonry buildings while in blue are RCC buildings.

Table 3
Distribution of surveyed building units, in percent, according to their time of construction.

Type of construction	Time of construction (in percent)						
	Before 1962	1962–65	1966–69	1970–83	1984–2001	2002–16	2017–19
Masonry	3.66	1.84	0.58	6.96	31.81	55.16	0.00
RCC	2.80	1.52	0.56	5.63	24.49	64.60	0.42

Table 4
District wise details of the walling material of the surveyed buildings (in percent).

District	Ashlar stone masonry in		Brick masonry in			CC block	Random rubble in			RCC frame
	cement mortar	lime surkhi	cement mortar	mud mortar	lime surkhi		cement mortar	lime surkhi	mud mortar	
Almora	4.38	0.48	60.00	0.29	0.00	0.00	11.08	3.00	21.01	0.00
Bageshwar	10.25	0.28	50.07	0.28	0.07	2.80	11.58	1.19	23.17	0.28
Chamoli	1.16	0.11	37.42	0.07	0.14	14.84	13.00	0.58	29.53	2.38
Champawat	6.32	0.00	91.66	0.0	0.00	0.57	0.28	0.00	0.00	0.28
Dehradun	0.00	0.15	94.74	0.30	0.15	0.46	3.86	0.00	0.30	0.00
Haridwar	0.00	0.00	98.26	1.73	0.00	0.00	0.00	0.00	0.00	0.00
Nainital	1.31	0.93	76.92	0.75	0.00	0.00	1.50	5.81	12.94	6.19
Pauri	3.42	0.00	72.44	0.34	0.00	1.12	11.36	0.30	9.28	1.69
Pithoragarh	9.63	0.14	34.74	0.29	0.00	16.16	7.17	0.63	19.45	11.54
Rudraprayag	0.16	0.08	53.07	0.24	0.00	19.22	3.61	0.16	23.33	0.08
Tehri	9.79	0.00	70.40	0.27	0.00	5.34	4.79	0.00	9.09	0.00
Udhamsingh Nagar	0.00	0.00	95.91	0.52	0.00	0.00	0.00	0.00	0.92	2.63
Uttarkashi	8.80	0.08	52.82	0.08	0.00	24.51	7.35	0.00	5.93	0.40
Average	4.24	0.17	68.33	0.39	0.02	6.54	5.81	0.89	11.91	1.95

Fig. 3. Primary school at Upkendra Tangsa, Dasholi (Chamoli district) located on high sloping ground.

observed to be built using CC blocks. These being remote hill districts of the province, popularity of CC blocks is associated with savings on transportation of bricks that are manufactured in the plains; mainly in Haridwar and Udhamsingh Nagar districts.

Stone being abundantly and economically available, appreciable proportion of the surveyed buildings in the hill districts, except Champawat and Dehradun are either Ashlar stone or random rubble construction and account for 37.02, 39.95, 44.38 and 46.47% buildings of Pithoragarh, Almora, Chamoli and Bageshwar districts.

3.6. Foundation type

Foundation transmits load of the structure to the sub-soil below and depending on soil conditions and load of the structure buildings are built using different types of foundation. 74.73% building units have stripped foundation, 23.05% have isolated column footing, while 1.28 and 0.93% respectively have raft and combined foundation. Only one surveyed building unit is observed to have pile foundation.

3.7. Foundation material

Stone being economically and abundantly available in the hills foundation of most building units (79.71%) are observed to be built using stone with brick (9.19%), RCC (7.68%) and cement concrete (3.42%) being other foundation materials.

3.8. Building location

Location of the structure affects the amplification of the ground motion during seismic shaking. In the present study building location is categorised as being (i) Plain where the ground slope is less that 5°, (ii) Mid slope where ground slope is 5–10°, (iii) High slope where ground slope is 11–30°, (iv) Hill top or crest, and (v) River bed.

Mid slope accounts for the location of most building units (35.06%) building units while 31.23% in high slope of hill and 25.91% in plain area. 6.23 and 1.57% are respectively observed to be located at hill top and river bed respectively.

3.9. Soil type

Soil is the ultimate load carrying element and its characteristics can either intensify or abate seismic vulnerability of a structure as the density of soil has a direct bearing on the amount of ground motion during an earthquake. Six soil types are identified in the present study; (i) Rock/hard soil, (ii) Soft soil, (iii) Reclaimed/filled land, (iv) Partially filled land, (v) Loose sand and (vi) Medium soil. Large proportion of the building units (79.53%) are observed to be constructed on medium soil

Fig. 4. Wide shear cracks in masonry wall of Government Inter College, Pitrdhar (Rudraprayag district) together with poorly constructed beam of non-uniform shape showing deflection.

Fig. 5. Poorly constructed roof with clearly visible reinforcement at Government Primary School Mhalchora in Bageshwar district.

while 10.54% are constructed over rock/hard soil, 6.83% over partially filled land and 2.05% on soft soil.

3.10. Ground slope

Codal provisions in India [33] recommend footing to be placed adjacent to a sloping ground when base of the footing are at different levels. In order to avoid damage to an existing structure, the code recommends (i) footing to be placed at a minimum distance of S from the edge of the existing footing, where S is the width of larger footing, and (ii) the line from the edge of the new footing to the edge of the existing footing to make an angel of less than 45°. Slope of 5.03% masonry and 7.24% RCC building units is observed to be more than 45° (Fig. 3).

3.11. Quality of construction

Construction with columns and beams of uniform size and shape having uniform non-segregated concrete with smooth finishing and without any structural defect or damage is considered high quality. Construction with minor non-structural cracks but without tilting of building elements is considered medium quality while building with structural cracks, non-uniform building elements and honeycombing in concrete is considered low quality.

The quality of construction of masonry buildings is assessed on the basis of (i) presence of openings in the wall; high, medium and low if the opening is less than, equal to or more than half the distance between adjacent cross walls, (ii) workmanship judged visually, (iii) settlement cracks; absence, presence and prevalence, (iv) dampness in the walls, (v) mortar cracks; absence, presence and prevalence, and (vi) efflorescence; high if nil or slight, medium if moderate and low if heavy or serious.

The study reveals that 52.73 and 46.89% of the masonry building units respectively have medium and low construction quality while only 0.37% depict high construction quality (Figs. 4 and 5). Amongst the surveyed RCC building units 6.92, 76.68 and 16.39% respectively depict high, medium and low quality of construction.

3.12. Building condition

Lack of maintenance, faulty design, poor quality of construction, corrosion of reinforcement, settlement of foundation and extreme loading are observed as being main causes of deteriorated condition of the surveyed buildings which is exhibited in the form of cracks in the building elements. Cracks in the wall or roof are observed to result in the corrosion of reinforcement due to its exposure to rainwater, moisture and air. Corroded reinforcement is often observed to result in vertical and horizontal cracks in columns and beams respectively.

Fig. 6. Reverse-T shaped hospital at Hawalabagh in Almora district.

Table 5
Percentage of the surveyed buildings having re-entrant corners.

Sl. No.	District	Type of construction (in percent)	
		Masonry	RCC
1.	Pithoragarh	28.26	15.22
2.	Chamoli	14.63	19.70
3.	Dehradun	12.63	5.52
4.	Pauri	11.98	5.22
5.	Tehri	8.46	5.82
6.	Uttarkashi	8.82	18.21
7.	Rudraprayag	4.95	25.37
8.	Bageshwar	4.73	1.79
9.	Champawat	2.51	1.49
10.	Almora	1.94	1.19
11.	Udhamsingh Nagar	0.79	0.15
12.	Nainital	0.22	0.30
13.	Haridwar	0.07	0.00

Some surveyed building units are also observed to have problems relating to seepage of water caused largely by defects in water supply line, sanitary fitments and drainage pipes. In some cases seepage of water is observed to be through roof and exterior walls. This is observed to result in damping of the concrete which might pose a threat to the structural safety of the buildings.

Condition of buildings is assessed on a 04 point scale; Excellent, Good, Damaged and Distressed. Condition of masonry building units is observed to be particularly vulnerable with 40.17% assessed as being damaged and another 30.87% distressed. Only 28.57% masonry building units are in good condition while the condition of only 0.39% is excellent. As against this, only 16.12 and 14.02% RCC building units are respectively in damaged and distressed condition. The condition of 65.40 and 4.45% RCC building units is observed to be good and excellent respectively.

Fig. 7. Re-entrant corners in Upkendra, Gauna, Dasholi in Chamoli district.

Fig. 8. Re-entrant corners Upper Primary School Balidhar, Dasholi in Chamoli district.

3.13. Irregularities

Buildings are sometimes designed as being irregular due to architectural, functional and economic reasons. This however adversely affects their seismic performance due to concentration of demand at certain structural elements from where cracks initiate and make structure vulnerable.

Most surveyed building units are observed to be free of vertical irregularities but 5.0% of both masonry and RCC building units have irregularity in shape. Classified as L, T and Reverse-T type, most L-type irregularities are observed in the surveyed building units in Chamoli, Bageshwar, Pithoragarh, Rudraprayag, Pauri, and Almora districts, T-type largely in Chamoli and Pithoragarh districts while Reverse-T type dominantly in Almora and Champawat districts (Fig. 6).

Fig. 9. Government Primary School, Bajpur in Udhamsingh Nagar district is vulnerable to pounding during seismic shaking.

Considerations related to aesthetics sometimes also result in asymmetric building shape making these relatively more vulnerable. 27.20% masonry and 38.17% RCC building units are observed to be asymmetric.

3.14. Re-entrant corner

Irregularities introduced in the building plan largely due to aesthetics related considerations result in re-entrant corners that are often badly damaged during seismic shaking because of the introduction of stresses for which these are not designed. Presence of re-entrant corners is a major plan irregularity that tends to produce differential motion between different wings of the building resulting in local stress concentration at the re-entrant corner, or “notch”. Moreover center of mass and centre of rigidity of such building forms do not geometrically coincide for all possible earthquake directions causing torsion which results in rotational motion.

Plan configuration of a structure and its lateral force resisting system contain re-entrant corners, where both projections of the structure beyond the re-entrant corner are greater than 15% of its plan dimension in the given direction [11]).

Vulnerability due to re-entrant is observed to be maximum in the surveyed buildings of Chamoli, Dehradun, Pauri, Pithoragarh, Rudraprayag, and Uttarkashi districts (Table 5). The defect is more in masonry buildings than RCC buildings (Figs. 7 and 8).

3.15. Pounding

As regards pounding codal provisions in India recommend adjacent units or buildings to be separated by a distance which is equal to response reduction factor (R) times the sum of calculated storey displacements, so as to avoid damage to the structures when these deflect towards each other during seismic shaking [11]. When two buildings are at the same elevation level, the factor R may be replaced by R/2. Safe separation distance or gap as recommended by the code between two building is 15, 20 and 30 mm for masonry, RCC frame and steel structure respectively. 26.81 and 19.33% of the surveyed masonry and RCC building units are respectively observed to be vulnerable to pounding (Fig. 9).

3.16. Overhang length

Overhangs are generally provided to shade the open spaces from undesired solar radiation as also to protect exterior walls, doors and windows from rainwater while keeping the foundation dry. Building bye laws permit 1.5 m wide balcony at roof slab level with area not exceeding 3.5 sq m per bedroom but not exceeding 3 in a flat. Of the ones surveyed under this study 0.56% masonry and 0.91% RCC building units are observed to have overhang related vulnerability.

3.17. Heavy mass at the top

Presence of heavy mass on the roof top increases seismic forces in the members of the building and thus increase vulnerability of the building. In the surveyed buildings water tanks are mainly observed at the roof top.

3.18. Engineering input

Engineered buildings are the ones designed and constructed according to desired codes while non-engineered buildings are spontaneously and informally constructed without any engineering input [34]. 82.6% of the surveyed building units are observed to be non-engineered. Overwhelming majority of these are masonry buildings. Only 8.0% of the surveyed masonry building units together with 51.1% RCC are observed to be engineered.

4. Seismic vulnerability of the building stock

For assessing vulnerability of the building units scores assigned to various surveyed constituents of the building units (BSH and PMF) are integrated and vulnerability of the structures is classified into five categories based on final Structural Score (S); < 0.80 = Grade 5, 0.81–1.60 = Grade 4, 1.61–1.80 = Grade 3, 1.81–2.00 = Grade 2 and > 2.00 = Grade 1. The grades represent the nature of damage the building is likely to sustain in a given earthquake in which the intensity exceeds VIII on MSK Scale as this is the expected seismic intensity in Zone IV and Zone V of Earthquake Zoning Map of India (Fig. 1 [11]).

Grade 1 and Grade 2 denote no and slight structural damage together with slight and moderate non-structural damage respectively which implies hair-line cracks in very few walls and cracks in many walls of masonry structure and fine cracks in plaster over frame members or in walls at the base with fine cracks in partitions and infills and cracks in column and beam of frames together with structural walls and cracks in partition and infill walls of RCC structure. The buildings falling in Grade 1 and Grade 2 are therefore considered as being safe in

Table 6
Assessed damageability grade of the surveyed masonry buildings.

Sl. No.	District	Units surveyed	Damageability grade					Percent safe
			Grade 1	Grade 2	Grade 3	Grade 4	Grade 5	
1.	Almora	791	64	73	80	521	53	17.32
2.	Bageshwar	1237	59	76	153	755	194	10.91
3.	Champawat	257	33	18	57	139	10	19.84
4.	Chamoli	2192	105	94	238	1549	206	9.08
5.	Dehradun	1074	134	129	266	540	5	24.49
6.	Haridwar	364	9	17	27	248	63	7.14
7.	Nainital	472	38	58	125	241	10	20.34
8.	Pauri	1914	179	244	341	1110	40	22.10
9.	Pithoragarh	1792	153	108	186	1072	273	14.56
10.	Rudraprayag	657	155	90	107	273	32	37.29
11.	Tehri	1233	61	81	133	851	107	11.52
12.	Udhamsingh Nagar	798	10	21	84	668	15	3.88
13.	Uttarkashi	1967	23	97	183	1485	179	6.10
Total		14,748	1023	1106	1980	9452	1187	14.44

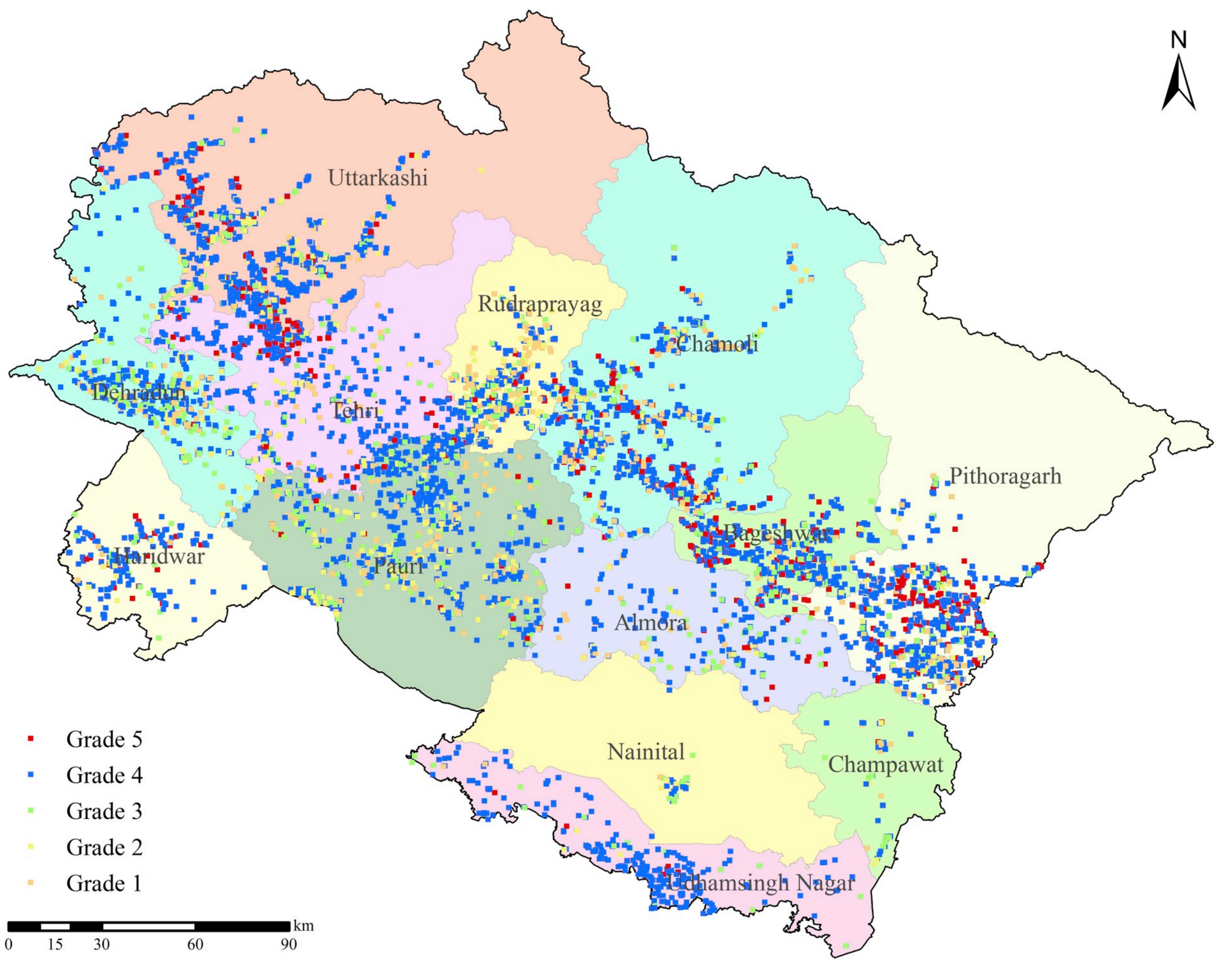

Fig. 10. Damageability of the surveyed buildings in the province of Uttarakhand.

an earthquake event.

Only 14.44% of the surveyed masonry units are observed to fall in Grade 1 and Grade 2 (Table 6), that are considered as being safe in a seismic event. Overwhelming large proportion of the surveyed masonry building units (85.56%) are therefore likely to sustain major damage in a seismic event and it is a serious issue warranting immediate corrective action. Of the surveyed masonry building units 8.05% fall in Grade 5 denoting very heavy structural damage or total or near total collapse. To add to it 64.09% fall in Grade 4 which denotes heavy structural damage implying serious failure of walls together with partial structural failure of roof and floor.

17.31, 15.68 and 15.23% of the surveyed masonry building units in Haridwar, Bageshwar and Pithoragarh districts respectively fall in Grade 5 while 68.13, 61.03 and 59.82 respectively fall in Grade 4 (Fig. 10). These districts are thus required to be accorded priority while planning corrective measures.

The state of RCC building units is relatively better but not satisfactory (Table 7). 49.13% of the surveyed RCC building units fall in Grade 1 and Grade 2 which implies that 50.87% of the RCC building units are unsafe and of these 5.58% fall in Grade 5 denoting very heavy

Table 7
Assessed damageability grade of the surveyed RCC buildings.

Sl. No.	District	Units surveyed	Damageability grade					Percent safe
			Grade 1	Grade 2	Grade 3	Grade 4	Grade 5	
1.	Almora	250	68	28	47	98	9	38.40
2.	Bageshwar	252	44	31	37	120	20	29.76
3.	Champawat	91	23	15	21	31	1	41.76
4.	Chamoli	749	400	132	62	147	8	71.03
5.	Dehradun	234	53	54	57	68	2	45.73
6.	Haridwar	31	3	5	6	17	0	25.81
7.	Nainital	95	21	17	13	41	3	40.00
8.	Pauri	439	146	71	71	144	7	49.43
9.	Pithoragarh	507	94	42	72	266	33	26.82
10.	Rudraprayag	611	196	90	68	235	22	46.81
11.	Tehri	268	47	49	30	131	11	35.82
12.	Udhamsingh Nagar	28	5	4	7	12	0	32.14
13.	Uttarkashi	532	244	126	111	51	0	69.55
Total		4087	1344	664	602	1361	116	49.13

Table 8
Department wise seismic vulnerability of the surveyed buildings.

Sl. No.	Department	Buildings surveyed	Damageability grade (in percent)				
			Grade 1	Grade 2	Grade 3	Grade 4	Grade 5
1.	Health	1309	19.63	11.69	15.81	48.51	4.35
2.	Education	15,036	12.17	9.32	13.93	58.15	6.43
3.	Administration	1578	9.89	7.29	10.96	55.58	16.29
4.	Police	298	13.42	8.72	15.77	57.05	5.03
5.	Fire and Emergency Service	32	6.25	18.75	18.75	40.63	15.63
6.	Others	582	14.78	11.68	11.86	55.50	6.19
Total		18,835	12.59	9.39	13.78	57.14	7.10

structural damage or collapse of ground floor or parts of buildings while 65.46% fall in Grade 4 implying heavy structural damage or large cracks in structural elements with compression failure of concrete and fracture of rebars, bond failure of beam reinforced bar, tilting of columns, collapse of a few columns or a single upper floor.

Department wise breakup of the vulnerability of the surveyed building units (Table 8) suggests that 21.98% fall in Grade 1 and Grade 2 that are considered as being safe in a seismic event. As against this only 7.10% falling under G5 damageability grade are likely to collapse during an earthquake event. As against this 57.14% fall in Grade 4 that are to sustain major structural and non-structural damage.

5. Discussion and conclusion

Seismic vulnerability assessment of 18,835 units of 11,239 buildings of lifeline departments in the province reveals that 72.14 and 36.14% of the masonry and RCC structures falling in Grade 5 and Grade 4 would not be in a position to deliver routine services immediately after an earthquake. Seriousness of the issue is highlighted by the fact that these figures includes 71.86% of the surveyed local administration buildings, 64.58% of schools, 62.08% of Police stations, 56.25% of Fire and Emergency Service stations, 52.86% of hospitals, and 61.68% of other departments. It implies that more than half (64.24%) of the critical infrastructure and facilities operated by the provincial government would not be in a position to operate and deliver routine services immediately after an earthquake. This would expose the remaining facilities to immense pressure and managing the situation would be an uphill task.

This would further jeopardize various post-disaster operations and add to the misery and trauma of the affected population. The situation thus calls for immediate corrective measures as this state of affairs is unacceptable by all norms. It is therefore recommended that all building units falling in Grade 5, Grade 4 and Grade 3 be analysed in detail and exercise of phased reconstruction and retrofitting of these be initiated without any further delay.

It is pertinent to note that all the surveyed buildings belong to different departments of the provincial government and these are invariably constructed by one or the other engineering department of the provincial government. In such a situation 92.0% masonry and 48.9% RCC building units being non-engineered, as brought out by the study, is a major cause of concern. This assertion is however corroborated by other findings of the study that include 46.9% masonry and 16.4% RCC building units depicting low quality of construction, irregularities in 5.0% of both masonry and RCC building units, asymmetricity in 27.2% masonry and 38.2% RCC building units, 26.8 and 19.3% masonry and RCC building units being vulnerable to pounding, 0.56% masonry and 0.91% RCC building units having overhang related vulnerability and placement of heavy mass at the top of many building units.

The study thus highlights the issue of non-compliance of seismic safety codes and negligence of established engineering norms which is a serious issue. Besides training, standard operating procedures are thus recommended for different stages of construction to eliminate chances of omission of any kind. Moreover, compromise with public safety amounts to culpable homicide and therefore it is recommended to fix personal responsibility of officials engaged in construction of public buildings together with harsh punitive measures.

Lack of maintenance is observed to be another cause of the vulnerability of the surveyed buildings resulting in 30.9 and 14.0% masonry and RCC building units being in distressed condition. Geographically dispersed nature of departmental infrastructure often makes it challenging to keep track of the state of individual buildings and allocate funds for routine maintenance and upkeep which results in deteriorated condition of the public buildings. Moreover many departments do not have engineering staff to assess the vulnerability and accordingly undertake appropriate corrective measures. It is therefore recommended that the responsibility of maintenance and repair of all public buildings be entrusted to one single department and instead of present practice of allocating building maintenance and repair budget to individual departments all maintenance related financial resources for public buildings be provided to this department. This would ensure regular assessment of building vulnerability and implementation of required corrective measures besides ensuring economy, accountability and transparency in building maintenance and thus improve the condition of public buildings.

The condition of public buildings is generally expected to be better than private infrastructure as trained team of engineers is invariably involved in their construction. Overall state of built environment in the province is hence not expected to be anyway better and it is therefore recommended that the implementation of building bye laws be made more stringent with compulsory demolition of all non-compliant constructions and doing away with the present practice of compounding that amounts to regularization of non-compliant buildings by penal monetary payment which is a disincentive for following the prescribed building bye laws.

Aggressive and massive awareness drive is recommended for risk communication and compliance of seismic risk reduction measures. If convinced of the risk and provided required technical support people would dovetail maintenance with retrofitting. Tax benefits and soft loans for the complying house owners together with affordable risk transfer options with differential hazard tagged premium can further motivate people to participate in this drive.

It is further recommended that seismic safety audit be made a precondition for operating any public service or business and be linked to their licensing. Uttarakhand is a major tourist and pilgrim destination and resilient business infrastructure would ensure that disaster incidences do not have sharp, negative and long term impact on the economy of the province.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ijdrr.2019.101168.

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