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Proposal of visual rating method for seismic capacity evaluation and screening of RC buildings with masonry infill

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ABSTRACT

In developing countries, there are enormous stock of vulnerable buildings which are to be required for detail seismic evaluation. Identifying most vulnerable buildings by visual inspection would reduce time and cost of detailed evaluation. However, existing visual screening methods have limitations to provide seismic capacity of building as discussed in this study. Therefore, this paper presents a Visual Rating method for seismic capacity evaluation to identify most vulnerable buildings. The proposed method is based on cross-sectional areas and shear strength of vertical elements (such as column, masonry infill, and concrete wall) as well as structural configuration, building deterioration, and age etc. This method provides a Visual Rating Index which is an approximated estimation of seismic capacity of building. Applicability of the proposed method has been investigated by applying to several existing RC buildings at Dhaka city in Bangladesh. The Visual Rating Index shows good correlation with detailed seismic evaluation results based on investigation of existing buildings. It has been revealed that the proposed method could be used as an effective tool for selecting those buildings have to be subjected to a more detailed assessment for a final decision on their seismic risk level.

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1 INTRODUCTION

Past earthquake damage in developing countries have been exhibiting the necessity of seismic evaluation and strengthening of existing buildings. In addition, enormous stocks of vulnerable buildings exist in those countries. Identifying vulnerable buildings using a quick and reliable evaluation procedure and prioritizing for retrofitting and/or strengthening would be of a great interest in terms of time and costs. Existing visual screening methods have limitation to provide seismic capacity because those methods do not consider the variation of cross-sectional area of structural elements (i.e. column, masonry infill and RC wall area etc.).

This paper presents a Visual Rating (VR) method focusing on the cross-sectional area of columns and masonry infills in existing infilled masonry-RC buildings. The method has been investigated by applying on existing RC buildings in Dhaka city, Bangladesh as a case study. The effectiveness of the proposed method has been verified by comparing with detail seismic evaluation of the investigated buildings.

2 STUDY ON SEISMIC CAPACITY OF EXISTING BUILDINGS BASED ON PAST EQ DATABASE

This section provides the correlation between seismic capacity and damage state of buildings experienced past earthquake using simplified procedure.

2.1 Overview of past earthquake damage database

53 buildings for the Taiwan earthquake, 2016 has been investigated, which are provided by post-earthquake damage survey database (Purdue University and NCREE 2016). Figure 1 shows distribution of RC buildings according to number of story. Most of the buildings are two to four storied. A typical survey datasheet used to record information as shown in Figure 2. Buildings have been categorized into three damage classes based on visual inspection (Purdue University and NCREE 2016). Damage definitions criteria are shown in Table 1.

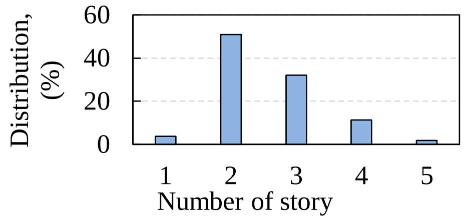

Figure 1: Distribution (%) with number of story

Table 1: Damage definitions

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

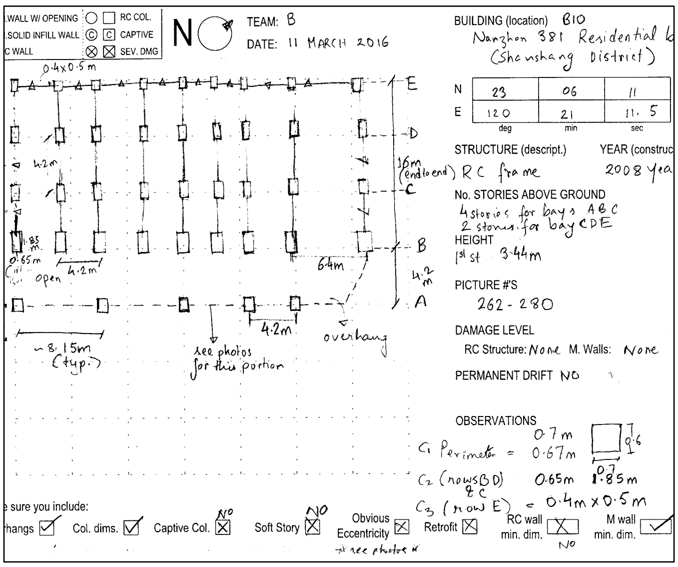

Figure 2: A typical survey datasheet

2.2 Calculation of seismic capacity index

The basic concept of seismic capacity is based on the Shiga Map (Shiga *et al*. 1698). However, the Shiga map does not consider the effects of masonry infill. In this study, the seismic capacity index has been considered as the summation of lateral strength of RC column, masonry infill and concrete wall normalized with total building weight (Maeda *et al*. 2018) as expressed by Equation 1.

Seismic capacity index= $\left[\frac{\tau_c . A_c}{n.A_f.w} + \frac{\tau_{inf}.A_{inf}}{n.A_f.w} + \frac{\tau_{cw}.A_{cw}}{n.A_f.w}\right]$ (1)

where A_c/A_f, A_{inf}/A_f, and A_{cw}/A_f refer to column area ratio, masonry infill area ratio, and concrete wall area ratio, respectively. *n* is the number of story. In the Equation 1, τ_c, τ_{inf}, and τ_{cw} are average shear strength of column, masonry infill, and concrete wall.

The following assumptions have been made for the seismic capacity computation in Equation 1:

(a) Average shear strength of RC column (τ_c)

The Japan Building Disaster Prevention Association (JBDPA 2001) considers the average shear stress for column is 1.0 MPa for first level screening procedure based on shear span ratio, where h_o/D ranged between 2 to 6 (h_o is the clear height of column, *D* is the column width). However, Tsai et al. (2008) summarized the detailed assessment results of school buildings in Taiwan and proposed the average ultimate shear strength of RC column as 15 kgf/cm^2 (1.47 MPa) for preliminary evaluation. In this study, therefore, τ_c is assumed 1.0 Mpa as conservative value.

(b) Average shear strength of masonry infill (τ_{inf})

ASCE seismic guideline (ASCE 41-06 2010) prescribes shear strength as 34 psi (0.24 MPa) for masonry infill wall. However, Chiou *et al.* (2017) proposed lateral shear strength for masonry infill as 4.0 kgf/cm^2 (0.39 MPa) for preliminary assessment of RC Buildings in Taiwan. In this study, average shear strength of masonry infill, τinf, as 0.2 MPa has been adopted as lower boundary of the lateral shear strength.

(c) Average shear strength of concrete wall (τ_{cw})

JBDPA standard (2001) considers τ_{cw} as 1.0 MPa considering without boundary column. Therefore, τ_{cw} has been assumed 1.0 MPa as lower boundary.

(d) Average unit weight per floor area (w)

The unit floor weight of existing buildings is found ranges from 10 to 12 kN/m^2 based on study of existing building (SATREPS 2015). In this study, the average unit weight per floor area, *w*, is set as 11kN/m^2.

2.3 Results and Discussion on Seismic Capacity with Damage state

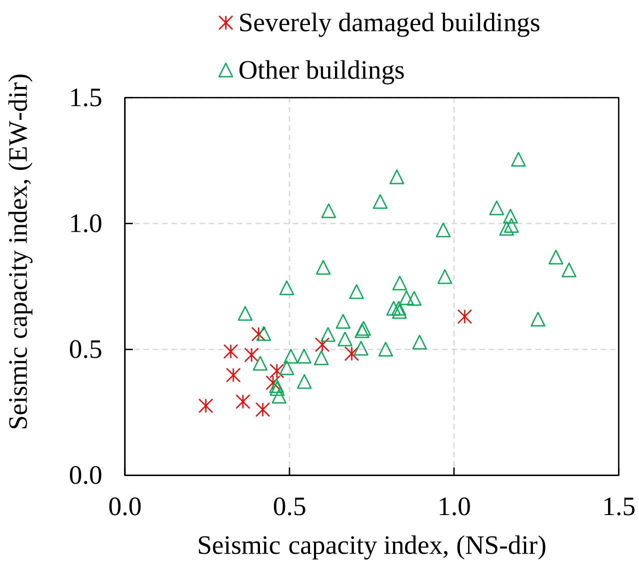

Figure 3: Seismic capacity index with damage state

Figure 3 shows seismic capacity index of surveyed buildings in two orthogonal (NS and EW) directions with actual damage state in the Taiwan earthquake, 2016. From Figure 3, it is obvious that the buildings having low seismic capacity index, i.e. low column and masonry area, experienced severe damage. The good agreement of the seismic capacity index with damage states implies that column area and masonry infill area ratio are very effective parameters for identifying the seismically vulnerable buildings.

Though, cross-sectional area of vertical elements (e.g. column, RC wall and masonry infill) and corresponding strength have profound influences on seismic capacity. However, screening of large numbers of existing buildings, using aforementioned method is quite challenging because it requires detail architectural drawings. If architectural drawings are not available, then as-built drawing preparation are necessary, which takes much time for seismic evaluation procedure. Hence, there is a need for developing very simple method based on visual inspection which takes less time and cost. In this aspect, existing rapid visual screening (RVS) methods in different countries are described in subsequent section.

3 STUDY ON EXISTING RAPID VISUAL SCREEING (RVS) METHOD

3.1 Discussion on Existing RVS Method

A number of guidelines/procedures are available from different countries for rapid screening out the vulnerable buildings. The following sub-sections describe three existing RVS methods briefly:

3.1.1 FEMA P 154

The FEMA P 154 (2015) has been proposed by the U.S. Federal Emergency Management Agency (FEMA) for seismic risk assessment and rehabilitation of existing buildings. This method provides score which predicts the probability of collapse. However, the FEMA final score is the summation of basic score and score modifiers due to other vulnerability parameters. FEMA considers a basic score for masonry infilled RC structure based on lateral force resisting system.

3.1.2 Turkish RVS Method

Middle East Technical University (METU) (Sucuoglu *et al.* 2007) proposed RVS method based on past EQ damages in Turkey. This method determines seismic performance score which is a combination of initial score, vulnerability score and score modifiers. The initial score is given with respect to the number of stories and the seismic intensity as well as study on past earthquake.

3.1.3 Indian RVS method

Jain *et al.* (2010) proposed RVS method for India based on damage database of past earthquake. This method predicts expected performance score which is summation of basic score, vulnerability score, and vulnerability modifiers. Basic score also considers local soil type and seismic zone.

3.2 Comparison between Existing RVS Method and Seismic Capacity Index

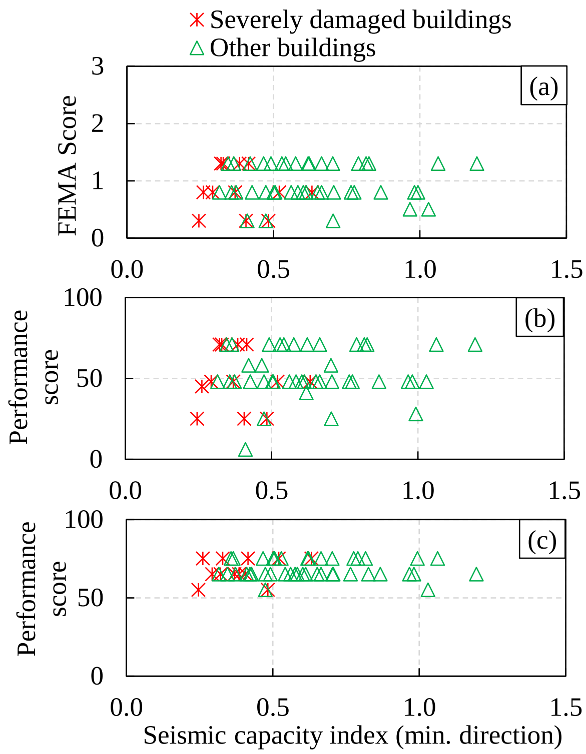

Figure 4: Seismic capacity index vs. the results of existing RVS method: (a) FEMA P 154, (b) Turkish method, (c) Indian method

The existing RVS methods described in the earlier section have been applied on the 2016 Taiwan EQ damage database (www.datacenterhub.org). Performance scores for each method are calculated based on survey information in the database. Afterward the performance scores of each method have been compared with previously calculated the seismic capacity index (minimum of two orthogonal directions) as shown in Figure 4. There is no clear correlation between seismic capacity and the performance scores for each method as shown in Figure 4.

Existing RVS methods do not consider the variation of cross-sectional areas of vertical structural elements (such as column area, masonry wall area and span length) which are very important factors influencing the seismic capacity. Therefore, this study presents a simplified way for estimation of column area ratio, masonry infill wall area ratio, and concrete wall area ratio thorough visual inspection. This method considers a score, reported as Visual Rating Index (I_{VR}), which is approximated seismic capacity of existing buildings, has been is described in the following section.

4 PROCEDURE OF VISUAL RATING METHOD

Visual Rating Index (I_{VR}) indicates the seismic capacity of existing buildings which is expressed by Equation 2.

$$I_{VR} = \frac{1}{n.w}\left[\tau_c.I_c + \tau_{\inf}.I_{\inf} + \tau_{cw}.I_{cw}\right] \quad (2)$$

where, I_c, I_{inf}, and I_{cw} are defined as column area ratio (A_c/A_f), masonry infill area ratio (A_{inf}/A_f), and concrete wall area ratio (A_{cw}/A_f) respectively.

The proposed method is based on visual inspection within a short duration, as it is not easy to measure all dimension of columns, masonry infills, and concrete walls, as well as floor area. Hence, a simplified way has been proposed for estimating the column, masonry infill and concrete wall area ratio using visual inspection.

4.1 Simplified Column Area Ratio

The cross-sectional area of column and floor area has been simplified using representative column size (b_c) and average span length (l_s), respectively. By visual inspection, the representative column size (b_c) has been chosen which represents the average of all column size of a building and average span length (l_s) represents the floor area of a surveyed building as shown in Figure 5 as a typical floor plan. Hence column area ratio is simplified as follows in Equation 3:

$$I_c = \frac{A_c}{A_f} \approx \frac{b_c^2}{l_s^2} \quad (3)$$

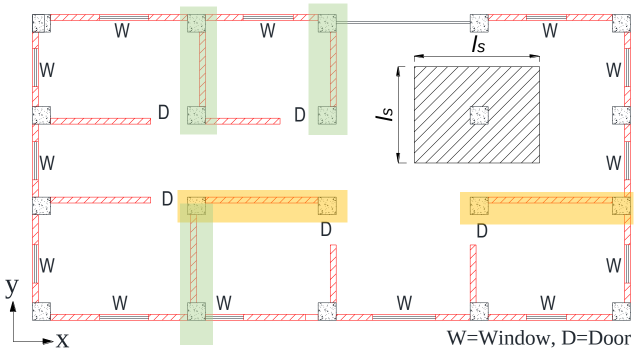

Figure 5: Typical floor plan showing the location of masonry infill

4.2 Simplified masonry infill area ratio

The masonry infill area ratio has been simplified by using masonry infill ratio (R_{inf}), thickness of masonry infill (t_{inf}) and average span length (l_s) as shown in Equation 4.

$$I_{\text{inf}} = \frac{A_{\text{inf}}}{A_f} \approx \frac{t_{\text{inf}}}{l_s}.R_{\text{inf}} \tag{4}$$

where, masonry infill ratio (R_{inf}) indicates the quantity of masonry infill as expressed by Equation 5. Masonry infill with opening due to door and window have not been considered in this method. R_{inf} shall be calculated for both orthogonal directions and the minimum value is considered.

$$R_{inf} = \frac{Number\ of\ masonry\ panel\ in\ a\ direction}{Total\ no\ of\ span\ in\ a\ direction} \tag{5}$$

For clarification of the way, an example has been shown in Figure 5. The total number of masonry infill panels are 2 and 3 in X and Y direction, respectively. On the other hand, the total number of spans are obtained as 16 and 15 in X and Y direction, respectively. Therefore, R_{inf} are to be found 2/16 and 3/15 for X-direction and Y-direction, respectively. Here, minimum R_{inf} value 2/16 has been considered for capacity prediction.

In general, the thickness of masonry infill is within a range of 125 to 250 mm as found in the field survey in Bangladesh (SATREPS 2015). However, this study assumes the masonry infill thickness (t_{inf}) as 125 mm for single layer of infill panel.

4.3 Simplified concrete wall area Ratio

The concrete wall area (I_{cw}) ratio has been simplified by using similar way of masonry infill area ratio (I_{inf}) as mentioned in the previous sub-section. Therefore, it is simplified by concrete wall ratio (R_{cw}), thickness of concrete wall (t_{cw}) and average span length (l_s) as shown in Equation 6.

$$I_{cw} = \frac{A_{cw}}{A_f} \approx \frac{t_{cw}}{l_s}.R_{cw} \tag{6}$$

where, concrete wall ratio (R_{cw}) indicates the quantity of concrete wall expressed as the ratio of the total number of solid concrete wall panel in a direction to the total number of spans for that direction as shown in Equation 7.

$$R_{cw} = \frac{Number\ of\ \text{concrete wall}\ in\ a\ direction}{Total\ no\ of\ span\ in\ a\ direction} \tag{7}$$

Only solid RC wall have been considered in this method. R_{cw} shall be calculated for both orthogonal directions and the minimum value is considered. In this study, the minimum thickness (t_{cw}) has been assumed as 200 mm as found from the survey.

Considering simplified form of column area ratio (I_c), masonry infill area ratio (I_{inf}), and concrete wall area ratio (I_{cw}), the Visual Rating Index (I_{VR}), the Equation 2 can be re-written as Equation 8.

$$I_{VR} = \frac{1}{n.w}\left[\tau_c\left(\frac{b_c^2}{l_s^2}\right) + \tau_{\inf}\left(\frac{t_{\inf}}{l_s}.R_{\inf}\right) + \tau_{cw}\left(\frac{t_{cw}}{l_s}.R_{cw}\right)\right] \tag{8}$$

(a) Damage due to torsional effect

(b) Collapse due to soft story effect

Figure 6: Damage due to irregularity in 2015 Nepal Earthquake (www.datacenterhub.org)

In addition, other parameters such as building irregularity, deterioration and year of construction have large influence on seismic capacity of buildings. Figure 6 shows some photographs of severely damaged building due to irregularity of buildings. Several studies (Sucuoglu *et al*. 2007, Jain *et al*. 2010) also focused on the importance of such parameters. After considering the influence of aforementioned parameters, the VR index in the Equation 8 can be expressed as:

$$I_{VR} = \frac{1}{n.w}\left[\tau_c\left(\frac{b_c^2}{l_s^2}\right) + \tau_{\inf}\left(\frac{t_{\inf}}{l_s}.R_{\inf}\right) + \tau_{cw}\left(\frac{t_{cw}}{l_s}.R_{cw}\right)\right]F_{IV}.F_{IH}.F_D.F_Y \tag{9}$$

where, F_{IV}, F_{IH}, F_D and F_Y are the modification factors for existence of vertical irregularity, horizontal irregularity, deterioration of concrete and year of construction respectively.

The basic assumptions about material properties are already described in earlier section. The basic assumptions for modification factors are described in the subsequent section.

4.4 Basic Assumption for Modification Factors

The following assumptions have been considered for seismic capacity modification factors based on concepts and values used in the JBDPA standard (JBDPA 2001):

(i) Vertical irregularity factor (F_{IV})

Vertical irregularity factor (F_{IV}) has been imposed to check balance of story stiffness distribution along the height, the inconsistency between adjacent floor, ground floor parking, soft story etc. The reduction factors for different vertical irregularity criteria are shown in Table 2 (JBDPA 2001).

Table 2: Factor for vertical irregularity (F_{IV})

Items	Regular	Nearly Regular	Irregular
Criteria	Regular	Small opening at ground floor	Soft story floor
FIV	1	0.8	0.6

(ii) Horizontal irregularity factor (F_{IH})

Horizontal irregularity factor (F_{IH}) affects the seismic capacity of existing buildings. The JBDPA (JBDPA 2001) proposes guidelines for different criteria of plan irregularity and reduction factor for modifying the seismic capacity. Criteria for plan irregularity are described in JBDPA seismic evaluation manual (JBDPA 2001) and the reduction factors are shown in Table 3.

Table 3: Factor for horizontal irregularity (F_{IH})

Items	Regular	Nearly Regular	Irregular
Shape	Regular	L, T or U shaped plan	L, T or U shaped plan
Projection area	≤ 10 % of floor area	≤30% of floor area	>30% of floor area
FIH	1	0.8	0.6

(iii) Deterioration factor (F_D)

Deterioration of concrete such as presence of cracks as well as spalling in structural elements indicates the degradation of seismic capacity of building. In this study, a reduction factor has been proposed based on JBDPA standard (JBDPA 2001) as shown in Table 4.

Table 4: Deterioration factor (F_D)

Item	None	Minor	Severe
Criteria	No deterioration	Some cracks in structural element	Spalling in concrete
F_D	1	0.9	0.8

(iv) Building year of construction factor (F_Y)

Generally, old building cannot be expected to have a good performance during earthquake due to old construction practices ignoring seismic detailing in the recent building codes. For example, in Japan, poor seismic performance has been observed in old building, specially to those constructed before adopting new seismic design code 1981, in the 1995 Kobe earthquake (Ohba 2000). The JBDPA standard (JBDPA 2001) proposed a reduction factor for F_Y as shown in Table 5.

Table 5 Year of construction factor (F_Y)

Item	New	Middle	Old
Criteria	<15 years	15-30 years	> 30 years
F_Y	1	0.95	0.9

The aforementioned assumed values for each parameter in Equation 9 could be adjusted later for each country based on suitable characteristics of buildings and materials strength properties in that region.

5 APPLICATION IN BANGLADESH AS A CASE STUDY FOR DEVELOPING COUNTRIES

In order to investigate the applicability of the VR method, 14 (Fourteen) existing buildings located in Bangladesh have been inspected under a technical research project SATREPS (SATREPS 2015). The VR method provides conservative values for both simplified column area ratio and simplified masonry infill area ratio as shown in Figure 7. Actual column area ratio normalized with simplified column area ratio, the average value 1.40 and coefficients of variation 19 % also shows good estimation of actual column area ratio.

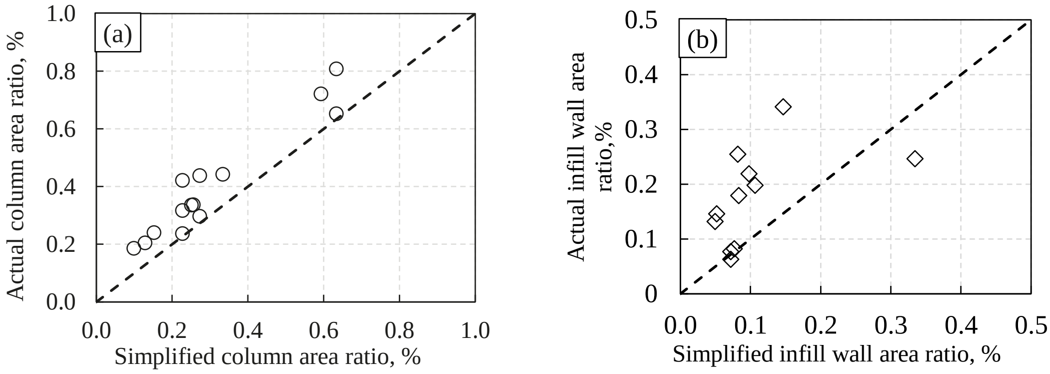

Figure 7: Comparison: (a) actual column area ratio vs. simplified column area ratio (b) actual masonry infill area ratio vs. simplified masonry infill area ratio

5.1 Application and comparison with detail evaluation

The Visual Rating Index (I_{VR}) has been calculated based on information found from building survey in Bangladesh. The calculated I_{VR} scores are shown in Table 6. In order to investigate the effectiveness of the method, the VR index has been compared with detail evaluation. The JBDPA standard (JBDPA 2001) proposes guideline for three level seismic evaluation for RC buildings. This study focuses on masonry infilled RC buildings which are not common in Japan. In order to apply the Japanese standard to masonry infilled RC buildings, Alwashali (2018) proposed seismic evaluation procedure for masonry infilled RC building which is based on Japanese standard. In this study, seismic capacity (first and second level evaluation for both directions) has been investigated for these buildings using the proposed seismic evaluation procedure for RC building with masonry infill (Alwashali 2018) and JBDPA standard (JBDPA 2001). The values of seismic index for first level and second level evaluation in minimum directions are shown in in Table 6.

Table 6: VR Index with minimum I_s in first and second level evaluation

Building ID	VR Index	Seismic Index, I_s	
		1st level evaluation	2nd level evaluation
Bldg # 1	0.51	0.47	0.64
Bldg # 2	0.08	0.09	0.17
Bldg # 3	0.20	0.21	0.29
Bldg # 4	0.20	0.23	0.45
Bldg # 5	0.18	0.31	0.35
Bldg # 6	0.24	0.35	0.51
Bldg # 7	0.20	0.25	0.44
Bldg # 8	0.23	0.32	0.53
Bldg # 9	0.13	0.27	0.42
Bldg #10	0.06	0.16	0.17
Bldg #11	0.26	0.49	0.40
Bldg #12	0.21	0.27	0.36
Bldg #13	0.11	0.31	0.35
Bldg #14	0.17	0.18	0.23

Fig. 8(a) and 8(b) show the comparison of Visual Rating Index (I_{VR}) score with the minimum value of seismic index for both first level (I_{S1}) and second level (I_{S2}) evaluation. It has been observed that the I_{VR} scores show conservative values both evaluation procedures. However, Seismic index of first level evaluation (I_{S1}) normalized with Visual Rating Index (I_{VR}), the average value 1.5 and coefficient of variation 36% also shows good estimation of seismic capacity. Therefore, it has been underlined that I_{VR} score can conservatively assess the seismic capacity which can be obtained with less effort than that of in detail evaluation.

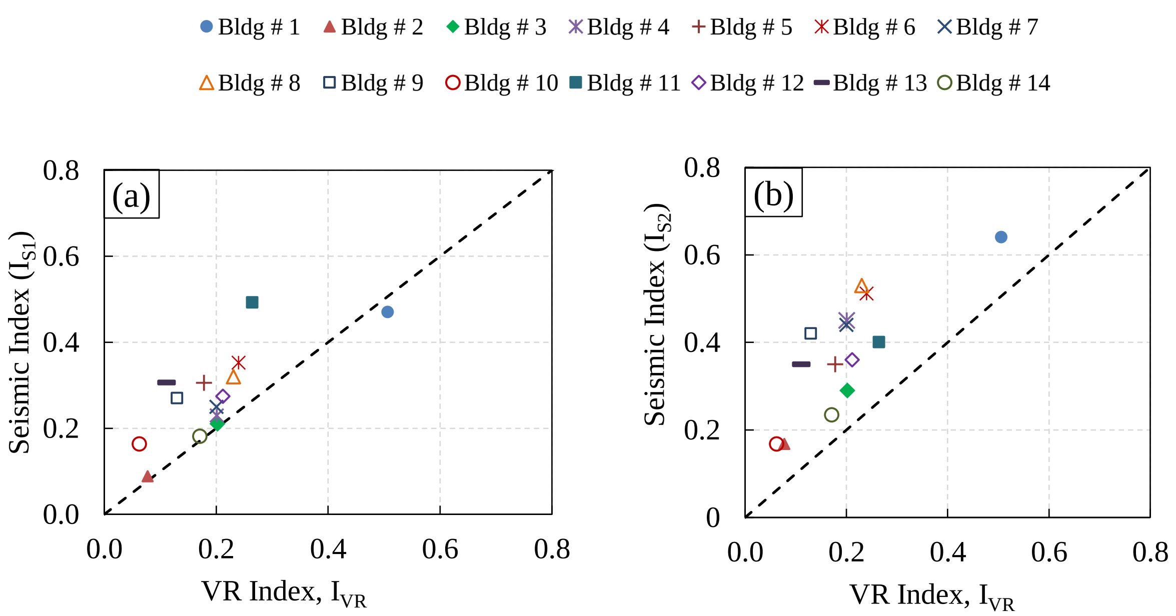

Figure 8: Comparison of Visual Rating Index (I_{VR}) with (a) First level evaluation(I_{S1}) (b) Second level evaluation, I_{S2}

6 CONCLUSIONS

This study describes a simple screening method for RC building with masonry infill based on visual inspection. The method calculates the Visual Rating Index (I_{VR}) which is an approximate estimation of seismic capacity of existing building. The Visual Rating Index (I_{VR}) has been calibrated with first level and second level evaluation by investigating of existing buildings located in Bangladesh as a case study in developing country. The following conclusions can be stated as follows:

1. The Visual Rating method considers the simplified column area ratio and the simplified wall area ratio, which approximately estimates the seismic capacity of buildings. The inclusion of those ratio in visual rating method is the new concept that have not been considered in the existing visual screening methods.
2. The Visual Rating Index (I_{VR}) score obtained in the study shows good agreement with seismic index of first and second level evaluation procedure.

However, the assumptions considered for column, masonry infill and concrete wall need further investigation for each countries according to local materials. Even though, this method is intended to buildings in Bangladesh, but could be easily adjusted to other countries by modifications for suitable characteristics of buildings and materials strength properties in the intended region.

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