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A PROPOSAL OF BUILDING DAMAGE FUNCTIONS IN KATHMANDU VALLEY REFLECTING A SURVEY BY 2015 GORKHA EARTHQUAKE

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Abstract

Introduction: A development of building damage functions is an important factor in the earthquake disaster risk assessment together with scenario earthquakes and a building inventory. This paper introduces a proposal of the damage functions developed for buildings in the Kathmandu Valley, the capital of Nepal reflecting a building damage survey by the April 25, 2015 Gorkha Earthquake and additional studies.
Development of building damage functions:
Ground motion due to the Gorkha Earthquake: According to the earthquake wave records observed in the Kathmandu Valley and opened to the public, the average of peak ground acceleration (PGA) is around 150 gal (cm/sec^2), and the average of peak ground velocity (PGV) is around 80 kine (cm/sec), which is relatively large compared with the acceleration. The acceleration response spectrum takes a large value for buildings with long natural period.
Building inventory and damage survey: A rapid visual survey of buildings for 2 pilot municipalities (all 15,000 buildings for Bhaktapur municipality and all 53,000 buildings for Lalitpur municipality (LSMC)) was conducted with respect to the structural type and the damage grade by EMS-98, etc.
Building damage functions: The main target was the low to middle-rise buildings, and PGA was applied for the ground motion. Each function is expressed as a cumulative function of lognormal distribution (expressed by a mean value and a standard deviation only) so that the calculation can be performed on a MS Excel file, which facilitates the technical transfer to local counterparts and the revision of functions in future.
Structural types: Based on the damage survey result, four types of masonry and two types of RC structure, a total of six structural categories were adopted.
Influence of the ground: The functions were divided into two, at the center and the perimeter area in the Valley, through the elastic seismic response analysis for middle to low-rise buildings incorporating the ground predominant period.
Contents of additional studies: Additional studies were conducted to evaluate the damage ratio at higher PGA. **a) Simple seismic assessment:** Masonry and RC structure were assessed for PGA causing the heavy damage based on structural design drawings and material data for typical house, government building, school, and hospital. **b) Time-history response analysis**: Assuming three different types of restoring force characteristics (RC frame, RC frame with brick wall infill, and brick wall masonry), the responses by total eight waves observed at four locations x two directions in the Valley were calculated.
Conclusion: Building damage functions expressed by EMS-98 damage grade and PGA were developed including the empirical judgment for six structural categories at the center and the perimeter area in the Valley. For high-rise and historical buildings, a draft function was presented for reference. A suggestion to improve the seismic performance of buildings was provided to reduce the seismic risk. This study was conducted as a part of the project between Ministry of Urban Development (MoUD) and Japan International Cooperation Agency (JICA), "The Project for Assessment of Earthquake Disaster Risk for the Kathmandu Valley in Nepal".

Keywords: Building damage function; Kathmandu Valley; 2015 Gorkha Earthquake; Earthquake disaster risk; Building structural type

1. Introduction

A development of building damage functions is an important factor in an earthquake disaster risk assessment together with scenario earthquakes and a building inventory. This paper introduces a proposal of the damage functions developed for buildings in the Kathmandu Valley, the capital of Nepal reflecting a building damage survey by the April 25, 2015 Gorkha Earthquake (M 7.8) and additional studies.

2. Ground motion due to the 2015 Gorkha Earthquake

2.1 Observed strong motion records

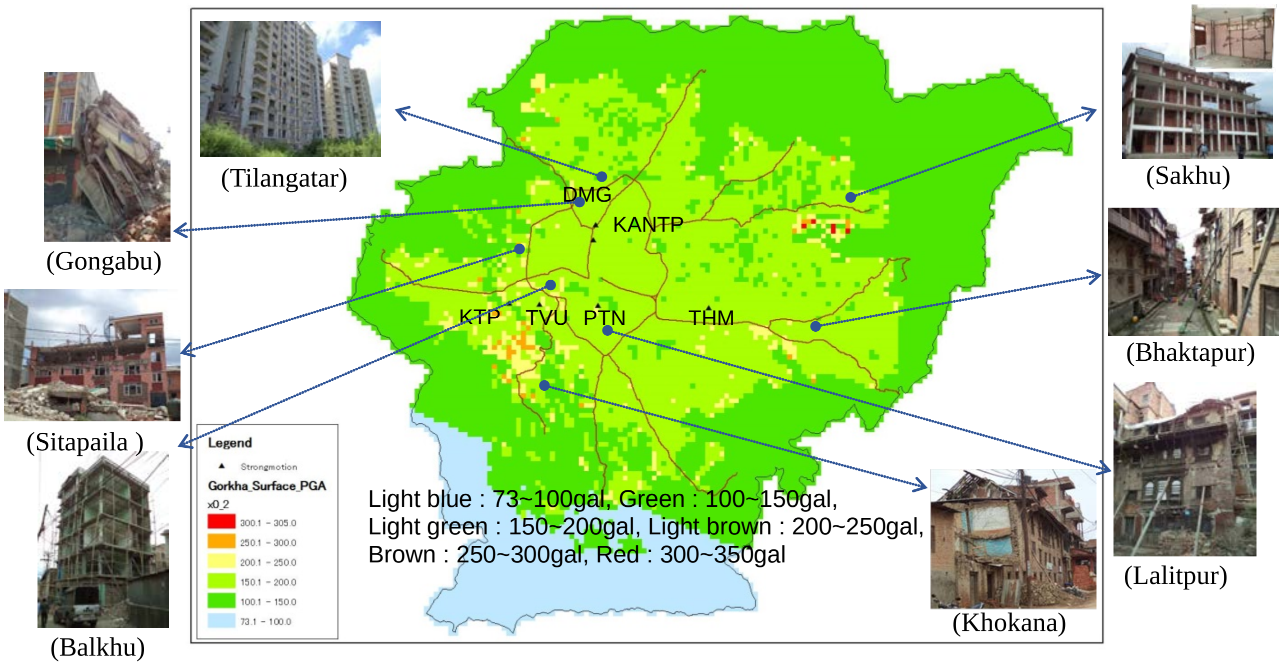
Observed records of Peak Ground Acceleration (PGA) and Peak Ground Velocity (PGV) in the Valley by the 2015 Gorkha Earthquake, which were opened to the public, are shown in Table 1. The records were taken at a ground floor level of a building. The average of PGA is around 150 gal, and the average of PGV is around 80 kine, which is relatively large compared with the acceleration. The acceleration response spectrum has large values for buildings with long natural periods. KTP is located near the rock area and TVU is located on an organic deposit at a hill. It is noted that no record was observed at the perimeter area in the Valley, especially at the north-west side such as Gongabu district where caused damages of RC buildings.

Table 1 - PGA and PGV of observed strong motion records by the 2015 Gorkha Earthquake

		KANTP (USGS)	DMG	KTP (H & T Univ.)	TVU (H & T Univ.)	PTN (H & T Univ.)	THM (H & T Univ.)
PGA (cm/sec^2)	NS	161	174	154	201	151	150
	EW	155	124	255	229	129	134
PGV (cm/sec)	NS	86	58	52	99	74	90
	EW	107	63	30	83	72	90

Source: KANTP (USGS), DMG (Department of Mining and Geology), KTP, TVU, PTN and THM (Hokkaido University and Tribhuvan University: H&T Univ.)

2.2 Analyzed PGA distribution in the Valley



Source: JICA Project final report (Photos were taken as of August 2015)

Fig. 1- Analyzed PGA distribution in the Valley by the 2015 Gorkha Earthquake with correction factor 0.2

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The earthquake ground motion by the 2015 Gorkha Earthquake was analyzed and reproduced. The result was much higher than the observed record. Then correction factor 0.2 was multiplied to meet the observed PGA. The distribution of PGA in the Valley can be read from Fig. 1. The locations of the strong motion stations are also shown. It can be said that in case of PGA is in the range of 150 gal to 200 gal at the center area in the Valley, then PGA more than 200 gal at some perimeter areas in the Valley was occurred.

Photos of damaged buildings are also shown in the figure, and a damage survey was conducted in Bhaktapur municipality and Lalitpur municipality (LSMC) respectively as shown in the next Section.

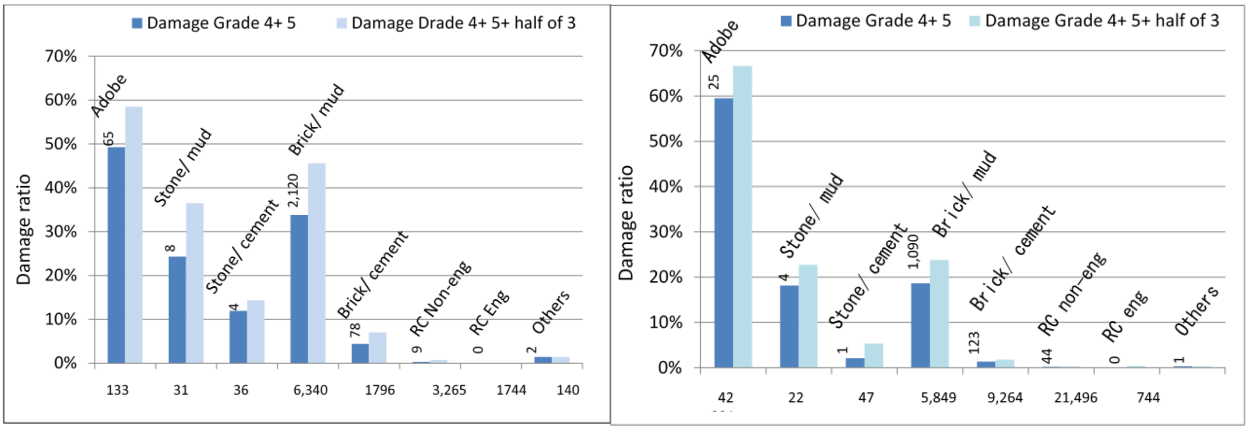
3. Building inventory and damage survey

A quick visual survey of buildings for 2 pilot municipalities in the valley (all 13,485 buildings at Bhaktapur municipality and all 53,000 buildings at Lalitpur municipality (LSMC)) was conducted with respect to the structural type and damage grade by EMS-98, etc. The damage grade of EMS-98 is shown in Reference Fig. These two municipalities are old historical areas with many brick houses. Bhaktapur municipality is located at the east side in the Valley, and Lalitpur municipality (LSMC) is located at the center in the Valley. Many houses of brick masonry with mud mortar joints were suffered the heavy damage.

3.1 Damage ratio of each structural type

The survey result of Bhaktapur municipality (total 13,485 buildings) is shown in the left of Fig. 2. The damage ratio (Grade 4+ 5) of EMS-98 is 33.4 % for “Brick masonry with mud mortar joints”, 4.4% for “Brick masonry with cement mortar joints” and 0.3 % for “RC non-engineered”.

The survey result of Lalitpur Sub-metropolitan city (total 37,785 buildings for Ward 1~22) is shown in the right of Fig. 2. The damage ratio (Grade 4+ 5) of EMS-98 is 18.7 % for “Brick masonry with mud mortar joints”, 1.3 % for “Brick masonry with cement mortar joints” and 0.2 % for “RC non-engineered”.



Source: JICA Project final report

Fig. 2 - Damage ratio of each structural type in Bhaktapur municipality (left) and in Lalitpur (LSMC) (right)

3.2 Roof (floor) type and constructed year for “Brick masonry with mud mortar joints”

The difference of damage ratio was studied for the roof type which is rigid type (RC roof) or flexible type (wooden roof), and the constructed year for “Brick masonry with mud mortar joints”. Number of buildings and the damage ratio by the damage grade per roof type of “Brick masonry with mud mortar joints”, are shown in Fig. 3.

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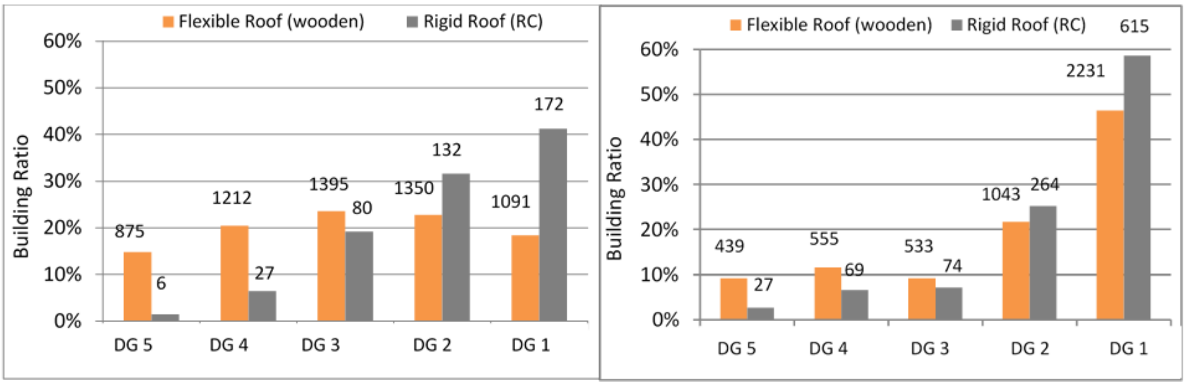
Bhaktapur (6,340 buildings) Lalitpur (Ward 1~22) (5,850 buildings)



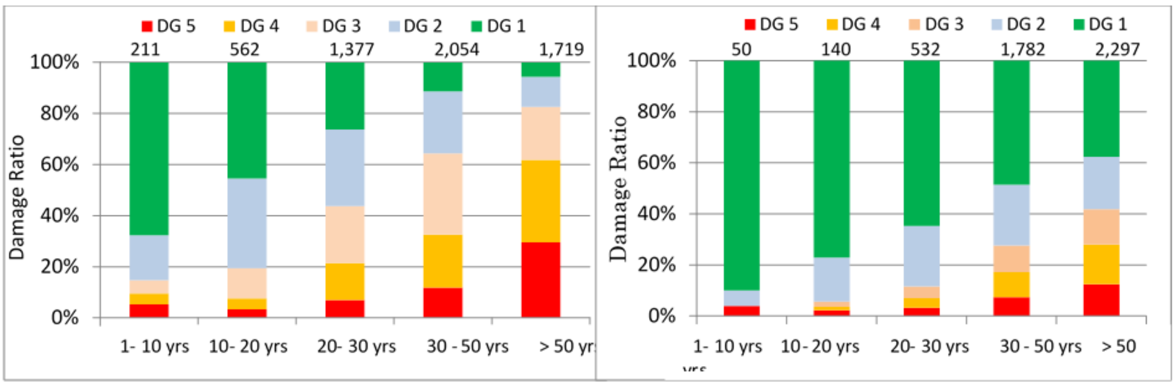
Source: JICA Project final report

Fig. 3 - Damage ratio by each damage grade per roof type of Brick masonry with mud mortar joints

The damage ratio by the constructed year per roof type is shown in Fig. 4 for flexible roof (wooden roof) and for rigid roof (RC roof) of "Brick masonry with mud mortar joints" respectively. The damage ratio of flexible roof is big, and the damage ratio of flexible roof constructed within 20 years is almost same to that of rigid roof. Then "Brick masonry with mud mortar joints" was separated into two categories.

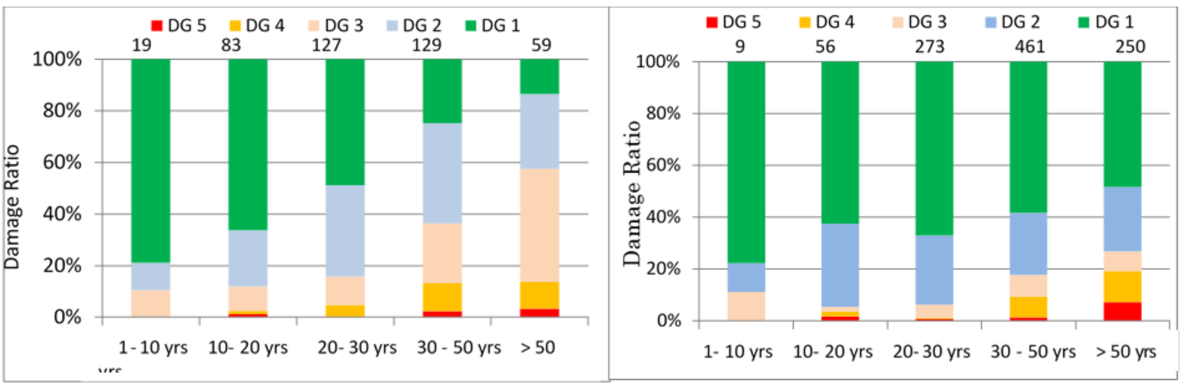
Flexible roof (wooden)

Bhaktapur (5,923buildings) Lalitpur (4,801 buildings, Ward 1~22)



Rigid roof (RC)

Bhaktapur (417 buildings) Lalitpur (1,049 buildings, Ward 1~22)



Source: JICA Project final report

Fig. 4 - Damage ratio by the constructed year for Brick with mud mortar joints and with roof type

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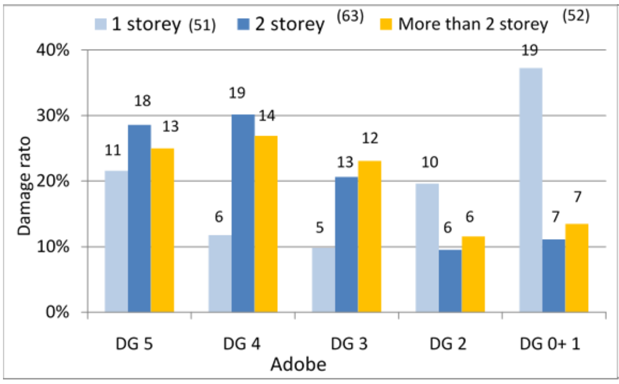
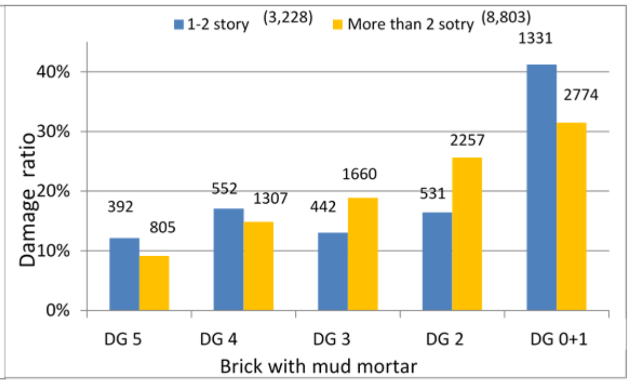
3.3 Damage ratio by the type and number of stories of masonry

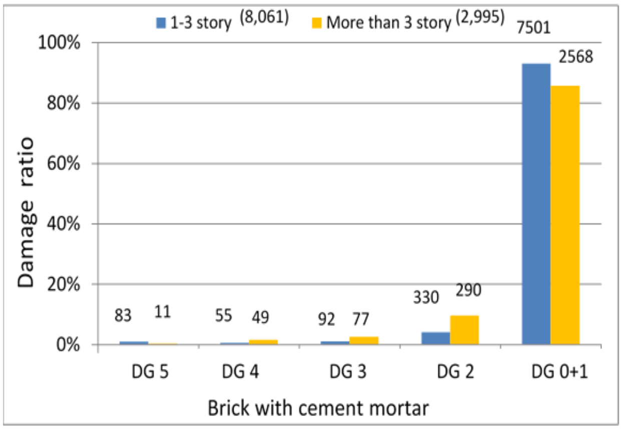
The damage ratio of the masonry type and number of stories were studied for the 2015 Gorkha Earthquake. The damage ratio was estimated for 1 story, 2 story and more than 2 story for “Adobe”, 1 to 2 story and more than 2 story for “Brick masonry with mud mortar joints”, 1 to 3 story and more than 3 story for “Brick masonry with cement mortar joints”. The result is shown in Fig. 5. There was clear difference of the damage ratio by the type of masonry. There was no clear difference by the number of stories.





a) Adobe, Bhaktapur municipality
+ Lalitpur sub-metropolitan city (LSMC) (Ward 1~22)

b) Brick masonry with mud mortar joints,
Bhaktapur municipality + LSMC (Ward 1~22)



Source: JICA Project final report

c) Brick masonry with cement mortar joints,
Bhaktapur municipality + LSMC (Ward 1~22)

Figure 5 - Damage ratio by the type of masonry and number of stories

4. Development of building damage functions

4.1 Building damage functions

The main target of damage functions was the low to mid-rise houses, those are typical buildings in the Valley, and PGA was applied for the expression of the ground motion. Each function is expressed as a cumulative function of lognormal distribution (expressed by a mean value and a standard deviation only) so that the calculation can be performed on a MS Excel file, which facilitates the technical transfer to local counterparts and the revision of the damage functions in future. Proposed method and related items for a development is shown in Fig. 6. A deterministic approach was taken in this study for the risk assessment of buildings. Existing damage functions including methodologies are shown in [3], [4] which are useful information.

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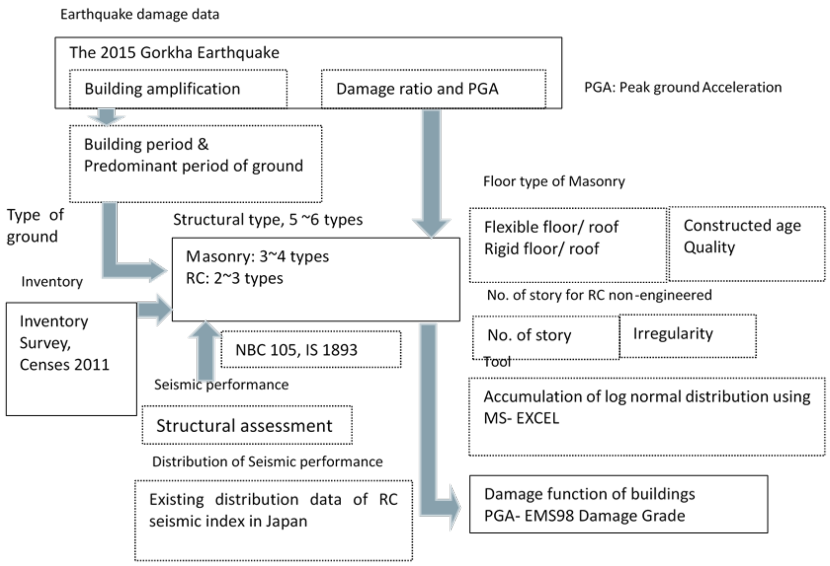

Source: JICA Project final report

Fig. 6 – A proposed methodology and related items for a development of building damage functions

4.2 Structural category of buildings

The buildings were classified into 8 structural types and 6 categories through the building inventory and damage survey. The number of buildings for “Stone with mud mortar” and “Stone with cement mortar” including “Others (Wooden, steel)” are not many, and the damage function of “Brick masonry with flex roof & 20 years and more”, and “Brick masonry with cement mortar joints” were applied respectively. Summary is shown in Table 2.

The ground of the Valley was divided into two areas based on its predominant period as explained later.

・Center area in the Valley : predominant period of the ground, Tg > 1.5 sec. & Tg ≤ 0.3 sec.

・Perimeter area in the Valley : predominant period of the ground 0.3 sec. < Tg ≤ 1.5 sec.

Table 2 - Category of damage functions and Structural types

Category of damage function suffix P denotes “Perimeter area”		Structural type (Numbering indicates the number of building inventory survey)	
1	Masonry 1, Masonry 1P	1. Adobe	
2	Masonry 2, Masonry 2P	2. Brick masonry with mud mortar, flex roof & 20 years and more	3. Stone with mud mortar
3	Masonry 3, Masonry 3P	4. Brick masonry with mud mortar, rigid roof, & flex roof with 1~20 years	
4	Masonry 4, Masonry 4P	5. Brick masonry with cement mortar	6. Stone with cement mortar, and Others
5	RC 1, RC 1p	7. RC non-engineered	
6	RC 2, RC 2p	8. RC engineered with low to mid-rise	

Source: JICA Project final report

4.3 Influence of the ground

4.3.1 Predominant period of the ground

The predominant period of the ground in the Valley is shown in Fig. 7. The center area in the Valley is longer than 1.5 sec. which is longer than building period of low to mid-rise buildings (such as the range of 0.3 to 0.7 sec.). On the other hand, the predominant period of the ground at the perimeter area is shorter than

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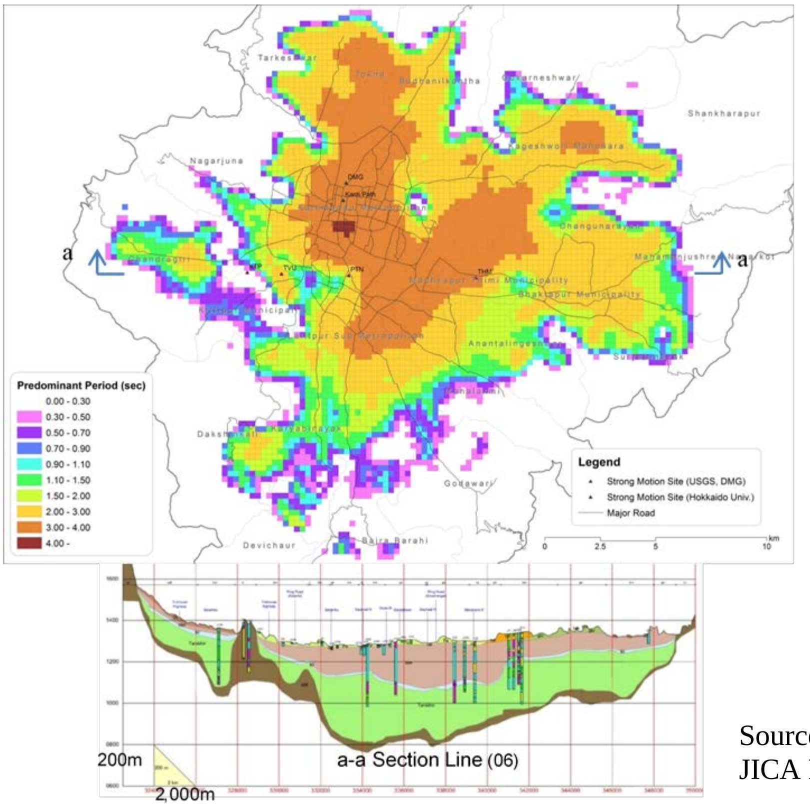
1.5 sec. which covers building periods of low to mid-rise. This difference of the predominant period of the ground will cause different response for buildings against an earthquake.



Source:
JICA Project final report

Fig. 7 - Predominant period of the ground (sec.) and a section (a-a section) of the ground

4.3.2 Response acceleration ratio of buildings and the area in the Valley

The distribution of the ground motion by the 2015 Gorkha Earthquake was analyzed as shown in Fig. 1. The peak ground acceleration (PGA) by the same Earthquake with correction factor 0.2 at each grid of 250m x 250m is shown in Fig. 8 a). Horizontal axis is the predominant period at each grid. It was supposed that a building period of low to mid-rise is 0.3sec. to 0.7sec. The average response acceleration with the building period of 0.3 sec. to 0.7 sec. is shown in Fig. 8 b). The average acceleration amplification ratio of the building period with 0.3 sec. to 0.7 sec. is shown in Fig. 8 c).

As far as the calculation of PGA by the 2015 Gorkha Earthquake with correction factor 0.2, calculated PGA is relatively high with a variation at the perimeter area, compared with PGA of the center area of the Valley as shown in Fig. 8 a). As far as the average acceleration amplification ratio of buildings with the period 0.3 sec. to 0.7 sec. is varied per the predominant period of the ground. The acceleration amplification ratio is relatively high at the peak value at 0.4 sec. and 1.0 sec. at the perimeter area in the Valley, and acceleration amplification ratio is smaller at the center area in the Valley as shown in Fig. 8 c).

From these Figures, it has been proposed to provide two kind of building damage functions allocating the ground in the Valley with the predominant period 1.5 sec. This was derived by the engineering judgement since the building period become longer depend on the stiffness decrease during the response. Then, the predominant period at the perimeter area was supposed as 0.3 sec. < Tg ≤ 1.5 sec., and the predominant period at the center area was supposed as Tg > 1.5 sec. & Tg ≤ 0.3 sec. as shown in Table 2.

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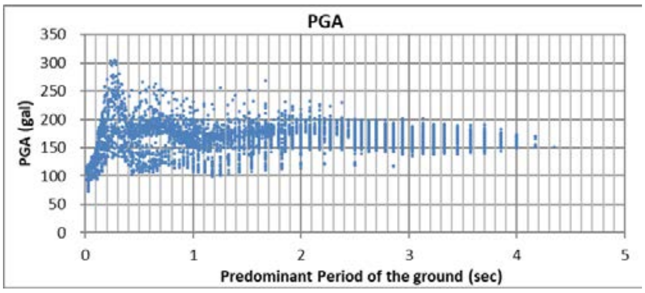
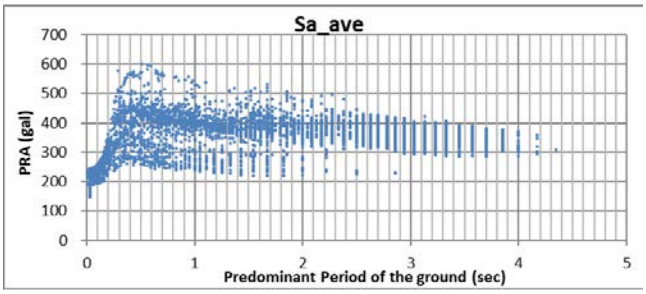
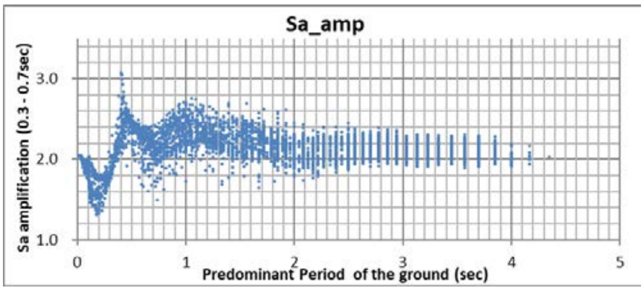


a) Predominant period and calculated PGA by 2015 Gorkha Earthquake with correction factor 0.2



b) Predominant period and average peak response acceleration of buildings

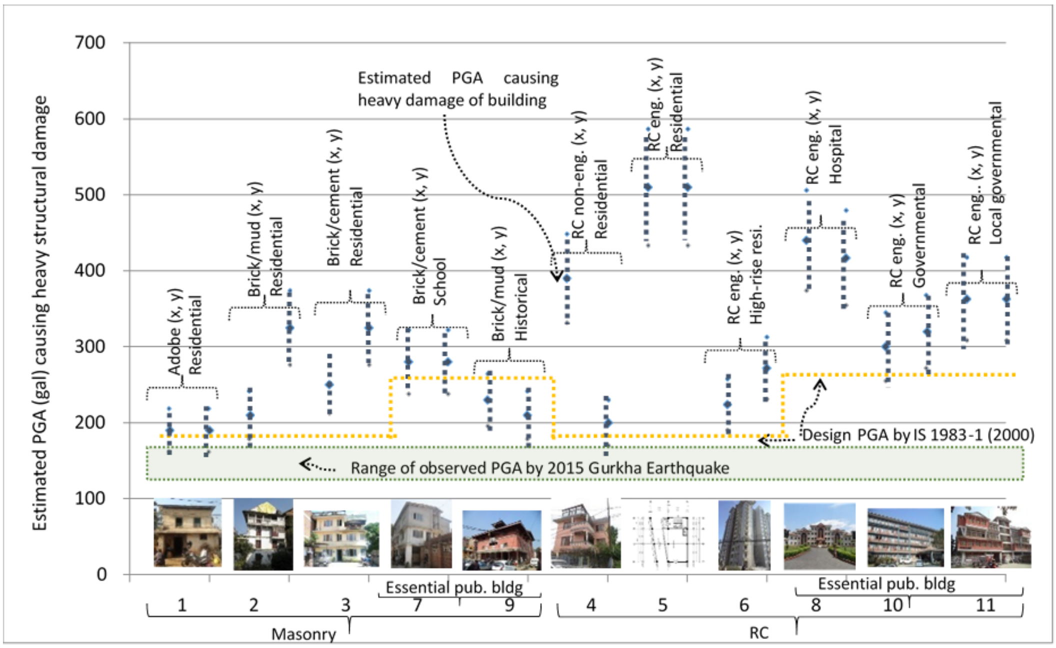


c) Predominant period and average acceleration amplification ratio of buildings   Source: JICA Project

Fig. 8 - Predominant period and calculated PGA by 2015 Gorkha Earthquake with correction factor 0.2, average response acceleration, and average acceleration amplification ratio of buildings with period 0.3 sec. to 0.7 sec.

4.4 Seismic assessment based on a detail building survey

Design drawings, material strength data and weights information of total 11 buildings were collected through a detail building survey, and the seismic capacity for both direction (x and y direction) of each building was assessed applying a simple method evaluating the strength and ductility. The summary is shown in Fig. 9.

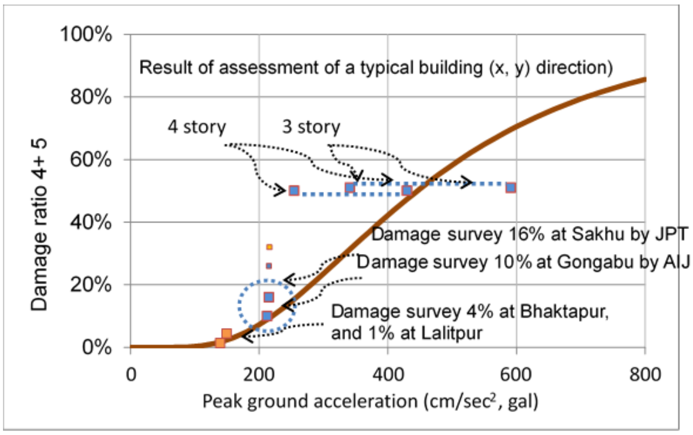


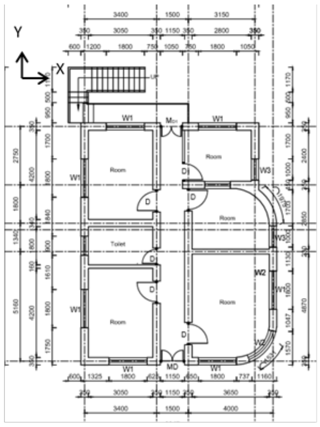
Note: Usage, 1~6: Residential, 7: School, 8: Hospital, 9: Historical building, 10 & 11: Governmental building, IS: Indian Standard 1983 (Part-1) 2016

Structural type, 1: Adobe, 2 & 9: Brick masonry with mud mortar joints, 3 & 7: Brick masonry with cement mortar joints, 4: Non-engineered RC, 5, 6, 8, 10 and 11: Engineered RC (including building designed by old design code) Source: JICA project final report

Fig. 9 - Risk assessment of 11 buildings based on a detailed building survey

The evaluated PGA causing the heavy damage has some range considering the variation of building response by earthquake waves and the reliable accuracy of the assessment (shown by a blue color dotted line). Effective PGA (gal) causing damage grade 4 (heavy damage) and more by EMS-98 was evaluated as the PGA causing 50% damage ratio of DG 4+5 for information. A “brick masonry with cement mortar joints” (Building No.3) is shown in Fig. 10 as an example. This is a residential building of 4 storied, and an assessment in case of 3 storied is also shown for reference.





Note: Gongabu [7] and Sakhu [9] are supposed as located at the perimeter area of the valley.

Fig. 10 - Result of assessment of a typical brick masonry with cement mortar joints and a proposed damage function (left), and a building plan with wall information (right) Source: JICA project final report

4.5 Time-history response analysis

Assuming restoring force characteristics for three different types (RC frame, RC frame with brick wall infill, and brick wall masonry), the responses by total eight waves (at four locations x two directions, likely to exhibit the valley features) observed in the Valley by the 2015 Gorkha earthquake were calculated. *K* value (Structural performance factor) of NBC105 (Seismic design of buildings in Nepal) [2] was applied, which is 4 for masonry, 2 for RC frame with infilled brick wall, and 1 for RC ductile frame. Degrading tri-linear model with shear type was supposed for RC ductile frame based on push-over analysis of a sample 3 story RC building (column sizes are 270mm square) of NBC205 [2]. The supposed limit of response ductility ratio is 4 to 5. The stiffness and strength were multiplied by two for RC frame with infilled brick wall and supposed ductility ratio is 2. Supposed ductility ratio is 1 for masonry. The damping constant was assumed as 4% for each case.

The result is shown in Fig. 11 (left). A red mark shows a response with the collapse state. As far as “brick masonry with cement mortar joints”, one case only out of eight cases was evaluated as the collapse. Since the value of strength divided by the building weight of “brick masonry with mud mortar joints” might be around 0.2 or less, many buildings were evaluated to be suffered the damages. As far as RC buildings, “RC frame with infilled brick wall” would be common, and buildings were evaluated to be suffered some minor and moderate damages but not heavy damages at the center in the Valley.

The responses by 8 waves with the input of PGA 300 gal, which are approximately two times of the observed values of the 2015 Gorkha Earthquake, against RC buildings with supposed several different restoring force characteristics are shown in Fig. 11 (right). A red mark shows a response with the collapse state. The result was utilized to evaluate the damage ratio and the variation of responses.

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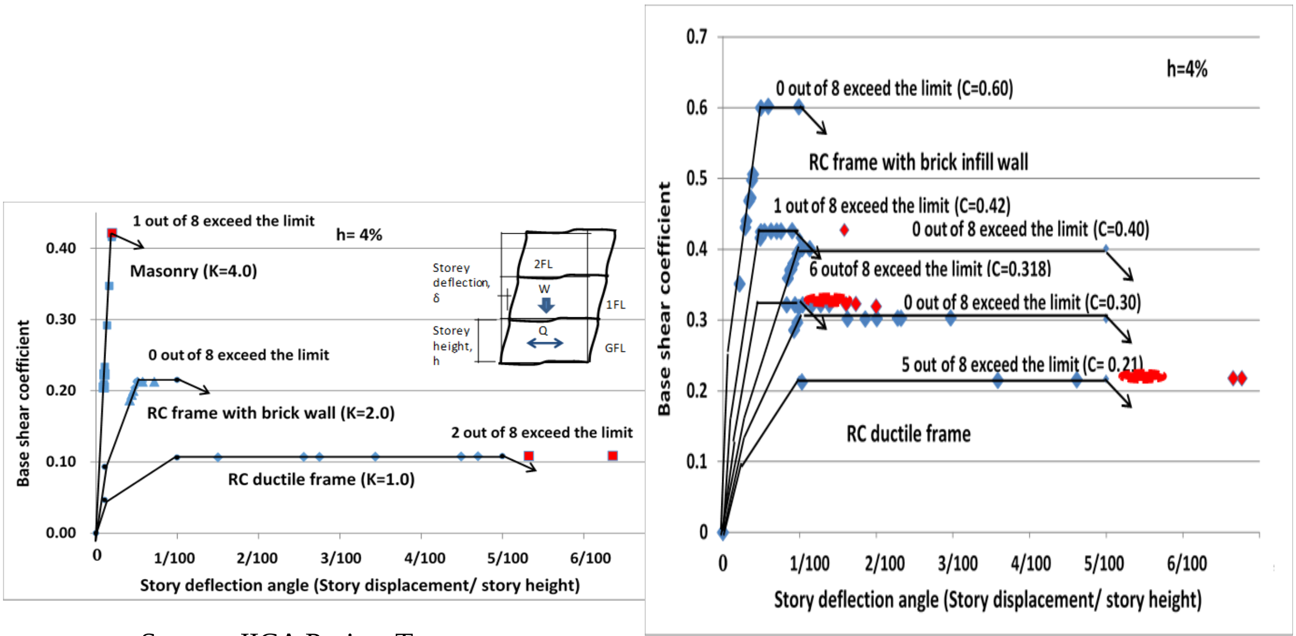


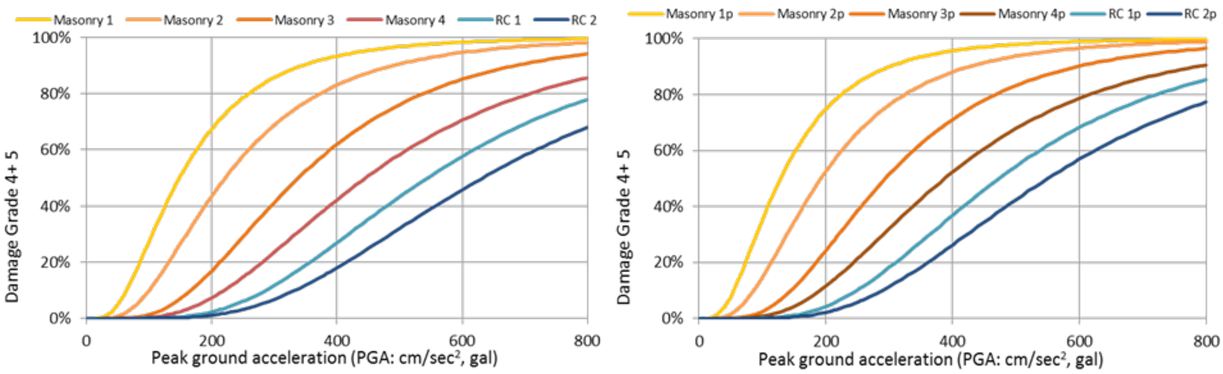
Source: JICA Project Team

Fig. 11 - Supposed 3 restoring force characteristics and responses by recorded 8 waves of the 2015 Gorkha Earthquake (left) and the responses with input of PGA 300gal of Gorkha Earthquake waves (right)

5. Proposed damage functions for buildings

5.1 Proposed damage functions for buildings

Proposed damage functions for buildings are shown in Fig. 12. Damage functions at the center area and the perimeter area in the Valley are provided per the predominant period of the ground. The main target is low to mid-rise buildings. The category of the damage functions and structural types are shown in Table 2. Damage functions of buildings show the damage ratio for buildings at each grid, and were supposed to show the damage probability for a specific structure such as a public building.



a) Center area in the Valley (predominant period of the ground, Tg > 1.5sec & Tg ≤0.3sec)

b) Perimeter area in the Valley, suffix p (predominant period of the ground, 0.3sec< Tg ≤ 1.5sec)

Source: JICA project final report

Fig. 12 - Proposed Damage Functions for DG 4+ 5 at the center area and the perimeter area

5.2 Proposed damage functions for each damage grade

5.2.1 Center area

Proposed damage functions for DG 4+5, DG 3+4+5, DG 2+3+4+5 at the center area are shown in Fig.13.

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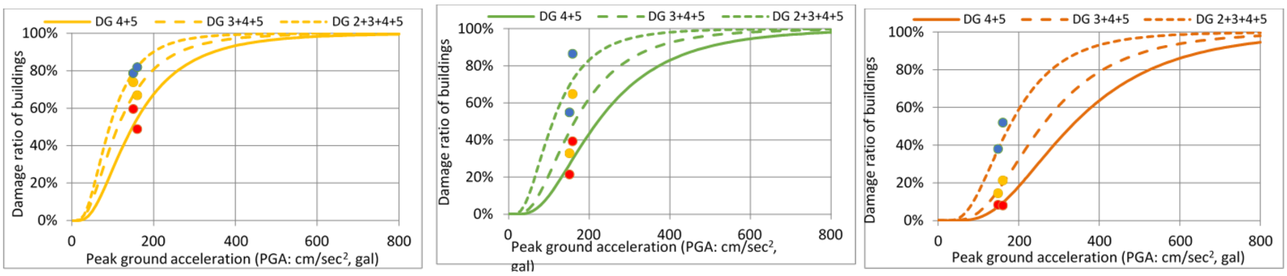
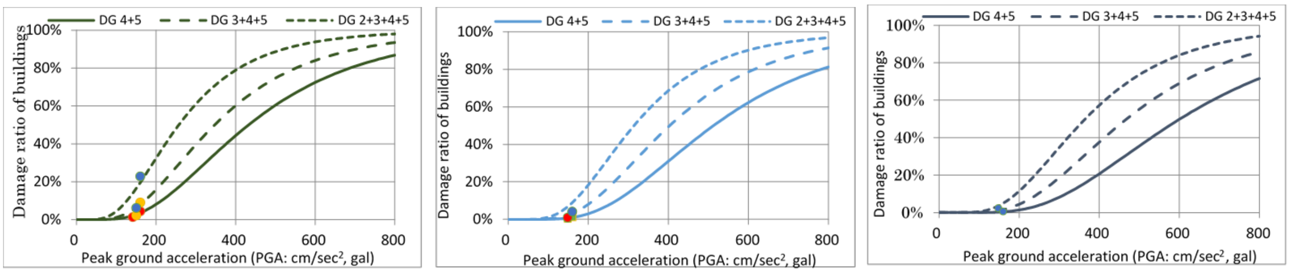
1) Masonry 1(Adobe) 2) Masonry 2 (Brick with mud mor.(1)) 3) Masonry 3 (Brick with mud mor. (2))



4) Masonry 4 (Brick with cement mor.) 5) RC 1 (RC non- engineered) 6) RC 2 (RC engineered)

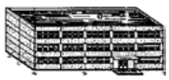
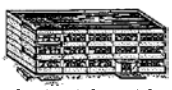
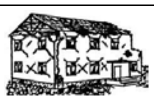
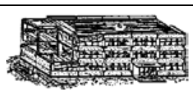


Legend: Damage data surveyed at Bhaktapur and Lalitpur (LMC, Ward 1~22) due to the 2015 Gorkha Earthquake Source: JICA Project Team ● : DG 4+5 ● : DG 3+4+5 ● : DG 2+3+4+5

Fig. 13 - Proposed damage functions of each damage grade at the center area

5.2.2 Perimeter area

Proposed damage functions at the perimeter area have been developed, and compared with the observed damage data, at Gongabu by AIJ [7], at Sankhu and Khokana by NIED [8], and at Sankhu by JICA Project Team [9], with supposed PGA 200gal and more for the comparison purpose.

Masonry		Reinforced Concrete	
 **Grade 1: Negligible to slight damage**	**Structural damage: No** **Non-structural damage: Slight** Hair-line cracks in very few walls. Fall of small pieces of plaster only. Fall of loose stones from upper parts of buildings in very few cases.	 **Grade 1: Negligible to slight damage**	**Structural damage: No** **Non-structural damage: Slight** Fine cracks in plaster overframe members or in walls at the base. Fine cracks in partitions and infills.
 **Grade 2: Moderate damage**	**Structural damage: Slight** **Non-structural damage: Moderate** Cracks in many walls. Fall of fairly large pieces of plaster. Partial collapse of chimneys.	 **Grade 2: Moderate damage**	**Structural damage: Slight** **Non-structural damage: Moderate** Cracks in columns and beams of frames and in structural walls. Cracks in partition and infill walls; fall of brittle cladding and plaster. Falling of mortar from the joints of wall panels.
 **Grade 3: Substantial to heavy damage**	**Structural damage: Moderate** **Non-structural damage: Heavy** Large and extensive cracks in most walls. Roof tiles detach. Chimneys fracture at the roof line; failure of individual non-structural elements (partitions, gable walls).	 **Grade 3: Substantial to heavy damage**	**Structural damage: Moderate** **Non-structural damage: Heavy** Cracks in columns and beam column joints of frames at the base and at joints of coupled walls. Spalling of concrete cover, buckling of reinforced bars. Large cracks in partition and infill walls, failure of individual infill panels.
 **Grade 4: Very heavy damage**	**Structural damage: Heavy** **Non-structural damage: Very heavy** Serious failure of walls; partial structural failure of roofs and floors.	 **Grade 4: Very heavy damage**	**Structural damage: Heavy** **Non-structural damage: Very heavy** Large cracks in structural elements with compression failure of concrete and fracture of re -bars; bond failure of beam reinforced bars; tilting of columns. Collapse of a few columns or of a single upper floor.
 **Grade 5: Destruction**	**Structural damage: very heavy** Total or near total collapse.	 **Grade 5: Destruction**	**Structural damage: very heavy** Collapse of ground floor or parts (e.g. wings) of buildings.

Reference Fig. - Damage Grade of EMS-98 for Masonry (left) and Reinforced Concrete (right), Source EMS

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6. Conclusion

Building damage functions play an important role in the earthquake risk assessment. The damage functions with six categories focusing on the low to mid-rise buildings expressed by EMS-98 damage grade and PGA have been developed taking account the empirical and engineering judgments. The damage functions have been expressed in a simple manner considering the technical transfer. Since PGA observed at the 2015 Gorkha Earthquake was at the similar level at the center area in the Valley, the structural assessment of typical structural types, which is expressed by PGA causing the heavy damage and more, was conducted to develop the functions. The functions have been proposed at the center and at the perimeter area respectively considering the difference of the ground predominant period in the Valley, because it was assessed that the building response at the perimeter area is higher than that at the center area. In the report [1], draft functions for high-rise and historical buildings, were presented for reference. A suggestion to improve the seismic performance of buildings was also provided to reduce the seismic risk. It is expected to improve and update the proposed damage functions especially for RC buildings, which have limited damage data, by the counterparts through the accumulation of research activities in future.

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