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ORIGINAL RESEARCH

An empirical method for seismic vulnerability assessment of Nepali school buildings

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Abstract

The 2015 Gorkha earthquake in Nepal damaged more than 28,000 school buildings across the affected areas. Nepali school buildings can broadly be categorized into special moment-resisting frame, brick masonry, stone masonry, timber, and composite construction (steel and masonry). This paper proposes a new methodology to designate seismic vulnerability of these building categories. The proposed methodology is based on the field study of around 3389 school buildings in central Nepal. Structural, non-structural, architectural, site conditions, seismic enhancement and retrofitting, and multi-hazard parameters are incorporated to develop a scoring system. Indexed based system is introduced using sensitivity analysis which allows the designation of total vulnerability scores to individual buildings. The scores are modified based on the level of seismic strengthening/retrofitting. Based on the total vulnerability score, a qualitative vulnerability level is assigned to the individual building. The results highlight that more than 90% of Nepali school buildings are moderate to very highly vulnerable.

Keywords Seismic vulnerability · School building · Gorkha earthquake · Brick masonry · Stone masonry · Timber frame

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1 Introduction

Damage to buildings is one of the most serious physical effects of earthquakes. Damaged buildings not only result in economic loss but can kill or seriously injure their occupants. It is one of the major causes of disruption in the society. Seismically vulnerable buildings reduce societal resilience to earthquakes. Seismic vulnerability of buildings in this context refers to their inability to resist earthquake shaking and provide expected safe, functional, and comfortable shelter to their occupants. A large proportion of seismic risk can be reduced by making buildings less vulnerable to ground shaking. A proper understanding of seismic vulnerability of existing buildings in a seismically active area is essential to estimate impending risk and manage it properly.

Seismic vulnerability assessment of buildings and other structures in seismically active regions is a widely addressed research area. Different frameworks making use of analytical, experimental, or empirical methods to estimate seismic vulnerability of buildings have been reported in the literature (e.g. Ortega et al. 2019a, b; Ahmad et al. 2012a, b, 2018; Ferreira et al. 2020, among others). Analytical methods of vulnerability assessment rely on mechanical modelling of building components and are associated with uncertainties that are inherent in nonlinear transient response of structures. Experimental methods can provide more direct assessment of seismic vulnerability, but they are costly and time consuming, and are more feasible for building components than whole buildings. Empirical methods rely on recorded data of damage caused by past earthquakes. Such records, when collected and organized properly, can provide a lot of insight on seismic vulnerability of buildings. Several seismic vulnerability assessment methodologies have been developed and implemented for various building types worldwide (e.g. Vicente et al. 2011; Azizi-Bondarabadi et al. 2016; Neves et al. 2012; Benedetti and Petrini 1984; Lagomarsino and Giovinazzi 2006; Ortega et al. 2019a, b), among others). Development and validation of vulnerability assessment frameworks generally depend on damage data from earthquakes. Such damage data help identify vulnerable elements and mechanisms in different types of buildings. Empirical data haven been successfully used to develop and validate new empirical seismic vulnerability assessment frameworks in Italy, Portugal, Iran, and other countries (see e.g. Del Gaudio et al. 2015, 2017, 2018; Azizi-Bondarabadi et al. 2016; Miano et al. 2019; Ferreira et al. 2017; among others). Damage data after strong earthquakes are recorded and stored at different levels of detail and completeness in different parts of the world. It is very rare, although has been reported in Iceland (Bessason et al. 2020; Bessason and Bjarnason 2016; Rupakhety et al. 2016), to have damage data at individual building level. Availability and quality of damage data concerning issues such as correctness, completeness, uniformity in geographical distribution and building typologies are often not optimal and need to be supplemented by some form of expert judgment (see e.g. Gautam et al. 2018a, b; Porter et al. 2007), which can vary in complexity from visual inspection to calculation of simplified models. FEMA P-154 (FEMA 2015), Bal et al. (2008), Gulay et al. (2011), Sucuoğlu et al. (2007), among others have used visual inspection for seismic vulnerability classification of building stocks. Vulnerability classification based on visual inspection by experts is cost-effective and quick and is therefore an important tool during post-earthquake safety and loss assessments. They can also be useful for quickly assessing potential seismic risk to many buildings, which becomes necessary for pre-disaster planning and risk mitigation measures.

The 2015 Gorkha earthquake in Nepal caused extensive damage to buildings and lifelines. More details about the earthquake, observed ground shaking, and damage to structures and lifelines can be found elsewhere (see e.g. Rupakhety et al. 2017; Rupakhety 2018; Gautam 2018; Gautam et al. 2018a, b; among others). About a million buildings were either collapsed or partly damaged and 8790 people lost their lives (National Planning Commission 2015). The magnitude 7.8 earthquake also caused extensive damage to school buildings: more than 28,000 buildings in 31 out of 75 affected districts were damaged (Adhikari and Gautam 2019). The damage statistics, fragility functions, and damage probability matrices of school buildings are reported by Adhikari and Gautam (2019). Although masonry buildings are expected to be more vulnerable than reinforced concrete buildings, several examples of higher damage to latter type were observed at similar levels of ground shaking. In most of these examples, the reinforced concrete buildings lacked adequate ductile detailing and were larger in size than masonry buildings. These observations support that taxonomical classification based on construction material alone is not reliable for vulnerability assessment. Various other factors contribute to seismic vulnerability of buildings. It is therefore important to identify relevant factors and properties of the existing building stock and develop a rational framework for their vulnerability classification. While other methods of vulnerability assessment such as those based on analytical modelling are presumably more rigorous, they involve large uncertainties due to inherent variability in material properties and difficulties associated with their numerical simulation. Analytical methods (see e.g. Federal Emergency Management Agency 1997; Liu and Kuang 2017) become more relevant when construction practices change. Analytical models of seismic vulnerability can be made more reliable by their calibration and/or validation against empirical data. In this context, a qualitative assessment method based on surveys and inspection can be useful for the overall assessment of building stocks. The aim of the proposed method is to develop a user-friendly seismic vulnerability assessment tool that can be used for rapid assessment of many buildings. Such assessment can be useful in prioritization of seismic intervention strategies (see, for example, Grant et al. (2007) and Mora et al. (2015)). They can also be used for rapid loss and needs assessment after an earthquake as well as for assessing safety to occupants against imminent aftershocks which follow large earthquakes. To this end, a method incorporating various characteristics of reinforced concrete (RC), load bearing (LB), steel frame (SF), and timber frame (TF) school buildings in central Nepal is developed and implement for their seismic vulnerability assessment.

2 Post-earthquake damage assessment

After the 2015 Gorkha earthquake, detailed assessment of school buildings in the 14 severely affected districts in central Nepal was conducted. Two separate forms were developed to collect the field data. The first form was developed to obtain information related to schools. Information such as their location, type of building, number of blocks, among others were collected in the first form. The second form collected more detailed information of individual buildings (blocks). These information include damage level, construction year, history of addition and modification, retrofitting, proximity to next block, plumb level check, plan shape, length, breadth, height, offset of the building, plan of the structure, building exposure against liquefaction, slope failure/rock fall hazard, number of stories, foundation type, continuity of plinth beam, and type of structure (reinforced concrete, masonry, steel frame, timber frame, etc.). In addition, information regarding floor structure, floor to wall/frame connection, damage to floor, masonry wall type, type of masonry (dressed/undressed), wall thickness, wall panel length, wall height, size of openings, distance of openings from the end of the wall, wall connection, horizontal and vertical bands on wall, story height, infill material, infill wall thickness, wall offset, size of column/beam, rebars and sizes, short/captive column, type of steel section are collected. Information on types of connections, type of timber, deterioration in masonry/concrete, deterioration in mortar, damage to the boundary wall, shape and type of roof, roofing structure, roofing material, roof structure connection to the main structure and roofing material, parapets and pediments, damage to parapet and pediment, structural redundancy, load path regularity, mass regularity, vertical regularity, weak and soft story, retrofitting type, type of seismic enhancement, construction quality, among others are also collected in the form. "Appendix" provides a combined version of the two forms. This form was used to collect data from 3389 buildings which were all inspected in detail in the field. These buildings represent reinforced concrete (RC), load bearing (LB), steel frame (SF), and timber frame (TF) structures in central Nepal. An example of the different types of these buildings is shown in Fig. 1.

3 Development of vulnerability analysis framework and application to Nepali school buildings

The collected field data was used to assess seismic vulnerability of individual school buildings. After a detailed study of the information collected from the 3389 buildings, four broad vulnerability factors, viz., (1) workmanship and age, (2) geometry, (3) structure, and (4) seismic components were identified, as shown in Fig. 2. The structure factor was further divided into three sub-factors viz., floor structure, roof structure, and wall/frame structure with relative weights of 30%, 20%, and 50%, respectively. Each of these factors and sub-factors are

Fig. 1 Building classes considered for development and implementation of the vulnerability assessment framework proposed in this study **a** reinforced concrete (RC), **b** stone masonry (LB), **c** brick masonry (LB), **d** steel frame, and **e** timber frame

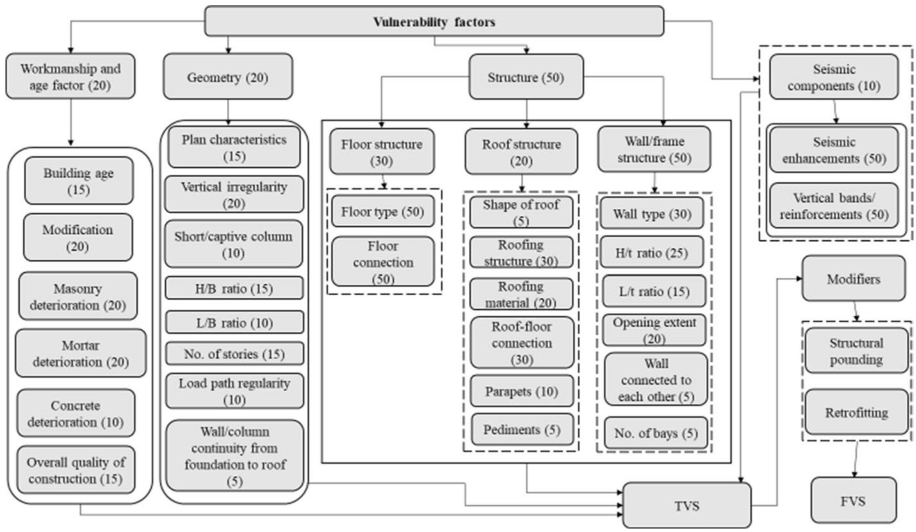

Fig. 2 Newly developed vulnerability assessment framework for school buildings in Nepal

assigned a numerical value/score in the range 1–5, with higher number representing higher vulnerability.

The score of the workmanship and age factor is based on six parameters. Building age, intermediate modification, deterioration of masonry unit, mortar deterioration, concrete deterioration, and overall quality of construction were respectively assigned weights of 15%, 20%, 20%, 20%, 10%, and 5%. The score of the geometry factor is based on plan characteristics, vertical regularity, short/captive column, height to width ratio (H/B ratio), length to width ratio (L/B ratio), number of stories, load path regularity, wall/column continuity from foundation to roof with respective weights of 15%, 20%, 10%, 15%, 10%, 15%, 10%, and 5%. For floor structure sub-factor, floor type and floor connection were considered with equal weights of 50%. Under roof structure sub-factor, shape of roof, roofing structure, roofing material, roof-floor connection, parapets, and pediments were considered with respective weights of 5%, 30%, 20%, 30%, 10%, and 5%. For wall/frame structure, wall type, height to thickness ratio (H/t), length to thickness ratio (L/t), extent of opening, wall connection, and number of bays were considered with respective weights of 30%, 25%, 15%, 20%, 5%, and 5%. The seismic components factor was further categorized into seismic enhancement and vertical bands/ reinforcements in masonry buildings with equal weights of 50%. The weights were assigned based on a previous study that studied component level damage probability matrices (Adhikari and Gautam 2019). The weights were also determined using the relative proportion of damage in each of each these factors and sub-factors and their potential effects in overall damage and failure modes. The vulnerability score corresponding to each of the four factors is defined as a weighted score of its sub-factors as depicted in Eq. (1).

$$
\begin{aligned}
\textit{Workmanship and age factor} = {} & 0.15 \times \textit{Building age} + 0.2 \times \textit{Modification} + 0.2 \\
& \times \textit{Masonry deterioration} + 0.2 \times \textit{Mortar deterioration} + 0.1 \\
& \times \textit{Concrete deterioration} + 0.05 \times \textit{Wall column continuity}
\end{aligned} \tag{1}
$$

Scores of the other three factors were estimated similarly using the weights mentioned above (see Fig. 1). The Total Vulnerability Score (TVS) was then estimated using Eq. (2) as follows:

$$\begin{aligned} TVS = {} & 0.2 \times Workmanship\ and\ age\ factor + 0.2 \times Geometry + 0.5 \times Structure \\ & + 0.1 \times Seismic\ components \end{aligned} \tag{2}$$

The total vulnerability contribution by the structure factor is given by Eq. (3):

$$\begin{aligned} Structure\ factor = {} & 0.3 \times floor\ structure + 0.2 \times roof\ \ structure + 0.5 \\ & \times wall\ or\ frame\ structure \end{aligned} \tag{3}$$

Contributions of floor, roof, and wall/frame component to the overall score are calculated separately as:

$$Floor\ structure = 0.5 \times floor\ type + 0.5 \times floor\ connection \tag{4}$$

Similar equations were used for roof structure and wall or frame structure considering their corresponding weights. A detailed overview of relative and absolute weights of different subcomponents is also shown in "Appendix".

As seismic components were rare in the inspected buildings, lesser weight was assigned to this factor. The TVS is subsequently modified using two parameters. The first is the risk of structural pounding which, if present, increases the overall score by 10%. The second is the retrofitting component, which, if present, decreases the score depending on the type of retrofitting. After these modifications, the Final Vulnerability Score (FVS) was obtained for each building. The final scores were then divided by 4 so that the normalized scores lie in the range 0–1. Thereafter, qualitative vulnerability levels corresponding to different ranges of values of FVS were defined. This definition, as for any qualitative scale, carries with it a certain degree of subjectivity. The levels described here were based on observations of damaged buildings. The descriptions of expected performance at different levels of shaking for each of these vulnerability levels is provided in Table 1. A limitation of descriptions is that they only provide a rough estimate of actual performance of buildings. This is due to lack of data detailed data on shaking intensity and a detailed quantitative estimate of damage. It is therefore expected that the vulnerability levels and their descriptions presented will need to be improved when more detailed data becomes available, for example after future earthquakes in the study area and other similar regions. It is also noted that none of the buildings studied in this work was classified in the 'Very low' class and therefore the description/designation of this class is based on expected performance rather than observed damage. Weights of the factors and sub-factors were adjusted in several trials in many case study buildings.

After the initial design of the vulnerability assessment method, several field visits were conducted to adjust the weights of the different factors and sub-factors. Different types of school buildings were covered in these field inspections. Similarly, mock assessments were conducted by the developers, practitioners, and experts to assure the reliability of the method. Three expert structural engineers having prior experience on seismic vulnerability assessment and numerical modeling of structures conducted field assessment of each type of building and the scores obtained from surveyors were tallied and adjusted. Furthermore, the weight for each component was also reviewed by the experts. Experience from damage caused by past earthquakes reported in the literature (see e.g. Gautam et al. 2016; Rupakhety et al. 2016; Ahmad et al. 2012a, b; 2014; Ali

Table 1 Correspondence between vulnerability score and vulnerability class. Moderate, strong and very strong shaking refer to PGAs of 0.1 g, 0.4 g, and 0.6 g, respectively

Vulnerability score	Vulnerability class	Description
0–0.17	Very low	No severe damage expected even at very strong shaking, some minor damage to infill walls and non-structural components might occur at strong to very strong shaking
0.17–0.34	Low	Most buildings are not damaged, some suffer minor non-structural damage at moderate to strong shaking but no structural damage at strong to very strong shaking
0.34–0.49	Moderate	Many buildings suffer minor non-structural damage at moderate shaking, many buildings suffer serious damage to infill walls at moderate shaking, few buildings suffer structural damage at strong shaking, no collapse at very strong shaking
0.49–0.59	High	Some buildings suffer major structural damage at moderate shaking, infill walls are severely damaged at moderate shaking, widespread non-structural damage at moderate shaking, some buildings partially collapse at strong shaking, many buildings need extensive repair/retrofit after moderate to strong shaking
0.59–1	Very high	More frequent major structural damage at moderate shaking, many buildings are near collapse at strong shaking, severe and widespread damage to infill walls and non-structural components at moderate shaking, many buildings need to be replaced after moderate shaking

et al. 2013) were helpful in assigning and refining the weights assigned to the different factors and sub-factors discussed above.

4 Results and discussion

The newly developed seismic vulnerability assessment framework was used to assess 3389 school buildings from 14 districts in central Nepal. Buildings were classified as reinforced concrete construction (RC), load bearing (LB), steel frame (SF), and timber frame (TF), which respectively constitute 968, 786, 1458, and 177 samples. Figure 2 shows types of buildings considered for the development and implementation of the newly proposed vulnerability assessment framework. The final vulnerability score was computed for each building and converted to a qualitative vulnerability level ranging from very low to very high as shown in Table 1.

The percentage of different building types in each of the 5 qualitative vulnerability classes is shown in Fig. 3. About 85% of buildings are in moderate vulnerability class or higher. None of the RC building is in very high vulnerability class. School buildings should have more stringent and continuous quality control and therefore better seismic performance than common residential buildings. Vulnerability of school buildings studied in this study seems to be high despite their need to be resilient to seismic action. The classification shows that, as expected, LB buildings are more vulnerable than RC buildings. About 30% of LB buildings have high seismic vulnerability. More than 95% of such buildings are classified in the moderate to very high vulnerability classes. The vulnerability of SF (steel frame) and RC buildings is similar except that slightly more of the former lie in high vulnerability class. Steel frame constructions were improved after the 1988 earthquakes in Nepal. Although the structural systems in such buildings are robust, other factors such as stone masonry infill walls increase their overall vulnerability score. All the TF (timber frame) buildings are classified in moderate and high vulnerability classes. It should be noted that the number of TF buildings analyzed in this study is limited. Although timber frame constructions are generally known to have better seismic performance than other constructions (see, for example, Bessason et al. 2020; Rupakhety et al.

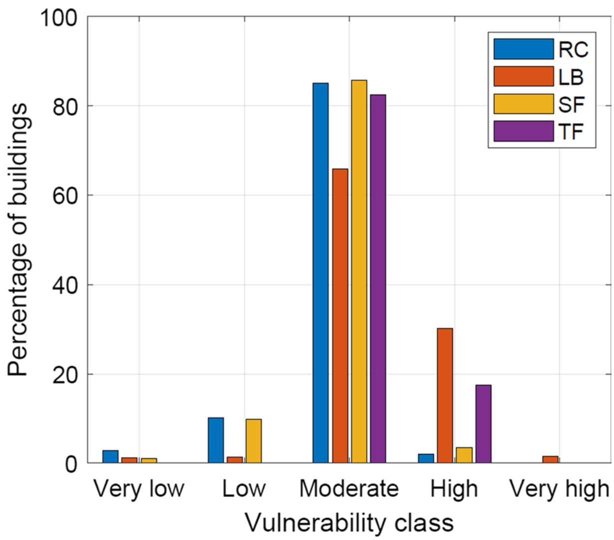

Fig. 3 Percentage of different building types in each of the five qualitative vulnerability classes used in this study

2016; Gautam et al. 2016), such constructions in the study area have deficiencies such as inadequate ductile detailing of joints and lack of other anti-seismic measures. The overall results show that a large proportion of school buildings could sustain significant damage during moderate or strong earthquakes. This could result in severe disruption of school activities, and in the worst cases serious injuries or fatalities if an earthquake occurs during school hours.

The proposed vulnerability scores are compared with the damages observed in the school buildings affected by the 2015 Gorkha Earthquake and its aftershocks. PGA at each of the buildings is estimated from the USGS Shakemap (United States Geological Survey 2017). An estimate of damage sustained by each of the buildings is made from the descriptions of damage collected during field surveys. The damage is quantified by damage ratio (DR) which varies from 0 for no damage to 1 for complete loss. Based on field observations and qualitative description of damage obtained from the survey forms, each building is assigned a DR. In an ideal scenario, for a given ground shaking, DR of a building should positively correlate with its vulnerability score. Deviations from this ideal behavior can be expected in practice due to lack of volume and quality of data. For example, the PGA estimated from Shakemap provides only a crude approximation of the actual shaking experienced by a building, and this parameter is known to be associated with large spatial variability even within small distances and is not very strongly correlated with damage (see, for example, Rupakhety et al. 2016). The other source of uncertainty lies in the estimated damage ratios. Since the estimates are based on approximations inferred from qualitative descriptions of damage rather than detailed engineering calculations, they lack in resolution and accuracy. Due to these factors, it is not meaningful to expect positive correlation between DR and vulnerability index (VS) of individual (or a few) building(s) located in a close vicinity. Nevertheless, on the average, buildings with higher VS should experience higher damage than those with lower VS when subjected to the same PGA. We investigate such dependence using data from 1047 damaged buildings of different typologies used in this study. PGA at these buildings are estimated to be in the range of 0.04–0.72 g. Most of the data comes from buildings with estimated PGA of 0.12 g, 0.28 g, 0.32 g, and 0.6 g, with respective frequencies of 158, 105, 352, and 55. Buildings exposed to each of these PGA values were grouped into different bins based on their DR. The mean DR and VS in each bin are then investigated separately for each of the PGA values. The results of this investigation are shown in Fig. 4. For each of the PGA values, buildings assigned higher VS proposed in this study sustained, on the average, higher damage. The Pearson correlation coefficient between DR and VS is 0.95, 0.89, 0.97, and 0.83 for buildings exposed to PGAs of 0.12 g, 0.28 g, 0.32 g, and 0.6 g respectively. These correlations are statistically significant at 5% confidence limit for 0.12 g and 2% confidence limit for 0.32 g PGA bins. The confidence limits for 0.28 g and 0.6 g bins, which contain fewer data, were higher at 11% and 17%. This might imply that the correlation is not statistically significant, but this observation needs to interpret with caution because the number of observations in these PGA bins is few.

5 Discussion and conclusions

Following the 2015 Gorkha earthquake in Nepal, an extensive field survey of school buildings was carried out in central Nepal. Based on the patterns and severity of damage observed during the field surveys, a new framework to assess seismic vulnerability of such buildings is proposed in this study. Vulnerability assessment in the proposed method is based on four main factors, viz., workmanship and age, geometry, structure, and seismic components. These four factors are subdivided into 30 other sub-factors

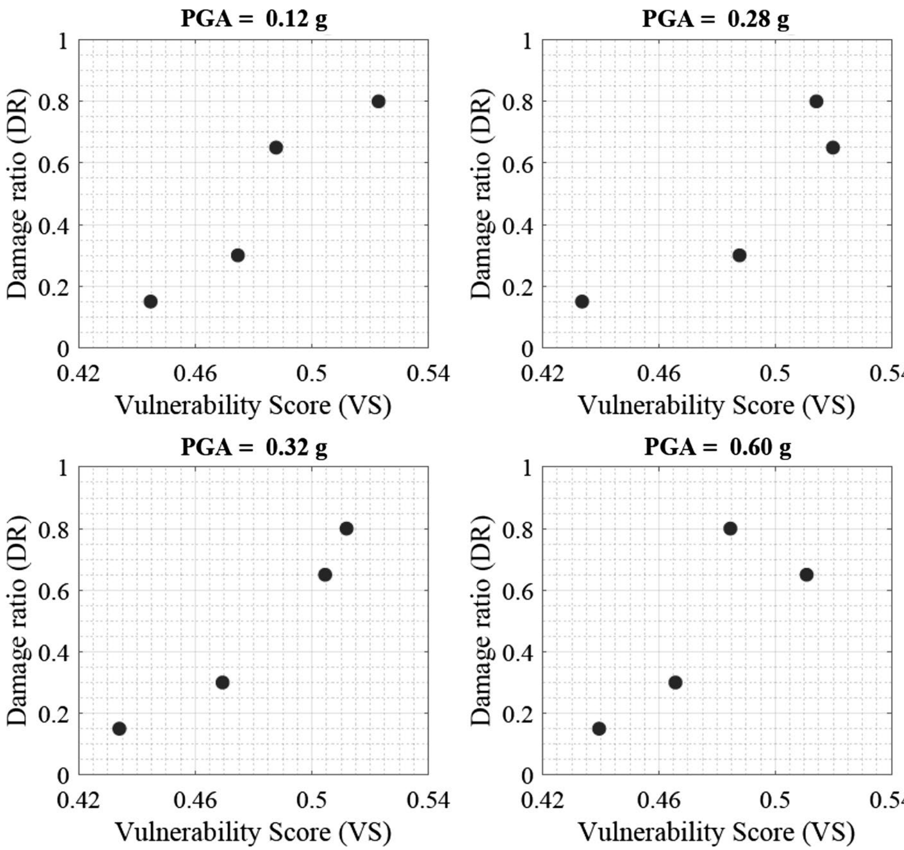

Fig. 4 Comparison between VI and DR of buildings damaged the 2015 Gorkha earthquake and its aftershocks

and scores in the range of 1–5 are assigned to each of them. A weighted sum of the vulnerability scores of the different sub-factors is defined as the total vulnerability score. Vulnerability modifiers are used to account for the risk of pounding and the presence of anti-seismic features. The modified total vulnerability is called the final vulnerability score, which lies in the range of 0–1.

The results show that most of the buildings are moderate to highly vulnerable. Damage data obtained from field surveys show that moderate to high vulnerability implies damage ratios in the range of 0.15–0.8 for PGAs in the range of 0.12–0.8 g. Even for ground shaking as moderate as PGA of 0.12 g, some of these buildings were found to sustain DR up to 0.65. Such high DR is due to partial damage to structural systems. Lower DR corresponding to minor damage to structural elements and significant damage to non-structural infill walls were more frequent. Although these types of damages do not necessarily cause the building to collapse, they can result in serious harm by seriously or even fatally injuring the building occupants. Moreover, these types of damages can result in loss of function of the building, which results in interruption of school activities.

A large proportion of timber frame buildings were found to have moderate to high vulnerability. Their vulnerability is associated more with inadequate connection between structural elements and fragility of non-structural elements such as infill walls rather than weakness of the structural elements. Even in case of steel frame buildings with robust structural elements connected properly, seismic vulnerability is moderate to high due to fragilities of infill walls and other non-structural elements. The overall results indicate an urgent need for improving seismic performance of school buildings in Nepal, not only from the perspective of structural performance, but also in terms of behavior of non-structural elements, in particular the commonly used heavy stone masonry walls, which pose grave threat to the building occupants.

The VS assigned to the school buildings were compared to damage sustained by these buildings due to ground shaking caused by the 2015 Gorkha earthquake and its aftershocks. Strong positive correlation exists between damage ratio and vulnerability score of buildings exposed to similar levels of PGA. The correlation was found be to statistically significant in most cases where sufficient data for statistical inference is available. This shows that the vulnerability scores assigned by the proposed framework in a good indicator of the actual vulnerability of school buildings in the study area.

The proposed methodology can be implemented quickly for a large population of buildings and is therefore useful for rapid vulnerability assessment of the building stock. Such assessments are useful for risk assessment, identifying weaknesses, and planning mitigation measures for earthquake disaster risk reduction. The proposed vulnerability is not intended to provide an accurate estimate of the actual vulnerability of a building type, but it provides a good classification of different building classes for overall planning of disaster mitigation activities. The proposed VS is not a quantitative measure of seismic vulnerability required for detailed seismic loss estimation. However, the proposed VS is based on similar principles as the Vulnerability Index (VI) used in the Vulnerability Index Method which is one first level of seismic risk assessment method in urban areas outlined in the RISK-UE project (Mouroux and Brun 2006). The VS, like the VI, can be converted, through empirical evidence, to expected damage conditioned on ground shaking intensity (see, for example, Ródenas et al. 2018). The volume, spatial density, and detail of damage data available in the study area is not sufficient yet for such applications. It is therefore essential to collect more detailed damage data after future earthquakes. The proposed study, in this sense, is the first step towards quantitative vulnerability description of school buildings in Nepal. The school building types covered in this study represent more than 90% of existing school buildings in Nepal. Due to similarities in construction systems, workmanship, and quality, the method developed in this study is expected to be useful throughout the country. This method could also be adapted to buildings in Bhutan, India, Pakistan, and Afghanistan as they share many common features in their construction systems and materials. Collection and sharing of ground shaking and damage data from future earthquakes in these areas will be crucial for further advancing the proposed method for quantitative seismic loss/risk assessment.

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Appendix

See Table 2.

Table 2 Vulnerability assessment checklist

Components	Component weight (%)	Sub-component	Sub-component weight (%)	Elements	Element relative weight (%)	Absolute element weight (%)	Vulnerability score (1–5) for elements					N/A
							1	2	3	4	5	
Workmanship and age	20			Building age	15	3	Post-code		By-laws		Pre-code	3
				Modification	20	4	= {0.5 × (Is addition of story) + 0.3 × (Is extension in plan?) + 0.2 × (Is change in occupancy?)} × 5					3
				Masonry deterioration	20	4	No				Yes	4
				Mortar deterioration	20	4	No				Yes	4
				Concrete deterioration	10	2	No				Yes	4
				Overall quality of construction	15	3	Very Good	Good	Regular	Poor	Very Poor	4
Geometry	20			Plan characteristics	15	3	Rectangular-compact		Rectangular long; Enclosed Courtyard	C, T, Other shaped	L-shaped	4
				Vertical irregularity	20	4	No weak or soft story			Soft story	Weak story	3

Table 2 (continued)

Components	Component weight (%)	Sub-component	Sub-component weight (%)	Elements	Element relative weight (%)	Absolute element weight (%)	Vulnerability score (1–5) for elements					N/A
							1	2	3	4	5	
				Short/captive column	10	2	No				Yes	4
				H/B ratio	15	3	≤ 1		$> 1; \leq 2$	$> 2; \leq 3$	> 3	4
				L/B ratio	10	2	≤ 2		$> 2; \leq 3$	$> 3; \leq 4$	> 4	3
				No. of stories	15	3	1		2	3	≥ 4	
				Load path regularity	10	2	Regular				Irregular	3
				Wall/column continuity from foundation to roof	5	1	All continuous				Not continuous	3
Structural	50	Floor structure	30	Floor type	50	7.5	OR (Single story, RC Slab)	OR (RC-Brick; Flexible with in-plane Bracing)		OR (Flexible without in-plane bracing, Other)		3
				Floor connection	50	7.5	OR (Single story, Fully Embedded)	OR (Bolted, Partially Embedded)	Other	Sits on Masonry		4

Table 2 (continued)

Components	Component weight (%)	Sub-component	Sub-component weight (%)	Elements	Element relative weight (%)	Absolute element weight (%)	Vulnerability score (1–5) for elements					N/A
							1	2	3	4	5	
		Roof structure	20	Shape of roof	5	0.5	Flat	Double Pitch	Other	Single Pitch		3
				Roofing structure	30	3	OR (RC Slab, Metal Truss with bracing)	OR (Metal Truss without in-plane bracing, Timber Truss with in-plane bracing)	OR (Timber truss without in-plane Bracing; Other)	Timber Joists Only		3
				Roofing material	20	2	CGI		Other	Slates/Clay Tiles		3
				Roof-floor connection	30	3	OR (Bolted, Fully Embedded)	Anchored to Wall	OR (Partially Embedded; Strapped)	Other		3
				Parapets (h/t ratio)	10	1	≤ 6	$> 6; \leq 9$	$> 9; \leq 12$	$> 12; \leq 15$	> 15	1
				Unanchored pediments	5	0.5	No				Yes	1

Table 2 (continued)

Components	Component weight (%)	Sub-component	Sub-component weight (%)	Elements	Element relative weight (%)	Absolute element weight (%)	Vulnerability score (1–5) for elements					N/A
							1	2	3	4	5	
		Wall/ frame structure	50	Wall type	30	7.5		Hollow Concrete Block	Brick in Cement	OR (Brick in Mud, Stone in Cement, Other)	Stone in Mud	4
				H/t ratio	25	6.25	≤ 6	$> 6; \le 9$	$> 9; \le 12$	$> 12; \le 15$	> 15	1
				L/t ratio	15	3.75	≤ 18		$> 18; \le 36$		> 36	1
				Opening extent	20	5	$\le 20\%$	$> 20\%; \le 30\%$	$> 30\%; \le 40\%$	$> 40\%; \le 50\%$	$> 50\%$	3
				Wall connected to each other	5	1.25	Yes				No	3
				No. of bays	5	1.25	≥ 2	< 2				3
Seismic components	10			Seismic enhancements (e.g. Bands, through stone, etc.)	50	5	Available				Not Available	3
				Vertical band / reinforcement	50	5	Available			Not Available		3
Total score						100						

Table 2 (continued)

Components	Component weight (%)	Sub-component	Sub-component weight (%)	Elements	Element relative weight (%)	Absolute element weight (%)	Vulnerability score (1–5) for elements					N/A
							1	2	3	4	5	
Multiplicative Modifiers	100	Seismic pounding	100	Drift Space (Ration of Gap to Height) [If result is more than 100%, take 100%]		×1.1	≤0.2%	>0.2%; ≤0.4%	>0.4%; ≤1%	>1%; ≤4%	>4%	2.5
Overwrite modifier	100	Retrofitting	100	Type of previous retrofitting [If existing value is more than the overwritten value, existing value is adopted]		100	0.99	0.59	0.49	0.34	0.17	0.99
Final Vulnerability Score (FVS)				0–100%								

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