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Derive empirical fragility functions for Nepali residential buildings

Dipendra Gautam*, Giovanni Fabbrocino, Filippo Santucci de Magistris

Structural and Geotechnical Dynamics Laboratory (StreGa), DiBT, University of Molise, Campobasso, Italy

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ABSTRACT

Fragility functions are the key components of damage analysis for the next generation performance-based earthquake engineering (PBEE-2) framework. Despite being widely discussed and researched topic in almost all seismically active regions, fragility functions for Nepali buildings are not widely researched to date. This paper derives empirical fragility functions for residential buildings using more than a million damage data from the 1934 Bihar-Nepal earthquake (M_W ~8.4), 1980 Chainpur earthquake (M_W 6.5), 1988 Eastern Nepal earthquake (M_W 6.8), 2011 Eastern Nepal earthquake (M_W 6.9), and 2015 Gorkha seismic sequence (M_W 7.8). A new damage classification system is proposed in this study and fragility functions for reinforced concrete, brick masonry, and stone masonry building classes are derived. As seismic site effects is one of the leading factor contributing damage in the case of Himalayan earthquakes, fragility functions considering seismic site effects are also derived for all three building classes. Finally, fragility functions derived in this study are compared with existing fragility functions and discussion regarding the discrepancies is presented. Together with the fragility functions, building taxonomy and vulnerability of all existing buildings in Nepal are outlined in this paper.

1. Introduction

Fragility functions are important parameters under damage analysis attribute of the second-generation performance-based earthquake engineering (PBEE-II). Fragility functions depict the probability of reaching or exceeding the damage state to a component or structure as a function of intensity measures (IMs). For both pre-disaster planning and post-disaster interventions, fragility functions are crucial. Initial contributions and implications of fragility functions were primarily focused on the nuclear facilities, meanwhile, a paradigm shift in terms of construction of fragility functions for residential building stocks and other infrastructures gained momentum after the 1990s. Derivation of fragility functions can be based on analytical (e.g. [1–5]), heuristic (e.g. [6,7]), empirical (e.g. [8–13]), and hybrid approaches (e.g. [14,15]). Each of the approaches has its own advantages as well disadvantages; detailed discussion regarding merits and demerits of each approach can be found in the works by Elnashai and Di Sarno [16] and Porter et al. [17]. Among four fundamental approaches, empirical fragility functions, that rely on earthquake damage data, are noted as the most reliable by Elnashai and Di Sarno [16]. Although there are diverse opinions regarding derivation and implications of empirical fragility functions, undoubtedly, empirical fragility functions can provide notable information on the seismic vulnerability of structures exposed to seismic forces. It is because empirical fragility functions are derived from the real-time damage records thus the uncertainties in modeling to experimental constraints can be avoided if the database is collected and managed carefully. It should be noted that empirical fragility functions should be carefully used especially when there is lack of unanimity in the collection, processing, and judgment of damaged components/structures. Several contributions on empirical fragility functions can be found worldwide (see: [8–13]); however, very few fragility functions are derived for Nepali buildings (e.g. Chaulagain et al. [41]).

Owing to the fact that the fragility functions developed for one context, type of structure/component, and region cannot represent other contexts, types of structures, and regions due to variation in the construction materials and construction technology, thus, use of empirical fragility functions is limited to the specific location only. Even within a neighborhood, that comprises similar building classes, may have structural variations in terms of construction technology, dynamic characteristics, coupling with subsoil conditions, installation conditions, age of buildings, and others, thus, global scale fragility functions are not preferred, generally. To this end, the aim of this paper is to derive fragility functions for residential building stocks in Nepal assuring maximum homogeneity of damage data. During each of the notable earthquake that struck Nepal Himalaya, it is evident that the seismic site effects has played a significant role in damage, hence, fragility functions for Nepali building stocks should also attribute the seismic site effects to be more representative. To fulfill this aim, we derived two sets of fragility functions considering peak ground acceleration (which does not account seismic site effects) and spectral

* Corresponding author.
E-mail address: dipendra.gautam@unimol.it (D. Gautam).

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acceleration (which accounts seismic site effects) as IMs for each building class. To estimate the IMs, ground motion prediction equation (GMPE) plays an important role especially in the case of sparsely instrumented regions, thus, the selection of GMPE is critical. The GMPEs developed for particular regions would be the most useful; whereas, in the case of unavailability GMPEs could be selected by matching the recorded parameters with the predicted ones from GMPEs.

An overview of the major earthquakes since the 20th century in Nepal Himalaya is presented in the following section of the paper. Thereafter, building taxonomy covering all existing buildings in Nepal is outlined along with the most likely vulnerability class per European Macroseismic (EMS-98) scale [18]. The methodology in terms of building class definition, damage grading system, and selection of intensity measure (IM) is outlined after the building taxonomy and vulnerability section. Finally, the implications and limitations of empirical fragility functions derived for Nepali residential buildings have been discussed.

2. Overview of major earthquakes in Nepal

Historical earthquake damage records since 1255 depict frequent occurrence of strong to major earthquakes in Nepal. Since 1255, earthquakes of 1260, 1408, 1681, 1767, 1810, 1833, 1834, 1837, 1869, 1897 and 1917 struck Nepal and caused severe damage in building structures apart from tens of thousands of casualties and injuries. Although comprehensive records of historical earthquakes did not exist in Nepal until the early 19th century; the first recorded earthquake is the 1833 event near Kathmandu valley. The Building Code Development Project highlighted that the 1833 earthquake ($M_L \sim 7.7$) caused 414 fatalities in Kathmandu valley and damaged at least 18,000 buildings [19]. However, details of damage and structural forms cannot be found for this earthquake either. Details of records regarding earthquake effects in Nepal Himalaya can be found for the great Bihar-Nepal earthquake (M_W 8.4) that struck eastern and central Nepal on January 15, 1934 [20]. After 1934 Bihar-Nepal earthquake, seismic events like 1936 ($M_L \sim 7$), 1954 ($M_L \sim 6.4$), 1965 (M_L 6.1), 1966 (M_L 6), 1980 (M_W 6.5), 1988 (M_W 6.8), 2011 (M_W 6.9) and 2015 (M_W 7.8) are the notable earthquakes that caused damage of various extent in Nepal. Among the notable events since the 20th century, records from 1934, 1980, 1988, 2011 and 2015 are used in this study to derive fragility functions for residential buildings. The damage statistics due to the notable earthquakes that struck Nepal Himalaya are presented in Table 1. The epicentral locations along with active faults in Nepal Himalaya is mapped in Fig. 1 and a brief account of each of the earthquake is presented in following sections.

2.1. Bihar-Nepal earthquake (1934)

On 15 January 1934, strongest earthquake in Nepal's modern history occurred in eastern Nepal (see Fig. 1). The magnitude of the earthquake was reported by several researchers between 8.1 and 8.4 in moment magnitude. Damage due to this earthquake mainly occurred in eastern and central Nepal and the Indian state of Bihar. There is no unanimous description regarding location, magnitude, focal depth, fault rupture and casualties as well as building damage. However, Rana [20] presented a comprehensive description of categorical building damage and effects of earthquakes on lifelines based on the database collected by 'Earthquake Relief Organization'. To clarify ambiguities arising from various researchers, Pandey and Molnar [21] reinterpreted the accounts and provided updates on damage records and epicentral location of the earthquake. As reported by Rana [20] Bihar-Nepal earthquake caused 8519 deaths in Nepal and 4296 injuries in Kathmandu valley; however, injuries outside Kathmandu valley were not assessed properly. At least 207,248 buildings were damaged due to Bihar-Nepal earthquake, among them, 80,893 buildings were collapsed. In Kathmandu valley, 12,397 buildings were collapsed and additional 55,739 buildings got damaged due to Bihar-Nepal earthquake. Apart from residential buildings, at least 492 historical and monumental buildings were damaged throughout the affected areas. Rana [20] reported that the effective duration of the earthquake was ~120 s and shaking was continued for nearly eight minutes. Building damage statistics showed that Kathmandu valley and eastern and central mountains were among the most affected areas due to high-density vulnerable building types, e.g. adobe, rubble stone construction, and unreinforced brick masonry buildings, as well as due to stronger shaking than the other areas. The morphological description of buildings in Kathmandu valley presented by Rana [20] confirms that more than 95% of total building stocks were brick masonry in mud mortar constructions without any seismic provisions. Such buildings can be classified under the vulnerability class A per EMS-98 scale.

Similarly, most of the building in mountainous regions of Nepal are the rubble stone masonry buildings which can be categorized as Vulnerability class A per the EMS-98. Although the damage was intense in the mountains, timber buildings were reported to be undamaged [20]. Similarly, in the case of central and eastern Indo-Gangetic plains, timber buildings were not affected, whereas brick masonry buildings sustained considerable damage in the other hand. Taking into consideration the accounts of construction technology and morphological descriptions, three broad categories of buildings can be identified in Nepal during 1934 earthquake as brick masonry, stone masonry, and timber buildings. Morphological descriptions depict that up to four storied residential buildings were in practice in Kathmandu valley and stone masonry and timber buildings in mountains and plains were at most three storied generally.

2.2. Chainpur earthquake (1980)

On July 29, 1980, strong earthquake of magnitude 6.5 struck far western mountains of Nepal (see Fig. 1). The focal depth of the earthquake was ~18 km [22] and it is one of the few strong earthquakes to hit the western section of Nepal Himalaya. Eastern and the central Himalayas are frequently observing strong to major earthquakes at regular intervals, unlike the western Himalaya. Building damage during Chainpur earthquake occurred in seven districts located near the Indian border. In terms of building taxonomy, more than 95% buildings were field stone masonry constructions which is similar to the eastern and central mountains. Consequently, the damage was confined to one to three storied stone masonry buildings which can be also categorized into EMS-98 vulnerability class A. Chainpur earthquake caused extensive damage to 12,817 buildings, moderate damage to 13,298 buildings, and slight damage to 6377 buildings [23]. Apart from severe losses in terms of building damage, 46 deaths and 236 injuries were caused by the Chainpur earthquake [23]. It is important to note that, the same areas were affected by three moderate earthquakes of magnitude 5.8, 5.1 and 4.9 between 16 and 18 December 1966. These earthquakes of 1966 destroyed ~1300 and damaged 6533 stone masonry buildings [19] and the buildings already damaged by the 1966 events would have contributed to greater collapse statistics due to progressive damage accumulation. Periodic maintenance and repairs of

Table 1
Damage statistics due to strong to major earthquakes since the 20th century in Nepal (modified from: [20,23,22,25], and [26]).

Earthquakes	Year	Moment magnitude	Deaths	Injuries	Building collapse	Building damage
Bihar-Nepal	1934	8.4	8519	-	80,893	126,355
Chainpur	1980	6.5	46	236	12,817	12,269
Eastern Nepal	1988	6.8	722	12,244	21,243	40,374
Nepal-Sikkim border	2011	6.9	6	134	6435	14,548
Gorkha	2015	7.8	8790	22,300	498,852	256,697