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Multi-hazard vulnerability of structures and lifelines due to the 2015 Gorkha earthquake and 2017 central Nepal flash flood

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Abstract

The 2015 Gorkha earthquake caused severe damage to structures in central Nepal. In 2017, a flash flood event occurred in the same area affected by the Gorkha earthquake and aggravated the damage to structures and lifelines. The present paper reports the damage of structures and lifelines subjected to multi-hazards in the affected area in central Nepal. Field investigations were performed after the Gorkha earthquake as well as the 2017 Chhatiune Khola flash flood. Specifically, damage associated with bridges, vernacular stone masonry buildings, roads, water supply systems, irrigation canals, electric poles, and road signs was assessed. Field measurement in terms of flow height was recorded in the case of vernacular buildings, and depth-damage curve due to the flash flood is depicted in this study. We have outlined the multi-hazards vulnerability of vernacular stone masonry buildings along the river banks susceptible to flash floods in this study. Moreover, a quantified damage scenario due to a strong earthquake and a flash flood is highlighted using field records.

Keywords: Multi-hazard vulnerability; earthquake; flash flood; structures; lifelines.

1. Introduction

The progress in assessment of vulnerability of structures from single event based studies to significant multi-hazards has become more common in recent years (see e.g. Mosqueda et al. 2007; Yankelevsky et al. 2011; Mardfekri and Gardoni 2015; Gardoni and LaFave 2016; Reed et al. 2016; Marasco et al. 2017, among others). Despite the global attention, Nepal still lacks systematic studies that address the multi-hazards damage to structures and lifelines. To the best of authors' knowledge, no cases of multi-hazard damage and vulnerability based on field reconnaissance are reported in existing literature, neither are there any reports that consider multi-hazards vulnerability perspectives in the post-events scenario. In some extent, the 2015 Gorkha earthquake highlighted some relevant examples of earthquake damage and several works are reported in terms of building and other structural performance and vulnerability (e.g. Gautam et al. 2016a; Gautam et al. 2016b; Gautam and Chaulagain 2016; Gautam 2017a), however flood and landslide damage to structures and lifelines cannot be found in Nepal. Limited works are performed in the case of seismic vulnerability of highway bridges (Gautam 2017b) but no case of multi-hazards was considered in the reported work when depicting the seismic vulnerability of highway bridges either. Nepal lies in one of the most active seismic regions of the world and is equally prone to flash floods and landslides due to fragile geology, as well as annual torrential precipitation. Furthermore, non-engineered construction practices are widespread, as most of the people (~70%) reside in non-engineered buildings that are constructed in hazard prone areas. To this end, future events may reveal more severe damage scenario if independent as well as cascading hazards are not considered at a time. Independent multi-hazards are rare globally, thus systematic case studies are not frequent in existing literature. However, individual hazards are reported by several scholars for the earthquake events (e.g. Gupta 1988; Rossetto and Peiris 2009; Zhao et al. 2009; Augenti and Parisi 2010; Romao et al. 2013; Gautam and Chaulagain 2016; Rupakhety et al. 2016; among others), and flood (e.g. De Falco et al. 2016; Santo et al. 2016; Elnazar et al. 2017; Laudan et al. 2017; among others). Per the recent trend, earthquakes and floods are being frequent in Nepal. For example, the Gorkha earthquake sequence was followed by several flash floods. Apart from this, some of the cascading events like landslides and avalanches after the 2015 Gorkha earthquake were reported by Gautam (2017c). The report is limited to earthquake effect on structures and lifelines and discusses the combined action of all hazards collectively; thus, lacks the segregated impact of each event. To this end, a comprehensive damage scenario may outline the prospect of damage in the case of independent extreme events; which is reported in this paper.

The aim of this work is to present the damage insights and create the depth-damage curve for the vernacular residential buildings of Nepal. Two independent multi-hazards are considered and damage to structures and infrastructures is presented using forensic approach.

2. Multi-hazards scenario in Nepal

Nepal is designated as the 20th most multi-hazard prone country by UNDP/BCPR (2004), whereas the impact of climate change, non-engineered development and infrastructures construction have increased the risk in recent decades thus it could be inferred that multi-hazards are common, if not frequent, in Nepal. Moreover, the impact of climate change is resulting in torrential precipitation that is leading to the failure of slopes that were made unstable by the earthquake. A combined impact of earthquakes, flash floods, and landslides was commonly observed in central Nepal after the 2015 Gorkha earthquake (Gautam 2017c). Especially, flash floods in Nepal are being common due to the impact of climate change that is leading to the enormous damage in terms of fatalities, injuries, and loss of habitat in riverine communities. The multi-hazard risk assessment does not exist for Nepal so it is not possible to quantify the multi-hazard damage scenario in the study area too. Even though there is not any multi-hazard mapping, to depict the scenario of 2015 earthquake and 2017 flood, epicenters and study area are plotted in Fig. 1. As shown in Fig. 1, the same area that was affected due to flood was exposed to two significant shakings during the Gorkha earthquake. The following section presents a brief overview of two major disasters that struck the same area and associated losses.

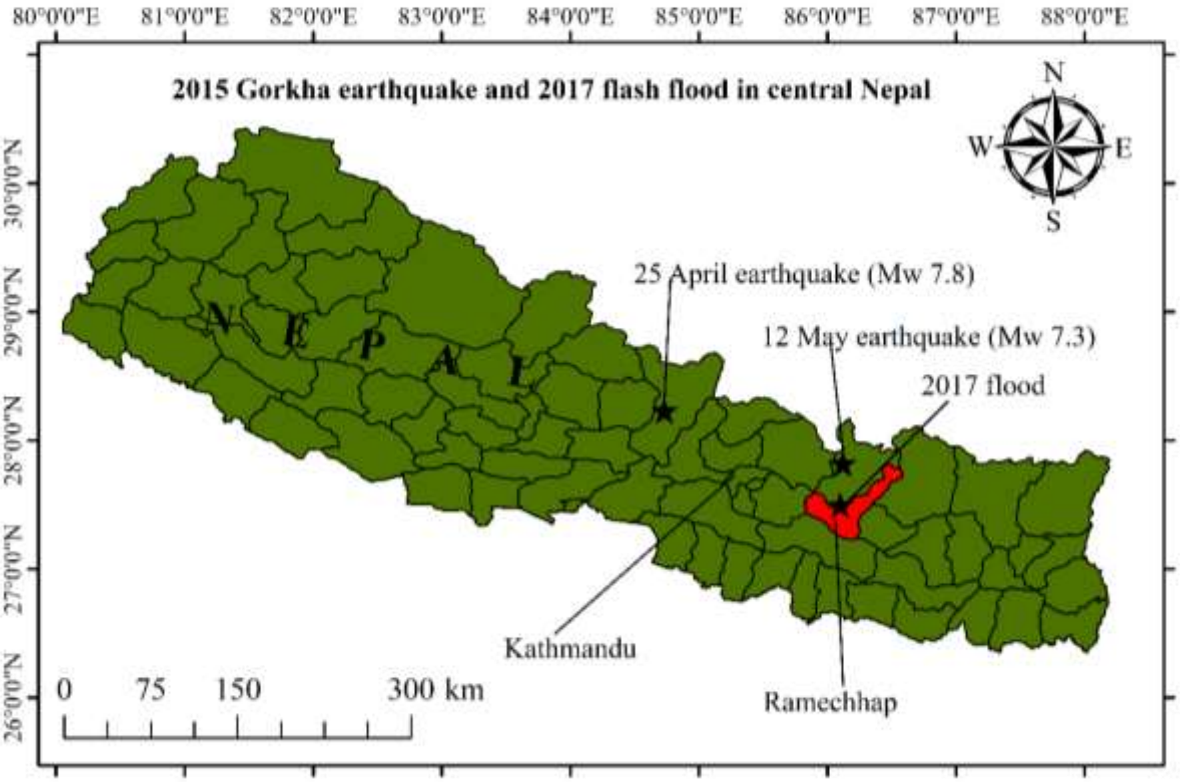

Fig. 1 Location of the affected area due to 2017 flood and 2015 earthquake

2.1. 2015 Gorkha earthquake

On April 25, 2015, a strong earthquake of moment magnitude (M_W) 7.8 struck central, eastern and part of western Nepal. The epicenter of the main shock was located near Barpak neighborhood (see Fig. 1) in western Nepal, whereas the M_W 7.3 aftershock of 12 May was near

Ramechhap district as shown in Fig. 1. The 2015 Gorkha earthquake sequence caused 8,790 fatalities and 22,300 injuries and in total one million buildings were affected (NPC 2015). Per the National Planning Commission of Nepal, the Gorkha earthquake sequence caused extensive damage in roads, hydropower plants and bridges too. The Ramechhap area considered as a case study site herein was also among the crisis-hit district (NPC 2015), however, USGS shake map shows that the peak ground acceleration was ~0.2 g in the neighborhood (USGS 2015). As many as 3600 small to large scale landslides were reported in the affected areas (NPC 2015), however, no cases of earthquake triggered interacting hazards were reported in the study area.

2.2. 2017 Chhatiune Khola flash flood

The torrential precipitation that lasted for four hours (21:00-1:00 local time) on July 15, 2017, caused a flash flood in Chhatiune Khola which caused severe damage to structures and lifelines in Khimti neighborhood of Ramechhap district in central Nepal. As there was no any rain gauge station, we were not able to quantify the exact precipitation. The flash flood occurred due to the heavy rainfall in the upstream mountain and the high velocity caused the debris flood in the downstream (Fig. 2). Five fatalities and four injuries were reported by the locals during the field visit conducted on August 5, 2017. The flood struck the same structures and lifelines that were affected by the Gorkha earthquake and displaced at least five families in the neighborhood. Apart from this, the feeder road connecting to the district downtown was also obstructed hence no connectivity was resumed until the first week of August. The flood also destroyed the rice fields of the families whose houses were in other neighborhoods. Until the first week of August, the displaced people were taking shelter in nearby village and relocation and reconstruction efforts were not conducted. Details of damage to each structure and lifeline are presented in the following section.

Fig. 2 Affected area due to the flash flood in Khimti neighborhood of Ramechhap district (highlighted with the polygon) (Modified from: Google Earth 2017)

3. Reconnaissance of damage due to multi-hazards

Field reconnaissance in the affected area was performed on 5 August 2017. Damage mechanisms were noted and forensically interpreted. Moreover, the peak flood level was measured and the details of damage were collected in-situ. Damage scenario and forensic interpretation of each structure and lifelines is presented in detail as following.

3.1. Damage to bridge

All the assessed structures and lifelines were affected during the 2015 Gorkha earthquake in Khimti neighborhood; whereas the damage level was increased in each structure and lifelines. The Chhatiune Khola bridge was constructed right before the 2015 Gorkha earthquake, however, no visible damage was occurred in the bridge due to Gorkha earthquake per the locals. The

Chhatiune Khola bridge was reinforced concrete single span bridge. The bridge span was 30 m with 10 m height from the previous river bed. Due to the July 2017 flood, the river channel was ~3 m deepened whereas the bridge was destroyed with no indication of parts of the superstructure (Fig. 3).

Fig. 3 Debris flood from the stream due to flash flood in the bridge site

The river channel was shifted ~10 m and the river is currently flowing through previous rice fields. Per the local people, flash floods of such extent were not observed in the last hundred years. Forensic interpretation depicts that there were no concerns of structural deficiencies, however, the hydrodynamic force arising from the turbulent water flow in the steep river channel could have destroyed the superstructure since superstructures are designed providing freeboard per the discharge without due consideration of hydrodynamic forces. In the case of piers, again due to the low discharge scenario, the forces considered during design would not have been adequate to assure the performance during turbulent flows as in the case of July 2017 flash floods.

3.2. Damage to lifelines

Performance of lifelines during multi-hazards is a seldom discussed topic in Nepal. We observed the damages in irrigation canals, water supply pipeline and electric poles, road network, and roadway sign posts due to the recent flash flood of 2017 which were exposed to Gorkha earthquake too. The damage in lifelines due to the 2015 Gorkha earthquake has been thoroughly reported by the National Planning Commission, Nepal (NPC 2015). To the best of authors' knowledge, limited reports and documents are available for the 2017 flash flood (e.g. Gautam et al. 2017). As shown in Fig. 4, one of the irrigation canal supplying water to nearest rice field was washed away by the flood, meanwhile, local people confirmed that there was no significant damage during Gorkha earthquake.

Fig. 4 Damage to the irrigation canals due to 2017 flash flood

Similarly, ~2 km long feeder road, that connects the neighborhood with the nearest highway, was damaged due to the flash flood as shown in Figs. 5a, 5b. The sign post (Fig. 5c) and slope protection structure (gabion wall) (Fig. 5d) were also damaged due to the flash flood. The damage extent was spread over nearly 200 m territory from the river channel. The feeder road was single lane unmetalled track along the river bank and no indication of the road was visible during the field visit. In the case of gabion wall, the damage occurred nearly 300 m from the river course.

Fig. 5 a) Road damage due to flash flood; ~2 km long stretch was washed away with no indication of road alignment; b) exposed subgrade of the road; c) damaged sign post along the road; and d) damage to the gabion wall

The water supply system was also destroyed by the flash flood as well (Fig. 6a); leading the affected families out of water supply for many days. The water supply pipes were found to be displaced and in many cases destroyed by the cobbles carried by flash floods. The electrical poles throughout the settlement were destroyed due to the flash flood (Fig. 6b). At least five electrical poles were observed to be washed away and the electricity supply was not resumed until the first week of August 2017.

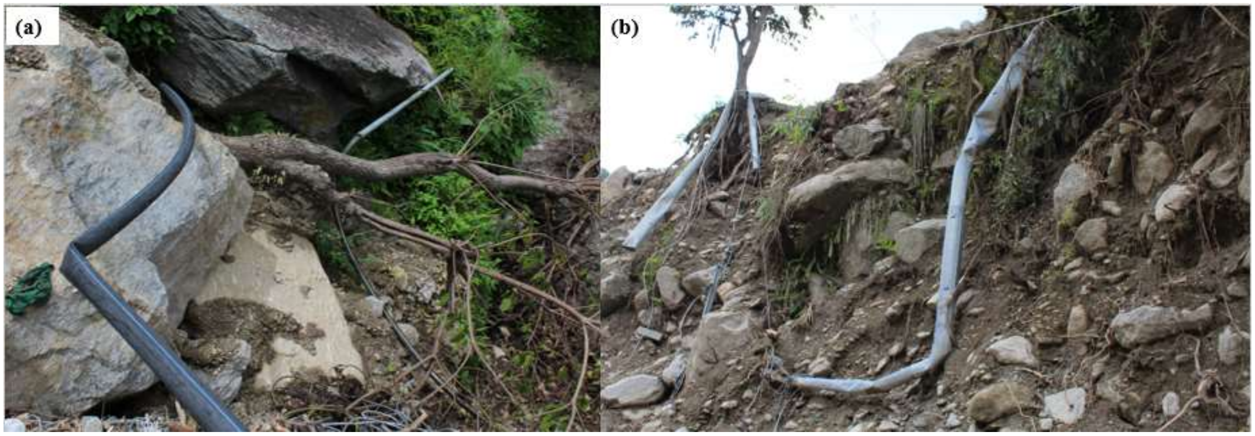

Fig. 6 a) Damage water supply pipeline and b) damaged to the electrical poles

3.3. Damage to vernacular buildings

In the Khimti settlement buildings constructed some 40 years ago were affected due to the Gorkha earthquake as well as the 2017 flash flood. Damage to the vernacular buildings due to the Gorkha earthquake is reported by Gautam et al. (2016), Gautam and Chaulagain (2016), and others. On the other hand, flash flood damage to the vernacular buildings has not been reported yet in Nepal to the best of authors' knowledge. Seismic vulnerability of vernacular buildings in Nepal is partly addressed by the work of Chaulagain et al. (2016); however, vulnerability due to multi-hazards is not found in existing literature. On the contrary, this study presents a reconnaissance based multi-hazard vulnerability scenario of vernacular stone masonry buildings in the middle mountains of Nepal. All the five buildings in the neighborhood were two storied vernacular stone masonry constructions with rectangular plans. Moreover, the buildings were non-engineered houses constructed as owner-built constructions using local resources and manpower. One of the buildings was destroyed with no remains left on the field due to the flood whereas all the surveyed buildings including the collapsed one were observed to be sustaining minor damage state (≤25% damage) due to the 2015 Gorkha earthquake. For this study, a generic damage classification considering the damage ratio obtained from the visual inspection was adopted as: minor damage (≤25%); major damage (26-50%); severe damage (51-75%); collapse (>75%). All the buildings were continued to use after the earthquake without any repair. The flow height for the destroyed building was estimated to be 3.5 m through the peak flood level measurement at the nearest point. All the four side walls were inundated in the case of the destroyed building thus the building should have been washed away. One of the buildings that sustained severe damage state (Fig. 7a) had dislocated wooden pillars and part of the wall was collapsed. Meanwhile, the building that sustained major damage had cracks on masonry walls (Fig. 7b). The building that sustained minor damage was not exposed to hydrodynamic forces (Fig. 8) thus the minor cracks due to the earthquake were not extended; unlike the building that sustained major damage. The building that sustained severe damage was exposed to the flow height of 3 m whereas the building that sustained major damage was exposed to the flow height of 1.5 m. The sum of observations concluded that hydrodynamic force was the major factor in damage aggravation and the extent of damage depended on the exposure percentage. In the case of collapse, severe damage, and major damage, the hydrodynamic forces along with boulders and cobbles may have played the vital role in damage aggravation if not collapse of the building. The collapsed structure was in the immediate vicinity of the flow thus the water current should have washed away the building.

Fig. 7 a) severe damage and b) major damage to vernacular buildings

Fig. 8 The flood unaffected but earthquake damaged (minor) vernacular building

3.4. Depth-damage curves and building vulnerability to multi-hazards

To the best of authors' knowledge, depth-damage curves for any type of Nepali structure do not exist. However, being a multi-hazard prone country, Nepal would observe frequent independent as well as cascading multi-hazards thus initial depiction of depth-damage curves integrated with the vulnerability scenario for vernacular stone masonry buildings are crucial to formulate. Depth-damage curves for vernacular buildings are particularly important in Nepal as most of the river settlements in the river banks have the vernacular mud-mortar stone masonry buildings and no flood and seismic countermeasures are provided. Moreover, consideration of multi-hazards is relatively new for Nepal, thus the changing context would be highlighting the need of depth-damage curves especially for the settlements near rivers and streams. A new approach of multi-hazards vulnerability depiction is presented in this study. This approach incorporates a plot showing both earthquake and flash flood vulnerability in the same depth-damage curve and one can easily distinguish the damage level and aggravation scenario due to individual event (Fig. 9). The percentage of damage as observed in the field are plotted along with the flow height in Fig. 8 to obtain the empirical depth-damage curve. Meanwhile, the depth-damage curve for vernacular Nepali residential buildings is compared with the existing depth damage curve proposed by Huizinga et al. (2017). As all buildings were sustaining minor damage state during the earthquake, exposure to flash flood led damage aggravation to each building that was exposed to flash flood. For instance, the building with minor damage state (≤25% damage) during earthquake was not exposed to the flood directly thus no further damage was occurred whereas the collapsed building was exposed to the hydrodynamic forces to all four facades during the flood event; hence got washed away. The flood damage was increased by 300% in the case of full inundation as observed during the field reconnaissance. The damage increment is calculated based on the existing damage level in all buildings (25%). For instance, if the building was now determined to have major damage level (50% damage), then the increment was obtained to be 100%. In the case of majority of inundation (3 m), the building damage was increased by 200% due to flash flood and in the case of half inundation, the damage was increased by 100% due to the flash flood in earthquake damaged building.

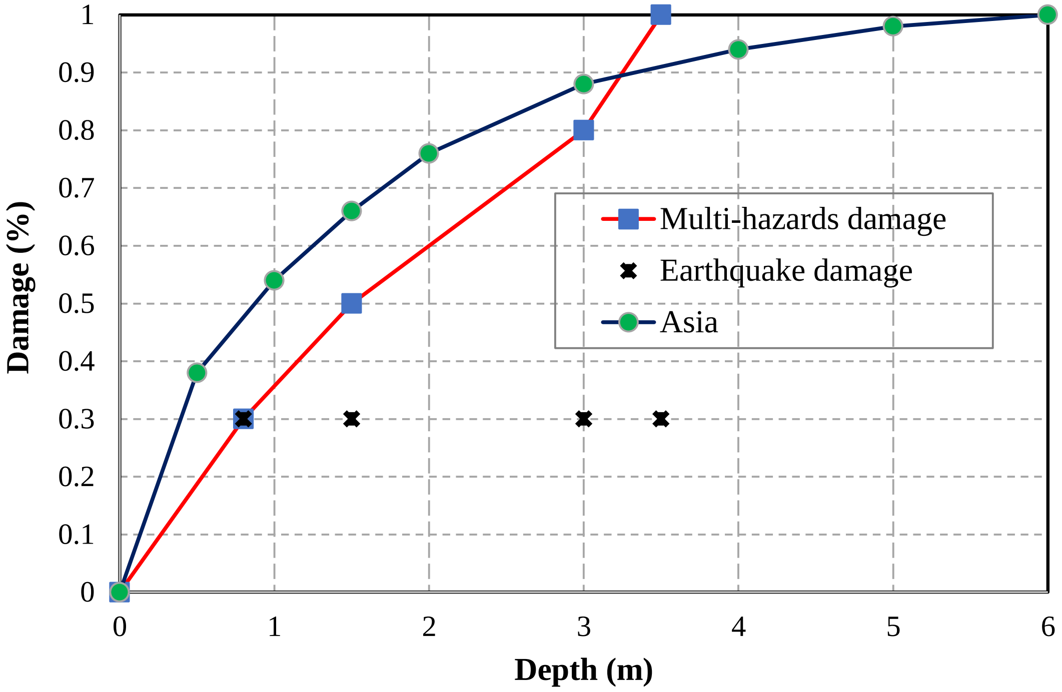

Fig. 9 Depth damage curve and earthquake damage scenario for vernacular buildings in Nepal

4. Discussion

A notable case of seismic excitation followed by the flash flood was depicted in central Nepal in between 2015 April and 2017 July. Due to lack of periodic repair and strengthening, the same buildings that sustained minor damage (≤25% damage based on visual inspection) during the Gorkha earthquake were exposed to the flash flood of 2017. As shown in Fig. 7, the damage was intensified due to independent multi-hazards (earthquake and flood). Empirically, the building damage could be related to the preceding event and exposure during the succeeding one. That is, if a building with minor damage during the earthquake is not exposed to hydrodynamic forces, then the damage aggravation would not be possible with the hydrostatic force alone. Whereas in the case of hydrodynamic forces, there is a possibility of damage aggravation by 300%.

As shown in Fig. 9, the depth-damage curve due to the flash flood in Nepal shows the damage in terms of residential buildings is slightly lower than the depth-damage curve for Asia (Huizinga et al. 2017). For example, at a depth of 1 m, 35% damage is expected in residential buildings, whereas in the case of the depth-damage curve for Asia, the damage is nearly 55%. It should be noted that the depth-damage curve depicted in this study is the one that incorporates multi-hazards damage scenario thus the actual damage in terms of a single event may be lower than 35%. Similarly, in the case of a higher depth, Nepali vernacular residential buildings sustain severer damage than the Asian depth-damage curve suggested by Huizinga et al. (2017). For example, Nepali residential buildings are expected to collapse at a depth of 3.5 m, whereas the depth-damage curve for Asia shows that the damage extent would be 90% only for the same inundation depth. Similarly, at a depth of around 3.2 m, the curves are intersected leading to similar damage state in the case of Nepal and Asia. It is worthy to note that unlike Europe and North America, local construction practices are greatly varied and such variation can be even grave within a country so exact comparison needs similar building types. Meanwhile, the confinement of collapse at the lower depth than the Asian collapse scenario should be attributed to the poor construction practice in Nepal wherein buildings usually do not consist lateral load resisting members and both the seismic and hydrodynamic forces may cause severe damage.

5. Conclusions

Effect of independent multi-hazards on structures and lifelines is studied forensically in this paper. Due to the rarity of notable independent multi-hazards, possible future damage scenarios are not well known as in the case of single events like earthquakes, floods, and landslides. To this end, the multi-hazards vulnerability analysis is gaining more attention globally and one of the notable examples was envisaged in central Nepal after the 2015 Gorkha earthquake and 2017

Chhatiune Khola flash flood. The sum of our observations highlights that the vernacular buildings in Nepal may suffer the damage aggravation up to 300% in the case of the earthquake followed by the flash flood. Various damage states (minor, major, severe, and collapse) and the damage extents (damage percentage based on visual inspection) are presented in terms of the depth-damage curve. The derived curve was compared with the depth-damage curve for Asian residential buildings. Our comparison depicts that Nepali vernacular buildings collapse at a lower depth than the other Asian counterparts whereas the damage extent at relatively lower depth is usually lower than other Asian residential buildings. The reason behind such lower damage could be attributed to short period of inundation due to terrain characteristics, whereas, in the case of higher depth of inundation, due to inherent vulnerability and extended use without any periodic repairs, collapse should have occurred at lower depth of inundation than in the case of other Asian residential buildings. Damage to bridge, roadway, roadway signals, electrical poles, and water supply in the case of multi-hazards are systematically presented in this study. As bridges in Nepal are designed providing free boards and this approach is not found to be fully rational in the changing climate when considering flash floods; improvements in design approaches are required in near future to downscale the damage to the superstructures of bridges. The depth-damage curves are derived in this study using small sample of damage occurrence, so further investigation is required for exhaustive comparison with the other curves

Being first of its type, this study focuses mostly on forensic approaches, however, numerical models can be incorporated in the future studies.

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