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Economics of seismic safety for earthquake-prone Himalayan province of Uttarakhand in India

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Received 23 February 2019
Revised 5 August 2019
16 September 2019
23 September 2019
Accepted 1 October 2019

Abstract

Purpose – The purpose of this study is to estimate the cost of seismic resilience of identified vulnerable lifeline public buildings in earthquake-prone Himalayan province of Uttarakhand in India.

Design/methodology/approach – Built area of the identified vulnerable lifeline buildings together with prevalent rate of construction has been considered for assessing the cost of seismic resilience while improvised rapid visual screening (RVS) technique, better suited to the built environment in the region, has been used for assessing seismic vulnerability.

Findings – Investment of US$250.08m is assessed as being required for ensuring seismic safety of 56.3, 62.1, 52.9, 64.6, 71.9 and 61.7% surveyed buildings, respectively, of fire and emergency services, police, health, education, local administration and other departments that are to become non-functional after an earthquake and result in a major socio-political turmoil. A total amount of US$467.71m is estimated as being required for making all the buildings of these departments seismically resilient.

Research limitations/implications – Actual investment estimates and reconstruction/retrofitting plans have to be prepared after detailed investigations as RVS technique only provides a preliminary estimate and helps in prioritising buildings for detailed investigations.

Practical implications – This study is intended to provide a snapshot of the state of seismic vulnerability together with the financial resources required for corrective measures. This is to help the authorities in planning phased mobilisation of financial and technical resources for making the built environment seismically resilient.

Social implications – This study is to bring forth awareness on this important issue and consequent public opinion in favour of safety of public facilities to ensure allocation of appropriate financial resources together with changes in techno-legal regime for the cause of earthquake safety. At the same time, this study is to motivate masses to voluntarily assess safety of their neighbourhood and undertake corrective measures.

Originality/value – This study is based on primary data collected by the authors.

Keywords Uttarakhand, Damageability, Lifeline buildings, Rapid visual screening (RVS), Seismic gap, Seismic vulnerability, Earthquake, Himalaya

Paper type Research paper

Funding support from the World Bank assisted Uttarakhand Disaster Recovery Project (UDRP) is acknowledged. All the engineers engaged in data collection are thanked while support, encouragement and cooperation of colleagues at Disaster Mitigation and Management Centre, particularly Shri Rahul Jugran and Shri Bhupendra Bhaisora and UDRP together with Secretary, Disaster Management Shri Amit Singh Negi and Secretary Incharge, Disaster Management Shri S.A. Murugeshan is acknowledged. Anonymous reviewers are thanked for painstaking and detailed review more than once and suggesting ways of improving the quality and content of the paper so as to be of interest to wider readership.

International Journal of Disaster Resilience in the Built Environment
Vol. 10 No. 5, 2019
pp. 317-342

1759-5908
DOI 10.1108/IJDRBE-02-2019-0007

1. Introduction

Continuing north-northeastward movement and subduction of the Indian plate beneath the Eurasian plate resulted in a continent–continent collision of around 55 Ma which caused metamorphism, upliftment, deformation and shearing of the sediments deposited in the Tethys ocean basin. This however, did not halt the drift of the Indian plate and global positioning system-based monitoring reveals that the Indian plate is underthrusting Tibet at a convergence rate of 45-51 mm/year (Gahalaut and Chander, 1999; Bettinelli *et al.*, 2006; Gahalaut and Kundu, 2011; Jayangondaperumal *et al.*, 2018) of which 18-20 mm/year is accommodated by Himalaya (Bilham *et al.*, 1997) while the rest is taken care of further north by Tibet and Asia (Armijo *et al.*, 1986; Avouac and Tapponnier, 1993; Peltzer and Saucier, 1996). This ongoing convergence is responsible for neotectonic and seismic activities in Himalaya, Tibet and the adjoining areas.

In the past 122 years, Himalayan region has witnessed 6 major earthquakes: 1897 Shillong (Mw approximately 8.0) (Oldham, 1899; Rajendran *et al.*, 2004), 1905 Kangara (Mw approximately 7.8) (Middlemiss, 1910; Ambraseys and Bilham, 2000), 1934 Bihar–Nepal (Mw approximately 8.2) (Dunn *et al.*, 1939; Bilham, 1995), 1950 Assam now Arunachal (Mw approximately 8.6) (Chen and Molnar, 1990; Priyanka *et al.*, 2017), 2005 Kashmir (Mw approximately 7.6) (Hussain *et al.*, 2009) and 2015 Gorkha (Mw approximately 7.8) (Avouac *et al.*, 2015).

However, there are some sectors in the Himalayan arc that show seismic quiescence and the province of Uttarakhand in India is located in one such sector to the west of Nepal and falls in Zone V and IV of Earthquake Zoning Map of India (Figure 1; IS, 1893, 2002). Though shaken by the 1991 Uttarkashi (Mw approximately 6.7) and 1999 Chamoli (Mw approximately 6.4) earthquakes, this sector has not witnessed a major seismic event since 1803 Garhwal (Mw approximately 7.6) earthquake and falls in the seismic gap of 1905 and 1934 earthquakes (Bilham *et al.*, 2001; Rajendran *et al.*, 2015; Jayangondaperumal *et al.*, 2018) which enhances seismic hazard over this region.

This region is, at the same time, traversed by a number of regional tectonic discontinuities from south to north and these are Himalayan Frontal Fault (HFF), Main Boundary Thrust, Main Central Thrust and South Tibetan Detachment. Of these, HFF is known to be active and palaeoseismic evidences indicate major movement along this tectonic discontinuity during earthquake events in 1344, 1505 and 1803 (Jayangondaperumal *et al.*, 2018). This discontinuity traverses densely populated and

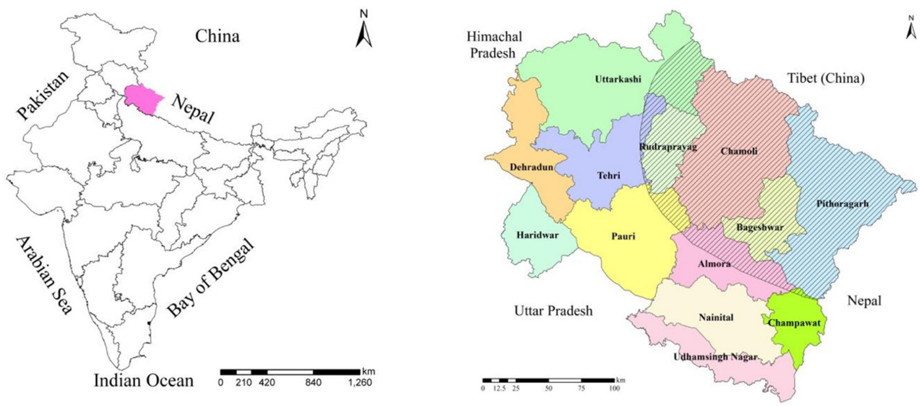

Figure 1.
Location map of the study area. Hatched area falls under Zone V of Earthquake Zoning Map of India while unhatched portion falls in Zone IV

urbanised southern and western extremity of the province enhancing possibility of major devastation even though these areas are located in Zone IV of Earthquake Zoning Map of India (IS, 1893, 2002).

Validation of the possibility of around 80,000 persons being killed in a 1905 Kangara-like event (Arya, 1990), 2005 Kashmir Earthquake (Owen *et al.*, 2008) highlights fast increasing seismic vulnerability of the region that is owed to rapid growth of population and infrastructure, breakdown for time-tested traditional construction practices, sudden change in construction material (stone–wood to brick–cement), neglect of the training of masons on the use of newly introduced construction material and non-compliance of building bye laws. Together these have resulted in proliferation of seismically unsafe infrastructure in the region (Rautela, 2005, 2015).

High-seismic hazard and continuously rising vulnerability of the region call for reviewing seismic safety of lifeline infrastructure and facilities that play an important role in reducing misery and trauma of the disaster affected population and ensuring prompt relief, rescue and recovery. These are required to be fully functional after any disaster incidence and include assets of different departments of the state: health, local administration, police, fire and emergency service, water and electricity supply, civil supplies and education. Major damage to the assets of these departments seriously hampers post-disaster search, rescue, relief and restoration operations besides significantly escalating loss of human lives. Particular care is therefore taken in the design and construction of these buildings that are accorded importance factor of 1.5 by the building codes applicable in India (IS, 1893, 2002).

Revision of the building codes with the passage of time together with lapses during construction, lack of maintenance and aging, make buildings susceptible to damage and therefore it becomes imperative to assess their vulnerability at regular intervals and accordingly undertake corrective measures, particularly for lifeline infrastructure.

The present study provides a preliminary financial estimate for ensuring seismic safety of the lifeline infrastructure in the province and this is to help in-phased and planned mobilisation of resources for making the infrastructure seismically resilient. Improvised vulnerability assessment methodology suiting the ground realities in the region has been used for the study that for the first time assesses seismic vulnerability of such a large lifeline building stock spread over vast geographical area. The study at the same time prioritises the surveyed buildings for corrective measures.

This study thus aims at drawing attention of policymakers and masses towards the cost of ensuring safety and vulnerability of lifeline buildings, so as to initiate mobilisation of resources for planned and phased seismic risk reduction.

2. Methodology

The present study uses rapid visual screening (RVS) technique that is recognised as being a cost effective tool for quickly assessing seismic vulnerability of large building stocks and categorising buildings for detailed assessment that is time-taking and resource intensive, and therefore, cannot be applied for all the buildings. RVS methodology is designed to be implemented without performing any structural calculations and is based on a scoring system that requires the evaluator to identify primary structural lateral load-resisting system of the building being investigated together with building attributes that modify seismic performance expected for that system. The inspection, data collection and decision-making process takes place at the building site and takes around an hour.

The screening is based on numerical seismic hazard and vulnerability scores that are determined on the basis of expected ground shaking and seismic design and construction practices prevalent in the region. These scores are founded on probability concepts and are consistent with advanced assessment methods. The RVS procedure can be integrated with geographical information system-based city planning database and can also be used with various risk analysis software.

On the basis of building parameters observed during the field survey, basic structural hazard (BSH) score and performance modification factors (PMF) for the surveyed building are assessed. These are subsequently integrated to generate final structural score (S) that relates to performance of the building during seismic shaking. For the purpose of the present study, the RVS methodology proposed for the Indian context by Agrawal and Chourasia (2007a, 2007b) is used with modifications in PMF score to suit the building stock in the region.

Agrawal and Chourasia (2007a, 2007b) categorise individual buildings as either reinforced cement concrete (RCC) frame buildings with unreinforced masonry infill walls or unreinforced masonry and assign BSH scores of 3.0 and 2.5, respectively, to these. Eight modifiers: number of stories, minimum gap between adjacent buildings, building site location, soil type, irregularity in elevation, soft storey, vertical irregularity and cladding are considered and scores are allocated to these based on damage surveys undertaken after previous earthquakes in India.

The present study further elaborates this methodology and includes roofing material, parapet height, re-entrant corner, heavy mass at the top, construction quality, condition/ maintenance and overhang length for PMF calculations and thereby proposes an improvised seismic vulnerability assessment methodology for Indian conditions, especially for the Himalayan region.

PMF relate to the deviation from the normal structural practice or conditions, or have to do with the effects of soil amplification on the expected ground motion and the present study uses PMF values of Joshi *et al.* (2019) that are summarised in Table I.

A form prepared on android platform using Open Data Kit framework is used for the field survey by a team of trained engineers.

Covered area of the buildings is calculated on the basis of data collected during fieldwork and the current schedule of rates for new construction of the state government departments have been used for assessing the cost of reconstruction of identified vulnerable buildings while the cost of retrofitting is assessed as being a function of the reconstruction cost.

3. Built environment: as observed in the field

A total of 18,835 units of 11,239 buildings spread across the Himalayan province of Uttarakhand in India are surveyed under the present study of which 10,496 units of 7,172 buildings are located in Zone V of Seismic Zoning Map of India (IS, 1893, 2002).

In all 69 per cent of the surveyed buildings represent schools while 13 per cent are of local administration, 10 per cent are hospitals and 2.4 per cent are police and fire and emergency service stations while the rest belong to other provincial government departments. The survey thus accounts for 67 per cent fire and emergency service stations, 64 per cent state-owned schools, 60 per cent police stations, 36 per cent state-owned hospitals and 18 per cent local administration buildings in the province (Figure 2).

3.1 Building typology

In all 80.3 per cent of the surveyed buildings are masonry structures while the rest are RCC structures. RCC structures are observed to be more common in hill districts of the state and 46.7, 28.5, 26.9, 18.5 and 18.2 per cent of the surveyed buildings in Rudraprayag, Champawat, Chamoli, Dehradun and Pithoragarh districts are RCC structures. Large proportions of the surveyed RCC buildings are accounted for by schools.

S. No.	Parameters	Specification/boundary	Modification factor
1.	Number of stories	< 2	0
		2-5	−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
		Galvanised iron sheets	0
		Asbestos sheet	−0.1
		Wooden building	−0.25
7.	Parapet	Secured	0
		Not secured	−0.2
8.	Re-entrant corner	$\leq 15\%$	0
		$> 15\%$	−0.25
9.	Regularity/ irregularity in elevation	Regular	0
		L-shaped	−0.3
		T-shaped	
		Reverse *T*- 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 I. PMF score considered for the purpose of present study

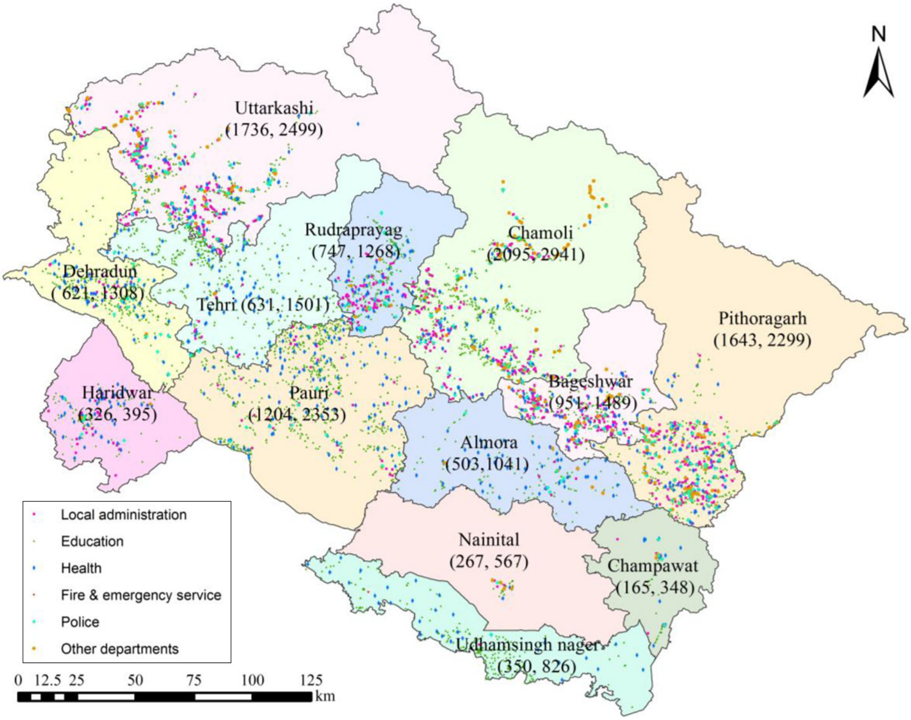

Figure 2.
Distribution of the buildings and units surveyed under the study; district (buildings and units)

3.2 Building height

In case appropriate engineering measures are not taken seismic vulnerability of a building increases with its height. In the present study number of stories in a building has been utilised for assessing its height. In all 90.4, 9.5 and 0.1 per cent of the masonry and 74.0, 6.0 and 1.4 per cent of the RCC building units are, respectively, single, double and triple storeyed. Only one RCC unit is observed to be five storeyed while two masonry and three RCC units are four storeyed.

3.3 Building age

Structures are built according to the prevalent building codes and for the assessment of seismic vulnerability buildings are classified in accordance with changes in building code in India (Table II). In all 3.7 and 2.8 per cent of the masonry and RCC building units are observed to be constructed before 1962, i.e. before the introduction of seismic code. Majority of the buildings units, 87.0 and 89.1 per cent of masonry and RCC, respectively, are however constructed between 1984 and 2016.

Table II.
Summary of the time of construction of the surveyed buildings

	Time of construction of the surveyed building units (in %)						
Type of building unit	< 1962	1962-1965	1966-1969	1970-1983	1984-2001	2002-2016	2017-2019
Masonry	3.66	1.84	0.58	6.96	31.81	55.16	–
RCC	2.80	1.52	0.56	5.63	24.49	64.60	0.42

3.4 Roofing material

Roofs of majority of the surveyed buildings (82.8 per cent) are observed to be RCC slab while 16.8 per cent have corrugated galvanised iron sheets. Only a few buildings have tiles, wooden and asbestos sheet as roofing material.

3.5 Walling material

Masonry walls of the surveyed buildings are built using dressed stone (ashlar stone), brick, cement concrete (CC) block and random rubble, while cement, lime surkhi and mud are used as mortar (Table III). Stones used in random rubble masonry walls are either undressed or roughly dressed while those used in ashlar masonry are finely dressed with courses of uniform height and all joints being regular, thin and of uniform thickness.

Even though stone and wood are the traditional building materials of the region (Rautela, 2005, 2015), walls of most surveyed buildings (68 per cent) are built using brick masonry in cement mortar. Even non-load bearing walls of RCC framed buildings are built using bricks.

Stone masonry, both random rubble and ashlar, is observed to be common in the hill districts where stone is abundantly and economically available and mud is used in large proportion as mortar. More than 20 per cent of the surveyed buildings in Almora, Bageshwar, Chamoli, Pithoragarh and Rudraprayag districts are observed to be built using random rubble in mud mortar while more than 10 per cent of the surveyed buildings in Almora, Bageshwar, Chamoli and Pauri Garhwal districts are built using random rubble in cement mortar. In all 10.25, 9.79, 9.63 and 8.80 per cent of the surveyed buildings in Bageshwar, Tehri, Pithoragarh and Uttarkashi are observed to be built using ashlar stone in cement mortar.

CC block is observed to be prevalent in remote hill districts where it saves transportation cost of bricks from the plains; 24.51, 19.22, 16.16 and 14.84 per cent of the surveyed buildings in Uttarkashi, Rudraprayag, Pithoragarh and Chamoli districts are observed to be built using CC block.

3.6 Foundation type

In all 23.1 per cent of the surveyed buildings are observed to have isolated column footing while 74.7 per cent have stripped foundation and 0.9 and 1.3 per cent, respectively, have combined and raft foundation. Only one surveyed building is observed to have pile foundation.

3.7 Foundation material

Stone being economically and abundantly available, particularly in the hills, foundation of most surveyed buildings (79.7 per cent) are built using stone. Brick (9.2 per cent), RCC (7.7 per cent) and CC (3.4 per cent) are other foundation materials used in the surveyed buildings.

3.8 Building location

Buildings location have been categorised into five categories:

(1) plain where the ground slope is less that 5 degree;

(2) hill top or crest;

(3) mild slope where ground slope is 5°-10°;

(4) high slope where ground slope is 11°-30°; and

(5) river bed.

Table III.
District wise details of the walling material of the surveyed buildings

District	Wall type (in %)									
	Ashlar stone masonry		Brick masonry				Random rubble			
	in cement mortar	in lime surkhi	in cement mortar	in mud mortar	in lime surkhi	CC block	in cement mortar	in lime surkhi	in mud mortar	RCC frame
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	0.00	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 Garhwal	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
Total	4.24	0.17	68.33	0.39	0.02	6.54	5.81	0.89	11.91	1.95

In all 25.9 per cent of the surveyed buildings are observed to be located in plain area while 35.1, 31.2, 6.2 and 1.6 per cent are respectively located in mild slope, high slope, hill top and river bed.

3.9 Soil type

Six soil types are identified for the purpose of the present survey:

(1) rock/hard soil;
(2) soft soil;
(3) reclaimed/filled land;
(4) partially filled land;
(5) loose sand; and
(6) medium soil.

Most buildings are observed to be constructed on medium soil (79.5 per cent) while 10.5 per cent are constructed over rock/hard soil, 6.8 per cent over partially filled land and 2.1 per cent on soft soil.

3.10 Ground slope

Codal provisions in India (IS, 1904, 1986) recommend that the footing be placed adjacent to a sloping ground when base of the footing is at different levels. So as to avoid damage to an existing structure, the code recommends that:

- footing be placed at least at a distance "S" from the edge of the existing footing, where "S" is the width of larger footing; and
- the line from the edge of the new footing to the edge of the existing footing should make an angel of less than 45°.

Of the surveyed buildings, 5.0 and 7.2 per cent masonry and RCC buildings, respectively, are observed to be built over ground with slope more than 45° (Plate 1).

4. Features affecting seismic performance of buildings

Certain attributes of the structures adversely affect their seismic performance and these are discussed in the sections below in the context of surveyed buildings.

4.1 Quality of construction

Assessed on the basis of predefined attributes (Table IV), 52.7 and 46.9 per cent of masonry buildings are observed to have medium and low construction quality with only 0.4 per cent depicting high construction quality. Among the RCC buildings, 6.9, 76.7 and 16.4 per cent depict high, medium and low quality of construction, respectively.

4.2 Building condition

Lack of maintenance, faulty design, poor quality of construction, corrosion of reinforcement, settlement of foundation and extreme loading are observed to be the main causes of deteriorated condition of the surveyed buildings which is exhibited in the form of cracks in the building elements (Plate 2).

Plate 1.
Primary school at Upkendra Tangsa, Dasholi (Chamoli district) located on high-sloping ground

Table IV.
Attributes used for assessing quality of construction of the surveyed buildings

Type of construction	Quality of construction: High	Medium	Low
Masonry	Workmanship judged visually as being high quality	Workmanship judged visually as being medium quality	Workmanship judged visually as being low quality
	Openings in the wall less than half the distance between adjacent cross walls	Openings in the wall equal to half the distance between adjacent cross walls	Openings in the wall more than half the distance between adjacent cross walls
	Absence of mortar cracks	Few mortar cracks	Prevalence of mortar cracks
	Efflorescence nil or slight	Efflorescence moderate	Efflorescence heavy or serious
RCC	Uniform sized and shaped columns and beams without any structural defect or damage	Minor non-structural cracks in columns and beams	Structural cracks in columns and beams
	Uniform non-segregated concrete with smooth finishing	No tilting of building elements	Non-uniform building elements
			Honeycombing in concrete

Cracks in the wall or roof are observed to result in the corrosion of reinforcement because of its exposure to rainwater, moisture and air (Plate 3). Corroded reinforcement is often observed to result in vertical and horizontal cracks in column and beam, respectively.

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.

Plate 2.
Wide shear cracks in masonry wall together with poorly constructed beam of non-uniform shape and deflection observed at Government Inter College at Pitrdhar (Augustmuni) in Rudraprayag district

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 posing threat to structural safety of the buildings.

Assessed on a four-point scale (excellent, good, damaged and distressed), observed condition of masonry and RCC buildings is summarised in Table V. It is important to note that only 28.9 per cent of the surveyed masonry buildings are assessed to be in excellent or good condition. With only 30.1 per cent being in damaged or distressed condition, the state of the RCC buildings is relatively better but not satisfactory.

4.3 Irregularities

Buildings are sometimes designed as being irregular because of architectural, functional or economic reasons. This however, adversely affects their seismic performance because of

Plate 3.
Poorly constructed roof with clearly visible reinforcement at Government Primary School at Mhalchora in Bageshwar district

Table V.
Condition of buildings as assessed in the field

S. No.	Building type	Building condition (in %) Excellent	Good	Damaged	Distressed
1.	Masonry	0.4	28.5	40.2	30.9
2.	RCC	4.5	65.4	16.1	14.0

concentration of demand at certain structural elements from where cracks initiate and make structure vulnerable.

Most surveyed buildings do not have vertical irregularities but 5.0 per cent of both masonry and RCC buildings have irregularities in shape. Building irregularities are classified as L, T and reverse-T type. L type irregularities are observed mostly in Chamoli, Bageshwar, Pithoragarh, Rudraprayag, Pauri Garhwal and Almora districts, T type are observed largely in Chamoli and Pithoragarh districts while reverse-T type dominantly in Almora and Champawat districts (Plate 4).

Considerations related to aesthetics sometimes also result in asymmetric building shape, making these relatively more vulnerable. In all 27.2 and 38.2 per cent of masonry and RCC buildings are observed to be asymmetric.

4.4 Re-entrant corner

Irregularities introduced in the building plan largely because of 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

Plate 4.
Reverse *T*-shaped hospital at Hawalabagh in Almora district

re-entrant corner, or "notch". Moreover centre 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 per cent of its plan dimension in the given direction (IS, 1893, 2002).

Vulnerability because of re-entrant is observed to be maximum in the surveyed masonry buildings of Pithoragarh, Chamoli, Dehradun and Pauri Garhwal districts and in surveyed RCC buildings of Rudraprayag, Chamoli, Uttarkashi and Pithoragarh districts (Table VI). This defect (Plates 5 and 6) is observed to be more prevalent in masonry buildings rather than in RCC buildings.

4.5 Pounding

To avoid damage to structures when these deflect towards each other during seismic shaking, 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 (IS, 1893, 2002). When two buildings are at the same elevation level, response reduction factor R may be replaced by R/2. Safe separation distance or gap as recommended by the code between two buildings is 15, 20 and 30 mm for masonry, RCC frame and steel structure, respectively.

In all 26.8 and 19.3 per cent of masonry and RCC buildings, respectively, are observed to be vulnerable to pounding (Plate 7).

4.6 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 meter wide balcony at roof slab level with area not exceeding 3.5 sq m per bedroom. There can however be only 3 balconies in a flat. Of the ones surveyed under this study, 0.56 and 0.91 per cent of masonry and RCC buildings are observed to have overhang related vulnerability.

S. No.	District	Buildings having re-entrant corners (in %) Masonry building	RCC building
1.	Pithoragarh	28.3	15.2
2.	Chamoli	14.6	19.7
3.	Dehradun	12.6	5.5
4.	Pauri Garhwal	12.0	5.2
5.	Tehri	8.5	5.8
6.	Uttarkashi	8.8	18.2
7.	Rudraprayag	5.0	25.4
8.	Bageshwar	4.7	1.8
9.	Champawat	2.5	1.5
10.	Almora	1.9	1.2
11.	Udhamsingh Nagar	0.8	0.2
12.	Nainital	0.2	0.3
13.	Haridwar	0.1	0.0

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

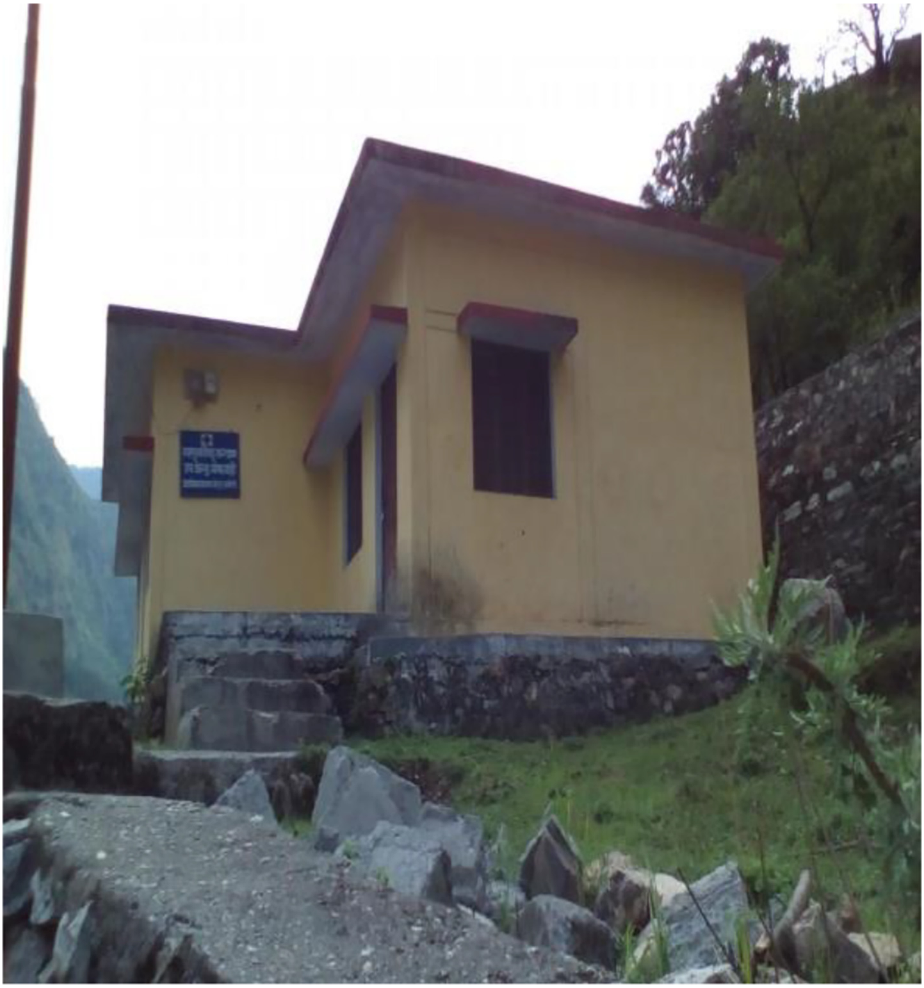

Plate 5.
Re-entrant corners in Upkendra Gauna (Dasholi) in Chamoli district

4.7 Engineering input
Non-engineered buildings are spontaneously and informally constructed without engineering input of any kind (Arya, 1997). In all 82.6 per cent of the surveyed buildings are observed to be non-engineered with masonry buildings representing the majority. It is important to note that only 8.0 and 51.1 per cent of the surveyed masonry and RCC buildings are engineered.

4.8 Heavy mass at the top
The presence of heavy mass on the roof top increases the seismic forces in the members of a building and thus increases vulnerability of the building. In the surveyed buildings water tanks are mainly observed at the roof top.

Plate 6.
Re-entrant corners Upper Primary School at Balidhar (Dasholi) in Chamoli district

5. Seismic vulnerability

For assessing seismic vulnerability of the surveyed buildings, scores assigned to various surveyed constituents of the building (BSH and PMF) are integrated and buildings are accordingly 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 damage likely to be incurred to the buildings falling in different damageability categories as provided by EMS-98 is summarised in Table VII.

Grades 1 and 2 denote no and slight structural damage together with slight and moderate non-structural damage, respectively; therefore, buildings falling in Grades 1 and 2 are considered as being safe in an earthquake event.

Of the surveyed masonry units only 14.4 per cent fall in Grades 1 and 2; therefore, overwhelmingly large proportion of masonry buildings (85.6 per cent) are likely to sustain major damage in a seismic event (Table VIII). It is important to note that

Plate 7.
Pounding related vulnerability in Government Primary School at Bajpur in Udhamsingh Nagar distric

overwhelmingly large proportion of the surveyed masonry buildings (64.1 per cent) fall in Grade 4 and are likely to sustain heavy structural damage and very heavy non-structural damage. Together with this significant proportion of masonry, buildings in Haridwar, Bageshwar and Pithoragarh districts fall in Grade 5, which is a cause of concern (Figure 3).

The state of RCC buildings is observed to be relatively better but not satisfactory (Table IX) as 50.9 per cent of the surveyed RCC buildings are assessed as being unsafe. In all 33.3 per cent of the surveyed RCC buildings fall in Grade 4 with significant proportion in Bageshwar and Pithoragarh districts falling in Grade 5, which is a cause of concern (Figure 3).

Of all the surveyed buildings, around 22.0 per cent fall in Grades 1 and 2, while only 7.1 per cent falling under Grade 5 are likely to collapse during an earthquake event (Table X). Significant proportion of the surveyed building units of

Table VII.
Damage likely to be incurred to the buildings falling in different damageability grade in a likely earthquake event

	Building type	
Damageability grade	Masonry	RCC
Grade 1	Negligible to slight damage (no structural damage and slight non-structural damage)	
	Hair-line cracks in very few walls	Fine cracks in plaster over frame members or in walls at the base
	Fall of small pieces of plaster only	Fine cracks in partitions and infills
	Fall of loose stones from upper parts of buildings in few cases	
Grade 2	Moderate damage (slight structural damage and moderate non-structural damage)	
	Cracks in many walls	Cracks in column and beam of frames and in structural walls
	Fall of fairly large pieced of plaster	Cracks in partition and infill walls; fall of brittle cladding and plaster
	Partial collapse of chimneys	Falling mortar from the joints of wall panels
Grade 3	Substantial to heavy damage (moderate structural damage and heavy non-structural damage)	
	Large and extensive cracks in most walls. Roof tiles detach	Cracks in column and beam column joints of frame at the bases and at the joints of coupled walls
	Chimneys fracture at the roof line; failure of individual non-structural elements (partitions and gable walls)	Spalling of concrete cover and buckling of reinforced rods
		Large cracks in partition and infill walls, failure of individual infill panels
Grade 4	Very heavy damage (heavy structural damage and very heavy non-structural damage)	
	Serious failure of walls; partial structural failure of roof and floors	Large cracks in structural elements with compression failure of concrete and fracture of rebars; bond failure of beam reinforced bar; tilting columns
		Collapse of a few columns or of a single upper floor
Grade 5	Destruction (very heavy structural damage)	
	Total or near total collapse	Collapse of ground floor or parts (e.g. wings) of buildings

local administration (16.3 per cent) and fire and emergency services (15.6 per cent) fall under Grade 5, while 66.6 and 59.4 per cent building units respectively, of these fall in Grades 4 and 3. This could adversely affect post-disaster relief and rescue operations.

Of the surveyed buildings, the ones falling in Grade 5 are to either sustain heavy structural damage or collapse, while those falling in Grades 4 and 3 are to sustain major structural and non-structural damage in an earthquake event and all these buildings would therefore not be in a position to deliver routine services immediately after an earthquake. This is a serious cause of concern as of the surveyed buildings, only 17.1 per cent of local administration, 21.5 per cent of schools, 22.2 per cent of

S. No.	District	Total units surveyed	Damageability grade (in %) G1	G2	G3	G4	G5
1.	Almora	791	8.1	9.2	10.1	65.9	6.7
2.	Bageshwar	1,237	4.8	6.1	12.4	61.0	15.7
3.	Champawat	257	12.8	7.0	22.2	54.1	3.9
4.	Chamoli	2,192	4.8	4.3	10.9	70.7	9.4
5.	Dehradun	1,074	12.5	12.0	24.8	50.3	0.5
6.	Haridwar	364	2.5	4.7	7.4	68.1	17.3
7.	Nainital	472	8.1	12.3	26.5	51.1	2.1
8.	Pauri Garhwal	1,914	9.4	12.7	17.8	58.0	2.1
9.	Pithoragarh	1,792	8.5	6.0	10.4	59.8	15.2
10.	Rudraprayag	657	23.6	13.7	16.3	41.6	4.9
11.	Tehri	1,233	4.9	6.6	10.8	69.0	8.7
12.	Udhamsingh Nagar	798	1.3	2.6	10.5	83.7	1.9
13.	Uttarkashi	1,967	1.2	4.9	9.3	75.5	9.1
Total		14,748	6.9	7.5	13.4	64.1	8.0

Table VIII. Assessed damageability grade of the surveyed masonry buildings

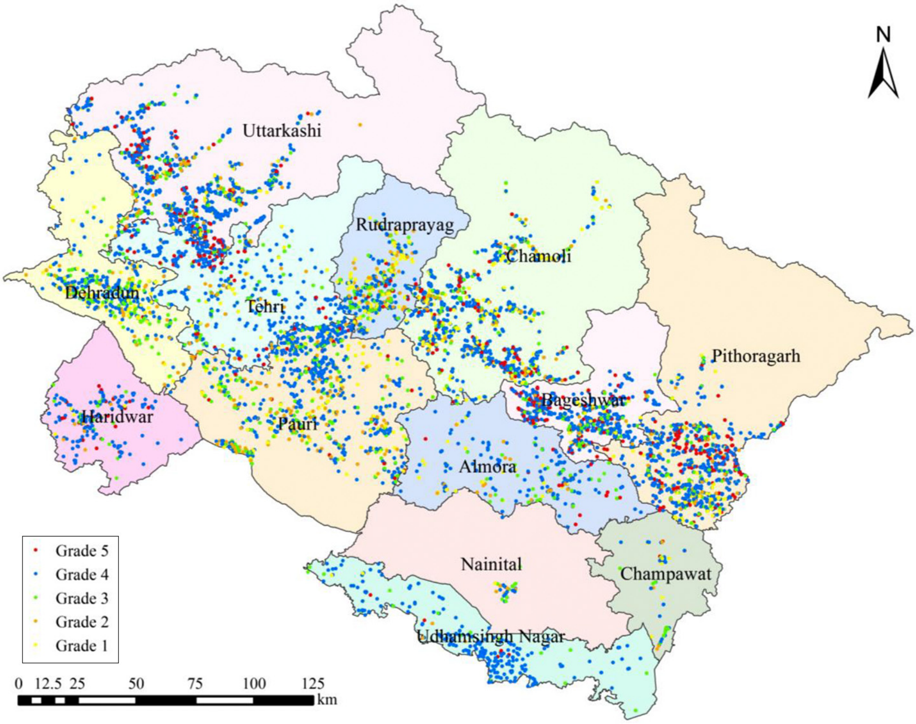

Figure 3. Distribution of different damageability grade buildings in the state of Uttarakhand

police stations, 25.0 per cent of fire and emergency service stations, 26.4 per cent of other departments and 31.1 per cent of hospitals are to remain functional after an earthquake.

Resultant depleted presence and functioning of local administration, police and fire and emergency service that are the first responders after any disaster incidence in

Table IX. Assessed damageability grade of the surveyed RCC buildings

S. No.	District	Total	Damageability grade (in %) G1	G2	G3	G4	G5
1.	Almora	250	27.2	11.2	18.8	39.2	3.6
2.	Bageshwar	252	17.5	12.3	14.7	47.6	7.9
3.	Champawat	91	25.3	16.5	23.1	34.1	1.1
4.	Chamoli	749	53.4	17.6	8.3	19.6	1.1
5.	Dehradun	234	22.6	23.1	24.4	29.1	0.9
6.	Haridwar	31	9.7	16.1	19.4	54.8	0.0
7.	Nainital	95	22.1	17.9	13.7	43.2	3.2
8.	Pauri Garhwal	439	33.3	16.2	16.2	32.8	1.6
9.	Pithoragarh	507	18.5	8.3	14.2	52.5	6.5
10.	Rudraprayag	611	32.1	14.7	11.1	38.5	3.6
11.	Tehri	268	17.5	18.3	11.2	48.9	4.1
12.	Udhamsingh Nagar	28	17.9	14.3	25.0	42.9	0.0
13.	Uttarkashi	532	45.9	23.7	20.9	9.6	0.0
Total		4,087	32.9	16.2	14.7	33.3	2.8

Table X. Department wise seismic vulnerability of the surveyed buildings

Department	Building units surveyed	Damageability grade (in %) G1	G2	G3	G4	G5
Health	1,309	19.6	11.7	15.8	48.5	4.4
Education	15,036	12.2	9.3	13.9	58.2	6.4
Local administration	1,578	9.9	7.3	11.0	55.6	16.3
Police	298	13.4	8.7	15.8	57.0	5.0
Fire and emergency services	32	6.3	18.8	18.8	40.6	15.6
Other departments	582	14.8	11.7	11.9	55.5	6.2
Total	18,835	12.6	9.4	13.8	57.1	7.1

India is sure to have adverse impact on search, rescue and relief operations. Moreover, with 68.7 per cent of the hospitals shut down because of earthquake induced damages the remaining would become non-functional because of extremely enhanced pressure.

School premises are used for various post-disaster functions in India and these include relief camps, rescue centres, warehouses and primary health centres. With 78.5 per cent schools damaged because of earthquake all these operations are to be disrupted. Besides this, damage to school buildings, in case earthquake happens during school hours, is to inflict severe trauma upon the affected community.

Damage to lifeline infrastructure is thus to severely escalate human miseries and overall death toll. Post-earthquake recovery is thus to be long drawn.

6. Economics of seismic safety

The surveyed buildings falling in Grade 5, 4 and 3 would have to be put to disuse immediately after an earthquake which implies that services being provided by almost 78.0 per cent of the surveyed public buildings, including 82.9 per cent of local administration and 68.7 per cent of hospitals, would be disrupted or go non-functional on the aftermath of an earthquake incidence in the region. The situation calls for timely and planned corrective measures.

Table XI. Details of retrofitting/reconstruction cost of surveyed masonry and RCC buildings

		Constructed area (in sq m)				Reconstruction/Retrofitting cost (in million US$)				
		Masonry structures		RCC structures		Masonry structures		RCC structures		
S. No.	Department	G5	G4 and G3	G5	G4 and G3	G5	G4 and G3	G5	G4 and G3	Total
1.	Administration	23,402	84,594	1,423	65,075	6.49	4.69	0.48	4.43	16.09
2.	Education	1,69,143	24,29,360	16,417	2,81,297	46.92	134.78	5.58	19.14	206.42
3.	Fire and emergency service	470	493	0	8,889	0.13	0.03	0.00	0.60	0.76
4.	Health	10,282	1,31,623	5,683	86,157	2.85	7.30	1.93	5.86	17.94
5.	Police	1,271	23,545	883	13,139	0.35	1.31	0.30	0.89	2.85
6.	Others	5,727	38,621	49	33,116	1.59	2.14	0.02	2.25	6
	Total	2,10,295	27,08,236	24,455	4,87,673	58.34	150.25	8.32	33.18	250.08

Different approaches have been used for assessing the cost of retrofitting and reconstruction of the surveyed buildings. Nasrazdani *et al.* (2017) used the Bayesian linear regression techniques to assess the retrofit cost based on 167 school retrofits in Iran. Arikan *et al.* (2005) used life cycle cost analysis approach to value the reconstruction or retrofitting alternatives to compare economically and concluded that the age of the building and the retrofit ratio are dominant parameters. Bhakuni (2005) used visual assessment tool to determine the structural PMF that help in assessing vulnerability of school buildings and providing a basis for next steps for necessary mitigation actions. Mora *et al.* (2015) assessed seismic resilience requirements based on seismic demand associated to specific return periods.

Ferreira and Proença (2008) assessed the seismic safety requirements of public educational buildings in Bucharest after studying building structure, pre-existing damage, non-structural hazards and their aggravating factors and thereby simulating building vulnerability and earthquake risk expressed in terms of the mean damage grade – varying from slight (1) to total collapse (5).

Like Ferreira and Proença (2008), the surveyed buildings in the present study have been categorised into five damage grades. The cost of improving seismic performance of buildings falling in Grade 5 is assessed as being high; it is therefore recommended that these be demolished and reconstructed. Retrofitting of the buildings falling in Grades 4 and 3 is recommended as this can be done with an average investment of around 20 per cent of their replacement value (Dowrick, 2003).

Actual built up area of the surveyed buildings as recorded during the field survey is utilised in the present study for assessing the cost of reconstruction (Grade 5) and retrofitting (Grade 4 and Grade 3) of the vulnerable buildings. Prevailing rates of new construction have been considered for assessing the cost of seismic resilience.

Total built up area of the buildings falling in Grade 5, Grade 4 and Grade 3 is calculated on the basis of covered area and number of stories. Prevailing schedule of construction rates of Public Works Department (PWD) of the state government is utilised for assessing the cost of construction of these buildings; Rs. 19,418 per sq m for masonry and Rs. 23,810 per sq m for RCC buildings. Prevailing exchange rate is utilised for currency conversion (1 US$ = Rs. 70). The cost of retrofitting is assessed as being a function of reconstruction cost (20 per cent).

US$58.34m is estimated as being required for reconstruction of masonry buildings of various departments falling in Grade 5, while retrofitting of the ones falling in Grades 4 and 3 is to cost US$150.25m (Table XI). Reconstruction and retrofitting of the surveyed RCC buildings of various departments falling in Grades 5, 4 and 3 is estimated to cost US$41.49m (Table XI). An investment of US$250.08m is thus estimated to make the surveyed lifeline

Table XII. Department wise cost of improving seismic performance of the buildings in the state

S. No.	Department	Building units		Reconstruction/retrofitting cost (in million US$)	
		Surveyed	Percent of total	Surveyed units	All
1.	Administration	1578	18	16.10	89.42
2.	Education	15,036	64	206.42	322.53
3.	Fire and emergency service	32	67	0.76	1.14
4.	Health	1,309	36	17.95	49.86
5.	Police	298	60	2.85	4.76
6.	Others	582	–	6.00	–
Total		18,835	–	250.08	467.71

buildings safe in an earthquake incidence that has high probability in the region (Table XI). It is worth noting that 82.5 per cent of this amount is required for ensuring safety of school buildings alone.

The proposed exercise of demolition, reconstruction and retrofitting is to, at the same time, save building contents that are to be lost in Grade 5 buildings during an earthquake incidence. For office buildings, the value of the contents is taken as being 50 per cent of the replacement cost, while for fire and emergency service, hospital and school buildings content value is taken as 200, 400 and 25 per cent of their replacement value (Dowrick 2003). Contents worth US$27.62m and 9.53m are thus to be saved, respectively, in Grade 5 masonry and RCC buildings.

The surveyed buildings constitute approximately 18, 23, 67, 36 and 60 per cent of the total buildings of local administration, education, fire and emergency service, health and police in the province (Table XII). It is thereby estimated that an investment of US$467.71m is to be required to make all the buildings of these important departments safe in a seismic event.

7. Conclusion

The study covers appreciably good proportion of the buildings of key departments of the state involved in post-disaster relief and rescue operations with an objective of assessing the challenges likely to be faced on the aftermath of a likely earthquake incidence and accordingly suggest remedial measures.

With 6.4 per cent of the schools collapsing and another 72.1 per cent sustaining major damage, the trauma of the affected community is sure to be escalated by manifold if the earthquake occurs at daytime on a working day. This at the same time is to hinder various post-disaster relief functions for which school premises are routinely used in India.

With 82.9 per cent infrastructure of local administration, together with 77.8 per cent of police and 75.0 per cent of fire and emergency service becoming non-functional, almost all activities related to search, rescue and relief are to be hit hard for quite some time after the earthquake. This is to, at the same time, pose difficulties in maintaining law and order.

Moreover with 68.7 per cent of the hospitals becoming non-functional there would be little chance of saving the ones who get rescued. With people in large numbers getting injured the remaining health-care facilities are to be overcrowded and become non-functional.

To add to it, 73.6 per cent infrastructure of other departments is to be damaged and therefore relief of any kind is hard to come immediately after the earthquake event. This delay in initial response is to severely delay the recovery. On the aftermath of the disaster, there is to be total lack of governance, social and political turmoil and state of utter confusion.

It is therefore recommended that the buildings falling in Grade 5 be reconstructed while those falling in Grades 4 and 3 to be retrofitted. This is estimated to cost public exchequer US$250.08m if only the surveyed buildings are targeted and this is to at the same time save contents worth US$37.15m that are otherwise to be lost during the earthquake.

Rather than taking up only the surveyed buildings, it is recommended to undertake seismic safety measures for all the lifeline buildings and this is estimated to cost US $467.71m. This can be taken up in a phased manner over 5-10 years and managing funds to the tune of US$50-100m annually should not be a major issue for the state.

Howsoever meticulously planned, this exercise is sure to require mobilisation of massive technical manpower and construction expertise for which networking with technical and academic institutions is recommended. The entire exercise is, however, to go futile and result in rebuilding vulnerabilities, despite massive financial investment, if the construction norms and building bye laws are not adhered to stringently.

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