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A SEISMIC CAPACITY EVALUAITON AND PRIORITY SETTING FOR RC BUILDING WITH MASONRY INFILL

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ABSTRACT

In developing countries, there are enormous stock of vulnerable masonry infilled RC buildings, which are required to be evaluated and/or strengthened to resist the future earthquake. Masonry infills are usually treated as non-structural elements and ignored in the seismic evaluation procedure. Therefore, development and adoption of the seismic evaluation method for the infills is a crucial point to mitigate the earthquake damage.
This study presents a simple screening procedure, based on the concept of Shiga Map which considers average shear stress of columns and RC walls, and wall area ratio (a ratio of the cross-sectional areas of RC walls to total floor area) as well as corresponding seismic demand. On the other hand, this study focuses on the cross-sectional areas of columns and masonry infills, and their shear strengths as well as local seismic demand. In this paper, the validity of the modified procedure is first investigated by using the survey databases after the recent earthquakes. This method is further applied to check vulnerability of buildings in other countries prone to major earthquake but with no recent recorded damage data. As a representative example, a case study of Bangladesh is carried out, where the proposed method is applied on about 65 surveyed existing buildings. The result revealed that more than half of surveyed buildings are likely to have severely damage and detail evaluation for strengthening and/or retrofitting. Also, the procedure has been proved to be effective and simple method for rapid screening and priority setting for detail evaluation and retrofitting.

Keywords: Seismic capacity evaluation; Existing RC building; Masonry infill; Developing country.

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, where the infill contributes to stiffness and strength of the RC frame. In addition, there are existence of enormous stock of vulnerable buildings in these countries. Identifying of 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 region based quick and reliable evaluation procedure to avoid catastrophic damages in the future earthquakes.
Many researchers developed simplified methods for quick identification of the vulnerable buildings using some building parameters based on survey of past earthquake-damaged buildings (Shiga, et al. 1968, Hasan and Sozen, 1997, Ozcebe et al. 2004, Donmex and Pujol, 2005, Gur et al. 2009). These

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methods consider a rough measure of the ratio of the capacity of structures to resist lateral loads to the seismic demand. In addition, these methods require only the dimensions of the vertical members and floor plan and define the rank based on a two-dimensional plot using column and infill area ratios (column and wall indices).

Shiga et al. (1968) proposed a practical method named as '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 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. This map is well known to show good agreement with the damage status of RC buildings in the 1978 Miyagiken-oki earthquake (Shibata, 2003). However, this method is applicable only for buildings with RC shear walls, which does not consider the effects of masonry infills.

Hasan and Sozen (1997) presented a simplified method with vulnerability indices (column and wall area index) to rank RC building according to their vulnerability against seismic damages. They investigate a group of damaged buildings in the 1992 Erzincan Earthquake, Turkey. Furthermore, this method has been used to classify the damage extent of existing buildings for future earthquake in Istanbul, Turkey (Ozcebe et al. 2004). Donmez and Pujol (2005) also verified the method with the database of 1999 Duzce and Bolu earthquake, Turkey. The indices was further tested to identify the performance of school buildings in the 1999 (Marmara, Duzce) and the 2003 (Bingol) earthquakes, Turkey (Gur et al. 2009).

O`brien et al. (2011) conducted post-earthquake survey on 2010 Haiti earthquake to investigate the extent to which these indices are sensitive to properties of local materials. In addition, they compared the results with those of the 1999 Duzce, Turkey earthquake, and concluded that this method is an appropriate tool to estimate the seismic vulnerability.

All the aforementioned studies proposed their method criteria after earthquake damage where these damage databases were used to recalibrate the existing vulnerability indices. However, there are no clear indication about theoretical background or application those method in other developing countries where in many cases recent damage database is not available.

In the present study, several existing buildings that are located in Bangladesh, an earthquake prone area, have been considered as a case study where damage database is not available. Due to rapid urbanization, over the past decades, the estimated number of existing RC buildings in Dhaka, the capital of Bangladesh is more than 200,000 (Inoue et al. 2017). Many of these buildings do not comply with the seismic requirement due to lack of upgraded building code, legal enforcement as well as improper design and construction practice which resulted in little resilience to earthquake. Identifying high vulnerable buildings is the key issue for setting the priority for seismic strengthening and reliable loss estimation due to expected earthquake. Thus, development of effective seismic assessment procedure is of utmost need for screening these huge building stocks.

This paper presents a screening method using the concept of Shiga Map (Shiga et al. 1968), focusing on the cross-sectional areas of masonry infills and columns in existing infilled masonry-RC buildings. First, 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. Finally, this approach is applied to investigate the seismic vulnerability of several existing buildings in Bangladesh as a case study for developing countries. The study outlines the application of seismic screening method considering masonry infill and development of theoretical background that can be used to recalibrate the Shiga map to be used for evaluation of existing buildings where damages databases are not exist and have different building characteristics.

2. DAMAGE DATABASE OF RECENT EARTHQUAKES

2.1 Overview of Database

From the earthquake damage databases, total 409 buildings have been selected for this study. Among these data, 30 buildings have been collected for the 1992 Turkey earthquake from Hasan and Sozen (1997). Other 141 buildings for the Nepal earthquake 2015, 65 buildings for the Taiwan earthquake 2016, and 173 buildings for the Ecuador earthquake 2016 are taken from post-earthquake damaged survey databases (Prateek et al. 2015, Purdue University and NCREE, 2016, Chungwook et al. 2017).

In inventories, buildings are classified into four categories (severe, moderate, light and none) according to their damage criteria, whereas for Ecuador buildings are identified by three categories (severe, moderate, light).

From database, approximately 65% of surveyed buildings are found severely damaged in Nepal, Ecuador and Taiwan earthquake, whereas only 45% of surveyed buildings have moderate to severe damage in Turkey earthquake. Figure 1 shows the distribution of the number of stories with respect to percentage of the buildings number investigated in each country. The number of buildings for each story number are also shown above every vertical bar. It has been observed that most of buildings are two to four storied.

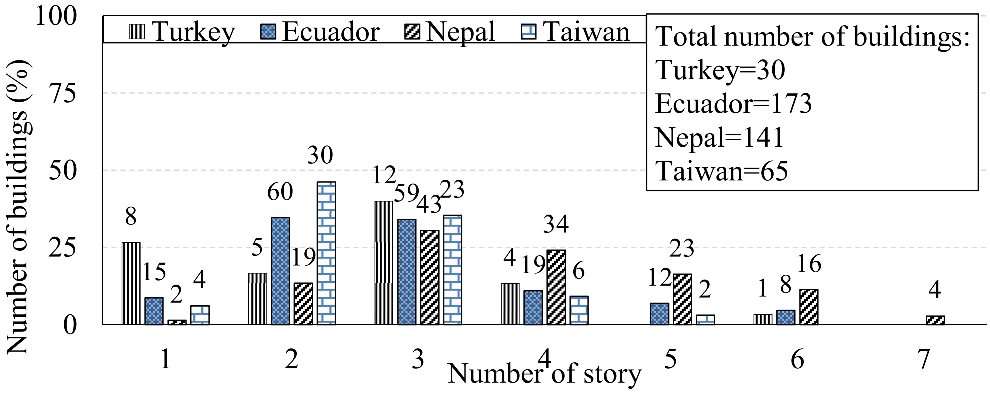

Figure 1. Distribution of Building Number in Percentage (%) with Number of story.

2.2 Seismic Ground Motion Characteristics

Acceleration response spectra of all ground motions in the investigated countries are shown in Figure 2 (Juan et al. 2016 and USGS). The peak response accelerations are found approximately 1.5g (EW direction), 1.3g (EW direction), 1.4g (NS direction) and 0.6g (EW direction) for Turkey, Ecuador, Taiwan and Nepal respectively.

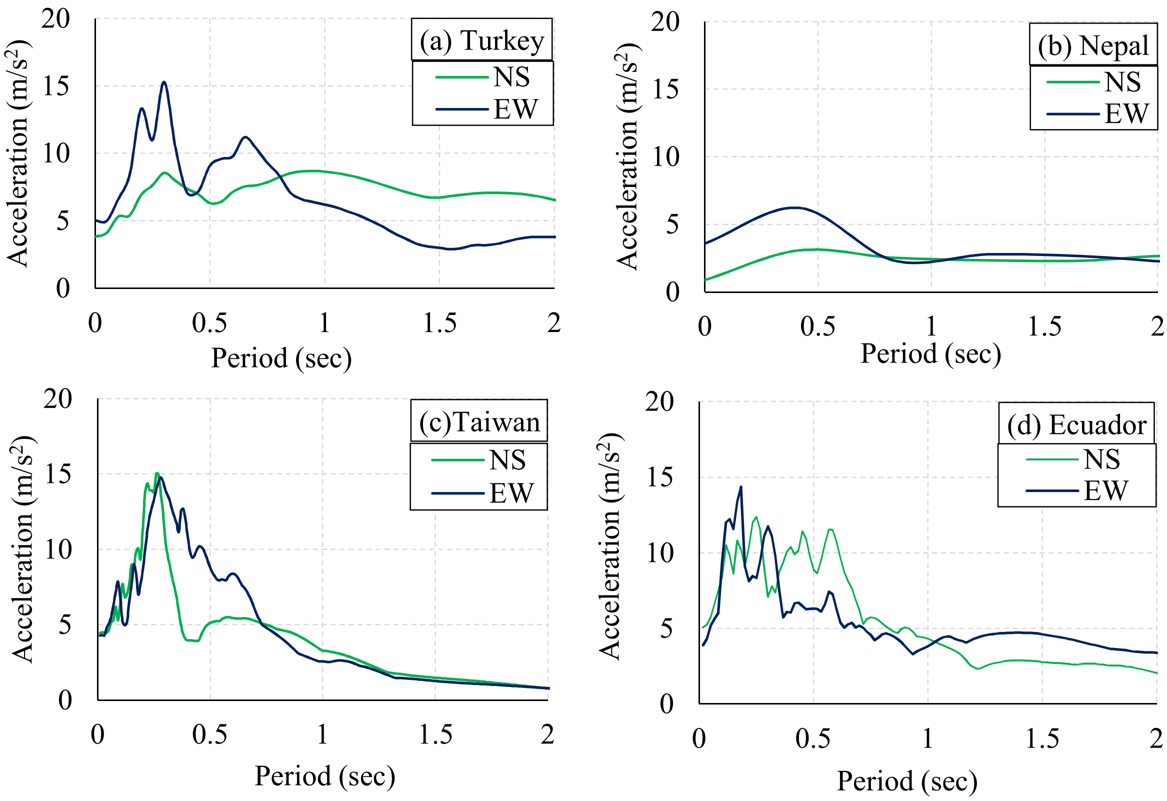

Figure 2. Acceleration Response Spectra of Different Earthquakes (a, b, c, d).

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. In this study, the estimated response acceleration (C_a) is roughly taken as 0.9g, 0.6g, 0.9g and 0.9g for Turkey, Nepal, Taiwan and Ecuador, respectively, based on the response spectra.

2.3 Building Characteristics

As mentioned earlier, all investigated buildings in the inventories are RC structures with masonry infill. For Turkey, typical column size is 230 mm and thickness of masonry infill is 250 mm (Hasan and Sozen, 1997). A survey of earthquake-damaged building in Nepal reported that the typical column size is 227 mm in square and rectangular column size is 227 x 305 mm (CAEE, 2016). The masonry wall thickness was observed 230 mm for exterior wall and 115 mm for interior wall for Nepal (Brzev et al. 2017). Tu et al. (2011) analyzed some damaged buildings after the 1999 Taiwan earthquake and found most common section of column is 300 x 400 mm. Usual practice for thickness of masonry wall ranged 200 mm ~300 mm (Chiou et al. 2017). The usual practice for other countries, the masonry wall thickness are 100 mm and 230 mm and commonly built with burnt clay bricks.

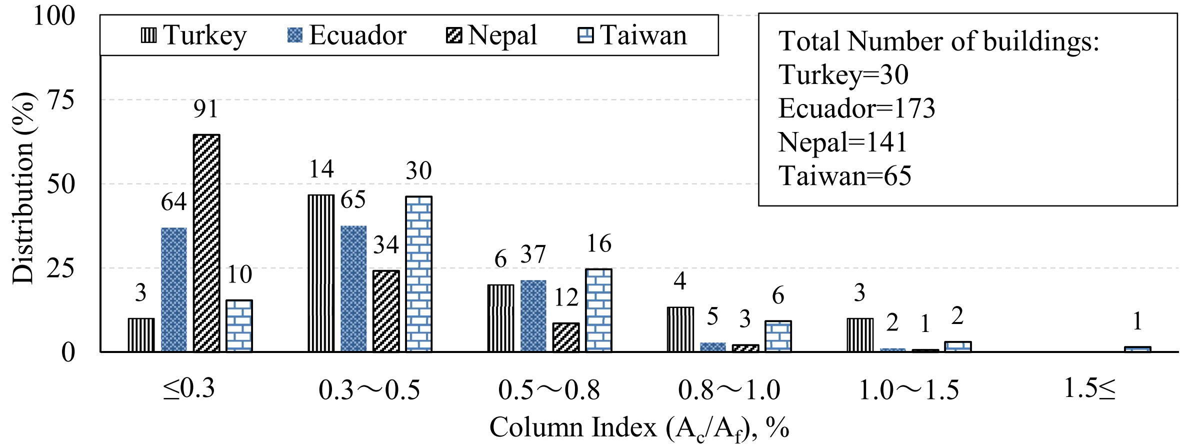

Figure 3. Distribution (%) according to Column Index in percentage.

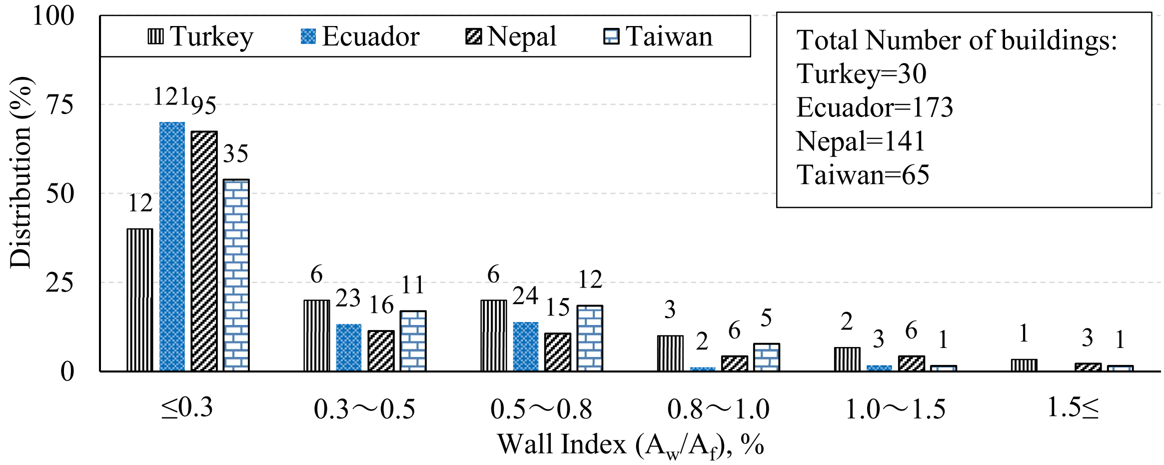

Figure 4. Distribution (%) according to Wall Index in percentage.

Figure 3 and 4 show the distribution of the ratio of column areas at first story to the total floor areas for all stories, defined as the column index (A_c/A_f), and the ratio of infill areas at first story to the total floor areas for all stories, defined as the wall index (A_w/A_f), for the surveyed buildings in existing database of the aforementioned countries. Column index and wall index are calculated using Equation 1 and 2.

$$\text{Column Index(CI)} = \frac{A_c}{A_f} \times 100 \quad (1)$$

$$\text{Wall Index (WI)} = \frac{A_w}{A_f} \times 100 \quad (2)$$

Where, A_c and A_w are the total cross sectional area of columns at first story and masonry infill in one horizontal direction respectively at first story. A_f is the total floor area including all stories in a building. In this study, solid infill wall within RC frame has been considered for calculating area of masonry infill. To be more conservative, infill wall with opening and/or partial infill wall are not considered. In order to calculate wall index, minimum wall area in one horizontal direction has been considered.
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 investigated buildings in these countries. The column area ratio ranged 0.3~0.5% in most countries except for Nepal, where the major value is lower than 0.3%.

2.5 Damage Criteria

The data collected (Prateek et al. 2015, Purdue university and NCREE, 2016, Chungwook et al. 2017) during these surveys consist of descriptions and photographs of damage, and visual inspection. A damage rating system was used in the surveys in order to classify the buildings conditions. Although the ground motion for Turkey was relatively strong, the survey report shows that there are no buildings suffered total collapse. Definitions of each damage state for Turkey (Hasan and Sozen, 1997) and for Nepal, Taiwan, and Ecuador earthquakes (Prateek et al. 2015, Purdue university and NCREE, 2016, Chungwook et al. 2017) are shown in Table 1.

Table 1. Damage Criteria for different Earthquakes.

Damage state	Turkey	Ecuador, Nepal and Taiwan
Light	Fine flexural cracks.	Hairline flexural cracks.
Moderate	Reinforcement buckled near joint.	Wider cracks, concrete spalling.
Severe	Structural failure of Individual elements.	At least one element has failed.

3. METHODOLOGY

The seismic capacity is then calculated with column and masonry infills strength, which is product of the average shear stress and cross sectional areas of columns and walls, as shown in the left side of Equation 3. It is noted that the Equation 3 is based on Shiga Map (Shiga et al. 1968). The seismic demand is the product of the total building weight (W), the response acceleration (C_a) and the reduction factor (D_s) considering the building ductility, which is shown in the right side of Equation 3.

Seismic Capacity ≥Seismic Demand

$$\tau_c.A_c + \tau_w.A_w \geq W.C_a.D_s \tag{3}$$

Where, τ_c and τ_w are the shear strengths of columns and masonry infills respectively.
Dividing both side of Equation 3 by A_f, which is the area of total floor considering all stories, Equation 4 is obtained.

$$\tau_c.A_c/A_f + \tau_w.A_w/A_f \geq W/A_f.C_a.D_s \tag{4}$$

Where, A_c/A_f and A_w/A_f is known as Column Index (CI) and Masonry wall Index (WI) in percentage.
W/A_f is known as unit weight of structure.
Then, the following assumptions have been made for the seismic capacity and seismic demand computations using Equation 4:

(a) τ_w ; For shear strength of masonry infill (τ_w), ASCE seismic guideline (ASCE/SEI 41-06, 2007) estimated 34 psi (0.24 MPa) for good masonry condition. Chiou et al. (2017) proposed lateral shear strength for masonry infill, after experimental verification and theoretical formulas, as 4.0 kgf/cm^2 (0.39 MPa) for preliminary assessment of low-rise RC Buildings in Taiwan. From the references above, considering material properties for other countries, a unique value of 0.2 Mpa, which is a conservative value, is adopted as lower bound of the lateral shear strength (τ_w) of Masonry infill.

(b) τ_c ; The shear strength of column depends on the failure criteria as either shear or flexure based on damage investigation and experimental data (Shiga et al. 1968, JBDPA, 2005). JBDPA (2005) standard proposed shear strength of column is 1.0 MPa for first level screening procedure based on shear span ratio, where h_o/D ranged 2 to 6 (h_o is the clear height, D is the column width). Tu et al. (2011) summarized the detailed assessment results for the bare frames of school buildings for the 1999 Chi-Chi earthquake and proposed the average ultimate shear strength of column is 15 kgf/cm^2 (1.47 MPa) for preliminary evaluation. In this study, therefore, the average shear stress for columns is roughly assumed 1.0 Mpa.

(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. As previously mentioned, W is the total building weight and A_f is the total floor area considering all number of stories.

(d) C_a ; As stated earlier, from Figure 2, response acceleration, C_a is roughly estimated for buildings with short period (less than 0.5 second), are 0.9g, 0.6g, 0.9g and 0.9g for Turkey, Nepal, Taiwan, and Ecuador respectively.

(e) D_s ; Two boundaries are assumed for identifying the building's damage categories. The lines proposed for boundaries are set according to reduction factor (D_s) considering building ductility. In this paper, reduction factor (D_s) of 1.0 is assumed for the buildings in elastic range after the earthquake. On the other hand, ASCE 7-10 (2010) considers R, the value is 1.5, as response modification factor for unreinforced masonry wall in Figure 5. 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.

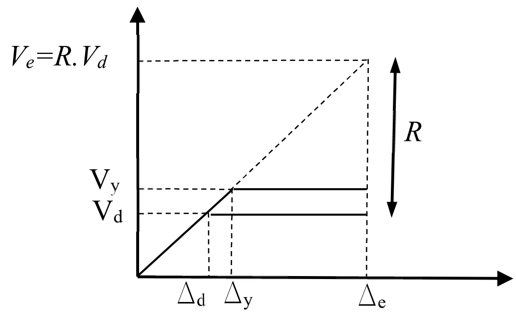

Figure 5. Equivalence of ductility and reduction factor (ASCE 7-10, 2010).

4. RESULTS AND DISCUSSION

The seismic vulnerability indices (column and wall indices) have been calculated for surveyed buildings of each earthquake damage database. These indices for both principal directions in plan were plotted as shown in Figures 6, 7, 8 and 9 for Turkey, Nepal, Taiwan and Ecuador, respectively. The lines drawn in each plot according to their seismic demand for each ground motion of corresponding earthquakes. These lines designated as upper boundary and lower boundary, defining the map into three different zones namely Zone A, Zone B and Zone C for describing light, moderate and severe respectively. Buildings placed 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. Damage ratios for each zone are calculated according to the seismic capacity and seismic demand for each ground motion. Figures 6, 7, 8 and 9 also show the damage ratio according to seismic capacity and different damage zones for different earthquakes.

For Turkey, the plot shows good agreement with damage ratio at each Zone. All severely damaged buildings are located at Zone C. In addition, there are no severely damaged buildings at Zone A except a few light damaged buildings.

For Ecuador, almost 80% of total severely damaged buildings are located at Zone C. From the damage ratio, it is shown that more than 50% of buildings at zone C are severely damaged. In addition, there are no severely damaged buildings at Zone A except a few moderately damaged buildings.

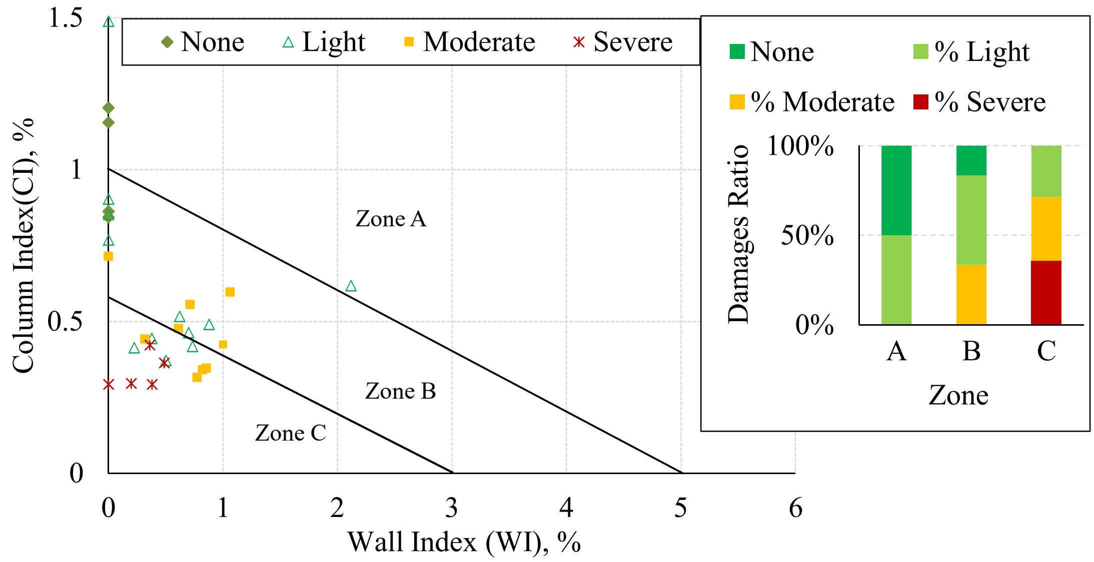

Figure 6. Evaluation map with WI and CI with Damage ratio for Turkey earthquake.

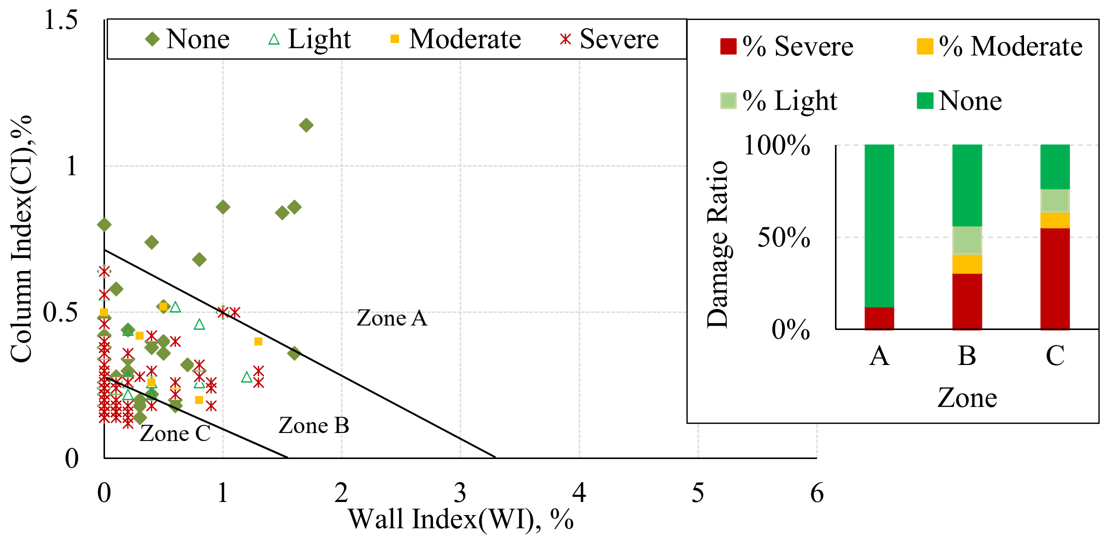

Figure 7. Evaluation map with WI and CI with Damage ratio for Nepal earthquake

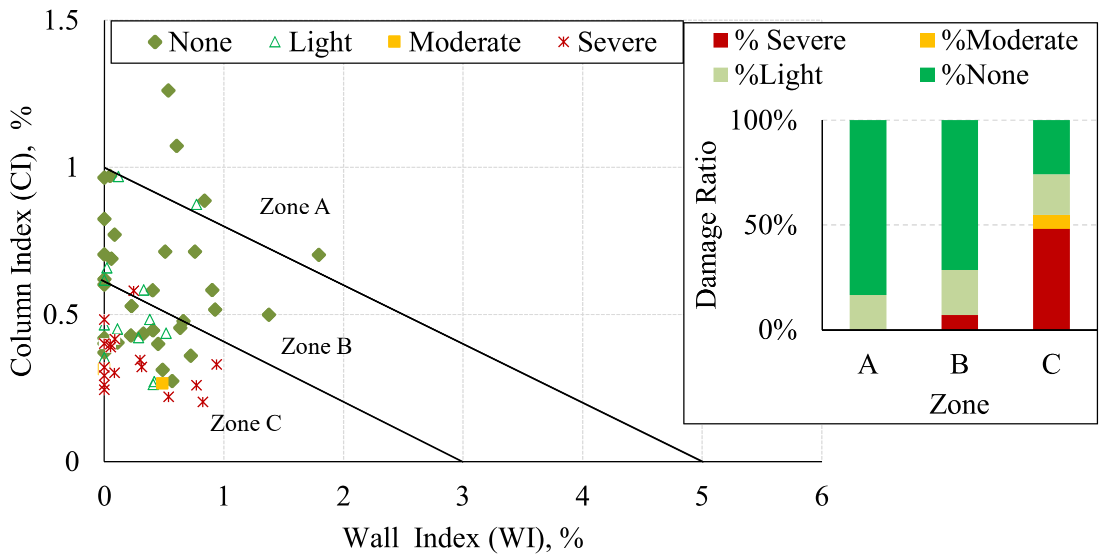

Figure 8. Evaluation map with WI and CI with Damage ratio for Taiwan earthquake.

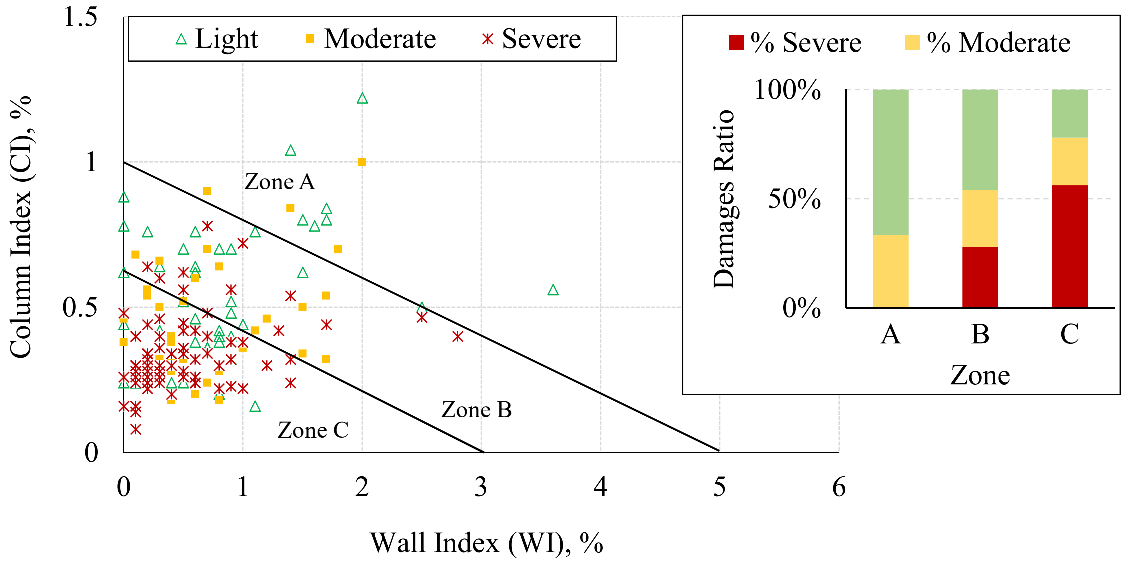

Figure 9. Evaluation map with WI and CI with Damage ratio for Ecuador earthquake.

Similarly, for Taiwan, 89% of total severely damaged buildings are located at Zone C. Damage ratio of this Zone shows that about 50% are severely damaged buildings of total buildings. Furthermore, 80% of buildings with lightly damaged are located at Zone A.

In case of Nepal, approximately 70% of total severely damaged buildings are located at Zone C and more than 55% buildings are severely damaged at this Zone. From the damage ratio, it is found that there are a few severely damaged buildings in Zone A.

Therefore, it is concluded that the boundaries of each earthquake show good agreement with damage ratio and damage states in Turkey, Ecuador and Taiwan earthquake. As for Nepal, the boundaries provide fair agreement with damage ratio of different zones, and the seismic capacity and the damages state indicate that the buildings were more vulnerable than those buildings surveyed in other countries. However, it also suggests that shear strength of column considered in the study ($\tau_c = 1$MPa) might not be conservative enough for Nepal and need further investigation.

From the results above, the method shows a promising approach for identifying the most vulnerable buildings. It also provides theoretical background for application of this method to other developing counties, where damage databases are not available. Therefore, this procedure is further applied on several existing buildings in Bangladesh as a case study for developing countries, where damage data is not available.

5. APPLICATION TO EXISTING BUILDING IN BANGLADESH

5.1 Building Characteristics and Material Properties

Total 64 buildings located at Dhaka in Bangladesh were selected for this study. Most of them are reinforced concrete (RC) frame with masonry infill. The building information with as-built architectural drawing along with location of masonry infill are collected from field survey conducted by Comprehensive Disaster Management Program (CDMP, 2009) under Ministry of Disaster Management and Relief, Government of Bangladesh.

Most of the surveyed buildings are residential buildings with four to six storied. A few of them are official and commercial complex. Figure 10 shows typical ground floor plan and elevation of typical building in Bangladesh. It is observed that ground floor are open for parking space as well as for commercial purposes, which is common practice in Bangladesh.

The usual practice for least dimension of typical column is 250 mm. The usual thicknesses of masonry infill are 250 mm and 150 mm for exterior and interior wall respectively. Figure 11 and 12 show the column and infill area normalized with total floor area at base. In about 50% of total buildings, the column area ratio is under 0.2% because the column size is smaller compared to the story number. On the other hand, due to open space for parking and other shop for commercial purpose, about 55 % of these buildings have lower wall density, as shown in Figure 12. It is noted that upper floor contains more wall density than ground floor which are usually typical.

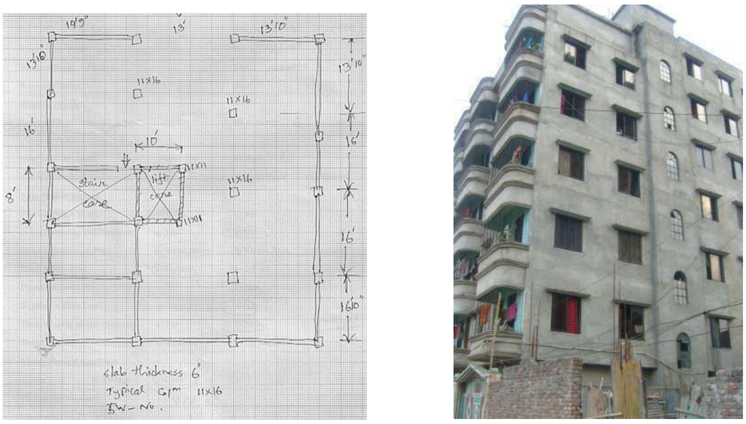

Figure 10. A typical As-built drawing for ground floor plan and photo of building (CDMP, 2009).

As previously mentioned, for shear strength of masonry infill (τ_w), a unique value of 0.2 Mpa, is also adopted for Bangladesh as lower bound of the lateral shear strength (τ_w) of Masonry infill. The average shear strength of column (τ_c) is roughly assumed 1.0 Mpa which is also common in other countries.

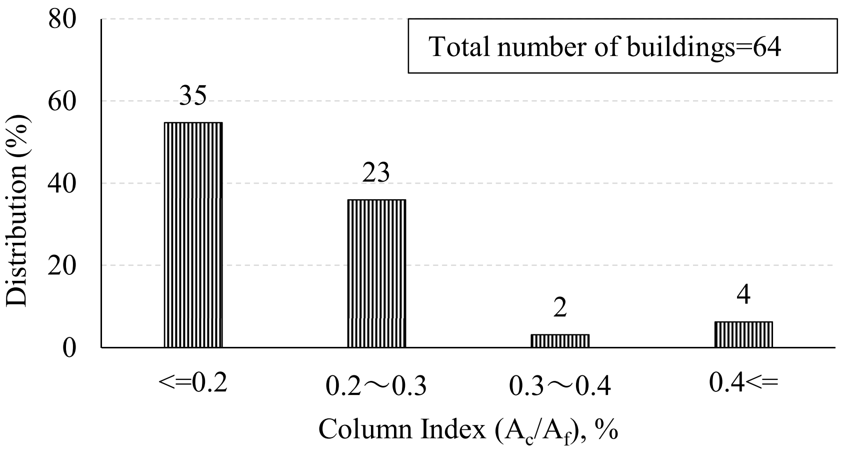

Figure 11. Distribution (%) according to Column Index.

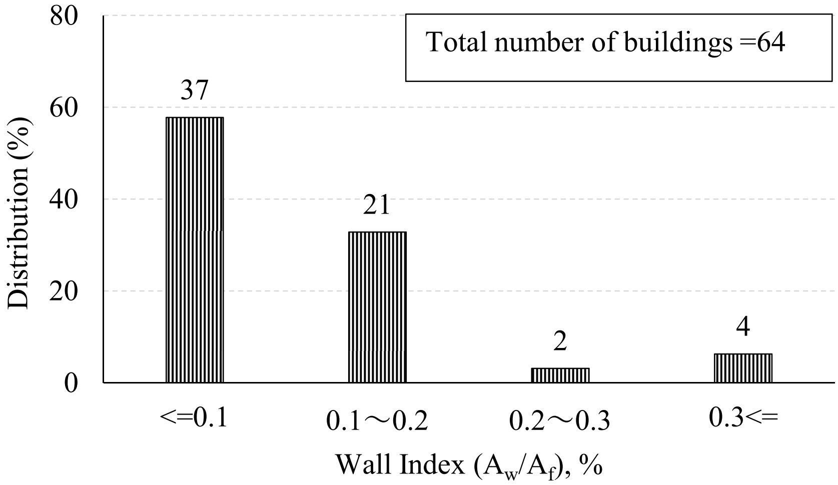

Figure 12. Distribution (%) according to Wall Index.

5.2 Seismic Demand in Bangladesh

Bangladesh National Building Code 1993, which has been legally enforced in 2006, first published seismic zoning map and follows seismic design procedures in Uniform Building Code 1991. After revision of its seismic design provisions, BNBC 2015 updated the seismic zoning map based on the concept of Maximum Credible Earthquake (MCE) with a return period of 2475 (Al-Hussaini et al. 2012). Construction site are classified based on soil properties as type SA, SB, SC, SD, SE, S1 and S2 in accordance with upper 30 meters of the site profile and evaluated soil properties (shear wave velocity, shear strength, soil type etc) (BNBC, 2015). Also, the new code suggests design response spectrum based on different site classification. Figure 13 shows the design response spectrum proposed by BNBC 2015 considering soil type SC and SD soil profile.

The surveyed buildings are located at Dhaka and most of the sites are classified as SC type soil profile. Therefore, in the calculation of seismic demand in Equation 4, the response acceleration (C_a) is assumed 0.38g in accordance with the design response spectrum of BNBC 2015 as shown in Figure 13.

In addition, for the seismic demand calculation in Equation 4, Unit weight is considered as 11kN/m^2 and similarly, reduction factor (D_s) of 1.0 for elastic range and that of 0.6 for inelastic range (ASCE 07-10, 2010) are set to provide boundaries for defining probable damages areas. Therefore, seismic demand, for the ground motion in BNBC 2015, are 0.42 and 0.25 for the upper and lower boundaries, respectively.

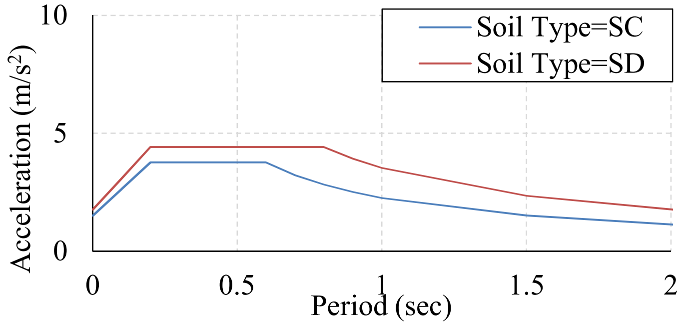

Figure 13. Design Response Spectrum proposed in BNBC 2015.

5.3 Evaluation Results and interpretation

As previously stated, total number of 64 buildings are selected in this study in order to investigate their seismic vulnerability. It is noted that the cross-sectional areas of columns and masonry infills were calculated from as-built architectural drawing from field survey. Column and masonry wall indices are calculated by normalizing with total floor area at base.

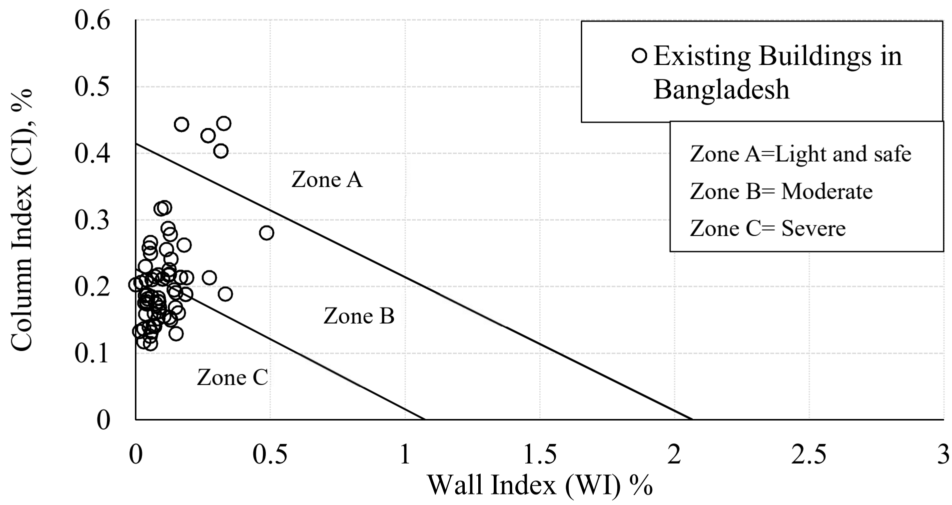

Figure 14. Proposed seismic evaluation map for Bangladesh.

Figure 14 shows the proposed seismic evaluation map where column and masonry wall indices for both principal directions are plotted. Boundaries defining the different damages zones A, B and C, are set according to seismic demand and design response spectrum considered in BNBC 2015. From Figure 14, almost more than 70% of the total buildings were located in Zone C which are likely to have severe damage, and only few buildings were located at Zone A which can be assumed to be safe. Buildings located at Zone A having higher CI and WI which indicates these buildings are classified as safe (less priority for further investigation). However, buildings having lower column and masonry wall indices (less than 0.2% for both indices), located at severe zone, might have higher priority for further detailed investigation.

From the above discussion, it can be emphasized that these indices has significant influence on seismic capacity of existing buildings. The boundaries are valid, if intensity of an earthquake ground motion is the same level with seismic demand in BNBC 2015. However, Turkey, Nepal, Taiwan and Ecuador earthquakes suggest that larger shaking may be possible even in Bangladesh and then induce devastating damage to existing buildings. Therefore, for evaluation of huge building stock, this method is an efficient tool for identifying the vulnerable buildings and for the priority setting of detailed seismic inspection to prepare for future earthquake.

6. CONCLUSIONS

This paper presents a rapid seismic evaluation procedure for identification of vulnerable buildings. From this study, it can be concluded that:

1. The vulnerability indices, Column Index (CI) and Wall Index(WI) showed good agreement with the damage state of surveyed building, based on past earthquake databases. The consistency between the observed damage distribution and boundaries supports the effectiveness of the proposed method. The proposed method was found to be a practical and easy approach for screening vulnerable building with masonry infill.
2. Column and Wall Indices were used to investigate the seismic vulnerability of several existing buildings in Bangladesh. This study shows that more than half of the building are in dangerous zone and likely to have severe damages based on the seismic demand of BNBC. Therefore, these buildings have high priority for further detail evaluation and need seismic retrofitting.

Further, the assumptions considered for column and masonry infill lateral strength needs further investigation for each countries according to local materials. Hence, material tests are recommended to future upgrade the accuracy of screening criteria.

7. ACKNOWLEDGMENTS

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