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Economics of seismic resilience of educational infrastructure in high earthquake hazard prone Himalayan province of Uttarakhand in India

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ABSTRACT

Seismic vulnerability assessment of around 63.87% of the state owned school buildings in the Himalayan province of Uttarakhand in India that falls in identified high earthquake risk zone; Zone V and Zone IV of Earthquake Zoning Map of India, reveals 78.51% to be put to disuse immediately after an earthquake. Particularly high vulnerability of school buildings in Haridwar, Bageshwar, Pithoragarh and Almora districts of the province is to pose challenges of various sort on the aftermath of a major earthquake incidence. Based on damageability assessment of the surveyed buildings earthquake is estimated to result in losses to the tune of US$ 219.55 million to the surveyed school infrastructure alone. An investment of US$ 206.42 million is estimated for ensuring seismic safety of the surveyed school buildings by way of demolition and reconstruction of Grade 5 buildings (US$ 52.50 million) and seismic retrofitting of buildings falling in Grade 4 (US$ 107.29 million) and Grade 3 (US$ 46.62 million). US$ 323.19 million is estimated as being the cost of ensuring seismic safety of all state owned schools in the province.

1. Seismic risk in the region

Himalayan region has been devastated by six high magnitude seismic tremors in previous 120 years; Mw~8.0 Shillong 1897, Mw~7.8 Kangara 1905, Mw~8.2 Bihar–Nepal 1934, Mw~8.6 Assam now Arunachal 1950, Mw~7.6 Kashmir 2005 and Mw~7.8 Gorkha 2015. Long seismic quiescence in certain portions of the Himalayan orogen has however been a cause of concern, both for the states and scientific community [1,2].

Despite two moderate magnitude earthquakes (Mw~6.7 Uttarkashi 1991, Mw~6.4 Chamoli 1999) Mw~7.6 Garhwal Earthquake of 1st September 1803 is considered the last devastating earthquake event [1–3] around Himalayan province of Uttarakhand, in India (Fig. 1) that is located in the seismic gap of 1905 and 1934 great earthquakes. Areas as far as Mathura [4], Aligarh and Delhi were devastated by this earthquake [5,6] that is attributed intensity of IX-X around Srinagar and Devprayag while the magnitude of this earthquake is assessed as being Mw 7.7 $\pm$ 0.4 [7] and Mw 7.5 [8].

Vulnerability of the built environment in this region is highlighted by losses incurred in previous moderate magnitude earthquakes (Table 1) which calls for necessary and timely investment on seismic resilience.

Schools comprise an important public infrastructure that is often utilised for various post-disaster purposes. Relief camps and community kitchens are organised around school infrastructure that is also utilised for warehousing relief supplies, accommodating rescue workers and organising medical and relief camps. Moreover, seismic tremor during school hours is sure to enhance the trauma of affected community by manifold. Particularly high vulnerability of school buildings and students is universally accepted and has been highlighted by previous disaster events.

Mw~7.6 Muzaffarabad Earthquake of 8th October, 2005 affected 7669 schools in Azad Jammu and Kashmir (AJK) and North West Frontier Province (NWFP) of which 5690 (74.19%) were primary and middle schools. 18,095 students and 853 teachers were amongst 86,000 persons killed in this earthquake 9,10] which is 22.0%of the dead.

87,150 persons were killed in Mw~7.9 Sichuan Earthquake of 12th May, 2008 and this included 10,000 students amounting to 11.5% of the dead [11–13]; 7000 classrooms collapsed in this incidence. Mw~9.0 Great East Japan Earthquake and Tsunami (GEJET) of 11th March, 2011 killed 15,893 and 6.5% of these were students [14]. In some isolated areas affected by this event proportion of the students killed was however much higher [13].

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Anticipated earthquake threat in Uttarakhand region coupled with high vulnerability of school infrastructure calls for detailed planning for incorporating seismic resilience, particularly in school infrastructure and this has to be necessarily based on realistic data and assumptions. Previous studies on seismic vulnerability in this region have not focused on school infrastructure and are at the same time restricted to a small geographical area [15–17] or limited number of lifeline structures [18]. These at the same time neither provide structural details of the surveyed buildings nor the causes of vulnerability. Previous studies at the same time do not provide realistic financial estimates for ensuring seismic safety of the school buildings and therefore these have been of little or no use to the policy makers.

The present study is thus the first attempt to holistically address the issue of seismic vulnerability of school infrastructure in this region and covers significant proportion of the infrastructure of the education department of the provincial government spread across a wide geographical area so as to (a) identify schools that are seismically vulnerable, (b) assess degree of seismic vulnerability, (c) prioritise school buildings for detailed assessment, retrofitting and reconstruction, and (d) assess the cost of making school infrastructure seismically safe.

The study thus aims at drawing attention of policy makers and masses towards both, the cost of ensuring safety and vulnerability of the school infrastructure, so as to initiate mobilisation of resources for planned and phased seismic risk reduction.

2. The strategy

Rapid Visual Screening (RVS) technique is utilised in the present study to assess seismic vulnerability of the surveyed school buildings. A team of trained engineers was accordingly deployed to identify primary structural lateral load-resisting system of the surveyed buildings along with attributes that could modify anticipated seismic performance for this system and to report this through a form specifically developed for this purpose under android platform using Open Data Kit (ODK) framework.

Based on predefined building parameters Basic Structural Hazard (BSH) score and Performance Modification Factors (PMF) were assigned to individual buildings through RVS and these were subsequently integrated to generate the final Structural Score (S) that was utilised for assessing the vulnerability of the buildings.

Present study utilises methodology developed by Agrawal and Chourasia [21] on the basis of pre-existing methodology of Federal Emergency Management Agency, FEMA [19,20], for Indian context with some modifications in PMF score. Individual buildings are categorised as being RCC frame buildings with unreinforced masonry infill walls and unreinforced masonry buildings that are respectively assigned BSH scores of 3.0 and 2.5. Besides eight modifiers; (i) building height, (ii) gap between adjacent buildings, (iii) building site, (iv) soil type, (v) irregularity in building plan, (vi) soft storey, (vii) vertical irregularity and (viii) cladding, utilised by Agrawal and Chourasia [21] for PMF calculations present study incorporates attributes related to (i) roofing material, (ii) parapet height, (iii) re-entrant corner, (iv) heavy mass at the top, (v) construction quality, (vi) building condition/maintenance, and (vii) overhang length related parameters [22]. PMF values used by Joshi and others [22]) have been utilised for the present study.

After identifying buildings requiring reconstruction or retrofitting actual built area of these buildings, as recorded in the field survey, is utilised in the present study for assessing the cost of incorporating seismic resilience in accordance with the current cost of new construction.

Table 1
Losses in previous moderate magnitude earthquakes in Uttarakhand.

Sl. No.	Nature of loss	Uttarkashi 1991 (Mw 6.7)	Chamoli 1999 (Mw 6.4)
1.	Human lives	768	106
2.	Injured persons	5066	395
3.	Farm animals lost	3096	327
4.	Fully damaged houses	20,242	14,724
5.	Severely/partially damaged houses	74,714	72,126

3. State of the surveyed schools

15,036 school buildings spread across the province of Uttarakhand accounting for 63.87% of the state owned schools are surveyed under the present study (Fig. 2).

3.1. Typology of the surveyed buildings

Identification of building type together with the material used for construction is the first step of vulnerability assessment. With buildings classified as being masonry and reinforced concrete (RCC) 80.11% of the surveyed school buildings are identified as being masonry structures

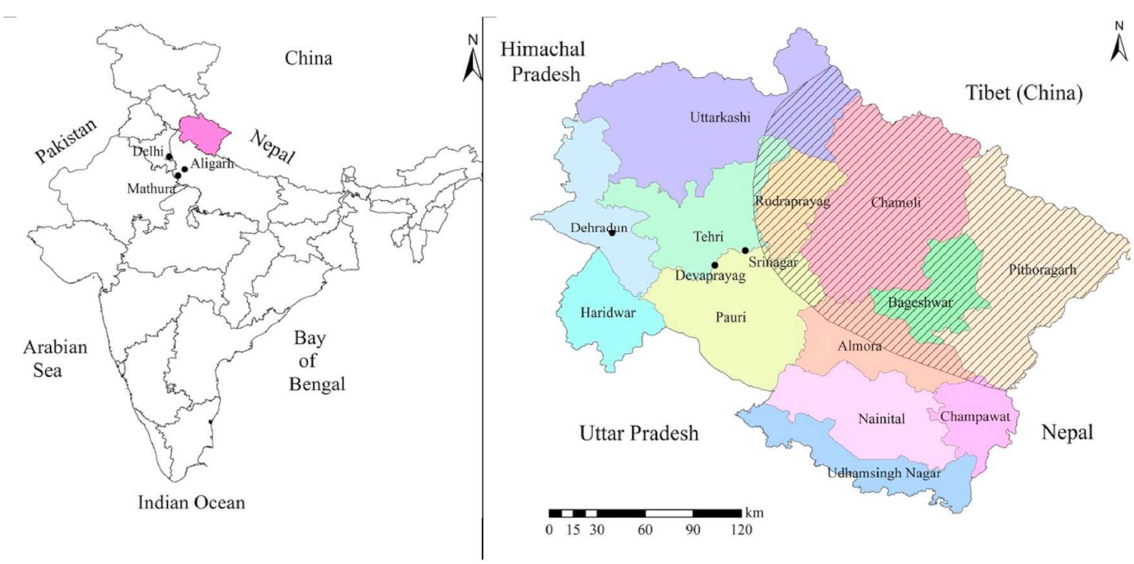

Fig. 1. Location map of the study area; Uttarakhand in India (left). Hatched area in the map of the province (right) represents Zone V of Earthquake Zoning Map of India while unhatched area represents Zone IV.

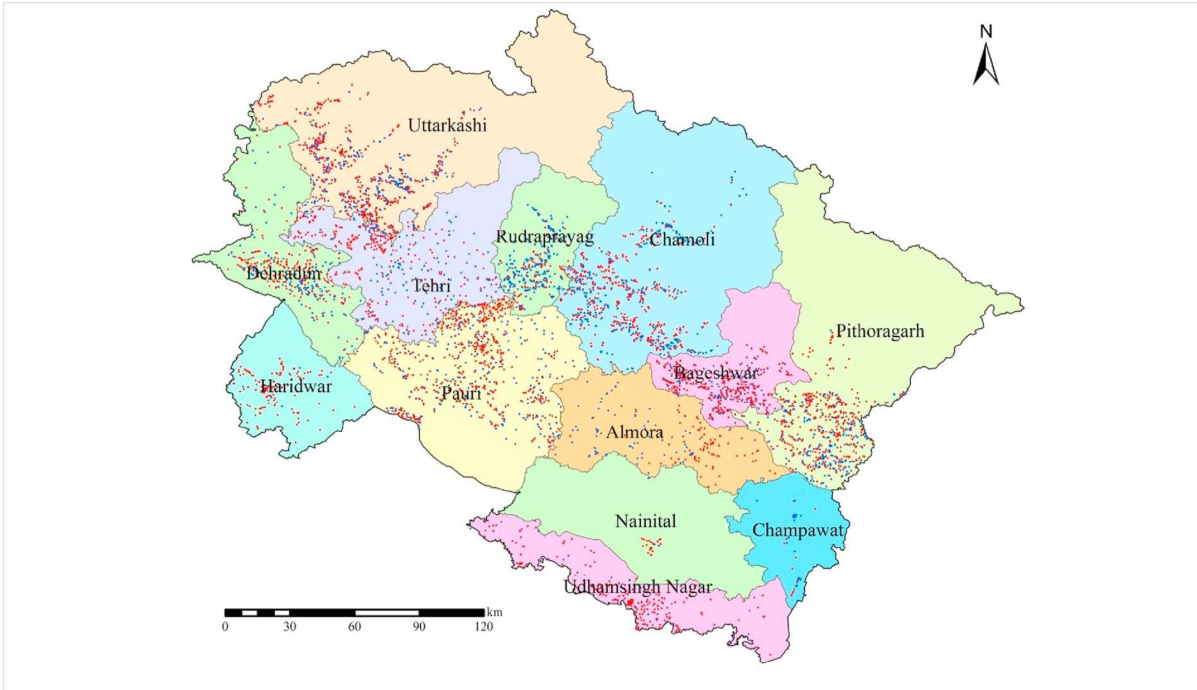

Fig. 2. Distribution of the surveyed state owned schools in the province of Uttarakhand with masonry and RCC school buildings depicted in red and blue respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

(Fig. 3).

With Rudraprayag, Chamoli, Uttarkashi, Pauri Garhwal and Pithoragarh accounting for 16.32, 16.25, 12.47, 12.04 and 10.70% of the surveyed RCC school buildings (Table 2) remote hilly districts of the province account for most RCC buildings. Haridwar and Udhamsingh Nagar, representing the plain districts of the province, have the lowest proportion of RCC buildings; 2.87 and 2.90% respectively.

3.2. Building height

Vulnerability of a structure generally increases with height if not countered by appropriate engineering inputs. Hight of the buildings has been assessed by number of stories; 9–10 feet per storey for residential and 12 feet per storey for commercial or office building [19].

Large majority of surveyed school buildings are observed to be single storied (Fig. 3), while only 10 masonry and 19 RCC buildings are triple storied (Fig. 4) with one building each of masonry and RCC being four storied (Table 3). More than 90% of the masonry buildings in all the districts of the province are single storied while double storied RCC buildings are less than 25% in Almora, Bageshwar, Chamoli, Dehradun, Pithoragarh, Rudraprayag and Uttarkashi districts.

Fig. 3. Single storeyed irregular masonry building of Government Inter College at Syunsi in Pauri Garhwal district having CGI roof.

Table 2
District wise details of the schools taken up under the present study.

Sl. No.	District	Masonry buildings	RCC buildings	Sl. No.	District	Masonry buildings	RCC buildings
1.	Almora	647	228	8.	Pauri Garhwal	1761	360
2.	Bageshwar	968	147	9.	Pithoragarh	1308	321
3.	Chamoli	1694	487	10.	Rudraprayag	535	488
4.	Champawat	190	48	11.	Tehri Garhwal	1139	232
5.	Dehradun	966	198	12.	Udhamsingh Nagar	737	22
6.	Haridwar	270	8	13.	Uttarkashi	1428	374
7.	Nainital	403	78	Total		12,046	2990

Fig. 4. Recently constructed three storeyed RCC Government Inter Collage building at Parkandi in Rudraprayag district having CGI sheets as the roofing material.

Table 3
Number of stories in the school buildings taken up under the present study.

Number of building stories	Masonry buildings (in %)	RCC buildings (in)
One	93.72	78.73
Two	6.18	20.60
Three	0.08	0.64
Four	0.01	0.03

3.3. Building age

Construction practices are generally related to the prevailing building codes which makes age of the building an important parameter of RVS procedure. Buildings are also sometimes rendered seismically deficient due to revision in building codes with time. Moreover, all buildings deteriorate with the passage of time.

Surveyed buildings are classified according to changes in building codes in India (Table 4) which reveals 4.23 and 0.10% of masonry and RCC buildings to be constructed before 1962, i.e. before the introduction of seismic codes in India. 12.92, 12.21 and 10.24% of the surveyed masonry buildings in Haridwar, Almora and Pithoragarh districts are observed to be constructed before 1962.

Majority of the surveyed buildings are observed to be constructed between 1984 and 2016; 84.29% of masonry and 98.89% of RCC. Of these only 8.56% of the RCC buildings are constructed between 1984 and 2001.

Table 4
Time of construction of the school buildings surveyed under the present study.

Sl. No.	Time of construction	Type of construction (in percentage)	
		Masonry	RCC
1.	Before 1962	4.23	0.10
2.	1962–65	2.13	0.00
3.	1966–69	0.67	0.03
4.	1970–83	8.49	0.37
5.	1984–2001	37.24	8.46
6.	2002–16	47.05	90.43
7.	2017–19	0.18	0.60

3.4. Roof

RCC slab is the most prevalent roofing material amongst the surveyed buildings (81.96%) while 17.58% have CGI sheets (Figs. 3 and 4). Only a few buildings are observed have tiles, wooden and asbestos sheet as roofing material (Table 5).

3.5. Walls

Walls in a building are either load bearing or non-load bearing/ partition. Brick, dressed stone (Ashlar stone), CC block and random rubble (RR) are observed to be common materials utilised for walling while cement, lime surkhi and mud are used as mortar (Table 6). RR

Table 5
Roofing material of the buildings taken up under the present study.

Sl. No.	Roofing material	Type of construction (in %)	
		Masonry buildings	RCC buildings
1.	CGI Sheets	21.35	2.37
2.	RCC Slab	78.08	97.59
3.	Tiles	0.03	0.00
4.	Wooden	0.39	0.00
5.	Asbestos	0.15	0.03

masonry walls are observed to be built using either undressed or roughly dressed stones while the stones used in Ashlar masonry are finely dressed, having courses of uniform height with most joints being regular, uniform and thin.

Despite stone and wood being traditional building materials of the region [23,24] most surveyed school buildings (54.18 and 75.95% of masonry and RCC building) are observed to be built using brick masonry in cement mortar. Even non load bearing walls of RCC framed buildings are built using bricks.

Masonry school buildings however exhibit varied wall types and particularly in remote hilly districts of the province significant proportion are built using stones that is available abundantly and cheaply. Use of stone at the same time amounts to saving the cost of transportation of bricks from the plains. 12.60, 12.69, 12.29 and 12.75% masonry buildings in Bageshwar, Pithoragarh, Tehri Garhwal and Uttarkashi districts are constructed using Ashlar stone in cement mortar while 16.54, 14.57, 15.64, 14.71 and 10.40% in Almora, Bageshwar, Chamoli, Pauri Garhwal and Pithoragarh districts are built using RR in cement mortar. 29.37, 33.06, 40.38, 12.21, 25.31, 48.13 and 11.94% of the masonry buildings in Almora, Bageshwar, Chamoli, Pauri Garhwal, Pithoragarh, Rudraprayag and Tehri Garhwal districts are built with RR in mud mortar. 22.96% of the masonry buildings in Haridwar (plain district of the province) are built using bricks in mud mortar.

3.6. Foundation

Foundation transmits the load of the structure to the sub-soil below and foundation of different types are utilised depending on soil condition, depth of the water table and load of the structure. 75.02 and 22.74% of the surveyed school buildings are observed to have stripped and isolated column foundation, with most masonry buildings having stripped foundation (Table 7).

3.7. Foundation material

Economic and abundant availability in the hills makes stone a favourite for foundation works (80.69%; Fig. 5). Brick (9.85%), RCC (6.25%) and cement concrete (3.21%) are other foundation materials observed to be utilised in the surveyed buildings (Table 8).

Table 6
Details of the walling material of the surveyed school buildings in the province of Uttarakhand.

Sl. No.	Walling material	Mortar	Building type (in %)	
			Masonry building	RCC building
1.	Ashlar stone	Cement	6.53	0.00
2.	Ashlar stone	Lime surkhi	0.58	0.00
3.	Brick	Cement	54.30	75.32
4.	Brick	Lime surkhi	0.08	0.00
5.	Brick	Mud	1.10	0.00
6.	CC block	Cement	8.33	16.69
7.	Random rubble	Cement	9.77	0.00
8.	Random rubble	Lime sukhi	0.30	0.00
9.	Random rubble	Mud	19.00	0.00
10.	RC frame building		0.00	7.89
11.	RC frame building with shear wall		0.00	0.10

Table 7
Details of the foundation type of the surveyed buildings.

Sl. No.	Foundation type	Building type (in %)	
		Masonry buildings	RCC buildings
1.	Combined footing	0.45	1.91
2.	Raft	1.42	1.71
3.	Isolated column	14.57	53.68
4.	Stripped	83.55	42.71

3.8. Building location

Geomorphic conditions often amplify ground motion during seismic shaking and for characterising this feature location of the school building is identified as being (a) Plain where the ground slope is less than 5°, (b) Mild slope where ground slope is 5–10°, (c) High slope where ground slope is 11–30°, (d) Hill top or crest, and (e) river bed.

3.9. Soil type

Soil is the ultimate load carrying element and soil density has a direct relationship with the amount of ground motion experienced at a particular place during an earthquake event. Characteristics of soil therefore have an important bearing upon seismic vulnerability of a structure and for the purpose of present study substratum or soil is identified as being (a) Rock/hard soil, (b) Soft soil, (c) Reclaimed/filled land, (d) Partially filled land, (e) Loose sand, and (f) Medium soil.

Most surveyed masonry school buildings (78.44%) are observed to be constructed on medium soil while 11.42% are constructed over rock/hard soil, 7.28% over partially filled land, 0.21% on loose sand, 0.68% on reclaimed filled soil and 1.94% on soft soil (Fig. 6). Of the RCC buildings 78.90% are constructed on medium soil while 9.92% are constructed over rock/hard soil, 6.85% over partially filled land, 0.43% on loose sand, 0.90% on reclaimed filled soil and 2.97% on soft soil.

3.10. Slope of the ground

Building codes applicable in India [25] recommend that the footing 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 be placed at least at a distance '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 should make an angel of less than 45°. Slope of 5.14% of the surveyed masonry and 8.15% of the RCC buildings is observed to be more than 45° (Fig. 7).

3.11. Engineering input

The buildings designed and constructed accordingly to the desired codes are engineered buildings while spontaneously and informally constructed buildings without any engineering input are non-engineered buildings [26]. 82.6% of the surveyed buildings are observed to be non-engineered (Fig. 8). Only 7.09% of the surveyed masonry and 50.00% of the RCC buildings are observed to be engineered.

3.12. Construction quality

Attributes summarised in Table 9 have been utilised for the purpose of present study to assess the quality of construction of the surveyed school buildings.

Of the surveyed school buildings quality of construction of only 1.34% is observed to be high while 57.04 and 41.61% respectively have medium and low quality. The quality of RCC buildings is relatively better but not satisfactory as only 5.75 of RCC buildings show high quality of construction (Fig. 9).

Fig. 5. Single storeyed Government Inter College building with CGI sheet as roofing material at Rau Lekh in Rudraprayag district is built using stone foundation.

Table 8
Details of the foundation material of the surveyed buildings.

Sl. No.	Foundation material	Building type (in%)	
		Masonry buildings	RCC buildings
1.	Brick	11.61	2.74
2.	Cement Concrete	2.12	7.63
3.	RCC	0.53	29.30
4.	Stone	85.74	60.33

22.81% of the surveyed buildings are observed to be located in plain area while 36.44, 33.32, 5.96 and 1.48% are respectively located in mid slope, high slope of hill, hill top and river bed.

3.13. Condition of the school buildings

Distress in the surveyed school buildings is mostly observed in the form of cracks in building elements which is attributed to inadequate maintenance, faults in design, poor workmanship, settlement of foundation, corrosion of reinforcement and extreme loading [22].

Cracks in the wall or roof of the school buildings and consequent exposure to rainwater, moisture and air is observed to result in corrosion of reinforced steel bars (Fig. 9), which is observed to result in vertical and horizontal cracks on column and beam respectively [22].

Defects in water supply line, sanitary fitments and drainage pipes are also held responsible for seepage of water in the surveyed school buildings. Seepage is sometimes also through roof and exterior walls which is observed to result in damping of the concrete which might pose a threat to the structural safety of the buildings [22].

On a 04 point scale; Excellent, Good, Damaged and Distressed, condition of 42.33 and 31.19% of the surveyed school buildings is assessed as being damaged and distressed. Only 26.22% of the masonry buildings are assessed to be in good condition while the condition of only 0.27% is excellent. As against this condition of 65.29 and 3.43% of the surveyed RCC buildings is observed to be good and excellent respectively (Fig. 10).

3.14. Irregularities

Reasons related to architecture, functionality and economics often result in irregular design of buildings which in turn adversely affects their seismic performance. Irregularity in the building design tends to concentrate demand at certain structural elements, from where cracks initiate and make structure vulnerable [22].

2.81 and 4.31% of the surveyed masonry and RCC building are respectively observed to have irregularity in shape (Fig. 11). Classified as L, T and Reverse-T type most buildings are observed to have L type irregularity.

3.15. Re-entrant corner

Aesthetics related considerations often introduce irregularities in building plan that result in re-entrant corners which are subjected to stresses for which these are not designed and therefore these are often damaged during seismic shaking. Moreover center of mass and centre of rigidity in such building forms do not geometrically coincide for all possible earthquake directions causing torsion which results in rotational motion [22].

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 [27]. Vulnerability due to re-entrant is observed in 7.87% masonry and 13.13% RCC buildings (Figs. 12 and 13).

3.16. Pounding

In order to avoid damage to the structures when these deflect towards each other during seismic shaking, building codes applicable in India recommend adjacent buildings to be separated by a distance which is equal to response reduction factor (R) times the sum of calculated storey displacements [27]. In case of buildings 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 [22,27]. 26.79 and 18.53% of the surveyed masonry and RCC buildings are respectively observed to be vulnerable to pounding (Fig. 14).

3.17. Overhang length

The purpose of providing overhangs is to avoid undesired solar radiation apart from protecting the exterior walls, doors and windows

Fig. 6. Government Inter Collage at Trijugi Narayan in Rudraprayag district having RCC slab as the roof and built over soft soil.

Fig. 7. Single storeyed Government Higher Secondary School at Raithal in Uttarkashi district having RCC slab as roof and built over sloping ground.

from rainwater and 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 [22]. Of the ones surveyed under this study very few buildings are observed to have overhung related vulnerability.

3.18. 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 were observed at the roof top [22].

4. Seismic vulnerability of the school buildings

Before planning and implementing measures to ensure seismic safety of the school buildings it is a must to assess their vulnerability for which the buildings scores assigned to various surveyed constituents of individual buildings (BSH and PMF) are integrated and structures are classified into five vulnerability classes based on final Structural Score (S);

Fig. 8. Primary School at Motichoor in Dehradun representing a non-engineered double storeyed masonry structure.

Table 9
Attributes utilised for assessing the quality of construction of the surveyed buildings.

Type of construction	Quality		
	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.

<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 grades relates to the expected intensity of earthquake in the area and as provided by European Macroseismic Scale, EMS-98 [28] the same is summarised in Table 10.

Grade 1 and Grade 2 denote no and slight structural damage together with slight and moderate non-structural damage respectively and therefore buildings falling in these damageability grades are assessed as being capable of withstanding seismic shaking. Only 14.31% surveyed masonry school buildings however fall in Grade 1 and Grade 2 (Table 11). Overwhelming large proportion of the masonry school buildings (85.69%) are thus likely to sustain significant losses. Of these

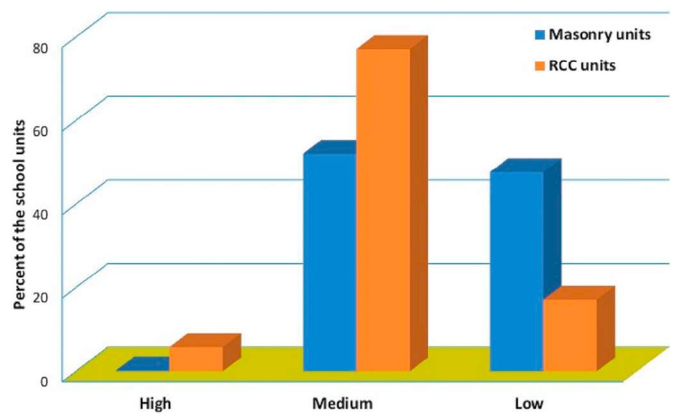

Fig. 9. Variation in the quality of surveyed school buildings in Uttarakhand.

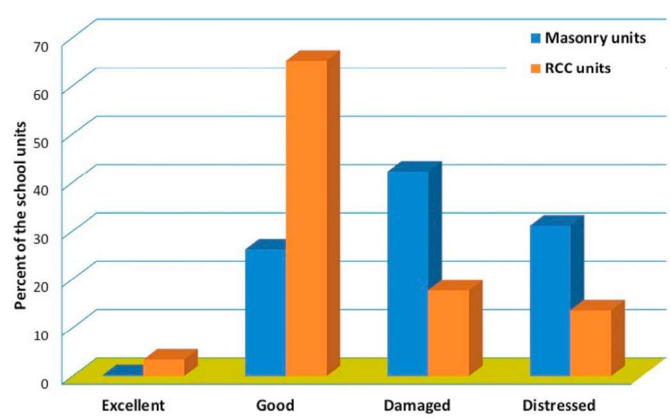

Fig. 10. Assessed condition of the surveyed school buildings in Uttarakhand.

8.50% fall in Grade 5 implying very heavy structural damage or near total collapse while 75.34% fall in Grade 4 which suggests heavy structural damage implying serious failure of walls together with partial

Fig. 11. Asymmetric building of Inter College at Jawalapur in Haridwar district.

Fig. 12. Single storeyed Government Inter Collage at Bairangana in Chamoli district having RCC slab as the roofing material and exhibiting re-entrant corner.

structural failure of roof and floor.

Haridwar, Bageshwar and Pithoragarh districts of the province require particular attention as 18.82, 16.32 and 15.60% of the surveyed masonry school buildings in these districts fall in Grade 5 while 69.00, 60.64 and 60.09% respectively fall in Grade 4 (Fig. 15). It implies that almost 75–90% of the masonry schools in these districts are likely to be severely damaged in an earthquake event (Table 11).

The state of RCC buildings is relatively better (Table 12) as 50.43% of the buildings fall in Grade 1 and Grade 2 and can be considered as being safe. This is however not satisfactory as 49.57% of the surveyed RCC buildings are to be damaged and of these 6.14% falling in Grade 5 are likely to collapse while 65.18% falling in Grade 4 are to sustain heavy structural damage.

Of all the surveyed school buildings in the province only 21.48% fall in Grade 1 and Grade 2 (Table 13). As against this only 6.44% of the buildings falling under Grade 5 are likely to collapse during an earthquake event. However, apart from these, the ones falling in Grade 4 and Grade 3 are to sustain major structural and non-structural damages. Large proportion of these are therefore not likely to be in a position to deliver routine services. This is a major cause of concern as it implies that 78.51% of the surveyed school buildings would go non-functional after an earthquake.

5. Economics of seismic safety

Analysis of the data collected from 63.87% of the state owned

Fig. 13. Re-entrant corners in Upper Primary School at Balidhar in Chamoli district.

Fig. 14. Government Primary School at Bajpur in Udhamsingh Nagar district; vulnerable to pounding during seismic shaking.

Table 10
Damage likely to be incurred to the buildings falling in different damageability grade in a likely earthquake event [28].

Damageability Grade	Building type	
	Masonry	RCC
Grade 1	**Negligible to slight damage** (No structural damage, 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, 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, heavy non-structural damage)	
	Large and extensive cracks in most walls.	Cracks in column and beam column joints of frame at the bases and at the joints of coupled walls
	Roof tiles detach	
	Chimneys fracture at the roof line; failure of individual non-structural elements (partitions, gable walls)	Spalling of concrete cover, buckling of reinforced rods
		Large cracks in partition and infill walls, failure of individual infill panels
Grade 4	**Very heavy damage** (Heavy structural damage, 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

schools in the province of Uttarakhand brings forth harsh and worrying reality that almost 78.51% of the surveyed schools or 50.15% of the total state owned schools would go non-functional on the aftermath of a major earthquake incidence in the region. This is to disrupt post-disaster operations generally organised around the school premises in India besides derailing routine education of the students of affected area for a long time. Moreover earthquake during school hours is to severely enhance trauma of the affected community. The situation calls for planned and phased strategy with clear cut prioritisation of tasks for reducing seismic vulnerability of the schools, as interventions at the scale warranted cannot be initiated without mustering adequate financial and technical resources.

Different approaches have been utilised for assessing the cost of retrofitting and reconstruction of surveyed buildings. Nasrazdani and others [29] used the Bayesian linear regression techniques to assess the retrofit cost based on 167 school retrofits in Iran. Arikan and others [30] utilised life cycle cost analysis approach to value the reconstruction and retrofitting alternatives and compared these economically to conclude that the age of the building and the retrofit ratio are dominant parameters. Bhakuni [31] used visual assessment tool to determine structural performance modification factors that help in assessing vulnerability of school buildings and providing a basis for next steps for necessary mitigation actions. Mora and others [32] assessed seismic resilience requirements based on seismic demand associated to specific return periods.

Ferreira and others [33] 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 others [33] 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 Grade 4 and Grade 3 is recommended as this can be done with an average investment of around 20% of their replacement value [34].

Built up area of the surveyed buildings having taken note of during the field survey, actual built up area of the surveyed buildings 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 constructed area of the surveyed school buildings is estimated as being 33,74,119 sq m of which 84.38% is accounted for by masonry construction (Table 14).

The economic losses likely to be incurred to the school buildings as also cost of ensuring seismic safety are assessed as being a function of the

Table 11
District wise damageability of the surveyed masonry school buildings in Uttarakhand.

Sl. No.	District	Total surveyed	Damageability grade (in %)				
			Grade 1	Grade 2	Grade 3	Grade 4	Grade 5
1.	Almora	647	8.66	9.12	11.13	62.13	8.96
2.	Bageshwar	968	4.34	5.89	12.81	60.64	16.32
3.	Chamoli	1694	4.01	4.13	10.45	72.85	8.56
4.	Champawat	190	14.21	4.74	25.79	52.63	2.63
5.	Dehradun	966	11.70	11.70	25.05	51.14	0.41
6.	Haridwar	270	2.21	2.95	7.01	69.00	18.82
7.	Nainital	403	7.44	13.15	26.55	50.37	2.48
8.	Pauri Garhwal	1761	8.63	12.55	17.43	59.34	2.04
9.	Pithoragarh	1308	8.10	5.50	10.70	60.09	15.60
10.	Rudraprayag	535	24.53	14.23	15.92	41.20	4.12
11.	Tehri Garhwal	1139	4.39	6.15	10.80	69.97	8.69
12.	Udhamsingh Nagar	737	1.09	2.17	9.23	85.62	1.90
13.	Uttarkashi	1428	1.40	6.30	10.85	76.47	4.97
Total		12,046	6.72	7.59	13.85	64.57	7.28

9.40, 7.81 and 5.70% of the surveyed RCC school buildings of Bageshwar, Pithoragarh and Almora districts fall in Grade 5 while 50.34, 54.06 and 34.65% respectively fall in Grade 4 implying that 40–60% RCC schools of these districts are to sustain major damages during an earthquake event (Fig. 15).

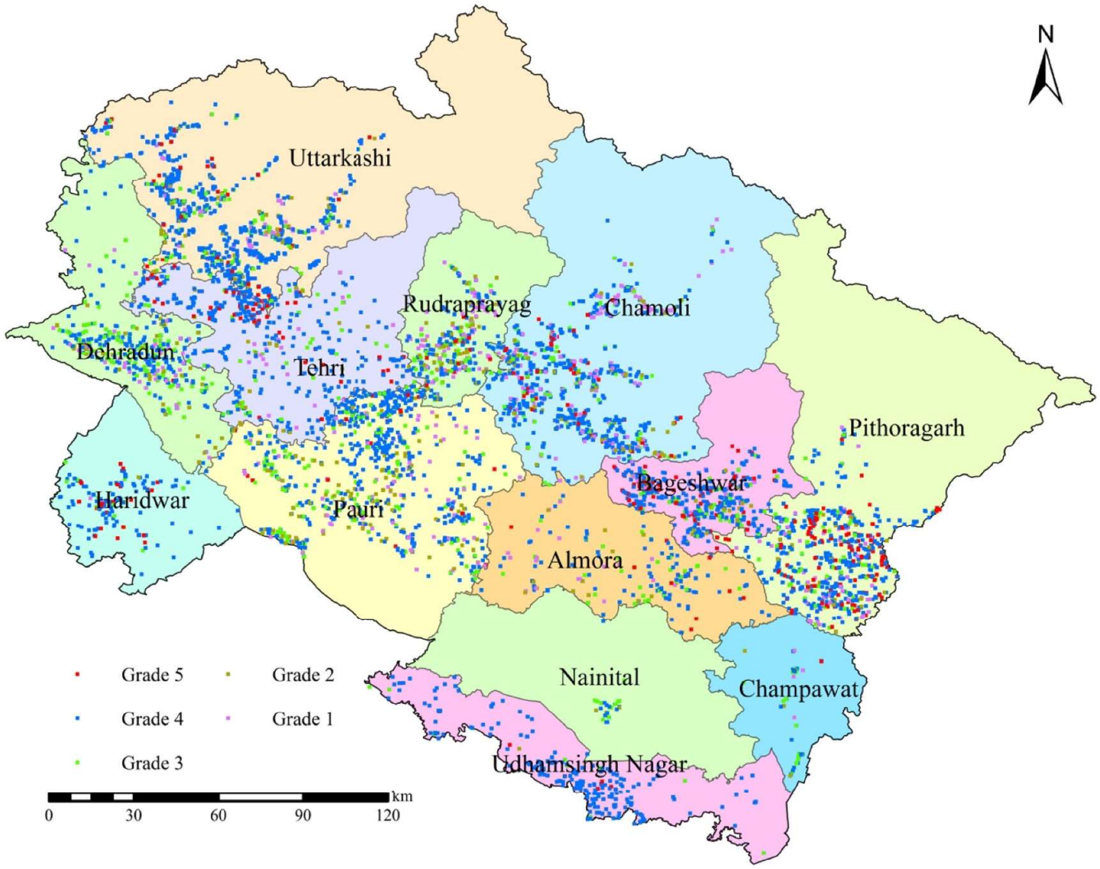

Fig. 15. Damageability of the surveyed school buildings in the province of Uttarakhand.

Table 12
District wise damageability of the surveyed RCC school buildings in Uttarakhand.

Sl. No.	District	Total surveyed	Damageability grade (in%)				
			Grade 1	Grade 2	Grade 3	Grade 4	Grade 5
1.	Almora	228	28.07	11.40	20.18	34.65	5.70
2.	Bageshwar	147	13.42	14.09	12.75	50.34	9.40
3.	Chamoli	487	55.97	19.55	7.61	15.64	1.23
4.	Champawat	48	16.67	16.67	33.33	33.33	0.00
5.	Dehradun	198	23.23	23.74	25.25	26.77	1.01
6.	Haridwar	8	12.50	12.50	12.50	62.50	0.00
7.	Nainital	78	20.51	19.23	15.38	42.31	2.56
8.	Pauri Garhwal	360	33.33	16.67	15.28	33.06	1.67
9.	Pithoragarh	321	17.50	7.81	12.81	54.06	7.81
10.	Rudraprayag	487	34.22	14.75	10.66	37.50	2.87
11.	Tehri Garhwal	232	18.10	16.38	11.64	50.00	3.88
12.	Udhamsingh Nagar	22	13.64	13.64	22.73	50.00	0.00
13.	Uttarkashi	374	54.96	20.64	17.16	7.24	0.00
Total		2990	34.11	16.32	14.21	32.31	3.04

Table 13
Damageability wise details of the surveyed school buildings in Uttarakhand.

Damageability	Surveyed buildings			Surveyed buildings (in%)		
	Masonry	RCC	Total	Masonry	RCC	Total
Grade 1	810	1020	1830	6.72	34.11	12.16
Grade 2	914	488	1402	7.59	16.32	9.32
Grade 3	1668	425	2093	13.85	14.21	13.92
Grade 4	7776	966	8744	64.57	32.31	58.15
Grade 5	878	91	969	7.28	3.04	6.44
Total	12046	2990	15036			

cost of new construction with equal covered area. The same is calculated using the present schedule of rates of Public Works Department (PWD) of the provincial government; Rs. 19,418 per sq m for masonry and Rs. 23,810 per sq m for RCC buildings, while prevailing exchange rate is utilised for currency conversion (1 US$ = Rs. 70).

Grade 5 buildings pose the most risk and therefore vulnerability of these has to be addressed first. Attempts to incorporate seismic safety features in these buildings are however not going to be economically viable and therefore it is suggested to undertake planned demolition and reconstruction of these buildings. This exercise would at the same time save the building content likely to be lost under collapsing buildings and is assessed to value around 25% of the cost of the school building [34].

Table 14
District wise covered area of the surveyed school buildings falling in different damageability grade (in sq m).

Sl. No.	District	Covered area of the buildings (in sq m)									
		Grade 5		Grade 4		Grade 3		Grade 2		Grade 1	
		Masonry	RCC	Masonry	RCC	Masonry	RCC	Masonry	RCC	Masonry	RCC
1.	Almora	9020	2206	61,165	12,705	13,812	5983	8222	2629	7219	8774
2.	Bageshwar	23,676	3847	66,768	13,454	15,480	1532	7124	2508	17,042	2651
3.	Chamoli	23,767	1197	66,769	14,180	15,480	7233	7125	15,571	17,042	39,658
4.	Champawat	12,468	0	19,751	7002	15,243	6503	1620	1153	4258	2032
5.	Dehradun	497	261	89,741	10,806	12,380	8179	12,380	7050	13,288	7048
6.	Haridwar	18,195	0	59,897	2425	2224	1202	1948	586	2091	0
7.	Nainital	2263	464	30,800	7700	12,954	1828	5262	5781	8395	2039
8.	Pauri Garhwal	11,675	1201	1,29,693	25,278	38,057	10,208	26,255	11,466	17,271	25,303
9.	Pithogagarh	40,600	3265	1,19,381	35,880	5,72,000	6339	8660	3550	14,272	8992
10.	Rudraprayag	2948	2044	3,78,714	21,813	8334	5810	8017	7302	17,608	21,753
11.	Tehri Garhwal	2948	1932	3,78,714	31,129	8333	6770	8017	9521	17,609	7769
12.	Udhamsingh Nagar	3741	0	1,21,693	9744	10,536	9493	3074	330	2468	611
13.	Uttarkashi	17,345	0	1,66,395	7228	15,046	10,873	7865	13,221	4362	22,110
Total		1,69,143	16,417	16,89,481	1,99,344	7,39,879	81,953	1,05,569	80,668	1,42,925	1,48,740

Constructed area of the masonry and RCC school buildings falling in Grade 5 is respectively 1,69,143 and 16,417 sq m. Nullifying the cost of demolition of existing vulnerable buildings with the reuse of construction material, US$ 52.50 million is estimated as being required for the reconstruction of the school buildings falling in Grade 5; US$ 46.92 million for masonry buildings and US$ 5.58 million for RCC buildings.

Having reconstructed Grade 5 buildings the vulnerability of the buildings falling in Grade 4 and Grade 3 has to be addressed. These buildings can be made earthquake resilient through appropriately designed retrofitting measures that are to cost approximately 20% of the cost of new reconstruction [34].

Constructed area of masonry and RCC school buildings falling in Grade 4 is 16,89,481 and 1,99,344 sq m respectively. Retrofitting of Grade 4 school buildings is thus to require US$ 107.29 million; US$ 93.73 million for masonry and US$ 13.56 for RCC buildings. Similarly, constructed area of masonry and RCC school buildings falling in Grade 3 is 7,39,879 and 81,953 sq m respectively. Seismic safety of Grade 3 school buildings is therefore to cost US$ 46.62 million; US$ 41.05 million for masonry and US$ 5.58 for RCC buildings (Table 15).

An investment of US$ 206.42 million is thus estimated for ensuring seismic resilience in the surveyed school buildings. The proposed exercise of demolition, reconstruction and retrofitting is to at the same time save school building content worth US$ 13.13 million that are to be otherwise destroyed in Grade 5 buildings during an earthquake incidence.

As the surveyed buildings constitute 63.87% of the state owned school infrastructure in the province, an investment of US$ 323.19 million is estimated as being required for ensuring seismic safety of the entire state owned school infrastructure. This is in turn estimated to ensure safety of building contents worth US$ 20.58 million.

Table 15
Economic loss likely to be incurred to the surveyed school infrastructure.

Head		Masonry	RCC	Total
Covered area (in sq m)	Grade 5	1,69,143	16,417	1,85,560
	Grade 4 and Grade 3	24,29,360	2,81,297	27,10,657
Reconstruction cost (in million US$) RCC @ Rs. 23,810/sq m Masonry @ Rs. 19,418/sq m	Grade 5	46.92	5.58	52.50
	Grade 4 and Grade 3	673.90	95.68	769.59
Content loss (in million US $) 25% of reconstruction cost	Grade 5	11.73	1.40	13.13
Repair/restoration cost (in million US$) 20% of reconstruction cost	Grade 4 and Grade 3	134.78	19.14	153.92
Total losses (in million US $) Reconstruction of G5 + Content lost in G5 + Restoration of G4 and G3		193.43	26.12	219.55

6. Discussion

Designed incorporating importance factor of 1.5 as provided by the building codes in India [27] and constructed by trained team of departmental engineers, school buildings are generally expected to be seismically resilient. The present study covering large proportion of the state owned schools (63.87%) however reveals 92.91 and 50.00% masonry and RCC buildings to be non-engineered. This observation is testified by other findings that include 47.69 and 17.12% masonry and RCC buildings depicting low quality of construction, irregularities in 2.81 and 4.31% masonry and RCC buildings, re-entrant corners in 7.87 and 13.13% masonry and RCC buildings, 26.79 and 18.53% masonry and RCC buildings being vulnerable to pounding, and placement of heavy mass at the top of many buildings.

The study thus highlights the issue of non-compliance of seismic safety codes and flaunting of established engineering norms in the construction of school buildings. This calls for training of onsite supervisory staff and putting in place standard operating procedures for ensuring compliance at different stages of construction. Moreover, lapses jeopardising life and safety of individuals is a serious issue and therefore it is recommended to fix personal responsibility of officials engaged in construction of school buildings with stringent punitive measures.

The study brings forth lack of maintenance as being another major cause of the vulnerability of the school buildings which is corroborated by 31.19 and 13.60% masonry and RCC buildings being in distressed condition. Spatially dispersed nature of school infrastructure and non-availability of engineering staff with education department often makes routine maintenance challenging. It is thus recommended that the responsibility of maintaining all state owned school buildings be entrusted to one single department which would ensure regular vulnerability assessment together with implementation of required corrective measures. This would also ensure economy, accountability and transparency as regards the safety and security of the students, teachers and other staff while at school.

The study further reveals that an overwhelmingly large proportion of school buildings are likely to be damaged and consequently put to disuse after an earthquake, even though only 6.44% falling in Grade 5 are likely to collapse. Besides causing major trauma to the affected community in case earthquake occurs during school hours, this is to seriously disrupt routine studies of the children for a long time.

Of the surveyed masonry buildings 6.44% are likely to collapse while 58.15% are to sustain heavy structural and non-structural damage. The vulnerability of RCC buildings is relatively low but still 49.56% of these are assessed as being unsafe with 3.04% likely to collapse.

The study thus highlights that only handful of school buildings are to remain operational immediately after an earthquake. Vulnerability of both masonry and RCC school buildings in Bageshwar, Pithoragarh, Haridwar and Almora districts of the province is observed to be particularly high and requires special attention.

7. Conclusion

In view of the safety of students and minimising trauma of the affected population on the aftermath of an earthquake it is recommended that the school buildings falling in Grade 5 be reconstructed and those falling in Grade 4 and Grade 3 be analysed in detail and exercise of seismic retrofitting of these be initiated without any further delay. Reconstruction of the school buildings falling in Grade 5 is estimated to cost US$ 52.50 million. Seismic retrofitting of Grade 4 and Grade 3 buildings is estimated to cost US$ 107.29 and 46.62 million respectively.

US$ 206.42 million is thus estimated as being the cost of seismic resilience of the surveyed school buildings while investment of US$ 323.19 million is estimated for bringing the entire school infrastructure of the provincial government under earthquake safety net. Investment of US$ 50–70 million spread over 5–7 years should not be a problem for the state for the cause of safety of life of students, teachers and staff therein.

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

At the end it is recommended that seismic safety audit be made a precondition for operating any education and training facility, including hostels thereof, and this be linked to their recognition and certification. Uttarakhand is growing fast as a major educational hub of North India and resilient educational infrastructure is to ensure steady growth in this sector.

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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.2019.101363.

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