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ORIGINAL RESEARCH

Preliminary assessment approach to predict seismic vulnerability of existing low and mid-rise RC buildings

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Abstract
This article presents an approach to rapidly predict the seismic vulnerability existing of low-to mid-rise residential reinforced concrete (RC) buildings. In this procedure, Capacity Index is computed considering the cross-sectional orientation and size and material properties of the components of the structural system. This index is modified considering the several coefficients of possible negative impacts of structural irregularities, which are frequently found in RC buildings. Accuracy of the proposed approach has been tested considering 196 RC buildings subjected to earthquakes. The procedure categorizes the buildings either as safe or as unsafe according to whether they meet the life-safety target performance requirement. The analytical results indicate that the consistency of the proposed approach in this paper is about over 90%. Therefore, the proposed approach can be used to asses the seismic performance and vulnerability levels of existing RC buildings.

Keywords Seismic vulnerability · Performance · Existing RC buildings · Evaluation · Earthquake engineering

1 Introduction

Considering the severe financial losses and damages to human life caused by earthquakes, it is observed that RC buildings exhibit inadequate seismic vulnerability and performance against earthquakes. The need to assess the seismic performance of existing RC buildings has led to an increase in the studies on the techniques to predict the possible seismic performance levels of RC buildings. In the literature, there are many studies and seismic reports related to seismic damages as well as seismic performance of existing RC buildings (Scawthorn and Johnson 2000; Dogangun 2004; Inel et al. 2013; Ozmen et al. 2013; Yon et al. 2013; Ozmen and Inel 2017; Puranam et al. 2018; Del Gaudıo et al. 2018; Dilmac et al. 2018; Furtado et al. 2018; Calderon and Silva 2019; Mahsuli et al. 2019; Rahimi and Mahsuli 2019; Pardalopoulos and Pantazopoulou 2019). In these studies, effects of short columns, infill walls, material quality, soft stories, lack of shear walls, large and heavy overhangs, and plan irregularities are reported to be the main causes of the damages in the buildings after earthquakes.

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For a rapid evaluation of buildings, FEMA 154 (1988), FEMA 310 Tier 1 (1998), and the Japanese system of assessment (Ohkubo 1991) were proposed to predict rapidly the seismic vulnerability of buildings taking into account relevant parameters, such as the number of stories, plan and vertical irregularities, soil parameter, age of the building, workmanship quality, and material properties. A more detailed evaluation is made with FEMA 310 Tier 2 (1998), which uses preliminary evaluation techniques. On the other hand, the best results for the precise prediction of the seismic performance of buildings are obtained through an in-depth assessment of the building using improved structural analysis (linear and non-linear analysis techniques). However, since these analyses are time-consuming and lengthy, preliminary assessment methods are most widely used to predict rapidly the seismic vulnerability of buildings when a rapid and reliable evaluation is needed.

Many researchers have proposed preliminary assessment methods for evaluating the seismic vulnerability of buildings. The wall index (*WI*) and the column index (*CI*) were developed by Hassan and Sozen (1997) and Gulkan and Sozen (1999), respectively. These indexes depend merely on the orientation and cross-sectional size of vertical components of low-to mid-rise RC buildings and are examined graphically to determine the relative vulnerability of a group of RC buildings. Yakut (2004) proposed a preliminary seismic performance assessment procedure named Capacity Index (*CPI*) for existing RC buildings. This index is computed by considering the orientation, size, and material properties of components with several coefficients that reflect the quality of workmanship and architectural features. Tekeli et al. (2017) proposed an alternative assessment procedure that focuses on determining the shear stress indicator (*SSI*) value for the ground floor. The procedure requires a total weight of the building and cross-section area of columns. The SSI value is calculated as a ratio of the elastic seismic story shear to the total cross-section area of columns. The validity of the *SSI* was examined considering 250 existing RC buildings.

In the past few decades, some of the RC buildings in Turkey were damaged due to a combination of the irregularities mentioned above. Hence, seismic performance assessment procedures that do not consider these factors would lead to mispredictions. In this study, a simple approach is proposed to predict the seismic performance of existing RC buildings considering the negative effects of irregularities. The approach aims to determine the potential seismic vulnerabilities or performances of low- and mid-rise RC buildings. In addition, an RC building can be wrongly marked as unsafe due to an inaccurate assessment procedure. These quick evaluations are highly needed because practicing engineers need rapid and simple methods to asses the seismic vulnerability of a given building stock.

In this study, the proposed approach for predicting seismic vulnerability of existing RC buildings is a new version of existing procedure proposed by Yakut (2004). The comparison of the procedure improved in the present study with similar procedure (Yakut 2004) reveals that the entire procedure involves the orientation and size of columns, shear walls, and infill walls. The proposed approach considers the strength of concrete and infill walls and the negative effects of vertical and plan irregularities with variety coefficients. It is aimed to improve Yakut (2004)'s approach and to obtain a more correct and more appropriate formulation.

2 Description of the proposed approach

The method is recommended for low- to mid-rise RC buildings. The proposed method considers the dimensions of the ground floor and size, orientation, and concrete strength of the components to determine the base shear capacity of the building. The shear capacity of each columns on the first story is computed based only on the concrete contribution using Eq. (1).

$$V_{ci} = \alpha \cdot f_{ctk} \cdot b_i \cdot h_i \tag{1}$$

$$f_{ctk} = 0.35\sqrt{f_c} \tag{2}$$

where V_{ci} is the shear capacity of a rectangular concrete member with dimensions b_i and h_i, f_{ctk} is concrete tensile strength, and f_c is concrete compressive strength in Eq. (2). The coefficient α represents the combined effect of strength reduction factor that is taken as 0.65 in encoded Turkish Design Code (TS500) (2000) for the design and construction of RC structures (TS500 2000).

Total shear capacity (V_c), can be calculated as the sum of areas of all lateral load-carrying component in the direction of each principal axis:

$$V_c = \alpha \cdot f_{ctk} \cdot A_e \tag{3}$$

where A_e is generally the total shear area of columns, shear walls and infill walls, and can be calculated by the equation given in Eq. (4). It is known that the presence of masonry infill wall increases the total shear capacity of the building. The influence of infill walls is generally taken into account using a percentage of their cross-sectional areas to explain the differences between shear strength of masonry and concrete (Yakut 2004; Shariq et al. 2008). Total shear area A_e can be calculated by considering the infill wall.

$$A_e = \sum k_c \cdot A_c + k_{sw} \sum A_{sw} + k_m \sum A_m \tag{4}$$

where A_c is the sum of the cross-sectional areas of the columns, A_{sw} and A_m are the sum of the cross-sectional areas of the reinforced concrete shear wall and infill walls in-plane direction, respectively.

For the orientation of the columns, the coefficient k_c is used, which is taken as 1.0 when the capacity in the longitudinal direction of the member is calculated and as 0.6 if transverse shear capacity is desired. For the reinforced concrete shear wall, k_{sw} is merely considered as 1.0 when the in-plane direction, the other side capacity is not considered. For infill walls, k_m is taken as Eq. (5) when the in-plane direction is considered

$$k_m = \frac{E_m}{E_c} \tag{5}$$

$$E_c = 5000\sqrt{f_c} \tag{6}$$

$$E_m = 550 \cdot f_m \tag{7}$$

where E_c and E_m are the elastic modulus of concrete and infill wall, respectively (Rahimi and Mahsuli 2019). The f_m is the compressive strength of infill walls that are taken as 6.2 MPa, 4.1 MPa, and 2.1 MPa by a factor as specified as good, fair, and poor masonry condition, respectively (ACI-530 1999).

The compressive strength of concrete is generally obtained by testing the section samples taken from the building. However, most of the time, taking core samples might be impractical as it is a destructive and elaborate. In such cases, either a well-correlated Schmidt hammer test can be used or the strength can be estimated through a visual

Table 1 Recommended concrete compressive strength values based on concrete quality (Yakut 2004)

Concrete quality (from visual inspection)	Recommended compressive strength (f_{ck}) (MPa)
Poor	< 10
Average	10–16
Good	> 16

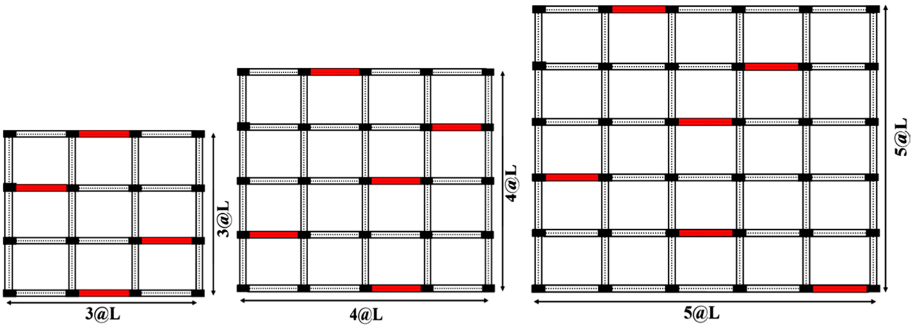


Fig. 1 Structural layouts of the RC building models and placement of infill walls (Tekeli et al. 2017)

inspection of concrete quality. When estimating the strength by means of visual inspection, the regional practice needs to be taken into account. The values indicated in Table 1 are recommended for Turkey, based on the experience and common construction practices (Yakut 2004).

2.1 Model descriptions

The story plans of the selected buildings are given in Fig. 1. The regular story height is 3 m. For the numerical implementation of the analysis, RC building models having 2, 3, 4, and 5 stories are considered to represent low- and mid-rise buildings located in high seismicity regions. The number of spans of the structural models in both *x* and *y* directions are selected as 2, 3, 4, and 5 having a length of 4 m. In Fig. 1, the infill walls that meet the requirements of FEMA 356 (2000) to form diagonal struts are shown with shaded areas. The other infill walls with openings that prevent diagonal strut formation are considered as dead load. The buildings have symmetrical floor plans to avoid any irregularity effects.

A three-dimensional model of each structure was created in SAP2000 (2000) to carry out pushover analysis. The beam and column elements were modelled as nonlinear frame elements with lumped plasticity by defining plastic hinges at both ends of the beams and columns. The longitudinal reinforcement ratio of the columns was modelled considering it to be between 1 and 1.2 per cent. The beams elements in all models have the cross-section of 0.25 m×0.50 m and have two bars with 16 mm diameter at the bottom and three bars with 16 mm diameter at the top of the cross-section of the beam as longitudinal reinforcement. The models with various characteristics were selected to establish a relationship between the total shear capacity (V_c) and the yield base shear capacity (V_y) of the building. The capacity curve of each building obtained from pushover analysis was approximated with a bilinear curve using guidelines given in FEMA 273 (1997) (Fig. 2). The ultimate base shear (V_u), yield base shear capacity (V_y), and code base shear (V_{code}) are presented in Fig. 2.

The averages of result values of yield base shear capacity over the total shear capacity (V_y/V_c) plots were achieved according to the number of stories, as shown in Fig. 3.

The relationship between V_y and V_c could be found in Eq. (8) depending on the number of stories. These results were generated as a proportional function of the number of stories (n) for each direction of model buildings as plots in Fig. 4

$$V_y = (0.37n + 0.30) \times V_c \tag{8}$$

The Basic Capacity Index (*BCPI*) can be computed by using Eq. (9) as given in Yakut (2004). The adverse effects of architectural features of buildings on the seismic performance are well recognized by the earthquake engineering community. Therefore, an improved Capacity Index (*CPI*) that incorporates these secondary effects is introduced. *BCPI* is modified by the parametric factors that reflect the architectural features (C_A) and construction quality (C_M) as shown in Eq. (10)

$$BCPI = \frac{V_y}{V_{code}} \tag{9}$$

$$CPI = C_A \cdot C_M \cdot BCPI \tag{10}$$

The coefficient C_A is determined by subtracting several other coefficients from the base value of unity, as indicated in Eq. (11). The coefficients C_{AS}, C_{ASC}, C_{AP}, and C_{AF} reflect the presence of a soft story, short column, plan irregularity, and vertical and in-plan discontinuity of frames, respectively. The coefficients of these irregularities are given in Table 2.

The relative scores reported in FEMA 154 (1988), Gulkan and Yakut (1994), Sucuoglu and Yazgan (2003), and Yakut (2004) are consistent with each other. These studies recommend scores based on construction, material quality, and architectural features

$$C_A = 1.0 - \left(C_{AS} + C_{ASC} + C_{AP} + C_{AF}\right) \tag{11}$$

The coefficients C_M are presented in Table 3 (Yakut 2004). The values presented by the alternatives in Table 2 are not very different from each other. Therefore, the relative

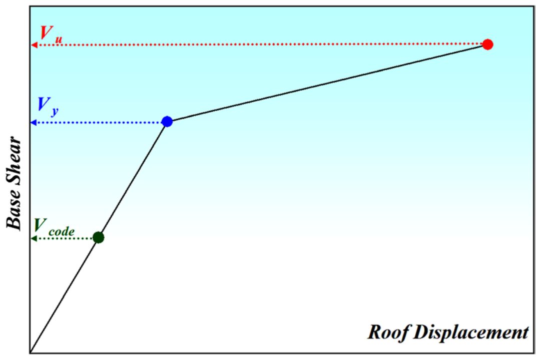


Fig. 2 Idealized static pushover curve (Yakut 2004)

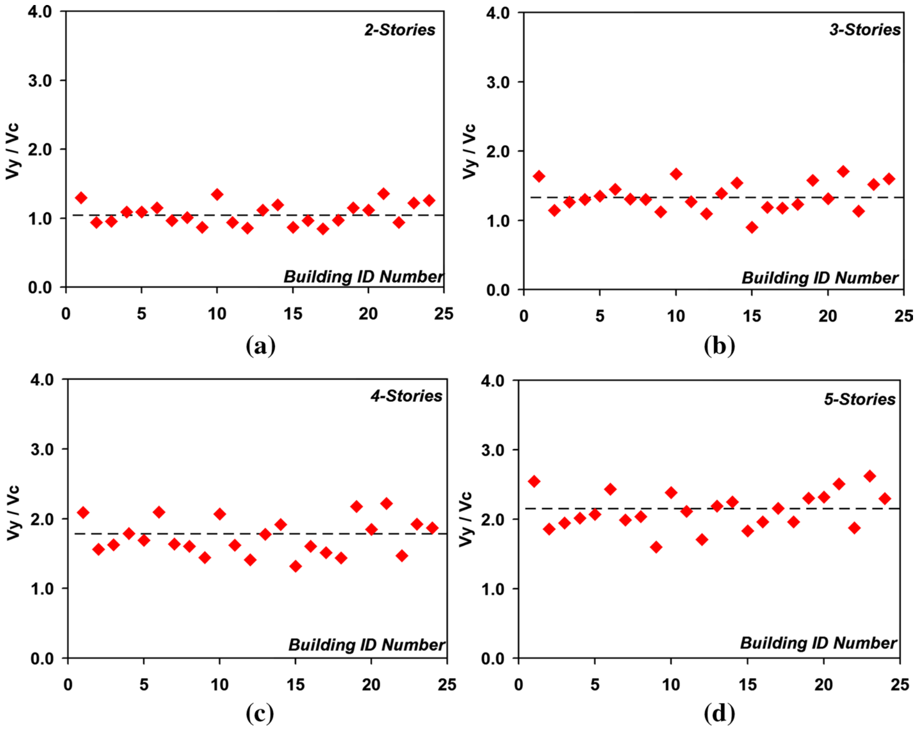
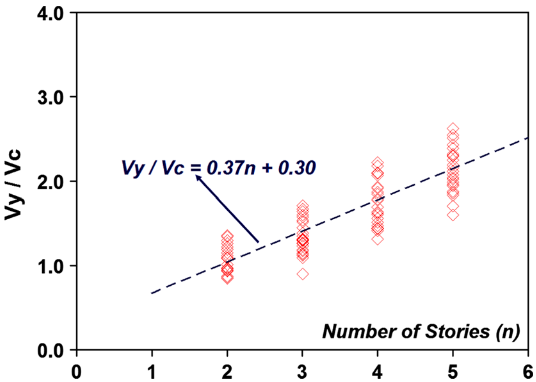


Fig. 3 Relationship between V_y and V_c

Fig. 4 Effect of number of stories on the V_y and V_c



significance value of the architectural features proposed in FEMA 154 (1988) is considered with the Q_r value as 0.55 to include the effect of the substandard construction and to calculate C_M value according to the quality of construction and workmanship in Table 3. As a result of the inferences from the some analytical studies (FEMA 154 1988; Yakut 2004), the $C_A = 0.85$ was considered to be reasonable a value in this study.

Table 2 The comparison of weighting coefficients for architectural factors

	Weighting coefficients				
	FEMA-154 (1988)	Yakut (2004)	Sucuoglu and Yazgan (2003)	Gulkan and Yakut (1994)	Current study
C_{AS}	0.36	0.39	0.32	0.50	0.38
C_{ASC}	0.18	0.15	0.11	0.25	0.16
C_{AP}	0.19	0.16	0.19	0.125	0.20
C_{AF}	0.27	0.30	0.38	0.125	0.26

Table 3 Recommended values of CM (Yakut 2004)

Quality of construction and workmanship	C_M
Poor	$1.0 - Q_r (1 - C_A)$
Average	$1.0 - Q_r (1 - C_A)/3$
Good	1.0

3 Determination of limiting values of Capacity Index (*CPI* $_{limit}$)

The seismic safety of an RC building is based on the seismic demand and the lateral load-carrying capacity of the structural system. Therefore, it is important to know the parameters affecting the seismic behaviour and performance of RC buildings. To determine the CPI_{limit} of the proposed method, a variety of existing RC buildings with different structural configurations and parameters (such as story and span numbers, presence of masonry wall, concrete strength, and steel yield stress) were taken into account. The determination of the CPI_{limit} was performed in two stages. In the first stage, the RC building models displayed in Fig. 1 were selected and modelled using SAP 2000 software (2000). In the second stage, each of RC building models was analysed under the dead loads and lateral seismic load considering the requirements set forth in Turkish Earthquake Code (TEC) (2007) and the deformation-based assessment of buildings is obtained from the analysis results. The deformation-based evaluation is implemented through the pushover analysis. The limiting values of steel strains and concrete compression strains and general rules are used as they are given in the code which is similar to those given in FEMA 356 (2000) as plastic hinge rotations. If the seismic performance level of the RC building model does not provide the target seismic performance level (LS), the pushover analysis is repeated by increasing the cross-section dimensions of columns as rectangular in certain quantities until the target seismic performance level is provided. This process was carried out separately for all structural parameters of each model building. The distribution of *CPI* values of the model buildings that provide and do not meet the target performance level was obtained from the analysis results. Considering the structural and architectural irregularities and workmanship factors, the *CPI* was further reduced by coefficients by using Eq. (10). The minimum and maximum *CPI* values of the model buildings that meet and do not meet the target performance level were determined, respectively. However, the most critical thresholds to consider in the performance evaluation are the largest *CPI* values of the red dots as shown in Fig. 5. The threshold values were determined to be outside the most critical *CPI* values.

The average results obtained from the analyses of model buildings are given in Fig. 5 according to the number of stories.

As it is seen, the average values of CPI_{limit} are designated as 0.55, 0.60, 0.65 and 0.70 for 2, 3, 4 and 5-stories respectively. The trend between CPI_{limit} and the number of stories (n) are displayed and formulated in Fig. 6 and Eq. (12)

$$CPI_{limit} = 0.05n + 0.45 \tag{12}$$

The proposed approach has taken into account the requirements specified in the code (TEC 2007) so that the approach can be adapted easily to any code. The masonry infill walls are modelled by using the equivalent strut model. The nonlinear behaviour of the infill walls was taken into consideration by using the plastic hinge model proposed by Panagiotakos and Fardis (1996).

In the proposed approach, the CPI_{limit} value for buildings with different number of stories (not to exceed 7-stories) may be obtained; therefore, the applicability of the proposed approach can be quite extensive.

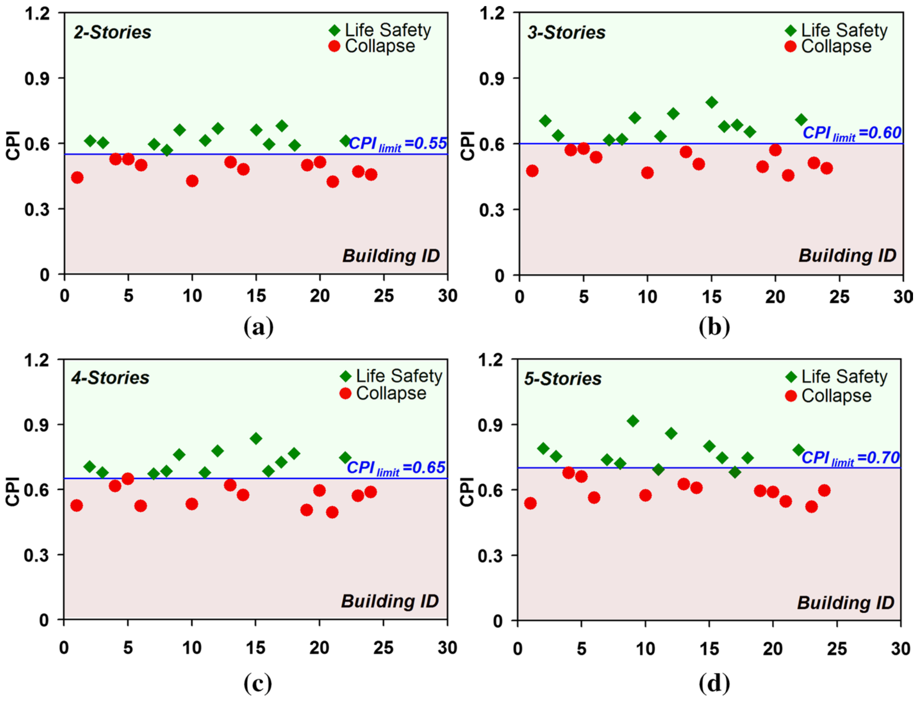


Fig. 5 The limiting values of *CPI* for each RC building models

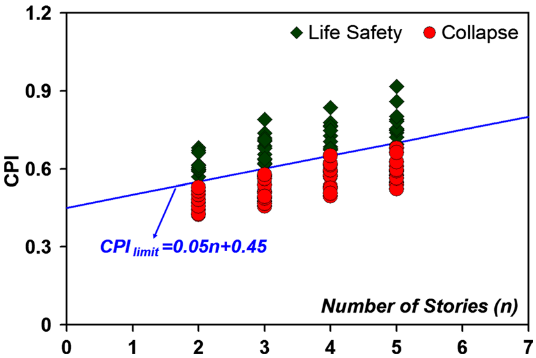


Fig. 6 The relationship between CPI_{limit} and the number of stories

4 Database of existing RC buildings

The earthquakes that occurred in the past two decades have caused severe financial loss and damages to human health in Turkey. Massive earthquakes revealed that existing building stocks in urban areas are significantly vulnerable to seismic hazard. The earthquakes that caused severe damage to both human health and economy and are categorized as very severe and destructive earthquakes in the Turkish seismology archives can be listed as follows: the earthquakes of magnitude 7.5 (M_w) on August 17 (1999) in Bolu, 7.1 (M_w) on November 12 (1999) in Düzce and Kaynaşlı, 6.5 (M_w) on February 3 (2002) in Afyon (named Sultandağı earthquake) and on May 1 (2003) in Bingöl in Turkey. The accuracy of the proposed approach is examined on 196 existing buildings selected from the cities of Bolu, Düzce, Kaynaşlı Afyon, and Bingöl, which are located within high seismic hazard zones in Turkey. The structural and architectural properties of the 196 existing buildings presented by Yakut (2004) and Pay (2001) are given in Tables 4, 5 (Yakut 2004) and Tables 6, 7, and 8 (Pay 2001) for Afyon, Bingöl, Bolu, Kaynaşlı and Düzce, respectively.

The post-earthquake damage levels of the selected buildings are classifieds as “none”, “light”, “moderate” or “heavy/collapse” (Yakut 2004; Pay 2001). Since the damage levels of RC buildings depend on their seismic performance levels of RC buildings, while “none”, “light” and “moderate” damage levels are considered “Life Safety (*LS*)” performance level, while “heavy/collapse” damage level is considered as “Collapse Prevention (*CP*)” in this study. The distribution of damage levels observed in RC buildings after the earthquakes and the decision on the recommended mitigation measures are presented in Figs. 7 and 8.

5 Implementation and compatibility of the proposed approach

The steps involved in the calculation of *CPI* are summarized below. Additionally, the following steps should be taken to determine the seismic performance of the buildings by comparing the CPI_{limit} of the calculated *CPI* values. Note that most of the recommended coefficients are valid for the buildings in Turkey and need to be adjusted for implementation in other places.

Step 1 Compute the total concrete base shear capacity (V_c) using Eq. (3) for x and y directions on the ground story. The smaller of the two values is considered to be

Table 4 Summary of Afyon Database (Yakut 2004)

Building ID	Number of stories	∑Floor area (m²)	Column area			Shear wall		Infill wall		f_{ck} (Mpa)	Construction quality	Short column	Plan irregularity	Frame irregularity	Soft story	Damage
			∑Acol (m²)	∑Acol-x (m²)	∑Acol-y (m²)	∑Asw-x (m²)	∑Asw-y (m²)	∑Amw-x (m²)	∑Amw-x (m²)							
AFY-B-01	4	1853	7.74	2.67	5.07	1.05	0.00	1.47	6.35	22.1	Average	Yes	No	No	Yes	Moderate
AFY-B-02	3	1042	6.37	0.30	6.07	0.00	0.00	1.05	1.81	31.5	Good	No	No	No	No	Light
AFY-C-02	3	386	1.50	0.90	0.60	0.00	0.00	0.90	0.00	16.0	Poor	No	No	Yes	Yes	Heavy
AFY-C-03	3	358	1.10	0.00	1.10	0.00	0.00	0.00	0.00	13.6	Poor	Yes	No	No	Yes	Heavy
AFY-C-05	4	561	1.60	0.50	1.10	0.00	0.00	0.51	1.71	28.9	Average	Yes	No	No	No	Moderate
AFY-C-06	3	359	1.60	0.20	1.40	0.00	0.00	0.33	4.37	20.4	Average	No	No	Yes	Yes	Moderate
AFY-C-07	4	544	2.22	0.72	1.50	0.00	0.00	0.00	1.01	22.1	Average	No	Yes	No	Yes	Heavy
AFY-C-11	4	1335	7.81	2.33	5.49	0.00	0.00	0.00	2.58	13.6	Average	No	No	Yes	Yes	Light
AFY-C-12	4	649	2.75	0.00	2.75	0.00	0.00	0.00	3.15	13.6	Average	Yes	No	No	Yes	Moderate
AFY-C-13	3	350	1.36	0.17	1.19	0.00	0.00	0.00	0.78	25.5	Average	No	Yes	No	Yes	Heavy
AFY-CO-01	3	745	3.30	1.95	1.35	0.00	0.00	2.45	0.79	17.0	Poor	No	No	No	No	Collapsed
AFY-CO-02	4	1029	3.72	1.63	2.09	0.00	0.00	0.00	2.20	16.1	Average	No	No	No	Yes	Heavy
AFY-CO-03	5	2304	7.65	3.42	4.23	0.00	0.00	1.79	10.0	17.0	Average	No	No	No	Yes	Heavy

Table 4 (continued)

Building ID	Number of stories	∑Floor area (m^2)	Column area			Shear wall		Infill wall		f_{ck} (Mpa)	Construction quality	Short column	Plan irregularity	Frame irregularity	Soft story	Damage
			∑Acol (m^2)	∑Acol-x (m^2)	∑Acol-y (m^2)	∑Asw-x (m^2)	∑Asw-y (m^2)	∑Amw-x (m^2)	∑Amw-x (m^2)							
AFY-CO-04	4	964	5.28	1.92	3.36	0.00	0.00	2.87	3.17	15.3	Poor	No	No	No	Yes	Light
AFY-CO-05	3	353	1.58	1.00	0.58	0.00	0.00	0.00	0.76	14.4	Poor	No	Yes	Yes	Yes	Heavy
AFY-M-02	4	2551	5.76	0.66	5.10	0.00	0.00	0.00	5.36	20.4	Good	Yes	No	No	No	Light
AFY-S-01	3	522	2.63	0.25	2.38	0.00	0.00	0.00	3.46	18.7	Average	Yes	Yes	No	Yes	Heavy
AFY-Y-01	3	806	6.40	6.40	0.00	0.00	0.00	0.00	0.00	20.4	Average	No	No	No	Yes	Heavy

Table 5 Summary of Bingöl database (Yakut 2004)

Building ID	Number of stories	∑Floor area (m^2)	Column area			Shear wall		Infill wall		f_{ck} (Mpa)	Construction quality	Short column	Plan irregularity	Frame irregularity	Soft story	Damage
			∑Acol (m^2)	∑Acol-x (m^2)	∑Acol-y (m^2)	∑Asw-x (m^2)	∑Asw-y (m^2)	∑Amw-x (m^2)	∑Amw-x (m^2)							
BNG-10-3-10	3	1958	10.13	3.38	6.75	0.00	0.00	1.23	11.58	14.00	Poor	No	No	Yes	Yes	Heavy/collapse
BNG-10-3-3	3	918	6.72	2.99	3.73	0.00	0.00	0.00	1.76	18.00	Poor	No	No	No	No	Moderate
BNG-10-4-4	4	3149	11.50	4.27	7.23	0.00	0.00	4.89	16.68	18.00	Average	No	Yes	Yes	Yes	Moderate
BNG-10-4-6	4	2408	13.78	8.39	5.40	0.00	0.00	8.72	0.00	30.00	Average	Yes	Yes	No	No	None/light
BNG-10-4-7	4	3311	16.42	5.82	10.61	0.00	0.00	0.00	4.59	20.00	Average	No	No	Yes	Yes	None/light
BNG-10-4-9	4	2201	5.37	2.33	3.04	3.15	3.85	3.63	12.52	22.00	Good	No	Yes	Yes	Yes	None/light
BNG-10-5-1	5	2918	8.12	4.82	3.30	0.00	2.78	6.87	8.19	18.00	Average	No	Yes	No	Yes	Moderate
BNG-10-5-11	5	460	2.65	0.99	1.67	0.00	0.00	1.42	4.01	32.00	Average	No	Yes	No	Yes	None/light
BNG-10-5-2	5	3363	5.31	1.77	3.54	1.44	0.78	0.00	8.04	20.00	Good	No	Yes	No	No	None/light

Table 5 (continued)

Building ID	Number of stories	∑Floor area (m^2)	Column area ∑Acol (m^2)	Column area ∑Acol-x (m^2)	Column area ∑Acol-y (m^2)	Shear wall ∑Asw-x (m^2)	Shear wall ∑Asw-y (m^2)	Infill wall ∑Amw-x (m^2)	Infill wall ∑Amw-x (m^2)	f_{ck} (Mpa)	Construction quality	Short column	Plan irregularity	Frame irregularity	Soft story	Damage
BNG-11-2-3	2	260	2.40	1.00	1.40	0.00	0.00	1.32	0.00	8.00	Poor	No	Yes	Yes	Yes	Moderate
BNG-11-4-1	4	1033	3.26	1.46	1.80	0.70	0.00	3.57	1.00	18.00	Poor	No	Yes	No	Yes	Heavy/collapse
BNG-11-4-2	4	580	2.13	0.92	1.22	0.00	0.00	1.68	3.80	20.00	Poor	No	Yes	Yes	Yes	Heavy/collapse
BNG-11-4-4	4	486	2.10	1.05	1.05	0.00	0.00	1.10	1.71	16.00	Poor	No	Yes	Yes	Yes	Moderate
BNG-11-4-5	4	583	3.00	1.45	1.55	0.00	0.00	1.83	2.42	13.00	Average	No	Yes	Yes	No	None/light
BNG-3-4-1	4	1954	8.50	4.15	4.35	0.00	0.00	2.12	5.48	18.00	Poor	No	No	Yes	No	None/light
BNG-3-4-2	4	1869	5.25	2.63	2.62	0.00	1.12	6.08	8.14	18.00	Average	No	No	No	No	None/light
BNG-3-4-4	4	1910	8.05	3.50	4.55	1.12	0.00	3.72	1.76	26.00	Average	No	No	Yes	No	None/light
BNG-5-5-1	5	1974	5.79	3.27	2.52	0.00	0.00	2.54	7.62	26.00	Average	No	Yes	Yes	Yes	None/light
BNG-6-2-8	2	233.1	1.50	0.50	1.00	0.00	0.00	2.95	0.00	12.00	Poor	No	Yes	No	No	Heavy/collapse

Table 5 (continued)

Building ID	Number of stories	∑Floor area (m²)	Column area			Shear wall		Infill wall		f_{ck} (Mpa)	Construction quality	Short column	Plan irregularity	Frame irregularity	Soft story	Damage
			∑Acol (m²)	∑Acol-x (m²)	∑Acol-y (m²)	∑Asw-x (m²)	∑Asw-y (m²)	∑Amw-x (m²)	∑Amw-x (m²)							
BNG-6-3-1	3	821.3	3.78	1.74	2.04	0.00	0.00	5.20	3.40	20.00	Average	Yes	Yes	No	Yes	Moderate
BNG-6-3-10	3	365.6	2.00	0.88	1.13	0.00	0.00	1.22	4.59	20.00	Good	No	Yes	Yes	Yes	None/light
BNG-6-3-11	3	705.3	3.90	1.95	1.95	0.00	0.00	1.61	2.97	14.00	Average	No	Yes	Yes	Yes	None/light
BNG-6-3-12	3	443.8	2.94	1.04	1.90	0.00	0.00	0.00	6.18	13.00	Average	No	Yes	Yes	Yes	None/light
BNG-6-3-4	3	343.9	1.80	1.05	0.75	0.00	0.00	3.10	0.00	18.00	Average	No	Yes	No	No	None/light
BNG-6-4-2	4	2021	6.30	2.70	3.60	0.00	0.00	3.31	14.92	18.00	Poor	Yes	Yes	Yes	Yes	Heavy/collapse
BNG-6-4-3	4	662.3	1.92	0.76	1.16	0.00	0.00	1.25	3.48	30.00	Poor	No	Yes	No	Yes	Heavy/collapse
BNG-6-4-5	4	398	2.25	0.80	1.45	0.00	0.00	0.58	4.16	20.00	Good	No	Yes	No	No	None/light
BNG-6-4-7	4	948.5	3.90	1.50	2.40	0.75	0.00	2.08	2.07	18.00	Poor	No	Yes	No	No	Moderate

Table 6 Summary of Bolu database (Pay 2001)

Building ID	Number of stories	∑Floor area (m^2)	Column area			Shear wall		Infill wall		Damage
			∑Acol (m^2)	∑Acol-x (m^2)	∑Acol-y (m^2)	∑Asw-x (m^2)	∑Asw-y (m^2)	∑Amw-x (m^2)	∑Amw-y (m^2)	
BL-B4	1	128	2.91	1.66	1.25	0.00	0.00	0.00	0.00	Light
BL-E11	2	214	2.16	1.20	0.96	0.00	0.00	3.47	1.94	None
BL-E18	2	286	2.37	1.05	1.32	0.00	0.00	0.00	0.88	None
BL-B5	3	350	1.49	0.52	0.97	0.00	0.00	3.16	0.00	Light
BL-C10	3	637	2.75	0.63	2.13	0.54	0.00	2.88	2.46	Heavy/collapse
BL-C12	3	322	2.35	1.10	1.25	0.00	0.00	0.29	1.52	Light
BL-C13	3	1783	5.10	1.80	3.30	2.43	2.92	6.81	12.46	None
BL-C14	3	1390	3.90	1.20	2.70	2.43	2.92	5.31	8.64	None
BL-D8	3	372	3.63	1.63	2.00	0.00	0.00	1.10	1.97	None
BL-E3	3	338	1.70	0.64	1.06	0.00	0.00	1.73	0.90	Light
BL-E5	3	426	2.55	1.33	1.23	0.00	0.00	0.52	0.33	Light
BL-E6	3	305	2.16	1.06	1.10	0.44	0.00	0.00	2.19	Light
BL-E8	3	337	2.20	1.13	1.08	0.00	0.00	1.72	2.03	Heavy/collapse
BL-E19	3	373	2.43	1.38	1.05	0.00	0.00	1.33	0.00	Heavy/collapse
BL-C2	4	851	3.52	1.55	1.97	0.00	0.00	0.83	1.20	Heavy/collapse
BL-C7	4	583	9.49	6.06	3.42	0.34	0.67	7.48	5.29	Heavy/collapse
BL-C9	4	514	2.09	0.95	1.14	0.00	0.00	0.56	0.93	Heavy/collapse
BL-C15	4	489	2.91	0.72	2.18	0.84	0.64	1.09	2.16	Light
BL-D1	4	1049	4.22	1.78	2.44	0.00	2.20	0.00	0.00	Moderate
BL-D2	4	468	1.55	1.43	0.13	0.00	0.00	0.70	1.22	Light
BL-D4	4	551	2.50	0.85	1.65	0.00	0.00	1.91	3.52	Light
BL-D5	4	569	1.81	0.82	0.99	0.68	0.44	1.31	3.52	Heavy/collapse
BL-D6	4	534	2.23	1.45	0.78	0.00	0.00	0.93	2.92	Moderate
BL-E9	4	574	2.91	1.39	1.52	0.00	0.00	1.83	1.06	Heavy/collapse

Table 6 (continued)

Building ID	Number of stories	∑Floor area (m^2)	Column area			Shear wall		Infill wall		Damage
			∑Acol (m^2)	∑Acol-x (m^2)	∑Acol-y (m^2)	∑Asw-x (m^2)	∑Asw-y (m^2)	∑Amw-x (m^2)	∑Amw-y (m^2)	
BL-E10	4	533	2.36	0.65	1.71	0.64	0.00	0.91	2.16	Light
BL-E12	4	567	2.43	1.72	0.71	0.94	0.32	1.87	1.13	Moderate
BL-E13	4	416	1.77	0.55	1.22	0.00	0.33	0.00	0.00	Moderate
BL-E14	4	617	2.80	1.68	1.12	0.00	0.00	0.00	0.00	Light
BL-E15	4	728	3.57	2.17	1.40	0.38	0.00	4.49	0.50	None
BL-E16	4	564	2.43	0.88	1.55	0.00	0.28	1.11	0.82	Light
BL-E17	4	509	2.61	1.12	1.49	0.00	0.00	0.36	1.66	None
BL-B3	5	1289	3.71	1.87	1.84	1.30	0.32	0.00	0.00	Moderate
BL-C1	5	846	2.77	0.77	2.00	0.00	1.23	0.42	1.64	Moderate
BL-C4	5	1199	3.18	0.38	2.80	1.04	0.92	0.46	1.08	Heavy/collapse
BL-C5	5	759	3.19	0.99	2.20	0.00	0.00	1.97	2.31	Light
BL-C6	5	602	2.85	1.44	1.42	0.00	0.46	0.00	0.00	Light
BL-C16	5	1225	4.25	1.38	2.87	1.05	0.71	1.67	2.98	Light
BL-C17	5	617	2.83	0.97	1.86	0.56	0.66	1.06	2.08	Light
BL-D7	5	710	1.77	0.80	0.97	1.00	0.28	2.15	1.47	Heavy/collapse
BL-E2	5	691	3.16	1.21	1.95	0.00	0.00	0.51	2.45	Moderate
BL-B1	6	1500	4.09	1.07	3.02	0.60	1.00	1.14	1.56	Heavy/collapse
BL-B2	6	1500	4.09	1.07	3.02	0.60	1.00	0.00	0.00	Heavy/collapse
BL-C3	6	1589	3.14	1.65	1.49	1.90	1.76	0.00	0.00	Light
BL-C8	6	3065	1.67	0.32	1.35	2.07	0.92	0.00	0.00	Light
BL-C11	6	2828	7.64	3.44	4.20	0.52	2.30	2.69	1.77	Moderate
BL-C18	6	1481	4.62	0.88	3.74	0.79	0.64	0.00	0.00	Light
BL-D3	6	2216	7.55	3.69	3.86	0.00	2.23	0.00	0.00	Heavy/collapse
BL-E1	6	1641	5.10	3.17	1.94	0.93	0.36	3.38	4.16	Moderate

Table 6 (continued)

Building ID	Number of stories	∑Floor area (m^2)	Column area			Shear wall		Infill wall		Damage
			∑Acol (m^2)	∑Acol-x (m^2)	∑Acol-y (m^2)	∑Asw-x (m^2)	∑Asw-y (m^2)	∑Amw-x (m^2)	∑Amw-y (m^2)	
BL-E4	6	3015	7.31	3.63	3.68	4.48	4.64	4.41	1.85	Moderate
BL-E7	6	1610	3.16	1.65	1.52	2.00	1.74	0.00	0.00	Light

Table 7 Summary of Kaynaşlı Database (Pay 2001)

Building ID	Number of stories	∑Floor area (m^2)	Column area			Shear wall		Infill wall		Damage
			∑Acol (m^2)	∑Acol-x (m^2)	∑Acol-y (m^2)	∑Asw-x (m^2)	∑Asw-y (m^2)	∑Amw-x (m^2)	∑Amw-y (m^2)	
KYN-C5	1	118	0.93	0.38	0.55	0.00	0.00	0.74	4.42	Light
KYN-C6	1	107	0.73	0.31	0.42	0.00	0.00	2.19	0.49	Light
KYN-D2	1	175	1.80	0.79	1.01	0.00	0.00	2.60	0.78	None
KYN-D3	1	101	1.08	0.54	0.54	0.00	0.00	1.20	0.00	None
KYN-D5	1	85	0.46	0.16	0.30	0.00	0.00	2.31	2.84	None
KYN-D12	1	162	2.09	0.55	1.54	0.00	0.00	1.84	1.36	None
KYN-D14	1	122	1.68	0.24	1.44	0.00	0.00	0.98	0.52	None
KYN-E4	1	111	0.96	0.80	0.16	0.00	0.00	0.70	0.00	None
KYN-E10	1	58	1.16	0.56	0.60	0.00	0.00	1.27	1.22	None
KYN-E13	1	168	2.39	1.62	0.77	0.00	0.00	1.26	1.29	Light
KYN-E15	1	52	0.54	0.27	0.27	0.00	0.00	1.37	0.77	None
KYN-E16	1	92	0.63	0.31	0.32	0.00	0.00	1.22	2.37	None
KYN-E20	1	131	1.54	0.74	0.80	0.00	0.00	0.00	3.34	None
KYN-E21	1	381	1.35	0.08	1.28	0.00	0.00	4.78	0.00	None
KYN-E24	1	63	0.72	0.36	0.36	0.00	0.00	1.54	0.00	None
KYN-F5	1	112	1.44	0.63	0.81	0.00	0.00	2.07	0.44	None
KYN-B1	2	220	0.80	0.40	0.40	0.00	0.00	1.99	0.70	Light
KYN-B2	2	368	1.90	1.30	0.60	0.00	0.00	2.11	1.42	Moderate
KYN-B3	2	177	1.12	0.80	0.32	0.00	0.00	0.38	1.70	None
KYN-B6	2	253	1.40	0.40	1.00	0.00	0.00	0.48	1.00	Light
KYN-B7	2	287	1.76	0.88	0.88	0.00	0.00	0.67	2.64	Light
KYN-B8	2	283	2.34	1.26	1.08	0.00	0.00	0.47	0.76	Light
KYN-B11	2	210	0.77	0.49	0.29	0.00	0.00	0.00	1.99	Light
KYN-B12	2	236	2.00	1.00	1.00	0.00	0.00	0.48	0.73	Moderate

Table 7 (continued)

Building ID	Number of stories	∑Floor area (m^2)	Column area			Shear wall		Infill wall		Damage
			∑Acol (m^2)	∑Acol-x (m^2)	∑Acol-y (m^2)	∑Asw-x (m^2)	∑Asw-y (m^2)	∑Amw-x (m^2)	∑Amw-y (m^2)	
KYN-B13	2	354	2.70	1.28	1.42	0.00	0.00	5.35	2.10	Moderate
KYN-B14	2	320	2.52	1.80	0.72	0.00	0.00	1.07	0.52	Light
KYN-B16	2	360	2.00	0.90	1.10	0.00	0.00	0.73	1.05	Light
KYN-C1	2	432	2.80	1.50	1.30	0.00	0.00	6.36	2.68	Light
KYN-C2	2	238	1.41	1.33	0.07	0.00	0.00	4.36	0.60	Light
KYN-C3	2	251	2.00	1.25	0.75	0.00	0.00	3.85	1.11	Light
KYN-C10	2	257	1.25	0.23	1.01	0.00	0.00	1.25	0.85	Light
KYN-C11	2	233	1.45	0.67	0.78	0.00	0.00	3.65	1.18	None
KYN-D1	2	391	2.70	1.00	1.70	0.00	0.00	1.22	1.23	Light
KYN-D6	2	223	1.60	0.30	1.30	0.00	0.00	0.61	4.68	Light
KYN-D7	2	246	1.28	0.64	0.64	0.00	0.00	0.81	1.09	Light
KYN-D8	2	239	1.30	1.05	0.25	0.00	0.00	1.23	0.81	Light
KYN-D11	2	298	1.60	1.20	0.40	0.00	0.00	0.72	2.89	None
KYN-D13	2	180	1.30	0.90	0.40	0.00	0.00	2.00	0.38	Light
KYN-D15	2	222	1.37	0.62	0.75	0.00	0.00	0.92	0.44	Light
KYN-D17	2	287	1.26	0.70	0.56	0.00	0.00	2.66	1.65	Light
KYN-D18	2	289	1.71	1.26	0.45	0.00	0.00	1.58	1.70	None
KYN-E2	2	201	1.24	0.68	0.56	0.00	0.00	0.68	2.56	None
KYN-E3	2	267	3.12	1.57	1.55	0.00	0.00	0.00	1.84	None
KYN-E5	2	226	1.54	0.54	1.00	0.00	0.00	2.28	2.75	None
KYN-E7	2	235	1.06	0.82	0.24	0.00	0.00	0.00	3.16	None
KYN-E8	2	171	0.93	0.45	0.49	0.00	0.00	1.40	0.65	None
KYN-E9	2	515	2.50	0.85	1.65	0.00	0.00	1.91	3.54	Light
KYN-E12	2	314	2.10	0.90	1.20	0.00	0.00	0.58	1.26	Light

Table 7 (continued)

Building ID	Number of stories	∑Floor area (m^2)	Column area			Shear wall		Infill wall		Damage
			∑Acol (m^2)	∑Acol-x (m^2)	∑Acol-y (m^2)	∑Asw-x (m^2)	∑Asw-y (m^2)	∑Amw-x (m^2)	∑Amw-y (m^2)	
KYN-E17	2	262	2.23	0.75	1.48	0.00	0.00	5.71	1.70	Moderate
KYN-E18	2	268	2.00	1.13	0.87	0.00	0.00	2.70	0.00	None
KYN-E19	2	245	1.80	0.70	1.10	0.00	0.00	1.20	1.60	Light
KYN-E25	2	156	1.32	0.60	0.72	0.00	0.00	0.76	1.54	None
KYN-E26	2	222	1.11	0.55	0.56	0.00	0.00	0.00	0.00	Light
KYN-F1	2	299	1.16	1.00	0.16	0.00	0.00	2.42	0.00	Light
KYN-F2	2	190	1.10	0.64	0.46	0.00	0.00	0.00	1.24	Light
KYN-F3	2	190	1.15	0.67	0.48	0.00	0.00	0.00	1.75	Light
KYN-F4	2	293	0.96	0.37	0.59	0.00	0.00	1.46	0.77	Light
KYN-B4	3	424	2.24	1.00	1.24	0.00	0.00	1.27	2.97	Light
KYN-B5	3	458	2.48	1.38	1.10	0.00	0.00	0.60	1.54	Moderate
KYN-B9	3	995	4.46	3.14	1.32	0.00	0.00	8.38	0.68	Light
KYN-D4	3	405	1.80	0.90	0.90	0.00	0.00	1.42	5.26	Light
KYN-D10	3	769	2.91	0.20	2.71	0.00	0.00	0.35	2.60	Light
KYN-D16	3	390	1.97	1.10	0.88	0.00	0.00	0.88	1.28	Light
KYN-E6	3	404	1.63	0.64	0.99	0.00	0.00	1.40	2.82	None
KYN-E11	3	343	2.50	1.20	1.30	0.00	0.00	0.00	0.00	Heavy/collapse
KYN-E14	3	486	2.14	0.94	1.20	0.00	0.00	2.46	0.77	None
KYN-E22	3	1405	8.35	2.15	6.20	0.00	0.00	0.70	6.26	None
KYN-E23	3	882	4.73	1.25	3.48	0.00	0.00	0.00	9.32	None
KYN-D9	4	508	1.48	0.56	0.92	0.00	0.00	0.55	1.25	Light
KYN-E1	4	1130	6.44	3.20	3.24	0.00	0.00	5.62	0.00	Light
KYN-B10	6	1026	1.88	0.25	1.63	0.00	0.36	0.00	0.00	Heavy/collapse
KYN-C7	3	491	2.45	1.33	1.13	0.00	0.00	2.85	1.84	Light

Table 7 (continued)

Building ID	Number of stories	∑Floor area (m^2)	Column area			Shear wall		Infill wall		Damage
			∑Acol (m^2)	∑Acol-x (m^2)	∑Acol-y (m^2)	∑Asw-x (m^2)	∑Asw-y (m^2)	∑Amw-x (m^2)	∑Amw-y (m^2)	
KYN-C8	3	448	1.82	0.60	1.22	0.00	0.00	1.97	2.77	Light
KYN-C9	3	331	1.28	0.80	0.48	0.00	0.00	2.09	1.05	None
KYN-B15	3	405	1.28	0.64	0.64	0.00	0.00	2.00	2.10	Light
KYN-C4	2	269	1.47	0.87	0.60	0.00	0.00	0.56	0.55	Light

Table 8 Summary of Düzce database (Pay 2001)

Building ID	Number of stories	$\sum$Floor area (m^2)	Column area			Shear wall		Infill wall		Damage
			$\sum$Acol (m^2)	$\sum$Acol-x (m^2)	$\sum$Acol-y (m^2)	$\sum$Asw-x (m^2)	$\sum$Asw-y (m^2)	$\sum$Amw-x (m^2)	$\sum$Amw-y (m^2)	
DZC-B3	1	88	0.72	0.16	0.56	0.00	0.00	0.00	0.00	Heavy/collapse
DZC-C4	2	927	3.90	1.20	2.70	2.43	2.92	5.31	9.49	None
DZC-C5	2	1189	5.10	1.80	3.30	2.43	2.92	6.81	13.05	None
DZC-D1	2	650	5.03	2.24	2.79	0.00	0.00	7.54	0.00	Moderate
DZC-F2	2	301	1.82	0.53	1.30	0.00	0.00	0.66	1.96	Moderate
DZC-B1	3	441	1.62	0.92	0.70	0.00	0.00	1.07	0.93	Moderate
DZC-B2	3	976	3.30	1.25	2.06	0.00	0.00	4.68	4.84	Light
DZC-C1	3	3355	9.13	4.51	4.62	1.82	3.26	4.54	1.80	Heavy/collapse
DZC-E1	3	1088	3.50	2.80	0.70	0.00	0.00	10.08	6.24	None
DZC-F1	3	291	2.19	0.36	1.83	0.00	0.00	0.00	0.00	Moderate
DZC-G1	3	334	1.50	0.75	0.75	0.00	0.00	0.98	0.59	None
DZC-C3	4	653	2.78	0.27	2.51	0.00	0.00	2.12	3.11	Light
DZC-C7	4	2377	5.10	1.80	3.30	2.43	2.92	6.81	12.46	Light
DZC-E2	4	1016	4.68	3.42	1.26	0.00	0.00	2.44	3.26	None
DZC-E3	4	615	2.85	1.35	1.50	0.00	0.00	2.76	6.61	Heavy/collapse
DZC-G2	4	1581	5.96	2.91	3.05	0.00	0.00	3.60	3.80	Moderate
DZC-G3	4	1592	7.56	2.88	4.68	0.00	0.00	3.03	1.06	Light
DZC-C2	5	1232	4.45	2.55	1.90	0.00	0.32	0.00	0.00	Heavy/collapse
DZC-C6	5	2972	5.10	1.80	3.30	2.43	2.92	6.81	12.46	Heavy/collapse
DZC-D2	5	558	2.53	0.50	2.03	0.00	0.00	0.00	0.00	Heavy/collapse
DZC-E4	5	682	3.29	1.49	1.80	0.00	0.00	0.00	0.00	Heavy/collapse
DZC-E5	5	1284	4.26	1.00	3.26	0.00	0.00	0.00	0.00	Heavy/collapse
DZC-G4	5	2146	6.27	0.52	5.75	1.08	2.04	1.67	4.17	Light
DZC-C8	6	1411	4.51	2.44	2.07	1.06	0.00	0.00	0.00	Moderate

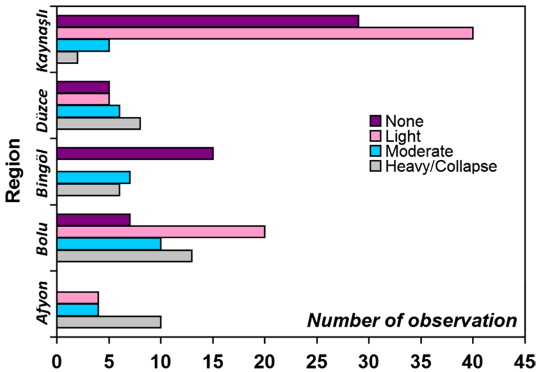


Fig. 7 Distribution of damage level of buildings according to region

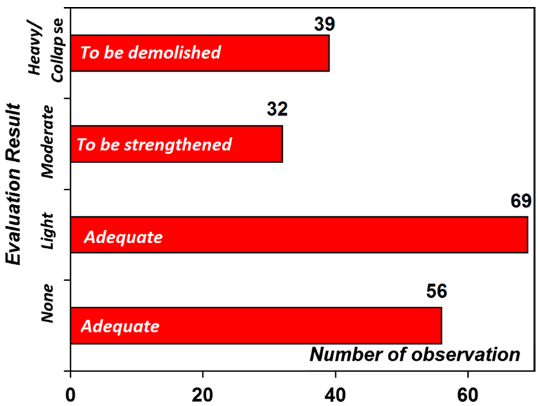


Fig. 8 Distribution of damage levels and classification of the buildings based on analytical assessment

the critical one. If concrete compressive strength could not be calculated by the test, use the values given in Table 1. The average values or lower limits may be used.

Step 2 Calculate the estimated yield base shear capacity (V_y) using Eq. (8).

Step 3 The *BCPI* coefficient is calculated by proportioning the obtained V_c and V_y value as in Eq. (9).

Step 4 The improved *CPI* value is calculated by considering the structural irregularity factors (C_A) and workmanship/construction quality (C_M).

Step 5 The calculated *CPI* value of the building is compared to the calculated CPI_{limit} value in Eq. (12).

Step 6 Whether the building is safe or unsafe is determined by CPI values.

Step 7 When the *CPI* value of the building is greater than CPI_{limit} values, the building has adequate LS performance. Otherwise, it is assumed that the building does not meet the LS performance level.

The validity of the proposed approach was examined considering the damage levels of the 196 exsiting buildings damaged in the aforementioned earthquakes. Also, the results of the proposed approach (*CPI*) were compared with the results of the method (CPI^Y) proposed by Yakut (2004).

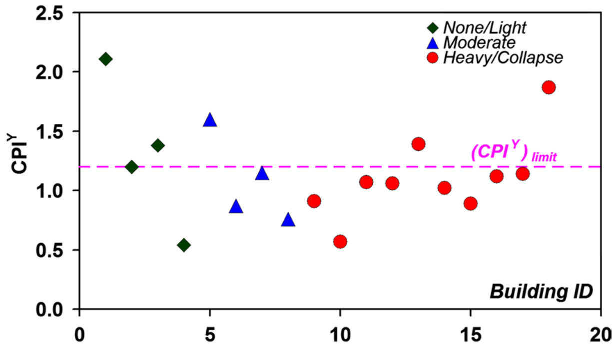


Fig. 9 The CPI^Y for buildings in Afyon

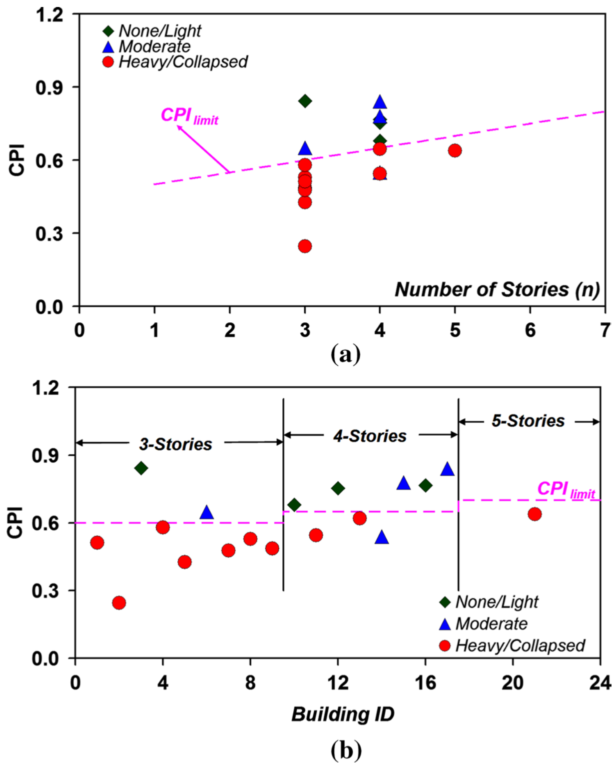


Fig. 10 The comparison of seismic performances obtained with proposed approach and damage levels of buildings in Afyon

The *CPI* and CPI^Y values were determined and computed for the buildings contained in the Afyon buildings database in Figs. 9 and 10. Using the proposed *CPI*, all four buildings with damage levels of "None/Light" were correctly predicted to meet adequate LS performance level. The CPI^Y results were also correctly estimated for three buildings. The classifications for four moderately damaged buildings reveal that one and three buildings met LS using CPI^Y and *CPI*, respectively. This Afyon database has ten buildings with a damage classification of "Heavy/Collapse" all of which were estimated correctly by using *CPI*. The CPI^Y results were correctly estimated for eight buildings. Both indexes indicated in the graphs are the minimum values of the two main directions

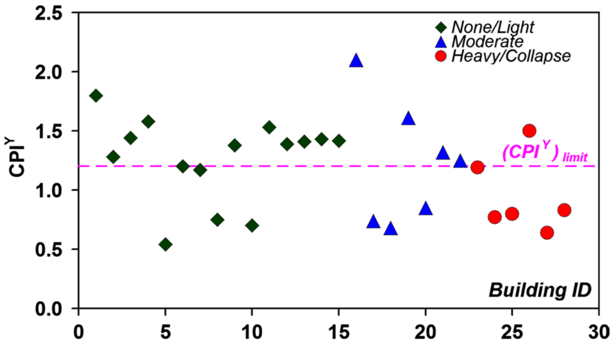


Fig. 11 The CPI^Y for buildings in Bingöl

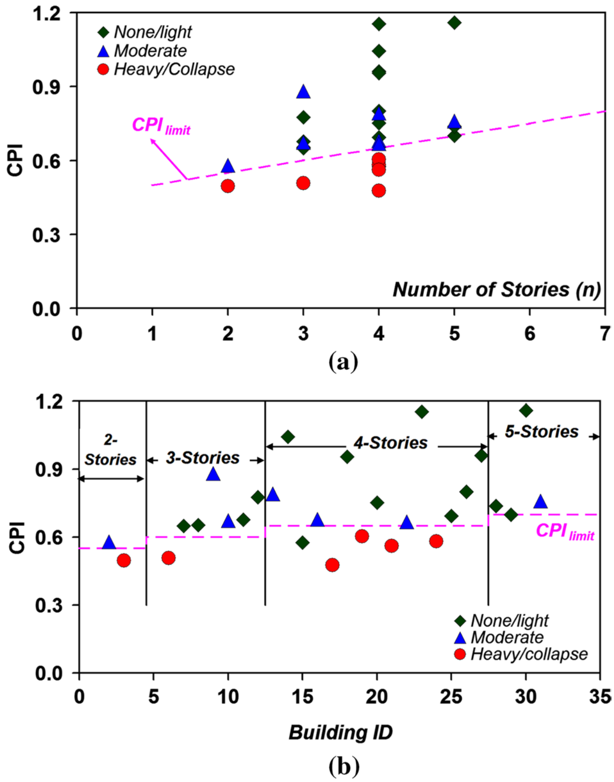


Fig. 12 The comparison of seismic performances obtained with proposed approach and damage levels of buildings in Bingöl

of the buildings; the information about the earthquake direction and building orientation are not reflected.

The proposed approach and CPI^Y were applied to Bingöl database to determine their ability to capture the damage observed. In Figs. 11 and 12, the *CPI* and CPI^Y values of this data were shown according to both indexes. Figures 11 and 12 reveal that the *CPI* provides a better estimate of the buildings with "None/Light" damage classification and that 14 of 15 buildings were classified correctly based on CPI_{limit} values according to the number of stories. The CPI^Y based on $(CPI^Y)_{limit}$ and *CPI* based on CPI_{limit} results were correctly

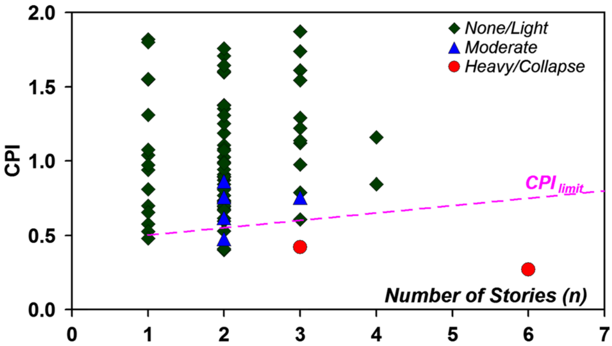


Fig. 13 The comparison of seismic performances obtained with proposed approach and damage levels of buildings in Kaynaşlı

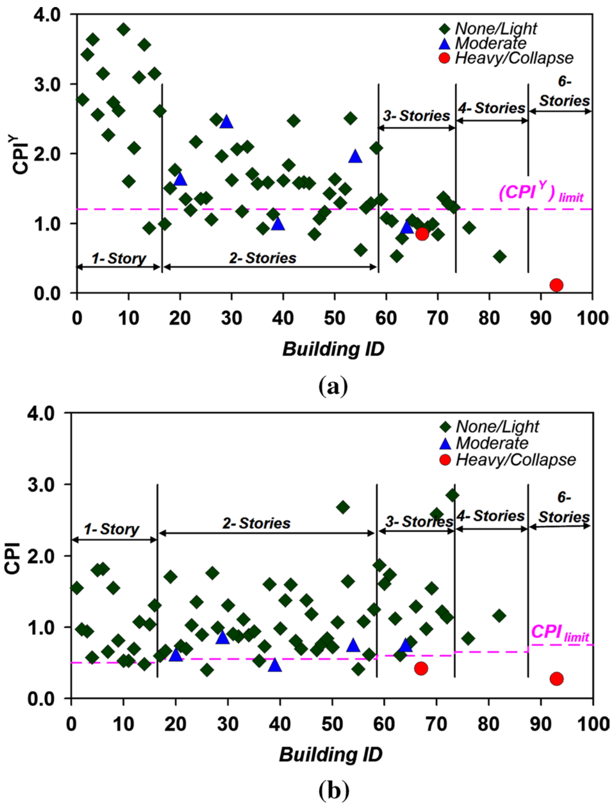


Fig. 14 The comparison of proposed **a** CPI^Y, **b** *CPI* for buildings in Kaynaşlı

estimated for 19 of 28 buildings and 27 of 28 buildings, respectively by considering all damage levels.

As a result of the analyses obtained from Kaynaşlı database, the distribution of the CPI_{limit} determined by the number of stories and the *CPI* values of the buildings is given in Fig. 13. In Fig. 14, and the results of *CPI* and CPI^Y are displayed for Kaynaşlı buildings database. The limits set for Kaynaşlı buildings inventory reveal that correct estimation rate for buildings with damage classifications of "None/Light" and "Moderate" is 96% using

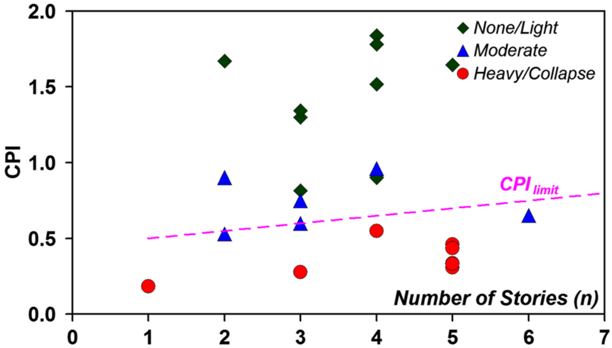


Fig. 15 The comparison of seismic performances obtained with proposed approach and damage levels of buildings in Düzce

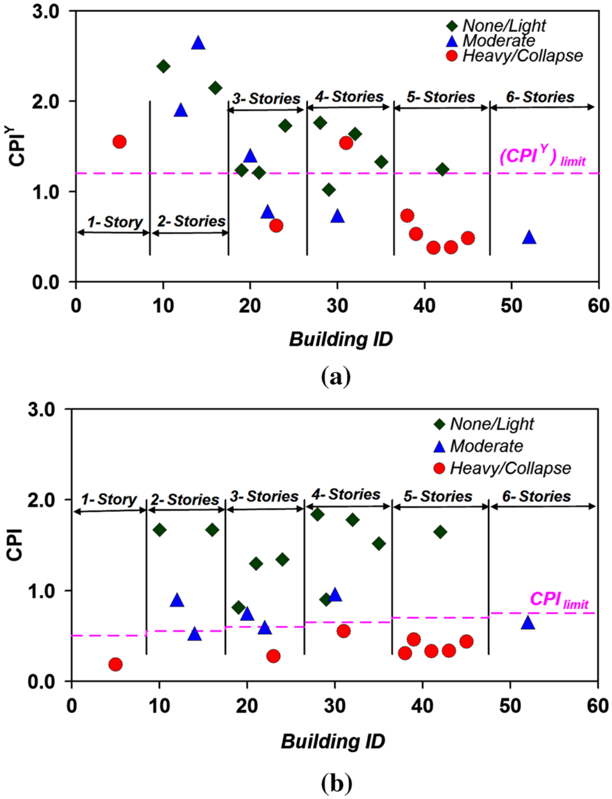


Fig. 16 The comparison of proposed **a** CPI^Y, **b** *CPI* for buildings in Düzce

CPI and 61% based on CPI^Y. On the other hand, 100% and 83% of unsafe buildings with a damage classification of “Heavy/Collapse” were predicted correctly with *CPI* and CPI^Y, respectively.

The buildings in the Düzce database were analysed and computed in Figs. 15 and 16. Using the proposed *CPI*, out of 16 buildings with a damage classification of “None/Light” and “Moderate” only one building was misestimated. For the same case, the CPI^Y results revealed incorrect estimates for four buildings. Of 8 buildings with a damage classification of unsafe, 8 and 5 were found unsafe using *CPI* and CPI^Y, respectively. Overall, the

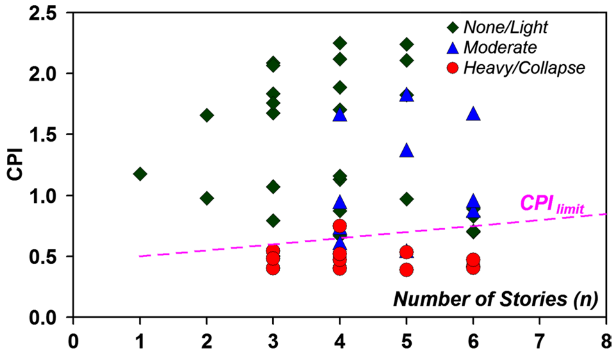


Fig. 17 The comparison of seismic performances obtained with proposed approach and damage levels of buildings in Bolu

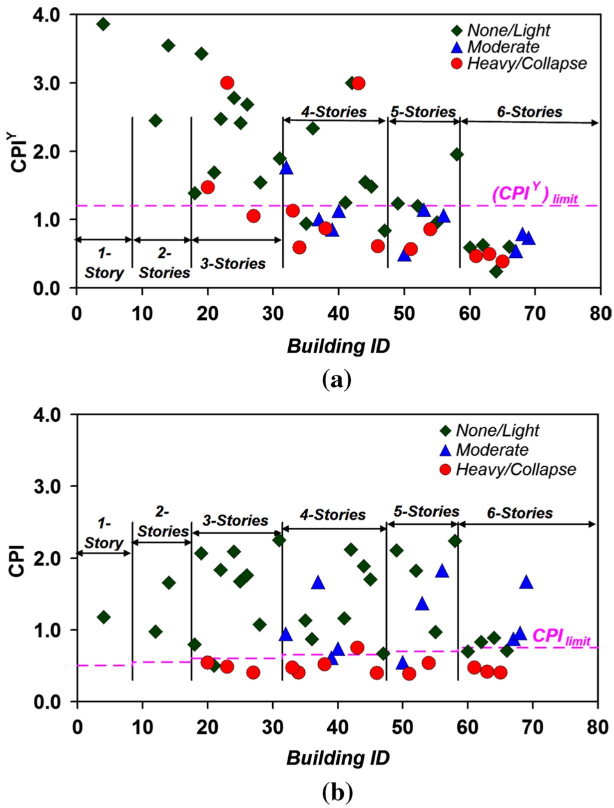


Fig. 18 The comparison of proposed **a** CPI^Y, **b** *CPI* for buildings in Bolu

seismic performance of all buildings in Düzce was estimated correctly at 88 per cent correctly using the *CPI*.

The Bolu buildings database comprised 50 RC buildings with different number of stories. Figure 17 displays the *CPI* values and CPI_{limit} values of 50 buildings. There are 27, 10, and 13 buildings with a damage classification of "None/Light", "Moderate" and "Heavy/Collapse", respectively. When comparing the calculated *CPI* values with the CPI_{limit} values, only 6 of 50 buildings could not be estimated correctly, as observed in Fig. 18.

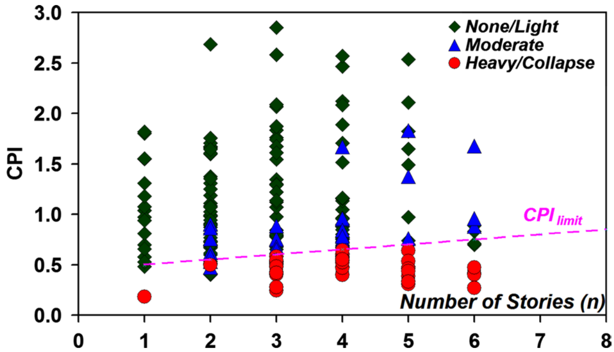


Fig. 19 The comparison of seismic performances obtained with proposed approach and damage levels of all buildings

Table 9 The consistency of proposed approach for all buildings

Location	Damage	The number of stories						The comparison of proposed by			
								CPI^Y (Yakut 2004)		Proposed approach	
		1	2	3	4	5	6	Consistency	Ratio (%)	Consistency	Ratio (%)
Afyon	None/light	–	–	1	3	–	–	3	75	4	100
	Moderate	–	–	1	3	–	–	1	25	3	75
	Heavy/coll	–	–	7	2	1	–	8	80	10	100
Bingöl	None/light	–	–	4	8	3	–	10	67	14	93
	Moderate	–	1	2	3	1	–	4	57	7	100
	Heavy/coll	–	1	1	4	–	–	5	83	6	100
Kaynaşlı	None/light	16	38	13	2	–	–	22	47	65	94
	Moderate	–	4	1	–	–	–	3	60	4	80
	Heavy/coll	–	–	1	–	–	1	2	100	2	100
Düzce	None/light	–	2	3	4	1	–	9	90	10	100
	Moderate	–	2	2	1	–	1	3	50	3	50
	Heavy/coll	1	–	1	1	5	–	6	75	8	100
Bolu	None/light	1	2	9	7	4	4	19	70	24	89
	Moderate	–	–	–	4	3	3	1	10	8	80
	Heavy/coll	–	–	3	5	2	3	10	77	12	92

The analysis of all buildings was carried out with the proposed approach by using the building inventory which includes structural and architectural features presented by Pay (2001) and Yakut (2004). The results of the proposed approach are given in Fig. 19. It can be seen that the proposed approach can be used to assess the seismic performance of buildings. Table 9 summarises the database comprising 196 RC buildings with different damage levels. Besides, the consistency number and rates of CPI^Y and CPI results and damage levels are given in Table 9 and displayed Fig. 20.

The 196 buildings were divided into three groups according to the mitigation measure needed and their expected seismic performance levels. The 125 RC buildings were detected to have sufficient capacity against a destructive earthquake and were considered to provide

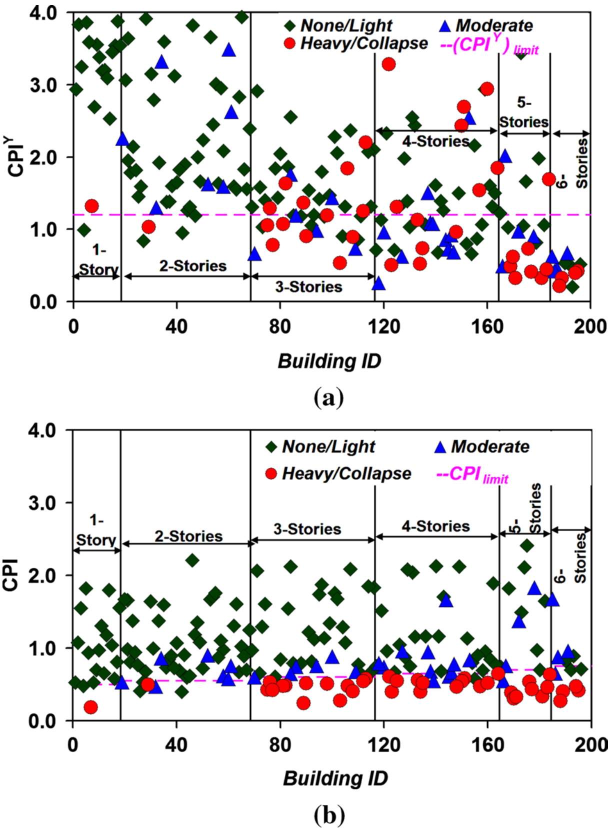


Fig. 20 The comparison of proposed for all buildings, **a** CPI^Y, **b** *CPI*

the target performance level of *LS* and were identified as "Adequate" as shown in Fig. 21a. The seismic performance of 32 RC buildings was evaluated as neither critical nor not critical (meaning that if a destructive earthquake occurs, it can receive significant damage without being collapse) and therefore, was identified as "To be strengthened" (Fig. 21b). The seismic performance of 39 RC buildings with extremely poor capacity was classified as "To be demolished" and displayed in Fig. 21c. In Fig. 21, while the calculated *CPI* values of 196 RC buildings and CPI_{limit} values are examined; 117, 25 and 38 of the buildings which are defined as "Adequate", "To be strengthened", and "To be demolished" were estimated correctly.

The difficulty of determining the appropriate CPI_{limit} is apparent. Reducing or raising the CPI_{limit} does not lead to an increase in the accuracy of estimating safe and unsafe buildings. Therefore, sensitivity and precision should be considered when assigning a lower and an upper limit for safe and unsafe buildings. It would be wrong to say that classifying unsafe buildings as safe buildings is more dangerous than classifying safe buildings as unsafe. However, considering the results of the analyses, the consistency rate of *CPI* values of safe buildings over the CPI_{limit} and *CPI* values of unsafe buildings below the CPI_{limit} is over 90 per cent.

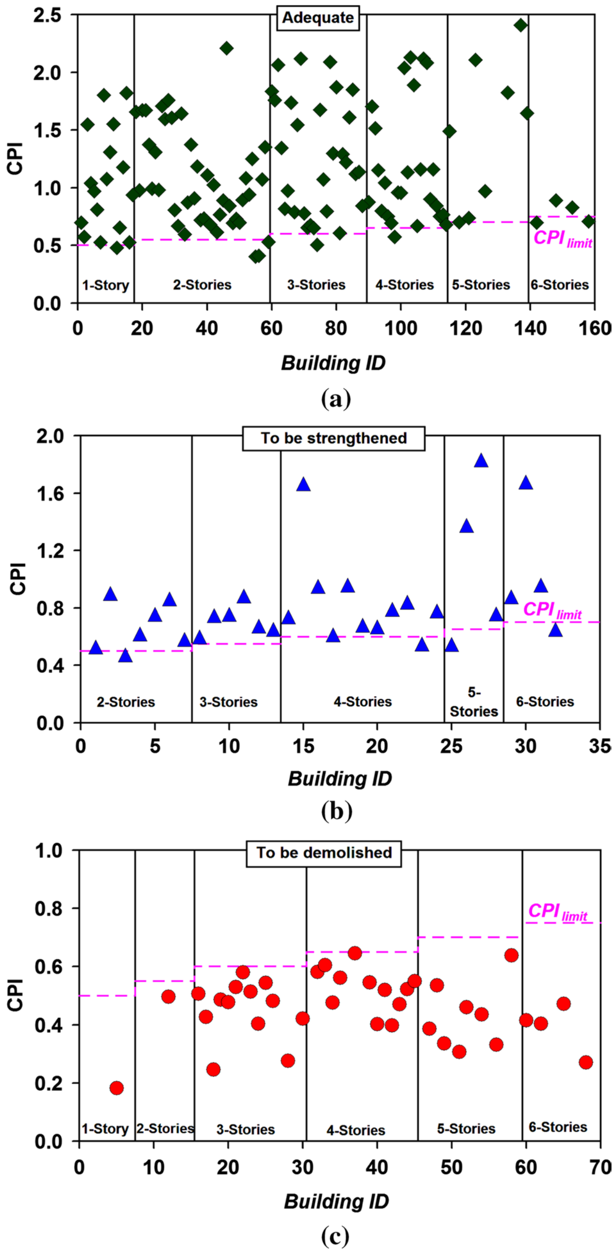


Fig. 21 Application of the proposed procedure

6 Conclusions

A new version of an existing procedure is proposed for predicting seismic vulnerability or performance level of RC buildings without the need for computer software. The new version of the procedure is introduced by making major modifications while taking into account the effects of parameters affecting building performance. Simple measurements and project information of RC buildings are required to determine the seismic performance level of RC buildings without the need for any linear or nonlinear analysis. The proposed approach is based on the size, orientation and concrete compression strength of columns, shear walls and masonry walls. The effects of structural irregularities (e.g., soft story, short column, plan, and frame irregularities, construction and workmanship quality) are taken into account to determine the seismic performance of RC buildings. The proposed approach has been developed and calibrated for a group of low-to mid-rise RC buildings by considering the structure conditions in Turkey. This approach can be applied equally to any other region while certain steps need to be changed to reflect region-specific applications.

An essential advantage of the proposed approach is the ability to combine the effects of regional seismicity and soil conditions via V_{code}. For this reason, the proposed approach can be used for possible future modifications in the calculation of V_{code}. Also, it is a suitable procedure for the prediction of seismic vulnerability or performance of a large number of RC buildings located in high-hazard zones, and it can be used in urban and regional planning studies. Additionally, the approach offers great convenience for engineers who need simple ways for the assessment of the seismic performance of RC buildings without applying complex analysis, and for insurers needing a correct prediction of the seismic performance of building.

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