- Technical Paper -

RAPID SEISMIC EVALUATION METHOD OF EXISTING RC BUILDINGS WITH MASONRY INFILL BASED ON EARTHQAUKE DAMAGE

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ABSTRACT

In developing countries, there are enormous stocks of vulnerable masonry infilled RC buildings, which are required to be identified for retrofitting and/or strengthening. This study presents a simple screening procedure, based on the concept of Shiga Map, which considers the cross-sectional areas of RC columns and masonry infills, and their shear strengths as well as corresponding seismic demand. This procedure is further improved by incorporating the effects of secondary factors such as plan irregularities and presence of soft story, which have influences on the seismic behavior.

Keywords: Seismic Capacity Index, Modified Shiga Map, Existing RC building, Masonry infill.

1. INTRODUCTION

Past earthquake damages in developing countries have been exhibiting the necessity of seismic evaluation and strengthening of existing buildings. These developing countries usually have masonry infilled-RC buildings as shown in Fig. 1, where the infill contributes to stiffness and strength of the RC frame. In addition, there exist enormous stocks of vulnerable buildings in these countries. Identifying these vulnerable buildings and prioritizing for retrofitting and/or strengthening are the key issues in terms of time and costs. Therefore, it is necessary to find out a quick and reliable evaluation procedure.

Fig. 1 Damage of Building with Masonry infill in 2015 Nepal Earthquake

Many researchers developed simplified methods for quick identification of the vulnerable buildings using some building parameters based on the survey of past earthquake-damaged buildings [1, 2]. These methods consider only the dimensions of the vertical members and floor plan for calculation of seismic capacity, and compare with the corresponding seismic demand.

Shiga et al. [1] proposed a practical method named ‘Shiga Map’ to rank low-rise RC buildings according to their seismic vulnerability after investigating the damaged buildings in the 1968 Tokachi-oki earthquake, in Japan. This method is based on the average shear stress of columns and RC walls, and wall area ratio, which represents a ratio of the cross-sectional areas of RC walls to total floor area. This method also considers seismic demand to set up boundaries for identifying buildings as unsafe or safe. However, this method is applicable only for the buildings with RC shear walls, which does not consider the effects of masonry infills.

Hasan and Sozen [2] presented a simplified method with vulnerability indices (column and wall area indices) to rank RC building according to their vulnerability against seismic damages. In order to define the rank or screen out the most vulnerable buildings, a two-dimensional plot was used considering two simple parameters; the ratio of column and masonry infill area to total floor area at the base (column and wall indices). They observed the vulnerability of reinforced concrete structures decreases with increasing the combination of column and masonry wall area ratio.

The aforementioned simple parameters can give a quite reasonable indication for seismic capacity evaluation of existing buildings, but actual damage survey reveals that there are other factors responsible for influencing the seismic behavior, despite of the adequate existence of column and masonry wall area ratio. Therefore, there remains a need for improvement in the accuracy of the evaluation procedure by considering other secondary factors that can be easily collected from rapid visual survey.

As previously mentioned, Shiga`s method is applicable for only buildings with RC shear wall and validated based on actual damage databases in Japan. However, the new points in this study are application and recalibration of Shiga`s method to masonry infilled RC structures considering seismicity in different region. Therefore, this paper presents a study on a rapid screening procedure using the concept of Shiga map,

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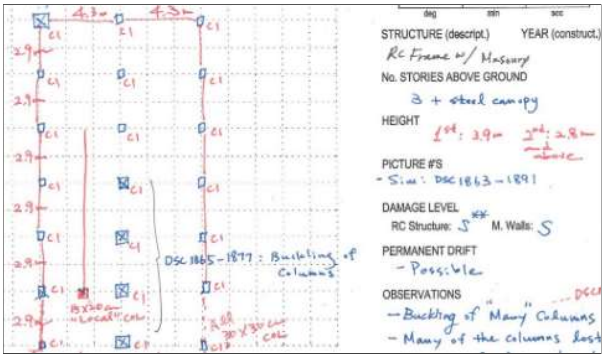
focusing on the cross-sectional areas of masonry infills and columns in existing infilled masonry-RC buildings. Firstly, the applicability of these parameters for seismic screening are verified, based on the past earthquake databases, and the boundary lines, determining expected damage states, are provided. Secondly, the accuracy of the procedure has been improved by taking into account the influence of structural configuration regarded as the secondary factors in addition to the structural elements (cross sectional area of column and masonry infill as well as their strength).

2. DAMAGE DATABASE OF RECENT EARTHQUAKES

2.1 Overview of Database

From the earthquake damage databases (www.datacenterhub.org), total 314 buildings have been selected for this study. Among these data, 173 buildings for the 2016 Ecuador Earthquake, 141 buildings for the 2015 Nepal Earthquake are taken from post-earthquake damaged survey databases [3, 4]. Fig. 2 shows a typical survey datasheet used to record the information during the survey.



DSC 1865–1877 : Buckling of Columns

STRUCTURE (descript.) YEAR (construct.)
RC Frame w/ Masonry
No. STORIES ABOVE GROUND
3 + steel canopy
HEIGHT
1st: 3.9m 2nd: 2.8m and above
PICTURE #S
- Sim: DSC 1863–1891
DAMAGE LEVEL
RC Structure: S** M. Walls: S
PERMANENT DRIFT
- Possible
OBSERVATIONS
- Buckling of "Many" Columns
- Many of the columns lost

Fig. 2 A Typical Survey Data Sheet [3, 4]

Fig. 3 shows the distribution of story number with the distribution percentage of building numbers, investigated in each country. Most of the buildings are from two to four storied buildings.

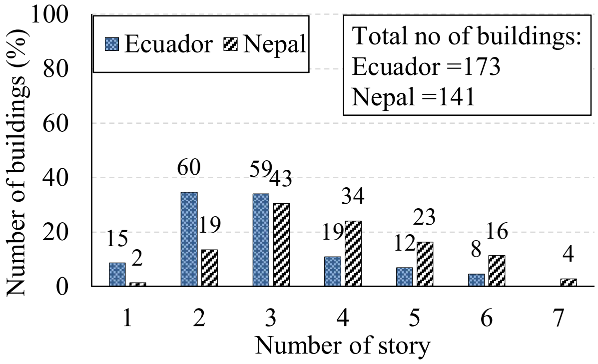


Fig. 3 Distribution (%) of Building Number with Number of Story

2.2 Seismic Ground Motion Characteristics

Acceleration response spectra of all ground motions in the investigated countries are shown in Fig. 4 [5, 6]. The peak response accelerations are found approximately 1.3g (EW direction), and 0.6g (EW direction) for Ecuador and Nepal, respectively considering 5% damping ratio. For estimation of seismic demand for each ground motion, approximate response acceleration has been considered for building with short period less than 0.5 second.

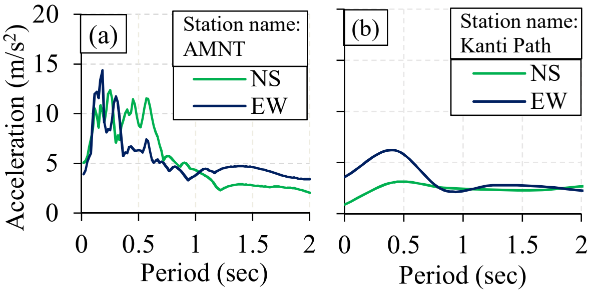
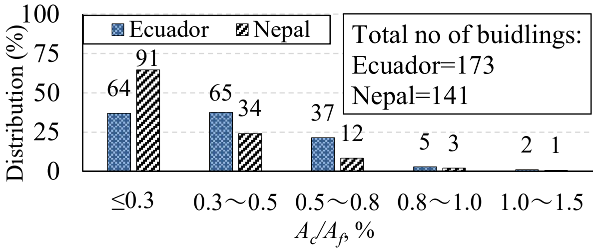


Fig. 4 Acceleration Response Spectra of (a) Ecuador earthquake, (b) Nepal earthquake

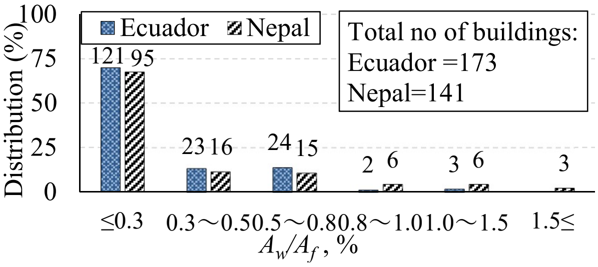
2.3 Building Characteristics

As mentioned earlier, all investigated buildings in the inventories are RC structures with masonry infill as shown in Fig. 1. A survey of earthquake-damaged buildings in Nepal reported that the typical column size is 227 mm in square and rectangular column size is 227 x 305 mm [7]. The masonry wall thickness was observed 230 mm and 115 mm for exterior and interior wall respectively for Nepal [8]. It has been observed that for the usual practice for Ecuador, the masonry wall thickness are 100 mm and 230 mm and commonly built with burnt clay bricks [3, 4].

Fig. 5 shows the ratio of column areas at first story to the total floor areas above first story, defined as the column index (A_c/A_f), and the ratio of infill areas at first story to the total floor areas above first story, defined as the wall index (A_w/A_f), for the surveyed buildings. Masonry infill area (A_w) has been calculated in two orthogonal directions and the minimum A_w has been considered to calculate the wall index. The wall and the column indices ranged from 0 to 2.0% and 0 to 1.5%, respectively. The major wall index is less than 0.3% for the most of the investigated buildings.



(a) Column Index



(b) Wall Index

Fig. 5 Distribution (%) according to (a) Column Index, (b) Wall Index, (in percentage)

2.4 Damage Criteria

The data recorded during these surveys [3, 4] consist of descriptions and photographs of damage, and visual inspection. Fig. 6 shows some photographs of severely damaged buildings. A damage rating system was used in the surveys in order to classify the damage conditions. Definitions of each damage state for Nepal and Ecuador earthquakes [3, 4] are shown in Table 1.

(a) Severely damage Irregular building

(b) Collapse due to soft story effect

(c) Severely damaged RC frame with Masonry infill

Fig. 6 Severe damage buildings [3, 4]

Table 1. Damage Criteria for both Earthquakes

Damage state	Damage Descriptions
Light	Hairline flexural cracks
Moderate	Wider cracks, concrete spalling
Severe	At least one element has been failed.

3. DESCRIPTION OF THE PROCEDURE

The main target of this study is to calculate seismic capacity index of structures which is based on seismic capacity of vertical members and Modification factors. Modification factors are generally based on the secondary parameters that influence the seismic behavior in addition to fundamental parameters. The following section has been described about the calculation of seismic capacity index, which is based on seismic capacity of vertical elements (column and masonry infills).

3.1 Calculation of Seismic Capacity Index

The basic concept for calculation of seismic capacity index is based on the concept of Shiga Map [1]. The seismic capacity index is calculated with column and masonry wall strength, which is product of the average shear stress and cross sectional areas of columns and masonry walls, as shown at the left side of Eq. 1. The seismic demand can be estimated from the product of the total building weight (*W),* the reduction factor (D_s), and the response acceleration (C_a) considering the building ductility (Eq. 1).

Seismic Capacity ≥Seismic Demand

$$\tau_c.A_c + \tau_w.A_w \geq W.D_s.C_a \tag{1}$$

Where, τ_c and τ_w are the average shear strength of columns and masonry infill walls. Dividing both side of Eq. 1 by A_f, which is the area of total floor above first story, Eq. 2 is obtained.

$$\tau_c.A_c/A_f + \tau_w.A_w/A_f \geq W/A_f.D_s.C_a \tag{2}$$

Where, A_c/A_f and A_w/A_f are known as Column Index (*CI*) and Masonry Wall Index (*WI*) in percentage. W/A_f is the unit weight of structure.

The following assumptions have been made for the seismic capacity and seismic demand computations in Eq. 2:

(a) τ_c ; The shear strength of column depends on the failure criteria as either shear or flexure based on damage investigation and experimental data [1, 9]. The Japan Building Disaster Prevention Association (JBDPA) standard [9] proposed shear strength of column is 1.0 MPa for the first level screening procedure based on shear span ratio, where h_o/D ranged from 2 to 6 (h_o is the clear height, D is the column width). In this study, therefore, the average shear stress for columns is tentatively assumed 1.0 Mpa.

(b) τ_w ; For shear strength of masonry infill (τ_w), ASCE 41-06 seismic guideline [10] estimated 34 psi (0.24 MPa) for good masonry condition. From the reference above, considering material properties for other countries, a unique value of 0.2 MPa, which is a conservative value, is adopted as lower boundary of the lateral shear strength (τ_w) of masonry infill.

(c) W/A_f ; For the calculation of seismic demand, the average weight per unit area (W/A_f) is approximately set 11kN/m^2, according to common design practice.

(d) D_s ; Two boundaries are assumed for identifying the building's damage categories. The lines, proposed for the boundaries, are set according to reduction factors (D_s) considering building ductility. In this paper, reduction factor (D_s) of 1.0 is assumed for the buildings in an elastic range after the earthquake. On the other hand, ASCE 7-10 [11] considers *R* factor*,* which is 1.5, as the response modification factor for reinforced concrete structure with unreinforced masonry wall. *R* is the ratio between elastic shear strength (V_e) to design shear strength (V_d) as shown in Fig. 7.

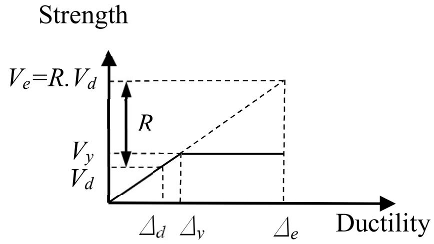


Fig. 7 Equivalence of ductility and Reduction factor based on ASCE 7-10 [11]

According to Fig. 7, V_e, V_y, V_d are the elastic, yield and design strength, and Δ_e, Δ_y, Δ_d are the corresponding deformation at each strength. Thus, for inelastic range, reduction factor (D_s) of 0.6 is adopted as lower boundary, which is inverse of R factor of 1.5 proposed in the standard.

(e) C_a ; As stated earlier from Fig. 4, the response acceleration, C_a, is roughly estimated for buildings with short period (less than 0.5 second) as 0.9g and 0.6g for Ecuador and Nepal respectively.

3.2 Results and Discussion on Seismic Capacity with Demand

The seismic capacity indices (column and wall indices) have been calculated for surveyed buildings of each earthquake damage database. These indices for both principal directions in plan are plotted as shown in Fig. 8 for Ecuador and Nepal, respectively. The two diagonal lines in the Fig. 8 are drawn according to their seismic demand for each ground motion of corresponding earthquakes. These lines designated as upper and lower boundary, defining the map into three different zones namely zone A, zone B and zone C. Each zone describes the light, moderate and severe damage, respectively.

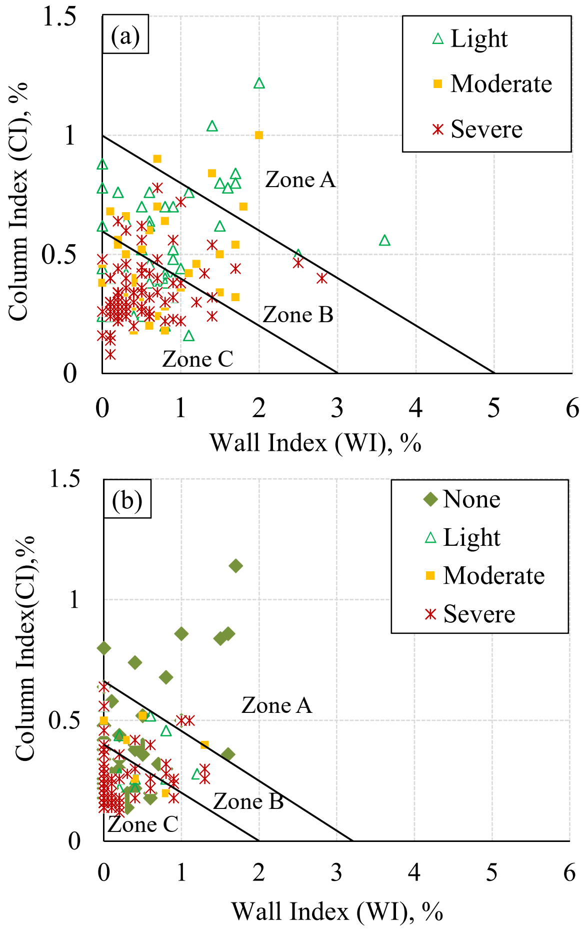


Fig. 8 Evaluation map with WI and CI with Damage state for (a) Ecuador, (b) Nepal Earthquake.

In Fig. 8, buildings located at zone C are considered the most vulnerable and expected to have severe damage. Buildings located at zone A are considered to have enough seismic capacity to avoid severe damage. For Ecuador, almost more than 80% of total severely damaged buildings are located in zone C. In addition, there are no severely damaged buildings at zone A except a few moderately damaged buildings. In the case of Nepal, approximately 70% of total severely damaged buildings are located at zone C and more than 55% of total buildings located at this zone are identified as severely damaged.

From the above discussion, it has been observed that zone A and B herein referred as light and moderate zone contain some severely damaged buildings, although the column and wall area ratio are quite high. It reveals that there are other factors, which are responsible to be severely damaged for these buildings. That is, seismic capacity of these buildings cannot resist against the seismic demand due to negative influence for these factors. In order to improve the degree of accuracy and reliability of this procedure, the effects of other factors have been included as modification factor in seismic capacity evaluation. The following sections are described the calculation procedure and the effectiveness for inclusion of these parameters.

4. CALCULATION OF MODIFICATION FACTOR

Many studies and post-earthquake observations exhibit that the seismic performance is amplified due to the buildings with irregularity in plan and elevation as well as by other vulnerable parameters. In order to include the effect of these parameters into seismic capacity evaluation, a modification factor has been considered in this study. The modification factor is a reduction factor which takes into account the negative influence of these prevalent architectural features. In this study, damage pattern and the information obtained through the survey has been used to identify the parameters for modification factors. Some common parameters such as horizontal imbalance or plan irregularity, aspect ratio and existence of soft story that are reported to be found in most of damaged buildings. Therefore, these parameters are employed for calculation of modification factor.

Japan Building Disaster Prevention Association (JBDPA) [9] proposed guideline for seismic capacity evaluation which does not cover masonry infilled RC buildings. In this study, JBDPA [9] manual is extended to be used for the masonry infilled RC structures for modifying the basic seismic index, according to horizontal and vertical irregularity. Therefore, the modification factor (MF) is computed by using Eq. 3 based on JBDPA standard [9].

Modification Factor (M.F.):

$$M.F. = C_{PI} \times C_{AR} \times C_{SS} \qquad (3)$$

Where, C_{PI}, C_{AR}, and C_{SS} are the degree of incidence for plan irregularity, aspect ratio, and soft story respectively.

According to JBDPA standard [9], the degree of incidence for each parameter is calculated by Eq. 4.

$$C\ (PI,\ AR,\ SS) = 1-(1-G) \times R \qquad (4)$$

Where, G and R are the grade index and the range adjustment factor for each parameter respectively.

The basic criteria for each parameter is described in JBDPA manual [9], and the brief descriptions are as follows:

(a) Regularity: Criteria for plan regularity are shown in Fig. 9. The following consideration are taken for plan irregularity:

(i) Regular: Structural balance is good, and the area of a projection part (a_2) is not more than 10% of the floor area.

(ii) Nearly regular: Structural balance is worse than regular, or the area of a projection part (a_2) is not more than 30% of the floor area with L, T or U shaped plan.

(iii) Irregular: Structural balance is worse than nearly regular, or the area of a projection part (a_2) is larger than 30% of the floor area with L, T or U shaped plan.

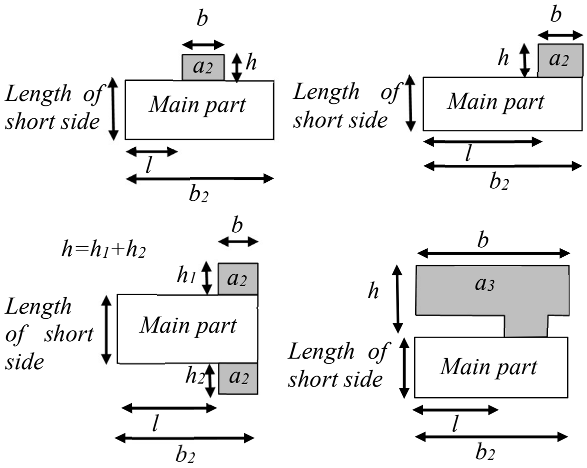


Fig. 9 Criteria for plan irregularity [9].

(b) Aspect ratio of plan: This is the ratio between long and short side (b=length of the long side / length of the short side as shown in Table 2).

(c) Soft story: In case that the building has the pilotis columns or the columns supporting the wall above are regarded as soft story. In addition, the pilotis columns are located eccentrically; it should be regarded as the eccentric soft story.

The factors for each parameter are shown in Table 2, according to JBDPA seismic evaluation manual [9].

Table 2. Items according to Values of factors [9]

Factors	Grade Index (G)			Adjustment factor (R)
	1	0.9	0.8	
Regularity	Regular	Nearly Regular	Irregular	1
Aspect Ratio	b≤5	5<b≤8	8<b	0.5
Soft story	No soft story	Soft story	Eccentric soft story	1

The following sections are discussed about the application of the above-mentioned procedure, results and comparison after application of modification factors in seismic capacity.

5. COMPARING SEISMIC CAPACITY FOR DAMAGED BUILDINGS BEFORE AND AFTER MODIFICATION FACTOR

In this section, severely damaged buildings are taken in order to verify and compare the effectiveness of these parameters in changing seismic capacity with respect to damage pattern for both earthquakes. The calculated seismic capacity index, which has been described in the previous section, is modified by multiplying with modification factor. The effectiveness of modification factor is verified by comparing the calculated seismic capacity, for both before and after modification, with seismic demand for each earthquake.

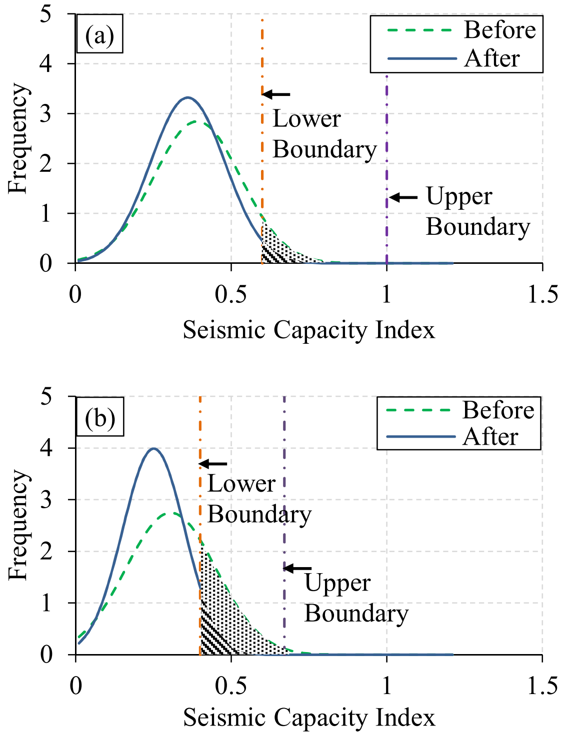
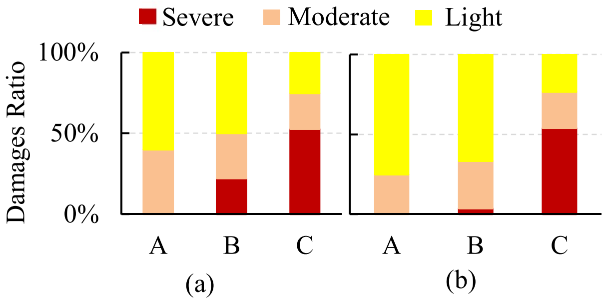


Fig. 10 Distribution of severely damaged buildings (a) Ecuador earthquake, (b) Nepal earthquake

In order to evaluate the effectiveness of the modification factor for identifying the vulnerable buildings, normal distribution for severely damaged buildings are plotted for each earthquake. Fig. 10 shows the frequency distribution according to the seismic capacity index before and after considering modification factors for severely damaged structures. For Nepal earthquake, approximately 74 % of total severely damaged building are located at severe zone without considering modification factors. After considering the modification factors, however, about 93% of total severely damaged buildings are identified as severe, which exhibited a much improvement in evaluation. Also for Ecuador, the probability of identifying severely damaged buildings are increased from 92% to 97% showing improvement after inclusion of modification factors. It has been concluded that the probability for identifying vulnerable buildings are increased by incorporating the modification factors while calculating seismic capacity index.

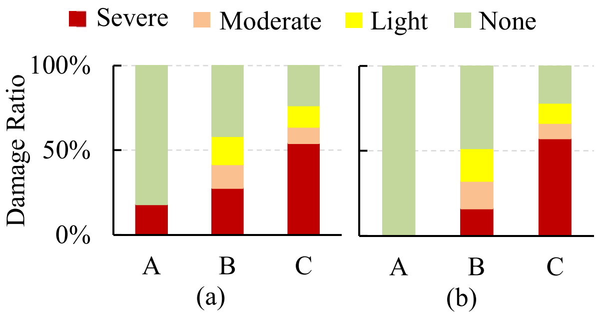
6. COMPARISON ON DAMAGE RATIO AFTER MODIFICATION FACTOR

Fig. 11 and 12 show the damage ratio distribution of surveyed buildings according to damage states and seismic capacity for different damage zone A, B and C. As mentioned earlier, zone A, B and C are for describing light, moderate and severe, respectively, as were shown in Fig. 8.



(a) (b)

Fig. 11 Damage ratio for Ecuador Earthquake
(a) Before, (b) after modification factor



(a) (b)

Fig. 12 Damage ratio for Nepal Earthquake
(a) Before, (b) after modification factor

Fig. 11(b) and 12(b) show the variation of damage ratio after inclusion of modification factors in seismic capacity index. From the damage ratio, it is shown that severely damage buildings are reduced from 22% to 3% at zone B for Ecuador. In case of Nepal, all severely damaged buildings at zone A moved toward zone B and C. This is an indication of effectiveness and/or increase the degree of accuracy for identifying buildings that are more vulnerable. Therefore, the accuracy of this procedure showed much improvement after considering the modification factors.

7. CONCLUSIONS

The conclusions from this study are as follows:

(1) The study concludes that modified Shiga map, considering Column Index (*CI*) and Masonry Wall Index (*WI*), showed good agreement with the damage state of existing buildings, based on past earthquake databases.

(2) The inclusion of modification factors increases the degree of accuracy and reliability for identifying the vulnerable buildings.

The parameters considered for modification factors was based on the information derived from survey database. However, the values considered for modification factors need further improvement considering other important parameters such as local building characteristics.

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