

Site-Specific Vulnerability Assessment of Buildings Exposed to Rockfalls



Aditi Singh, Shilpa Pal and D. P. Kanungo

Abstract A landslide is one of the most common hazards occurring in mountainous region in response to a number of natural and anthropogenic processes. In particular, South Asian nation including India is the worst hit by landslides. Thus the vulnerability assessment towards landslides becomes an important aspect, as it pose risk to human life, environment, buildings, and infrastructures. From the perspective of natural and engineering sciences, vulnerability is defined as the degree of loss, or damage to a set of element at risk within the affected area due to landslides. It acts as a primary component in the evaluation of landslide risk, and its accurate estimation is necessary in making a reasonable prediction of the landslide consequences. The present paper aims to produce a framework for assessing the physical vulnerability of building exposed to rockfall using the empirical formula proposed by Li et al. (Landslides 7(2):125–134, 2010 [3]) in terms of resistance offered by building and the intensity of rockfall. The proposed methodology permits to obtain an estimate of vulnerability of buildings when hit by three different intensities (low, medium and high) of rockfall. Finally, application of this proposed framework is illustrated through a case study from Chamoli district, Uttarakhand (India).

Keywords Landslide · Rockfall intensity · Resistance factor
Physical vulnerability

1 Introduction

Landslide are the most common natural hazards affecting large parts of India, especially the Himalayas, the Northeastern ranges, the Western Ghats, the Nilgiris, the

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Eastern Ghats and the Vindhyas. The most vulnerable to landslides are the Himalayas and Western Ghats regions. Therefore, the built-up areas in these regions are also affected by landslides on a variety of spatial and temporal scales [1]. The damage to built environment such as buildings and other vital infrastructures (bridges, dams, etc.) due to the occurrence of rapid landslides (e.g., debris flow) and generally rock-falls can be most severe causing complete destruction of buildings within the affected area. Slow-moving slides may also lead to damaging impact in the affected area [2].

Therefore, it is necessary to consider a methodology that analyzes the magnitude of damage due to landslide occurrences in order to assess the consequences of landslide impact on humans and their activity since the methodologies to assess a building's vulnerability subjected to rockfalls are scarce. Therefore, a framework has been proposed for assessing the vulnerability of buildings exposed to rockfall based on the empirical formula proposed by Li et al. [3]. The present paper focuses on the previously developed methodology to assess physical vulnerability of buildings in the mountainous region using rockfall intensity and the resistance offered by building has been done. Li et al. [3] proposed a quantitative model for vulnerability of structures based on landslide intensity and the resistance of exposed elements, but the developed model was limited to only debris flow type of movement. To overcome this limitation, a new methodology has been proposed specifically for rockfall type, to study the impact of different intensities on the buildings. Further, the methodology has been illustrated by studying six buildings located on Chamoli district of Uttarakhand state.

2 Vulnerability of Buildings Due to Rockfall Impacts

A rockfall is generated by the detachment of a rock volume from the slope that falls, rolls, and bounces along its trajectory and may occur singly or in clusters. Rockfalls can be very destructive due to high velocities and there high energies that can reach during their downslope propagation [4]. Nevertheless this loss can vary for small to medium-sized events. Thus, the houses, roads, and bridges constructed in mountainous areas which are exposed to the danger of rockfalls may suffer from significant structural and non-structural damage. Although many methods exists for the analysis of the stability of rocky slopes [5], but the vulnerability assessment of buildings due to rockfalls is poor through empirical relations which results in uncertain loss predictions [6]. Empirical evaluations are mostly quantified without differentiating between typological classes for assessing rockfall vulnerability [1, 7]. Mavrouli and Corominas [8, 9] and Mavrouli et al. [10] presented a method for the assessment of vulnerability of reinforced concrete (RC) buildings. However, these results cannot be generalized and transferred to different structural typologies from the studied ones, as the structural performance of a building depends on various factors such as geometry, materials, and the load-bearing system of the elements.

Heinimann [11] and Uzielli et al. [12] presented a vulnerability value for buildings at regional scale according to the typology. Dai et al. [13] proposed a general frame-

work for the classification of the physical vulnerability of buildings to landslides, at a global and site-specific scale, taking into account their individual characteristics (such as age, nature, and type). The methodology requires past event data for the statistical analysis. During the Fiumelatte event, Agliardi et al. [7] proposed a vulnerability function for rockfalls based on observations and back analysis of the damage of individual buildings.

Several rockfall events in Andorra have been reported by Corominas et al. [14, 15], during one such event of 1997, a block of 25 m³ volume penetrated the slabs of a residence building, ending down to its basement. Further, the building did not suffer any extensive damage. Another such event occurred in 2004, Segovia, Spain, when boulders fell on the roof of the Fuencisla Sanctuary [16]. Additionally various events of landslide have been registered at Hong Kong [17], Canada [18] and United States [19, 20]. Since, empirical or heuristic approaches for the quantification of the vulnerability, requires historical recorded data for rockfalls, which are rarely available. Implementation of numerical and analytical models can be an appropriate alternative for the quantification of vulnerability.

3 Description of Method

According to UNDP/UNESCO 1982 [21], four main groups of methods exist for assessing the level of vulnerability of a structure: (i) categorization methods, which is based on the typological classification of structures into typological classes; (ii) inspection and empirical (rating) methods, where numerical value is attributed to each structure; (iii) analytical methods, based on the analysis of a structure depending on the resistance offered at an hazard event; and (iv) experimental methods, includes tests for the determining the structural properties of the whole structure and its components. In this study, a framework has been developed taking into account method (i), (ii) and (iii). These three methods are integrated together to assess site-specific vulnerability of buildings exposed to rockfall.

The very first step is to categorize different typologies of building. Since, every country follows their unique structural typology, construction material, and construction techniques depending on the geomorphological and geological conditions of that particular area. In India, the most common type of structural typology in Himalayan region is reinforced concrete, brick masonry and stone masonry. Second step involves the inspection of the structure and then assigning numerical value to each structure using rating (empirical) methods, therefore the buildings are first inspected and then numerical value is assigned based on the rating scheme developed. In the third step, resistance of buildings is calculated using an empirical formula. Finally, by integrating all three steps vulnerability of the buildings is calculated.

4 Proposed Framework to Assess Vulnerability of Buildings Exposed to Rockfall

Taking into account the previous work of Li et al. [3], a framework has been proposed to assess the building (physical) vulnerability exposed to rockfall. Li et al. [3] defined physical vulnerability (PV) as a function of landslide intensity (I) and resistance ability (R) of the buildings to withstand the threat. The modified equation is given as follows:

$$PV = f(I, R) = \begin{cases} 2 \frac{I^2}{R^2} & \frac{I}{2} \leq 0.5 \\ 1 - \frac{2(R-I)^2}{R^2} & 0.5 < \frac{I}{R} \leq 1.0 \\ 1.0 & \frac{I}{R} > 1 \end{cases} \quad (1)$$

where I is the rockfall intensity, R is the resistance of the buildings exposed to rockfall. Physical vulnerability (PV) is non-dimensional and quantified on the scale of 0 (i.e., no loss) and 1 (i.e., total loss or complete destruction). During rockfall the building might experience some structural and non-structural damages and the impact may vary depending upon the intensity and resistance offered by the building.

4.1 Rockfall Intensity

There are several parameters to quantify magnitude such as velocity, volume, depth, run-out, and area extent to quantifying the magnitude of a landslide. However, it is considered that there is one magnitude value for a landslide event, but infinite intensity values. For example impact energy, average velocity, or depth of potentially erodible soil zones can be used to express intensity [22]. For simplification, in this study intensity values have been proposed on the scale of 0 and 1 based on the scheme developed by Lateltin et al. [17] (who considered rockfall intensity, I parameter in terms of kinetic energy in his study). Hence three levels of intensity are considered in this study as I_1 , I_2 , and I_3 referring to low, medium, and high intensities respectively as shown in Table 1.

Table 1 Proposed values of rockfall intensity

Rockfall intensity	Intensity = I	Kinetic energy, E	Proposed values
Low	I_1	<30 KJ	0.2
Moderate	I_2	30–300 KJ	0.6
High	I_3	>300 KJ	1

4.2 Resistance of Buildings

The resistance of a building reflects its capacity to withstand a landslide action of varying impact [3]. There are several factors (or an indicator) that affects the resistance of a building such as building typology, construction techniques, number of floors, state of maintenance etc. In literature many researchers such as Heinimann [11], Bell and Glade [14], Spence et al. [23], Papathoma-Köhle et al. [6], Zêzere et al. [24], Silva [25] have proposed a wide range of indicators for the resistance of structures.

Hence, in this study four primary structural parameters (or indicators) have been considered and resistance factors have been proposed for each indicator (as shown in Table 2) based on the literature survey.

- (i) *Structural typology*: It is one of the important key factors in assessing vulnerability of buildings exposed to landslides [5]. A post-event survey was conducted in Italy after a catastrophic landslide. The results after survey showed about 60% of the buildings were made of stone and 40% made of masonry were destroyed. However, those made of concrete were not destroyed [13].
- (ii) *Construction quality*: Safety of occupants residing in the building is directly dependent on the construction quality. Construction quality may be hampered due to poor construction practices, low quality material, improper design, or

Table 2 Proposed resistance factor assigned to structural indicators

Structural indicators	Categories	Resistance factors
Structural typology (R1)		ξ_1
	Brick masonry	0.3
	Stone masonry	0.6
	Reinforced concrete	1
State of maintenance (R2)		ξ_2
	Damaged	0.2
	Distressed	0.4
	Good	0.8
	Excellent	1
Construction quality (R3)		ξ_3
	Low	0.2
	Medium	0.5
	High	1
Number of floor(s) (R4)		ξ_4
	3	1
	2	0.5
	1	0.2

poor workmanship. Therefore it is an important parameter for assessing physical vulnerability [1].

- (iii) *State of maintenance*: It is another important parameter for all the structural and non-structural components. Since it provides resistance to buildings in reducing the impact of landslides. In this study, state of maintenance is expressed in five classes as: very poor, poor, medium, good, very good.
- (iv) *Number of floors*: The number of floors (or storeys) in a building also plays a crucial role in deciding the response of buildings to landslides. In the Indian Himalayas, the maximum three floors of buildings are observed. Hence, in this study three different floors were distinguished as Ist Floor, IInd Floor, and IIIrd Floor. Here, in case of rockfall we assumed that the top-most floor of the building will suffer more damage due to the impact of unstable fragments of rocks than those having two or more floors. However, in case debris flow which can be rapid landslides, taller buildings having three or more floors are likely to suffer less damage than low-rise buildings (i.e., one floor). This is due to the fact that intrusion of material in low-rise building is easy through the openings than in the high-rise buildings.

Thus resistance of the buildings exposed to landslide can be quantified using the empirical formula used in the study by Li et al. [3], as shown in Eqs. 2 and 3.

$$R = \left(\prod_{i=1}^{n_s} \xi_i \right)^{1/n_s} \quad (2)$$

where resistance factors are expressed as ξ_i which is a non-dimensional quantity; ξ_i is the i th of $n_s \geq 1$, contributing to the definition of various parameters used in the study.

Hence, the resistance of buildings (R) based on these four parameters can be quantified as follows:

$$R = (\xi_1 \cdot \xi_2 \cdot \xi_3 \cdot \xi_4)^{1/4} \quad (3)$$

5 Case Study

The application of the modified methodology has been illustrated by analyzing physical vulnerability of six buildings in the Chamoli district (Uttarakhand, India). Figure 1 shows an assumed landslide scenario in the Gopeshwar Township of Chamoli district, which is prone to rockfall type of landslide. At first the buildings exposed to rockfall (highlighted in blue color) in the study area were inspected and then the resistance rating is assigned to each indicator based on their severity. Four structural indicators namely structural typology (R1), state of maintenance (R2), construction quality (R3) and number of floors (R4) having resistance factors ξ_1 , ξ_2 , ξ_3 , and ξ_4 respectively were recorded during survey of each building to assess their total resistance. Each

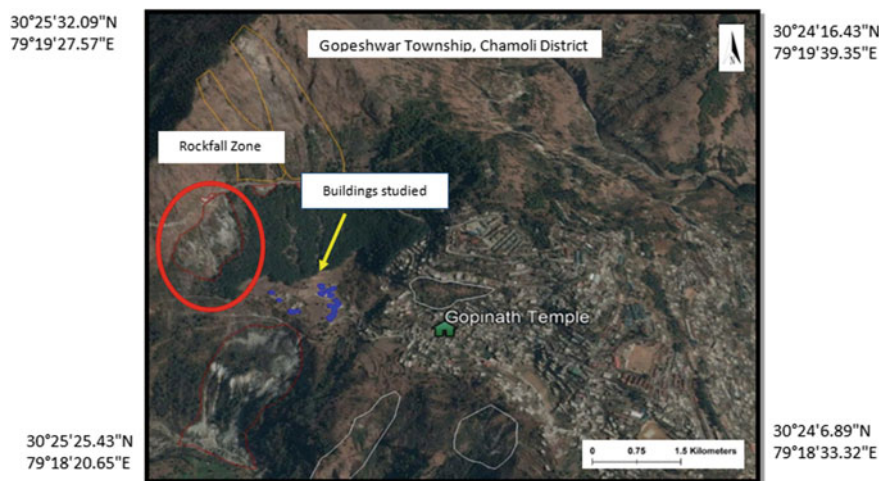


Fig. 1 Study area showing the rockfall zone and the buildings studied (highlighted in blue color) for assessing the physical vulnerability

Table 3 Resistance factor of buildings obtained from the study area

Building ID	ξ_1	ξ_2	ξ_3	ξ_4	Resistance, R
1	1	0.8	1	0.5	0.80
2	0.3	0.8	0.5	0.5	0.49
3	0.6	0.2	0.2	1	0.39
4	1	0.8	0.5	1	0.80
5	0.6	0.2	0.2	1	0.39
6	0.6	0.2	0.2	1	0.39

Table 4 Physical vulnerability of the buildings for three different rockfall intensities (PV1—at low rockfall intensity; PV2—at medium rockfall intensity and PV3—at high rockfall intensity)

Building ID	Resistance R	PV1	PV2	PV3
1	0.80	0.13	0.88	1
2	0.49	0.33	1	1
3	0.39	0.53	1	1
4	0.80	0.13	0.97	1
5	0.39	0.53	1	1
6	0.39	0.53	1	1

building under study was assigned a building ID and resistance factor corresponding to each parameter and the total resistance of the building, thus obtained is shown in Table 3. The total resistance of the building is calculated using Eq. 3.

Further, the results of physical vulnerability (shown in Table 4) of each building at three different intensities is obtained using Eq. 1.



Fig. 2 Resistance of six buildings considered in the study area

6 Conclusion and Discussion

The potential physical loss of buildings when they are affected by large moving masses of debris or rock fragments of some intensity is referred to as physical vulnerability of buildings. Relatively limited methodologies exist based on analytical approach for the quantifying physical vulnerability of buildings (in context to its resistance and intensity) which are subject to actions due to unstable slope and landslides when compared to other components of quantitative landslide vulnerability assessment [19]. In this paper, a framework has been proposed for assessing the physical vulnerability of buildings exposed to three different intensity of rockfall. The resistance of the buildings plays a significant role in reducing the impact of rockfall, since stronger structures (in context to appropriate structural typology, good state of maintenance and construction quality, etc.) will lead to comparatively less damage in case of landslide. Therefore, the proposed framework has been illustrated by studying six buildings in the rockfall zone. The output of the weighted vulnerability ranges from 0 (i.e., no loss) to 1 (i.e., complete loss).

To test the proposed framework six buildings exposed to rockfall zone were analyzed. The resistance of the buildings was determined after field survey and physical vulnerability is quantified at three different intensities. Figure 2 shows the resistance of each building and Fig. 3 shows the physical vulnerability (PV) of buildings exposed to rockfall at three different intensities (PV1: physical vulnerability at low intensity, PV2: physical vulnerability at medium intensity and PV3: physical vulnerability at high intensity). From the results, it is observed that as the rockfall intensity increases, there is an increase in vulnerability of buildings. However, it must be noted that the vulnerability may be reduced if higher resistance is offered by structural indicators to the buildings.

Thus, the vulnerability of buildings in rockfall prone areas provides an objective parameter from the perspective of cost–benefit analysis for the protection interventions. The proposed vulnerability assessment framework is designed to be applied

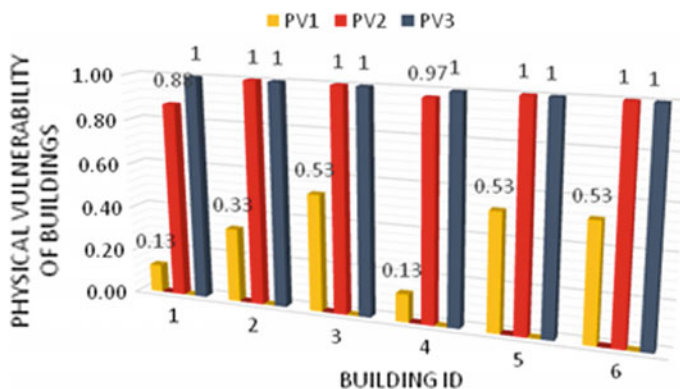


Fig. 3 Plots showing physical vulnerability (PV) of buildings exposed to rockfall at three different intensities (PV1: physical vulnerability at low intensity, PV2: physical vulnerability at medium intensity and PV3: physical vulnerability at high intensity)

on a site-specific scale in areas affected by rockfall activity (from low to moderate) by assessing vulnerability of each and every building (individually), in the case of a single block impact on it. However, in this study only four structural indicators are included, for calculation of resistance. In the future work, more structural parameters need to be included to determine the overall resistance offered by the buildings.

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