SECOND EUROPEAN CONFERENCE ON EARTHQUAKE ENGINEERING
AND SEISMOLOGY, ISTANBUL AUG. 25-29, 2014

EARTHQUAKE LOSS ESTIMATION FOR THE KATHMANDU VALLEY

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ABSTRACT

The capital city, Kathmandu, is the most developed and populated place in Nepal. The majority of the administrative offices, headquarters, numerous historical monuments, and eight World Heritages sites are in the Kathmandu Valley. However, this region is geologically located on lacustrine sediment basin, characterized by a long history of destructive earthquakes. The past events resulted in great damage of structures, losses of human life's and property, and interrupted the social development. Therefore, earthquake disaster management is one of the most serious issues in highly seismically active regions such as the Kathmandu Valley. In recent years, the earthquake risk in this area has significantly increased due to uncontrolled development, poor construction practices with no earthquake safety consideration, and lack of awareness amongst the general public and government authorities. In this context, this study explores the realistic situation of earthquake losses due to future earthquakes in Kathmandu Valley. To this end, three municipalities: (a) Kathmandu metropolitan city (KMC), (b) Lalitpur Sub-Metropolitan City (LSMC) and (c) Bhaktapur Municipality (BMC) are selected for study. The earthquake loss estimation in the selected municipalities is performed through the combination of seismic hazard, structural vulnerability, and exposure data. For what concerns the seismic input, various earthquake scenarios considering four seismic sources in Nepal were adopted. Regarding the exposure, data about the type of existing buildings, population, and ward level distribution of building typologies is estimated from the recent national census survey of 2011. The economic losses due to the scenario earthquakes are determined using fragility functions. The commonly used standard fragility curves are adopted for adobe, brick/stone with mud mortar buildings, and brick/stone with cement mortar buildings. For the reinforced concrete structures, a new fragility model was derived considering four construction typologies: i) current construction practices (CCP), ii) structures according to the Nepal buildings code (NBC), iii) structures according to the modified Nepal building code (NBC+) and iv) well designed structures (WDS). In this study, a set of fragility functions is converted into a vulnerability model through a consequences model. Finally, the ward level distribution of damage for each building typology, building losses and the corresponding economic loss for each scenario earthquake is obtained using the OpenQuake-engine. The distribution of damage within the Kathmandu Valley is currently being employing in the development of a shelter model for the region, involving various local authorities and decision makers.

Keywords: Nepalese buildings; Kathmandu Valley; scenario earthquake; fragility curves

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1 INTRODUCTION

Nepal is located in a seismically active region with a long history of devastating earthquakes. The main cause of earthquakes in Nepal is due to the subduction of the Indian plate underneath the Eurasian plate. The major damaging earthquakes in Nepal took place in the years of 1255, 1408, 1681, 1803, 1810, 1833, 1934 and 1988 (Bilham *et al.*, 1995; Pandey *et al.*, 1995). As presented in figure1, Nepal and adjoining Himalayan arc has experienced some great historical earthquakes including the 1897 Shillong earthquake, 1905 Kangara earthquake, 1934 Bihar-Nepal earthquake, and 1950 Assam earthquake. These earthquakes scenario evidently indicate that the entire Himalayan region is one of the most active zones in terms of seismic hazard. Recent research on fault modeling of Nepal Himalayan arc has also shown continuous accumulation of elastic strain to reactive older geological faults, which may generate earthquakes strong magnitude (Chamlagain and Hayashi, 2004 and 2007).

The Kathmandu Valley is situated almost in the middle of Nepal, and is constituted by three administrative districts: Kathmandu, Lalitpur, and Bhaktapur. This region is composed by lacustrine sediments, which are considered to have high earthquake wave amplification capacity. The urbanization has been rapid throughout the Valley, and all of the urban settlements exhibit rapid growth around their periphery. Amongst the major earthquakes in recorded history, the Great Bihar-Nepal Earthquake of 1934 with a maximum intensity of X (MMI) caused extensive damage in the Kathmandu Valley (Dunn *et al.*, 1939; Pandey and Molnar 1988). The total death toll in Nepal was 8,519, from which 4,296 occurred in the Kathmandu Valley alone. In this earthquake about 19% of the building stock collapsed and 38% experienced significant damage just in the Kathmandu Valley (Pandey and Molnar 1988; Rana 1935). Furthermore, past studies showed that the human and economic losses due to earthquake are related with the development index of a country (Erdik and Durukal, 2008). The 1987 Loma Prieta earthquake (USA) caused only 62 deaths in the Bay Area, but the economic loss was estimated to be $4.7 billion. In a similar scale earthquake in Spitak (Armenia), over 20,000 people perished, but the economic loss was in the order of $570 million (Chatelian *et al.,* 1999). As an underdeveloped country, earthquake consequences in Nepal might be more tragic than what was observed in Spitak.

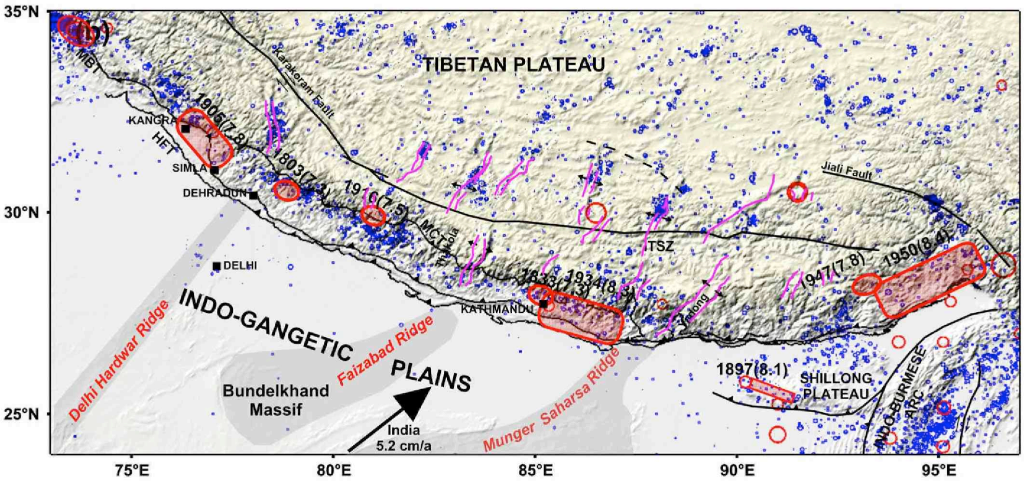


Figure 1. Major tectonic features and seismicity in the Himalayan arc. The ruptures of earthquakes of Mw> 7.2 of past 200 years in the Himalayan arc are shown by red rounded rectangles and ellipses. Earthquakes of Mw> 7 > 7.2 are also shown by red circles (Gupta and Gahalaut, 2014)

This study explores the realistic situation of losses and damages due to the four scenario earthquakes. The three damage states are used to estimate the distribution of damage. Two damage states of criteria are considered in these analyses: inter-storey drift, and global drift for each prototype building. The static pushover to incremental dynamic analysis (SPO2IDA) tool is employed for the derivation of fragility functions for Nepalese reinforced concrete (RC) buildings. It provides a direct connection between the static curve and the results of incremental dynamic analysis (Vamvatsikos and Cornell, 2006). The results of the analysis are summarized into their 16%, 50%, and 84% fractile IDA curves. In this study, sets of fragility functions for each building type are converted into vulnerability functions through the employment of consequence models. In this process, the percentage of buildings in each damage state is computed at each intensity level, and multiplied by the respective damage ratio. These results can be used for seismic risk reduction or mitigation measures.

2 EARTHQUAKE LOSS ESTIMATION

2.1 Earthquake scenarios

Regarding the earthquakes in and around Nepal Himalaya, the epicentral distribution map indicates that seismicity is active in the western and eastern part of Nepal. The central part of Nepal has suffered relatively few earthquakes (Pandey *et al.,* 1999). Pandey *et al.*, (1999) describes four (250-400 km) long segments that could produce earthquakes comparable to the M=8.3 (Mw) Bihar Nepal earthquake that struck eastern Nepal in 1934. Scenario earthquakes 1, 2, and 3 are selected considering past studies, orientation of active faults and seismicity in and around Nepal Himalaya where as earthquake 4 is based on the historical event (1934 Bihar- Nepal earthquake). The characteristic of scenario earthquakes is presented in Table 1. Location of vertical project of the fault rupture surfaces for the four scenarios is shown in figure 2.

Table 1. Characteristics of scenario earthquakes in Nepal

S.N	Scenario EQ	Magnitude (Mw)	Hypocenter		Fault trace			
					Fault coordinate 1		Fault coordinate 2	
1	EQ 1	6.0	28.08	85.17	27.929	85.288	28.244	85.050
2	EQ 2	7.0	27.00	85.48	27.263	84.551	26.751	86.407
3	EQ 3	8.0	28.42	82.93	27.816	83.664	29.018	82.225
4	EQ 4	8.2	27.56	87.07	27.757	85.958	27.365	88.183

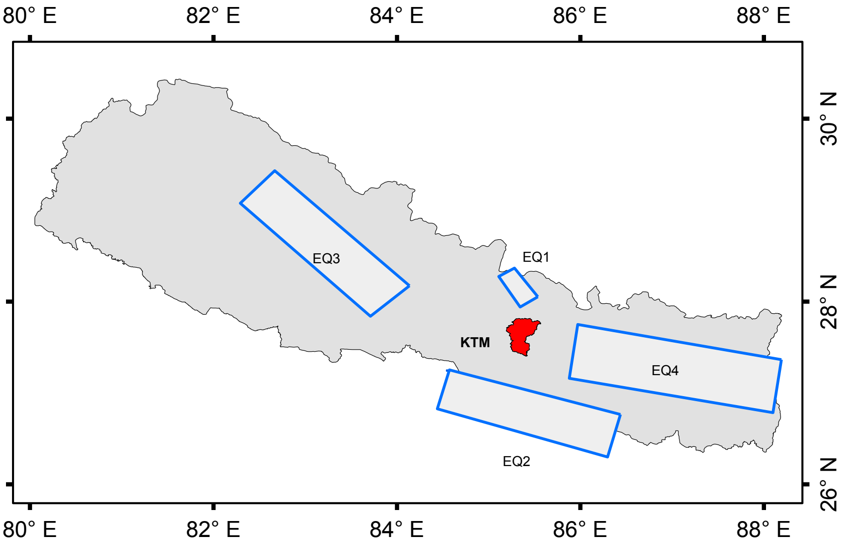


Figure 2. Location of fault trace for scenario earthquakes in Nepal

2.2 Characteristics of the building stock in Kathmandu Valley

The characterization of the buildings in Kathmandu Valley was performed during the National Population and Housing Census in 2011 (CBS, 2012). The information obtained from the National Census Report includes: types of foundation of house, type of outer wall and type of roof of the house. The distribution of building structures in Nepal and location of Kathmandu Metropolitan City (KMC), Lalitpur Sub-Metropolitan City (LSMC) and Bhaktapur Municipality (BMC) is presented in figure 3.

The distribution of building according to the building taxonomy in studied municipalities is presented in Table 2. The census survey data indicates that mud bonded bricks/stones (BM/SM), cement bonded bricks/stones (BC/SC), and reinforced concrete (RC) buildings are the most common building typologies in the Kathmandu Valley. In this study, the mixed buildings like stone and adobe, stone and brick in mud, brick in mud and brick in cement are considered as a single typology (adobe), since their structural vulnerability is identical. Four types of reinforced concrete buildings are considered in the present study. The first type corresponds to a moment resisting frame designed according to the current construction practices in Nepal (CCP structure); the second design type is based on Nepal building code based on Mandatory Rules of Thumb (NBC structure); the third type of structure follows a modified version of the Nepal building code (NBC+ structure) and the last type of RC frame represent the moment resisting frames which are designed based on the Indian standard code, which contains adequate seismic provisions (Well Designed Structures - WDS) (Chaulagain *et al.*, 2013).

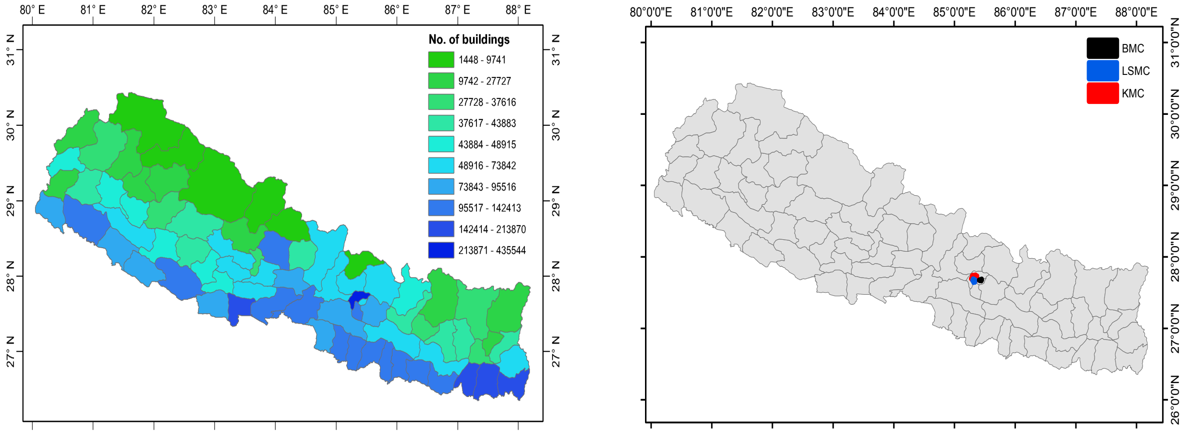


Figure 3. (a) Distribution of building structures in Nepal and (b) Location of case study Municipalities in Kathmandu Valley

Table 2. Buildings in Kathmandu Metropolitan City, Lalitpur Sub-Metropolitan City, and Bhaktapur Municipality

Location	A	BM	BC	CCP	NBC	NBC+	WDS
BMC	531	5468	4761	5229	551	551	551
LSMC	1635	14739	16374	16593	1746	1746	1746
KMC	4629	59807	89699	76144	8013	8013	8013

2.3 Development of exposure model

For the development of exposure model, a new set of building classes have been defined to distinguish each construction typology according to its seismic vulnerability. As discussed in section 2.2, adobe, mud bonded brick, mud bonded cement, cement bonded brick, cement bonded stone, RC buildings (CCP, NBC, NBC+, and WDS buildings) are the most common typologies in the Kathmandu Metropolitan city, Lalitpur Sub-Metropolitan City and Bhaktapur Municipality. For the sake of simplicity, the vulnerability of buildings classified as mixed and other not stated categories in the national census survey are considered to have a similar performance as adobe. The fractions of CCP, NBC, NBC+ and WDS structures are considered as 76%, 8%, 8% and 8% respectively (Dixit 2004; Shrestha and Dixit, 2008). Considering the classification of buildings and their respective volume tabulated in Tables 3, a ward level exposure model containing the number of buildings from each vulnerability class was created. The vulnerability class and its corresponding volume is based on JICA, 2002; NPHC, 2012; and Chaulagain *et al.*, 2013 study. For the purpose of computing the seismic hazard for each asset, it was assumed that all of the buildings are equally distributed within the whole ward, which is a common assumption when performing seismic risk assessment at a large scale (e.g. Bommer *et al.*, 2002; Crowley *et al.*, 2008).

Table 3. Vulnerability classes for building stock in Kathmandu Metropolitan city, Lalitpur Submetropolitan city, and Bhaktapur Municapility

SN	Building Types	% of buildings Kathmandu Metropolitan city	Lalitpur Submetropolitan city	Bhaktapur Municipality
1	A	2	3	3
2	BM/SM	26	27	31
3	BC/SC	33	30	27
4	CCP	30	31	30
5	NBC	3	3	3
6	NBC+	3	3	3
7	WDS	3	3	3

2.4 Estimation of economic value

The spatial distribution of building count is fundamental component for earthquake scenario damage assessment, which can then be used to create post-disaster emergency plans or to design risk mitigation strategies. However, in order to estimate the associated economic losses, it is necessary to attribute a building cost to each typology. In the present study, the building cost is established as the required monetary value to construct a building with the same characteristics according to the current costs, herein termed as the replacement cost. This value naturally depends on the location and total area of the building. However, for the simplicity, same building cost is applied to the whole country. Table 4 presents the construction type, area per building type and corresponding construction cost.

Table 4. Area and corresponding construction cost of existing Nepalese building stock

SN	Construction type	Area per building (m^2)	Construction cost (€/m^2)
1	A	60	150
2	BM	70	225
3	BC	80	275
4	CCP	80	300
5	NBC	80	325
6	NBC+	80	350
7	WDS	90	375

2.5 Fragility function for Nepalese building structures

In the present study, for the earthquake loss estimation of the cities in Kathmandu Valley, the commonly used standard fragility functions and a new fragility functions are used. The analytical methodology is used to generate new fragility curves. The structural models for RC buildings are created considering the geometrical and material properties of Nepalese RC buildings (Chaulagain *et al.,* 2013). The SPO2IDA, excel sheet program developed by Vamvatsikos and Cornell (2006) is employed for converting static pushover curve to incremental dynamic analysis. SPO2IDA represents a tool that is capable of recreating the seismic behavior of oscillators with complex multi-linear backbones at almost any period. It provides a direct connection between the static pushover curve and the results of incremental dynamic analysis, a computer-intensive procedure that offers thorough (demand and capacity) prediction by using a series of non-linear dynamic analyses under a suitably scaled suite of ground motion records. The results of the analysis are summarized into their 16%, 50%, and 84% fractile IDA curves. It offers effectively instantaneous estimation of demands and limit-state capacities, in addition to conventional strength reduction R-factor and inelastic displacement ratios, for any SDOF whose SPO curve can be approximated by such a quadrilinear backbone. The mean (λ) and standard deviation (ζ) per damage state for each building typology in terms of spectral acceleration at the yielding period (Ty) and in terms of peak ground acceleration is presented in Tables 5 and 6.

Table 5. The mean (λ) and standard deviation (ζ) per damage state for each building typology in terms of spectral acceleration at the yielding period (Ty)

Building	T	Moderate		Extensive		Collapse	
typology	(sec)	(λ)	(ζ)	(λ)	(ζ)	(λ)	(ζ)
CCP	0.38	0.25	0.13	0.71	0.17	1.22	0.27
NBC	0.32	0.35	0.17	0.85	0.20	1.35	0.32
NBC+	0.25	0.45	0.17	1.00	0.35	1.57	0.32
WDS	0.21	0.57	0.20	1.33	0.30	1.73	0.38

Table 6. The mean (λ) and standard deviation (ζ) per damage state for each building typology in terms of peak ground acceleration

Building	Moderate		Extensive		Collapse	
typology	(λ)	(ζ)	(λ)	(ζ)	(λ)	(ζ)
Adobe	-3.22	0.65	-1.99	0.77	-1.45	0.64
BM	-2.14	0.72	-1.66	0.72	-1.05	0.66
BC	-1.82	0.68	-1.06	0.67	-0.62	0.72

2.6 Consequence model employed to convert fragility curves into vulnerability curves

Consequence models can be used to convert a set of fragility functions into a vulnerability function. In this process, the percentage of buildings in each damage state is computed at each intensity measure level, and multiplied by the respective damage ratio, obtaining in this manner a loss ratio for each level of peak ground acceleration or spectral acceleration. Consequence model used in the development of the vulnerability model for the Nepalese RC building stock is presented in Table 7.

Table 7. Consequence model used in the development of the vulnerability model for the Nepalese RC building stock

Damage state	Damage ratio
Moderate damage	0.30
Extensive Damage	0.60
Collapse	1.00

2.7 Site effects

Site conditions play a major role in establishing the damage potential for incoming seismic waves from major earthquakes. Damage patterns in Mexico City after the 1985 Michoacan earthquake demonstrated conclusively the significant effects of local site conditions on seismic response of the ground. The bed rock outcrop motions were amplified about five times. In the 1989 Loma Prieta earthquake, major damage occurred on soft soil sites in the San Francisco – Oakland region where the spectral accelerations were amplified two to four times over adjacent rock sites (Housner 1989), and caused severe damage. It shows that surface-level peak ground acceleration and spectral acceleration values can be different from bedrock values, depending on local soil conditions. In fact, shaking is stronger where the shear wave velocity is lower. Amplification of amplitudes of soil particle motion from vertically propagating shear waves occurring from bed rock depends upon the geotechnical properties of overburden soil. The soil types, pore-water pressure, and the level of water table are other significant site parameters. All these evidence clearly indicates that seismic design should incorporate the amplification effects of local soil conditions. To account for this shaking amplification effect, the average shear wave velocity in the top 30 m of a site (V30) is universally adopted as the classifying parameter. The National Earthquake Hazards Reduction Program (NEHRP) has defined 5 soil types namely A, B, C, D, and E based on their shear-wave velocity (Vs). This site classification according to NEHRP-USA (BSSC, 2001) is shown in Table 8. The site effect in the present study is considered according to V30 values in and around Kathmandu Valley.

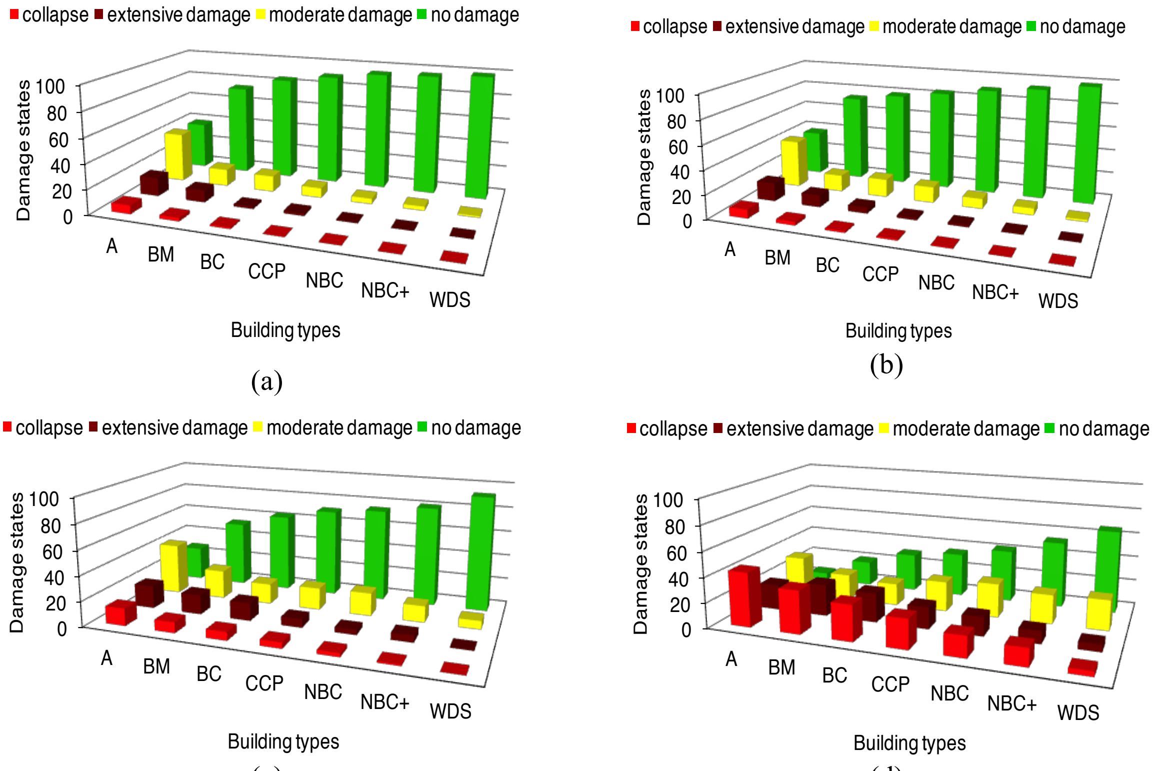
Table 8. Site classification according to NEHRP-USA (BSSC, 2001)

Site class	Range of V_{30} (km/s)	Description
A	$V_{30} > 1.5$	Includes unweathered intrusive igneous rock
B	$0.76 < V_{30} \leq 1.5$	Includes volcanics, most Mesozoic bedrock, and some Franciscan bedrock
C	$0.36 < V_{30} \leq 0.76$	Includes some Quaternary sands, sandstones and mudstones
D	$0.18 < V_{30} \leq 0.36$	Includes some Quaternary muds, sands, gravels, silts and mud. Significant amplification of shaking by these soils is generally expected
E	$V_{30} \leq 0.18$	Includes water-saturated mud and artificial fill. The strongest amplification of shaking due is expected for this soil type

3 RESULTS

3.1 Damage distribution per taxonomy in Kathmandu

The damage distribution for each building typology in selected municipalities are determined using OpenQuake-engine. The tool is capable of estimating the distribution of buildings in each damage state due to the occurrence of a single event. The damage distribution for the deterministic seismic event was estimated using the fragility model. The damage distribution output is comprised of a set of damage nodes for which the amount of buildings in each damage state is described. The OpenQuake-engine provides a damage distribution per buildings typology or the total damage distribution.



(a)

(b)

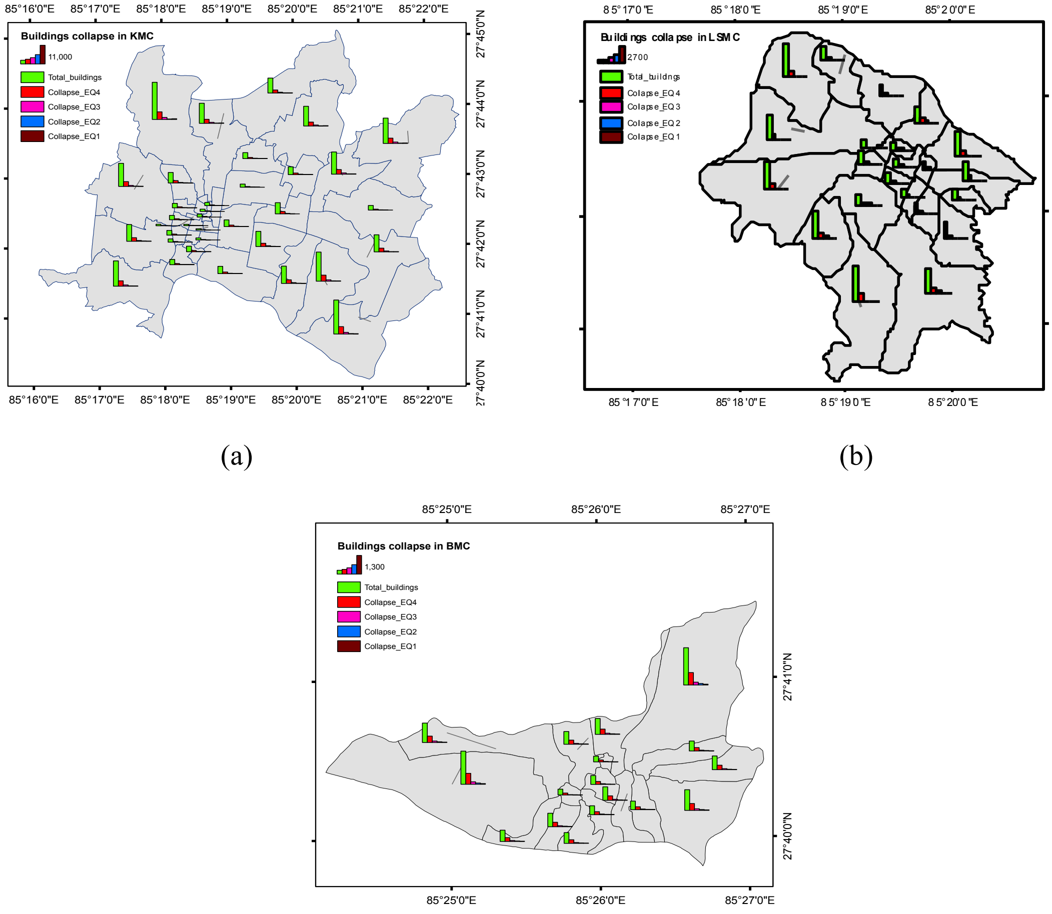
(c)

(d)

Figure 4. Building damage due to earthquake scenarios: a) EQ1, b) EQ2, c) EQ3 and d) EQ4

The structural damage to Nepalese buildings is classified into four groups: (1) no damage, (2) moderate damage, (3) extensive damage, and (4) collapse. The results indicates that there was three different damage patterns were observed in all four earthquake scenarios. The first scenario (EQ1) yields very low damage levels. The second and third scenarios (EQ2 and EQ3) yields intermediate damage levels. The fourth scenario (EQ4) yields much higher level of damage. From figures 4 and 5, it can be seen that about 49% of adobe buildings collapsed in BMC due to scenario earthquake 4. The amount is limited to 40% in LSMC and KMC. There is a remarkable collapse rate in BM, BC, and

CCP buildings. From the results, it is also seen that the maximum amount of buildings are collapsed due to scenario earthquake EQ4. The amount is 33% in BMC, 23% in LSMC and 21% in KMC. As expected, scenario EQ1 results minimal damage. The collapse of buildings as a result of EQ1 is limited to 2.06% in BMC, 1.06% in LSMC and 1.15% in KMC. Scenario earthquakes EQ2 and EQ3 result the intermediate building damage.



(a)

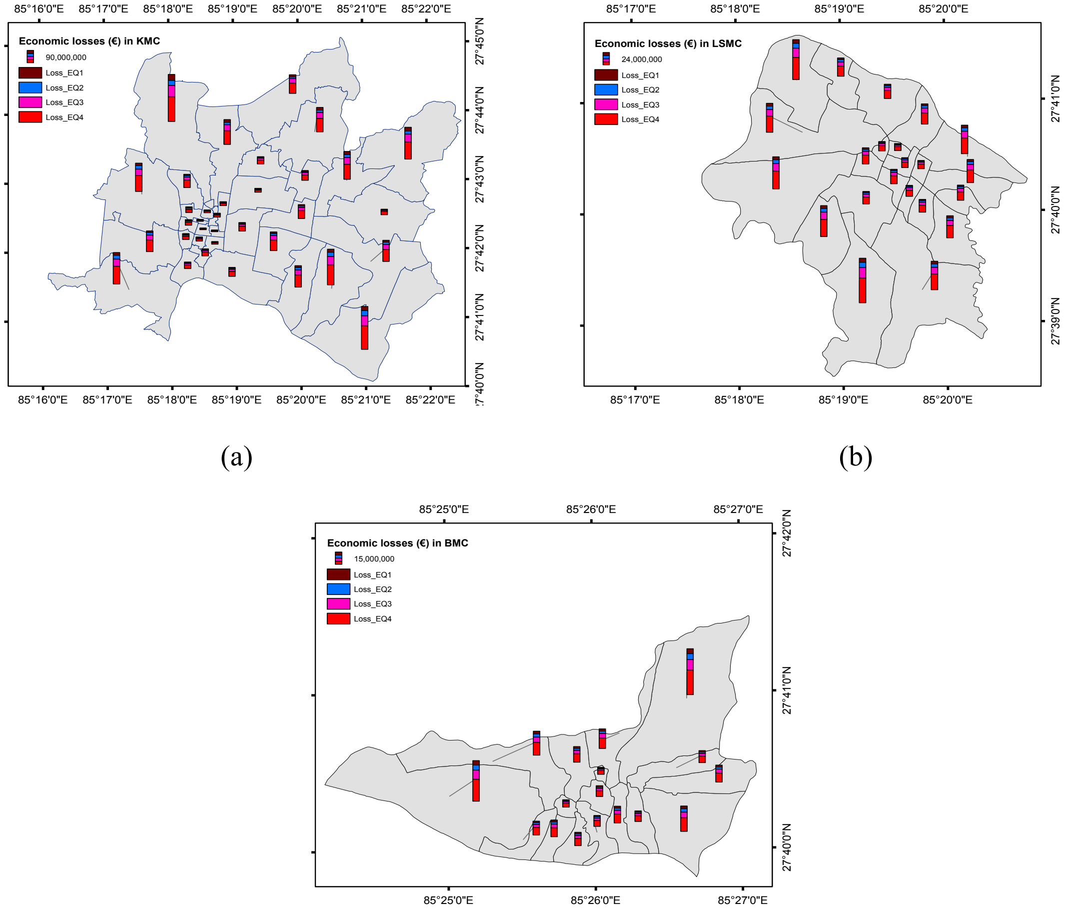
(b)

(c)

Figure 5. Ward level distribution of building collapse in (a) KMC, (b) LSMC and BMC

3.2 Economic loss map

The ward level distribution of economic loss map as a result of four scenario earthquakes in Kathmandu Metropolitan city, Latipur Sub metropolitan and Bhaktapur municipality is presented in figure 6. The economic loss due an earthquake scenario EQ1, EQ2, EQ3 and EQ4 in Bhaktapur Municipality is 3.83, 4.65, 8.11, and 19.56 million Euros respectively. The amount is increased by 7.75, 10.36, 20.15, and 47.74 million Euros respectively in Lalitpur Sub-Metropolitan City. The economic loss is maximum in Kathmandu Metropolitan City. The cost is 36.82, 42.21, 89.48, and 208.97 million Euros respectively for an earthquake EQ1, EQ2, EQ3 and EQ4.



(a) (b)

(c)

Figure 6. Ward level distribution of economic loss in (a) KMC, (b) LSMC and BMC

4 CONCLUSIONS

The rapid urban development in Kathmandu Valley has lead to increase in the exposure levels of the urban vulnerability. Due to the steadily increasing population with improper land-use planning, inappropriate construction techniques and inadequate infrastructure systems, associated with an existing high hazard level, Kathmandu is one of the most risky city in the south Asian region. Considering these facts, this study tries to explore the situation of earthquake losses in three municipalities located in Kathmandu Valley. We evaluate an earthquake losses in three cities determined as a convolution of seismic hazard, vulnerability, and exposure of infrastructures.

Regarding the damage distribution, three damage patterns are observed in the four scenario earthquakes. The earthquake EQ1 yields low damage level. The maximum damage is observed in the scenario earthquake EQ4. The result also shows that about 49% of adobe buildings collapsed in BMC due to EQ4. The amount is limited to 40% in LSMC and KMC. There is a remarkable collapse rate in BM, BC, and CCP buildings. From the outcomes, it is also seen that the maximum amount of buildings are collapsed due to EQ4. The amount is 33% in BMC, 23% in LSMC and 21% in KMC. As expected EQ1 results minimal damage. The collapse is limited to 2.06% in BMC, 1.06 in LSMC and 1.15 in KMC. Scenario earthquakes EQ2 and EQ3 result the intermediate building damage. The economic loss due an earthquake scenario EQ1, EQ2, EQ3 and EQ4 in Bhaktapur Municipality is 3.83, 4.65, 8.11, and 19.56 million Euros respectively. The amount is 7.75, 10.36, 20.15, and 47.74 million Euros respectively in Lalitpur Sub-Metropolitan City. The economic loss is higher in Kathmandu Metropolitan City. The cost is 36.82, 42.21, 89.48, and 208.97 million Euros respectively for an earthquake EQ1, EQ2, EQ3 and EQ4.

Acknowledgements

This research was partially developed under financial support provided by "FCT - Fundação para a Ciência e Tecnologia", Portugal, through the research project PTDC/ATP-AQI/3934/2012. This research was also supported by the Eurasian University Network for International Cooperation in Earthquake (EU-NICE), through the fellowship for PhD studies of the first author.

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