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Quantifying the Potential Benefits of Some Risk-mitigation Strategies on Future Seismic Losses in Kathmandu Valley

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ABSTRACT

Risk-mitigation measures have been shown to significantly reduce structural damage and casualties in various regions worldwide. However, these benefits remain unknown or improperly quantified for potential future events in some hazard-prone areas such as Nepal, which this paper addresses. The work specifically investigates the effect of hard mitigation measures (that influence physical vulnerability) on future financial and human losses in Kathmandu Valley, Nepal. The analysis involves a replicate of the 2015 Gorkha earthquake (Mw 7.8) scenario, which is combined with three different exposure inventories representing different development trajectories that Kathmandu Valley could experience in the next 10 years. The results show that under a "no change" pathway for 2031 (Scenario B), where the quality of the building stock remains the same as in 2021 (Scenario A), financial losses and fatalities will increase by 19% and 24%, respectively. In contrast, a gradual improvement of the building stock's quality for 2031 (Scenario C) will decrease financial losses and fatalities by 12% and 50%, respectively. Moreover, the largest fatality rates in all scenarios are associated with the low-income population. The main findings of this paper can be used to inform decision-makers about the benefits of investing in forward-looking seismic risk-mitigation efforts.

Introduction

Nepal is one of the most seismically active countries due to its location on the Main Himalayan Thrust that is the world's largest active continental megathrust fault. Consequently, Nepal has experienced several earthquakes with large magnitudes over the past years, some of which has produced devastating losses in Kathmandu Valley [1]. The 2015 Gorkha earthquake (moment magnitude, Mw, 7.8) – the country's strongest event since the 1934 Bihgar-Nepal Earthquake (Mw 8.1) – caused over USD 7 billion in economic losses, 9,000 deaths, and 22,300 injuries across the country [2]. This recent event highlighted the destructive effects of high exposure to seismic hazard coupled with a vulnerable population and building stock.

The 2015 Gorkha earthquake emphasized an urgent need to promote and enforce effective urban planning, building codes and seismic retrofitting programs in Nepal. These risk-mitigation measures have

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proved to significantly reduce earthquake fatalities and damage in the United States, New Zealand and Japan [3]. However, building codes are poorly enforced in Nepal and, despite some successful experiences, there are still challenges with implementing large-scale retrofitting programs [4], partially because the resulting benefits are not well understood/quantified by various stakeholders. Additionally, haphazard urbanization is creating densely populated and poorly designed urban areas, leading to increased exposure and vulnerability [5]. For instance, Kathmandu Valley is among the fastest-growing metropolitan areas in South Asia [6], with a current population of 3.3 million and a future population projected at 3.8 million by 2031 [7]. Therefore, it is essential to quantify the benefits of appropriate mitigation efforts on growing seismic risk in urban areas, for informing and promoting risk-sensitive decision making. This study contributes to the required effort by performing a scenario-based seismic loss estimation for Kathmandu Valley, considering three potential present and future exposure and vulnerability scenarios.

Data and methods

Kathmandu Valley encloses the entire Bhaktapur and Kathmandu districts and approximately 50% of the Lalitpur district. Each district contains several village development committees (VDCs). Three different exposure scenarios are developed for this analysis, based on the National Population and Housing Census 2011 [8] and various assumptions on the estimated population and number of households for 2021 and 2031. The proposed scenarios represent different urban development trajectories for the valley in terms of building code compliance for new buildings, seismic retrofitting efforts, and the prevalence of varying building types. Seven building typologies are used in the exposure scenarios: adobe (A), brick/stone masonry with mud mortar (BSM), brick/stone masonry with cement mortar (BSC), wood (W), current construction practices reinforced concrete (RC-CCP), well-designed reinforced concrete (RC-WDS), and reinforced masonry (RM).

Table 1. Summary of exposure scenarios for Kathmandu Valley

	Scenario A	**Scenario B**	**Scenario C**
Year	2021	2031	2031
Population	3,151,741	3,792,232	3,792,232
Number of buildings	789,898	943,606	943,606
Aggregated structural value (€)	17,865,467,250	21,071,950,800	26,182,740,500
Building types	A, BSM, BSC, W, RC-CCP, RC-WDS	A, BSM, BSC, W, RC-CCP, RC-WDS	W, RC-WDS, RM

The building inventory for Scenario A is developed as follows. Firstly, the 2021 population per VDC is derived from the 2011 census population (per VDC) and the 2021 medium-variant of population projections (per district) reported by the national authorities [7]. It is assumed that the population in all VDCs of the same district grew at a constant rate over the 2011-2021 period. Secondly, the estimated population per VDC is divided by the respective 2011 average household size to obtain the number of households in 2021. Each household is assumed to have a separate building. Thirdly, the population and number of buildings per VDC are further disaggregated in terms of the aforementioned building types, which are defined using the 2011 census data (i.e., type of wall, type of foundation). The 2011 proportion of each building type is multiplied by the 2021 number of buildings to estimate their distributions per VDC.

The building inventories for Scenario B and Scenario C are constructed as follows. Firstly, the 2031 population per VDC is derived from the 2031 medium-variant of population projections (per district) [7] and the 2031 built-up areas (per VDC) forecasted with an urban growth model [9]. Scenario B and C account for the expected spatial differences in urban growth across the valley. Therefore, the population in each VDC is scaled up using distinct scale factors (proportional to its predicted increase in built-up area by 2031) to match the overall projected population in each district. Secondly, the number of buildings per VDC is computed in the same way as Scenario A. The proportion of each building type from Scenario A are also used for Scenario

B, and the number of buildings per building type are estimated in the same way. Scenario C assumes that, over the 2021-2031 period, all unreinforced masonry buildings (i.e., BSM, BSC and A) will be replaced by RM structures and all RC-CCP buildings will be converted to RC-WDS. These transitions represent potential mitigation/seismic retrofitting policies that could be implemented to produce a more earthquake-resistant building stock. Then for each scenario, the aggregated structural costs are calculated using estimates of building area and construction costs for Kathmandu Valley from Chaulagain et al. [10]. The specifications of each scenario are summarized in Table 1.

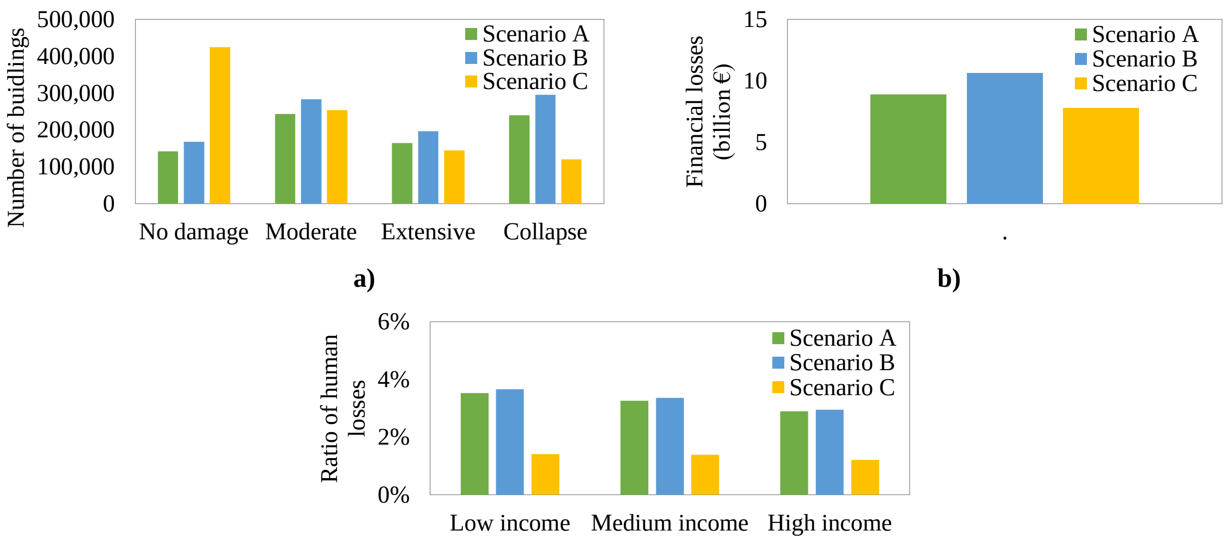
A scenario-based approach (i.e., a specific hazard event scenario) is employed to compute structural and human losses, using the OpenQuake engine [11] developed by the Global Earthquake Model. The selected scenario is a replicate of the 2015 Gorkha earthquake (Mw 7.8). Considering the significant impact of this event on the economic core of the country and its recent occurrence, this scenario was ideal for demonstrating how changes in the building stock could influence financial and human losses due to seismic events in the future. The earthquake rupture is modelled using a complex fault rupture based on the United States Geological Survey (USGS) finite fault representation [12]. Three ground-motion models (GMMs) – Youngs et al. 1997 [13], Atkinson and Boore 2003 [14], and Boore et al. 2014 [15] – are used to simulate ground-motion fields (GMFs) for the study area in an equally-weighted logic-tree approach. These GMMs have been previously employed to characterize subduction interface and active shallow crustal events in Nepal, [e.g., 16,17]. To account for the aleatory uncertainty of the GMFs, 500 realizations of each required intensity measure are simulated with a truncation value of 2 (only 2 log-standard deviations of the ground motion distributions are accounted for). Moreover, site conditions are characterized with a global Vs30 (time-averaged shear-wave velocity to 30-meters depth) USGS database [18] and recent findings from De Risi et al. [19].

Fragility functions for each considered building typology are obtained from various sources. The fragility functions for A, BSM, BSC and W building types are those commonly applied by the National Society for Earthquake Technology of Nepal [10]. The fragility functions for RC-CCP and RC-WDS are acquired from Chaulagain et al. [10]. The fragility functions for RM (moderate code) are provided by FEMA [20]. In most cases, the available fragility functions describe three damage states (i.e., moderate, extensive and collapse). Thus, the RM slight damage state fragility function is excluded, and all RM buildings in the complete damage state are assumed to collapse, for general consistency across all building typologies. The fragility functions are combined with a structural consequence model [10] and a fatality consequence model [20] to estimate financial and human losses. To apply the fatality consequence model, the building types are translated to those provided in FEMA [20] based on similarities in structural characteristics, as follows: A, BSM, BSC are mapped to URML; W is mapped to W1; RC-CCP and RC-WDS are assumed to correspond with C3L; and RM is mapped to RM1L. Finally, populations at the VDC level are classified as low, middle, or high-income [9], to facilitate disaggregation of loss per income level.

Results

The mean statistics on building damage distribution, financial losses and ratio of human losses (disaggregated in terms of income level) are provided in Fig. 1. In addition, a summary of the changes in various mean loss metrics is given in Table 2. The seismic losses estimated in Scenario A are considerable, with nearly € 9 billion in financial losses and 100,000 fatalities. The number of damaged buildings and economic cost for this scenario is comparable with figures from past reports for the 2015 Gorkha Earthquake, [e.g., 21, 22], but a significant discrepancy arises in terms of the number of fatalities (Rafferty et al. [22] reported only 9,000 deaths for this event). This inconsistency can be attributed to various factors, such as the difference in quality/numbers between the 2015 building stock and the assumed 2021 building stock, assumptions made in the loss estimation process, the accuracy of the GMFs, the discrete set of damage states considered, and potential inaccuracies in past reports. However, validation of the obtained loss estimations is not critical; instead, the primary purpose of this study is to measure relative variations in losses between the distinct developmental pathways represented by the three scenarios.

Scenario B and Scenario C have effectively highlighted how “no action” and “gradual improvement” of the building stock could affect seismic risk in Kathmandu Valley. On one hand, Scenario B shows that a larger population can easily lead to greater losses due to earthquakes when risk mitigation is neglected. In this scenario, human losses increased by 23,258 (+24%), and reconstruction costs increased by more than € 1.7 billion (+19%) compared with Scenario A. On the other hand, Scenario C demonstrates that, despite a growing population, better building codes and seismic retrofitting can significantly reduce losses. As a result, there were 47,871 fewer fatalities (-50%) in this scenario and around € 1.1 billion fewer economic losses (-12%) compared with Scenario A. Finally, the three scenarios indicate that the highest fatalities rates are consistently associated with the low-income population.



c)

Figure 1. Mean statistics for the three scenarios on a) building damage distribution, b) financial losses, and c) human losses.

Table 2. Mean loss metrics for Scenario A, and relative changes in these metrics for Scenario B and Scenario C.

	Scenario A	**Scenario B**	**Scenario C**
Human losses	96,544	+ 23,258	- 47,871
Human losses as a proportion of total population	0.031	+ 0.001	- 0.018
Financial losses (€)	8,892,608,772	+ 1,728,570,268	- 1,093,672,282
Financial losses as a proportion of total building structural value	0.50	+ 0.01	- 0.20

Conclusions

This study illustrates the level of the present (2021) and future (2031) seismic risk in Kathmandu Valley, considering a single-event scenario that replicates the 2015 Gorkha Earthquake. Results reveal that building code enforcement and seismic retrofitting plans can significantly reduce building damage, financial losses and human losses in the future relative to equivalent current levels. In addition, these future losses are substantially lower than those that would result in the future if hard mitigation measures were not introduced. These findings are relevant because the benefits of seismic mitigation measures are currently not well understood/quantified by various stakeholders in Nepal. As this paper is focused on a single hazard scenario, future research could investigate other possible events in Kathmandu Valley to provide more robust results. In addition, the uncertainty involved in the characterization of exposure and vulnerability scenarios could also be addressed.

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