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RESEARCH PAPER

A Detailed Comparison of Preliminary Seismic Vulnerability Assessment Methods for RC Buildings

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Abstract

Tier 2 (preliminary) evaluation methods seem to be efficient in determining seismic vulnerability of buildings in large building stocks because they can be used to determine the seismic performance of a single building when compared to Tier 1 evaluation methods (street survey). Besides, they require less time as opposed to detailed evaluation methods (Tier 3). Eleven preliminary vulnerability analysis procedures are compared considering the data of 192 buildings experienced either 2011 Van Earthquakes, 2003 Bingöl Earthquake or 2002 Afyon Earthquake. Comparisons are made in terms of the number of parameters, influence of parameters on final seismic score, weighing factors of the parameters, the success rate of predicting the seismic performance of the examined buildings. Investigated procedures use at least four parameters and at most 22 parameters. Although number of stories have adverse effect on the seismic performance, concrete strength, area of shear walls and columns seem to have positive effect. Among the main parameters used in all procedures, area of shear walls is found to be the most influential parameter; however, concrete strength is one of the least effective parameters. As for the rate of correct vulnerability estimate of the 192 buildings, it is found that the best prediction rate belongs to Sucuoglu and Yazgan (in Wasti and Ozcebe (eds) Seismic assessment and rehabilitation of existing buildings, NATO science series (series IV: earth and environmental sciences), Kluwer Academic Publishers, London, 2003) with 79.2%. All the procedures except Ozcebe et al. (in Wasti and Ozcebe (eds) Seismic assessment and rehabilitation of existing buildings, NATO science series (series IV: earth and environmental sciences), Kluwer Academic Publishers, London, 2003) have correct estimate rate equal to or higher than 63%.

Keywords Tier 2 evaluation · Preliminary evaluation · Seismic performance · Reinforced concrete building · Vulnerability

1 Introduction

Thirteen earthquakes with $M_w \geq 7.0$ hit Turkey in 80 years, and the time of consecutive earthquakes is found to be 16 years (Erzurum Kars Earthquake 1983; Duzce Earthquake 1999) approximately. Besides, it is stated that an earthquake with $M_w = 5.2$ is probable in every 4.5 years. When the magnitude increased to $M_w = 7.7$, the occurrence interval increases to 27 years (Özel and Solmaz 2012). Each earthquake results in economic losses, and some kills people. In Turkey, it is found that approximately 1003 people lose their life and 7094 buildings collapse in each year due to earthquakes (KOERI 2017).

For the reasons mentioned above, existing buildings should be evaluated to avoid future loses. Considering the number of buildings in Turkey, using detailed evaluation techniques for all the buildings is not feasible since they require a great amount of time, cost and skillful engineers. To save time and money, preliminary techniques are used to distinguish the vulnerable buildings from the safe ones. By determining the vulnerable ones, the engineer performs detailed evaluation techniques to verify the seismic performance of buildings and if applicable strengthens or retrofits them for future seismic events.

There are several preliminary seismic evaluation methods for RC buildings; Hassan and Sozen (1997), FEMA310 (1998), Otani (2000), Japan Building Disaster Prevention Association (JBDPA) (2001), Ozcebe et al. (2003), Sucuoglu and Yazgan (2003), Yakut (2004), Boduroglu et al.

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(2004), Boduroglu and Çaglayan (2007), Temur (2006), Tezcan et al. (2011), İlki et al. (2014), Sucuoğlu et al. (2015), ASCE 41-17 (2017) and Kaplan et al. (2018). Mainly, all procedures try to evaluate a building's seismic performance by simple relationships between capacities and demands of structural and non-structural elements. Although some procedures like FEMA310 (1998), İlki et al. (2014) (known as PERA) and ASCE 41-17 (2017) require structural analysis, remaining methods utilizes simplified capacity and demand equations. Since the aim of this study is to make a fair comparison between the available procedures, the ones requiring structural analysis are eliminated.

These procedures can be classified into two: the ones utilizing capacity and demand relations directly (Hassan and Sozen 1997; Otani 2000; JBDPA 2001; Yakut 2004; Boduroglu et al. 2004; Boduroglu and Çaglayan 2007; Temur 2006; Sucuoğlu et al. 2015; Kaplan et al. 2018) and the other ones making predictions from the predetermined scores gathered from statistical data, i.e., indirect use of capacity and demand relations (Ozcebe et al. 2003; Sucuoglu and Yazgan 2003; Tezcan et al. 2011).

All the procedures developed from capacity and demand relations calculate shear capacity of the critical story utilizing the area of the columns, shear walls and total floor area; update the shear capacity considering the architectural properties and compare the final capacity with the predetermined base shear demand. The simplest procedure among all is proposed by Hassan and Sozen (1997), who use column, shear wall and infill wall parameters to obtain column and wall indexes which are presented in a graphical format. They stated that damage in a building will increase if the column and wall indexes are small enough. Capacities and statistical considerations are explicitly available in the given method. While constructing his approach, Yakut (2004) takes a total of 220 buildings located in four different cities of Turkey. The examined buildings experienced either moderate or severe earthquakes. The approach relies on shear capacities vs. demands. Shear capacities are calculated considering columns, shear walls and infill walls, whereas demands are the total base shear force calculated from the earthquake code. It is stated that since irregularities in elevation and plan have negative effects on the seismic performance, their contribution will reduce the final ranking of the building. Sucuoğlu et al. (2015) update Yakut (2004) procedure by disregarding the architectural properties and implementing the contribution of shear reinforcements to the shear capacity. In the method proposed by Otani (2000), interaction between seismic zone, soil type, period of the building, structural irregularities, concrete strength, area of the columns and shear walls, ductility information of the columns and shear walls is formulized to end up with a seismic score which then compared with a cut-off value to comment on the seismic performance. JBDPA (2001) utilizes a similar procedure as Otani (2000), but the available procedure requires some additional data like topographical factors and time-dependent deformations. Boduroglu et al. (2004) modified the JBDPA (2001) considering the properties of the buildings in Turkey. Temur (2006) developed a procedure called DURTES which evaluates the shear capacity of the building from structural and architectural properties, and then compares the capacity with the calculated base shear demand. DURTES procedure was then modified by Kaplan et al. (2018).

The statistical based method proposed by Ozcebe et al. (2003) was developed considering the information gathered from 484 buildings damaged during 1999 Duzce Earthquake. The method uses number of stories, ratio of the overhangs, strength and stiffness indexes and other parameters such as soft story, frame discontinuity etc. Utilizing discriminant analysis, they ended up performance scores for Life Safety and Immediate Occupancy. Sucuoglu and Yazgan (2003) modified their Level 1 approach (walk-down approach) by utilizing the redundancy and strength index factors given in Ozcebe et al. (2003). Tezcan et al. (2011) constructed P25 Method which evaluates the performance of a building using many structural parameters, such as strength and stiffness indexes, interaction of fourteen structural and architectural parameters, short column, weak/soft story, frame discontinuity, pounding, liquefaction, soil type, water table level etc. With all those parameters, seven different scores are calculated, and the minimum score is selected. Afterward, this score is multiplied by the correction factors to calculate the final performance score of the building. Performance score is then compared with a cut-off value.

The aim of this study is to compare the abovementioned Tier 2 evaluation procedures considering:

- The number of parameters
- The influence of parameters on final seismic score
- The weighing factors of the parameters
- The success rate of predicting the seismic performance of the evaluated buildings.

2 Materials and Methods

It is important to discuss the properties of the buildings to be used to assess their seismic performance according to the aforementioned Tier 2 procedures. 192 buildings were considered in this study. 146 of them was in Van City Center located in Eastern Turkey and 32 of them was in Erciş which is one of the northern towns of Van City (Erdil 2017). Those buildings were shaken by 23 October 2011 Tabanlı and 9 November 2011 Edremit Earthquakes, i.e., both earthquakes are known as 2011 Van Earthquakes. Besides, 18 buildings experienced 2002 Afyon Earthquake and 28 buildings hit by

2003 Bingöl Earthquakes whose data were picked up from SERU Database (SERU 2017).

It is seen from Table 1 that 42.2% of the buildings had light damage, 8.8% of them damaged moderately, the percentage of severely damaged buildings are 30.2 and 18.8% of the buildings collapsed during the earthquakes. Considering the severely damaged ones, it is visualized that 10 of the 58 buildings were damaged in Afyon, 5 of them were in Bingöl and 41 of the buildings damaged severely in Van Earthquakes.

Construction year is an important parameter because it is directly related to the released seismic code and the useful life of a building. It is shown in Table 2 that 35.6% of the buildings in Van, 33.3% of the buildings in Afyon and 8.7% of the buildings in Bingöl were older than 20 years at the time when those earthquakes occurred. From the seismic code point of view, it is found that 3 buildings were constructed after the release of TERC1968, 141 buildings built according to TERC1975, 39 buildings utilized the criteria given in TERC1997 and 4 buildings were constructed using TERC2007.

Plan and vertical irregularities adversely affect the load transfer between structural members and in some cases; they become the major parameter responsible for the damage. Therefore, their contribution to the seismic performance should not be ignored. There are several irregularities defined in seismic codes. However, only four of them were discussed herein: short column, soft/weak story, heavy overhang and irregularity in plan/torsion. Table 3 summarizes the number of buildings having the mentioned irregularities. It is seen that 24.5% of the buildings had short column, 44.8% of them had soft/weak story, 35.9% had heavy overhangs and 62.5% built with irregularity in plan. Direct relation of those irregularities with the damage was not determined, i.e., damage in those buildings was found to be due to the combination of structural parameters and irregularities.

Table 1 Damage states of the buildings experienced Van, Afyon and Bingöl earthquakes

Damage state	Afyon	Bingöl	Erciş	Van	Total
Light damage	4 (22.2*)	15 (53.6)	3 (9.3)	59 (51.7)	81 (42.2)
Moderate damage	3 (16.7)	7 (25.0)	1 (3.3)	6 (5.3)	17 (8.8)
Severe damage	10 (55.6)	5 (17.9)	2 (6.2)	41 (36.0)	58 (30.2)
Collapse	1 (5.5)	1 (3.5)	26 (81.2)	8 (%7.0)	36 (18.8)
Total	18	28	32	114	192

*Values in parenthesis show the percentage

Table 3 Irregularities of the investigated buildings

Irregularity	Short column	Soft/weak story	Heavy overhang	Irregularity in plan/torsion
Number of bldg.	47	86	68	120

In addition to the irregularities, structural parameters should also be discussed because they were stated to be directly related to the damages. Table 4 shows the structural properties of the investigated buildings. In the table, N stands for the number of stories, A_{sw} shows the shear wall area in the ground floor, A_c represents the column area in the ground floor, A_{gf} is the area of the ground floor and f_c shows the concrete strength. From the table, it can be seen that 87.5% of the buildings had 2–5 stories and 76.6% had ground floor area less than 400 m^2. It is interesting that one of the buildings had a concrete strength of 2.3 MPa which was much more less than the one specified in the codes. On the other hand, some buildings were found to have concrete strength of 32 MPa. Although there is a huge difference between the concrete strength, the average was calculated as almost 8 MPa (77.1% of the buildings had less than 15 MPa concrete strength) which is also well below the minimum value specified in Turkish Earthquake Resistant Codes (TERC). Investigating the load carrying vertical members, it was deducted from the table that 41.7% of the buildings had no shear walls and the ratio of the vertical load carrying members to the ground floor area of 45.3% of the buildings were below 0.5. Those deficiencies together with the lack of reinforcing details seem to be ended up with such damages (Erdil 2017; Bayraktar et al. 2015).

Table 2 Construction year of the investigated buildings

Construction year, Van	Number of bldg.	Construction year, Afyon	Number of bldg.	Construction year, Bingöl	Number of bldg.
1970–1980	2	1970–1980	6	1970–1980	2
1980–1990	50	1980–1990	3	1980–1990	4
1990–2000	78	1990–2000	4	1990–2000	12
2000–2011	16	2000–2002	5	2000–2002	5
				Undetermined	5
Total	146	Total	18	Total	28

Table 4 Some of the structural parameters used in this study

N	# of Bldg.
2	12
3	34
4	79
5	43
6	15
7	7
8	2
Total	192

A_{sw}, m^2	# of Bldg.
$A_{sw} = 0$	80
$0 < A_{sw} \leq 5$	83
$5 < A_{sw} \leq 10$	18
$10 < A_{sw} \leq 15$	4
$15 < A_{sw} \leq 20$	6
$20 < A_{sw}$	1
Total	192

f_c, MPa	# of Bldg.
$0 < f_c \leq 5$	4
$5 < f_c \leq 10$	90
$10 < f_c \leq 15$	54
$15 < f_c \leq 20$	29
$20 < f_c$	15
Total	192

A_{gf}, m^2	# of Bldg.
$A_{gf} \leq 200$	44
$200 < A_{gf} \leq 400$	103
$400 < A_{gf} \leq 600$	25
$600 < A_{gf} \leq 800$	15
$800 < A_{gf}$	5
Total	192

A_c, m^2	# of Bldg.
$A_c \leq 5$	97
$5 < A_c \leq 10$	74
$10 < A_c \leq 15$	20
$15 < A_c \leq 20$	1
Total	192

$(A_c + A_{sw})/A_{gf}$, %	# of Bldg.
$(A_c + A_{sw})/A_{gf} \leq 0.5$	87
$0.5 < (A_c + A_{sw})/A_{gf} \leq 1.0$	89
$1.0 < (A_c + A_{sw})/A_{gf} \leq 1.5$	11
$1.5 < (A_c + A_{sw})/A_{gf}$	5
Total	192

3 Results and Discussions

Preliminary seismic vulnerability analysis procedures available in the literature were compared considering the number of parameters used in the methods, the influence of parameters on the final seismic score, the weighing factors of the parameters and the success rate of predicting the seismic performance of the 192 buildings discussed above. Since eleven procedures were taken into account in this study, in order to keep the size of tables and figures small, their names were shortened as follows: Hassan and Sozen (1997) "HS," Ozcebe et al. (2003) "OEA," Sucuoglu and Yazgan (2003) "SY," Yakut (2004) "*Y*," Boduroglu et al. (2004) "BEA," Temur (2006) "*T*," Tezcan et al. (2011) "P25," Sucuoğlu et al. (2015) "SEA," Kaplan et al. (2018) "KEA," Otani (2000) "*O*," and JBDPA (2001) "*J*."

3.1 Comparison I: Number of Parameters in the Methods

The first comparison was made in terms of the number of parameters used in each procedure as shown in Table 5. For each procedure key parameters were collected and a total of 33 parameters were ended up. It is seen that all methods need different number of parameters to comment on seismic vulnerability of RC buildings. HS requires the least number of parameters, i.e., four parameters, whereas P25 utilizes the most; 22 parameters. Remaining procedures have 10–17 parameters.

Since almost all procedures implicitly or explicitly need the shear capacity and base shear demand, area of the columns and shear walls seem to be the main parameters because only those parameters were used in all procedures. Although concrete strength is one of the key parameters to be used in shear capacity calculations, two procedures (HS, OEA) do not implicitly need that information. Soft/weak story and total floor area are considered in 9 procedures, and after that, it is seen that 8 procedures utilize number of stories and seismic zone information. Corrosion, ground water table, load distribution effect, mezzanine story and strong column criteria are only adopted in P25.

3.2 Comparison II: Effect of Parameters on the Performance Scores

In this section, effect of some key parameters (column area, shear wall area, infill wall area at the ground story, concrete strength and number of stories) on the final performance score is evaluated. Other parameters are discussed in following sections.

Since all procedures utilizes different formulation and come up with different performance score, normalized performance scores are used to make a reasonable comparison. To normalize a performance score, all performance scores for a specific procedure is summed up and PS_o is obtained. Then, by keeping all the parameters the same, only the concerned parameter changed from minimum value to a specified maximum value and for each changing value, performance score of the buildings are recalculated and summed

Table 5 Parameters used in the investigated procedures

	Parameters	HS	OEA	SEA	Y	SY	O	J	BEA	T	KEA	P25	Number of procedures used the concerned parameter
1	Column area (A_c)	X	X	X	X	X	X	X	X	X	X	X	11
2	Shear wall area (A_{sw})	X	X	X	X	X	X	X	X	X	X	X	11
3	Soft/weak story		X		X	X	X	X	X	X	X	X	9
4	Total floor area	X	X	X	X	X	X		X	X	X		9
5	Concrete strength (f_c)			X	X	X	X	X	X	X	X	X	9
6	Number of Stories			X		X	X	X	X	X	X	X	8
7	Seismic zone			X		X	X	X	X	X	X	X	8
8	Infill wall area (A_{iw})	X	X	X	X	X				X		X	7
9	Frame discontinuity		X		X	X	X	X	X			X	7
10	Short column				X	X		X	X	X	X	X	7
11	Soil factor			X			X	X	X	X	X	X	7
12	Weight of the bldg.			X	X		X		X	X	X		6
13	Building type			X				X	X	X	X		5
14	Torsion				X		X			X	X	X	5
15	Construction year							X	X	X	X		4
16	Heavy overhang		X		X	X						X	4
17	Period of the bldg.			X			X			X	X		4
18	Stiffness factor		X				X	X				X	4
19	Basement							X		X	X		3
20	Foundation									X	X	X	3
21	Quality of the construction				X	X		X					3
22	Story height		X						X			X	3
23	Plan dimensions								X			X	2
24	Ductility						X		X				2
25	Ground floor area (A_{gf})		X			X							2
26	Pounding					X						X	2
27	Time-Dependent defr.							X	X				2
28	Topography					X		X					2
29	Corrosion											X	1
30	Ground water table											X	1
31	Load distribution effect											X	1
32	Mezzanine story											X	1
33	Strong column criteria											X	1
	Number of parameters	4	10	11	12	14	14	16	17	17	17	22	

up ending up PS_i. The normalized performance score is calculated by diving each PS_i to PS_o and figures given in this section were drawn accordingly.

3.2.1 Effect of Concrete Strength on Performance Score

Concrete strength affecting axial load, shear force, moment capacities and bond between reinforcement plays a significant role in determining the seismic performance of buildings. Figure 1 shows the effect of concrete strength on the performance score for the methods considered in this study. As can be seen, nine procedures (except HS and OEA) used concrete strength directly in calculations. From all procedures, it can be seen that performance scores increase with the increase in concrete strength. However, the rate of increase is different. For example, in *T*, KEA and BEA methods, concrete strength is linearly proportional to the performance score, whereas in P25, *O*, *Y* and SEA there exist a nonlinear relationship, i.e., as concrete strength increases the rate of its effect on performance score decreases. Since SY utilizes predetermined scores and concrete strength is explicitly given in the quality of construction, the curve has two bounces indicating the change in the quality. As the method given in *J* is not recommended for the buildings having low strength concrete and Structural Seismic Index (E_o) requires modification factors for concrete strength below 20 MPa,

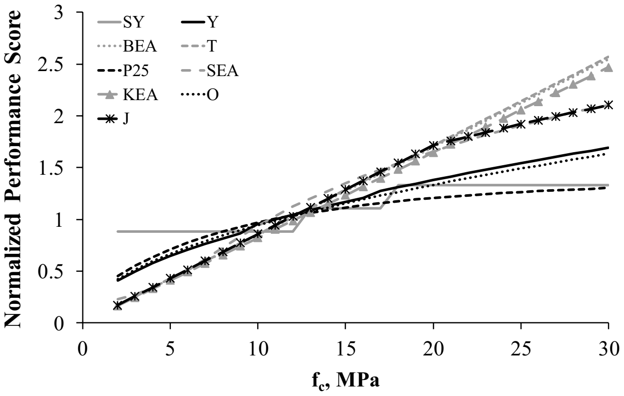


Fig. 1 Effect of concrete strength on performance score

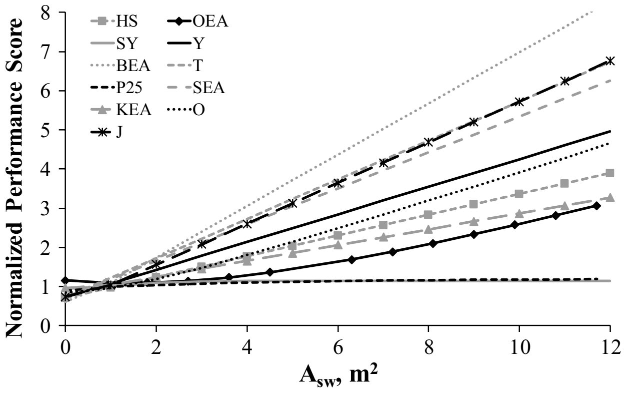


Fig. 2 Effect of shear wall area on performance score

the rate of increase in performance score is great for low strength concretes but it slows down after 20 MPa.

Formulations given in *T* and KEA have almost the same, because KEA is the modified version of *T* which gives almost the same rate of change. Although BEA is the modified version of *J*, they deviate from each other after 20 MPa. Since *Y* and *O* use the tensile strength of concrete and multiplied it by the area of column and shear wall areas in the concerned earthquake direction to find the shear capacity of the building, they have almost the same rate of change in performance score. In P25 method, a coefficient similar to the modification coefficient used in *J* was used, but since the modification coefficient does not change after a certain value, this effect was observed as a parabolic curve instead of a clear break in the graph and the effect of the concrete strength on the performance score is seen to be less after 12 MPa.

3.2.2 Effect of Shear Wall Area (A_{sw}) on Performance Score

All methods considered herein takes the shear wall area into account when calculating performance scores. It is clear in Fig. 2 that, as shear wall area increases, performance scores increase in almost all methods except SY and P25. P25 uses shear walls to calculate the stiffness of vertical load carrying members. Those stiffness values are implemented in the first performance score (P_1), and this score is then compared with the six other performance scores. The minimum of the seven performance scores are taken as the base performance score. Since the procedure seeks the minimum performance score, increasing shear wall area and shear wall stiffness P_1 starts to be greater than other performance scores, and thus, it starts to be eliminated. As P_1 disappears from the calculations, its effect on performance score also diminishes. It is because of that; no change is seen in the figure for P25. As for SY, shear wall area is used to calculate the strength index and that index has three different ranges. If shear wall area is low it means strength index is "weak," if it is greater than the specified strength index then it is called "strong," between those, strength index is "moderate." Performance score seems to increase with shear wall area up to a certain value (4 m^2 in this study); however, since strength index becomes "strong" after that value its effect on performance score remains same. Other than these procedures, remaining ones has almost linear increase in performance scores with shear wall areas, but the rate of change in each procedure changes considerably. Although in *O*, performance score increases 3 times with a shear wall area of 11 m^2, it is 8 times in BEA. An interesting curve is seen in OEA. In this one, performance score decreases with shear wall area up to a certain value (almost 2 m^2 in this study) and then starts to increase parabolically. The reason of this phenomenon may be due to the statistical basis that procedure developed on.

It is interesting to note that modifying the procedure in *T*, KEA reduces the effect of shear walls; updating the parameters in *J* according to the building quality in Turkey, BEA increases the effect of shear walls; eliminating some architectural parameters in *Y*, SEA also increases the effect of shear wall.

3.2.3 Effect of Infill Wall Area (A_{iw}) on Performance Score

It is known that infill walls contribute to the stiffness of a frame considerably, but being brittle, having low load carrying capacity and being vulnerable against out-of plane loading, their contribution to the load carrying capacity are mostly ignored or limited to some extent. It is because of that some researchers do not take infill walls into account while assessing a buildings seismic performance (*O*, *J*, BEA and KEA). Although OEA, P25 and SY require that information, its effect on performance score seems to be insignificant as illustrated in Fig. 3. The reason can be attributed to the fact that those procedures use infill wall area to calculate the strength index considering column and shear wall area

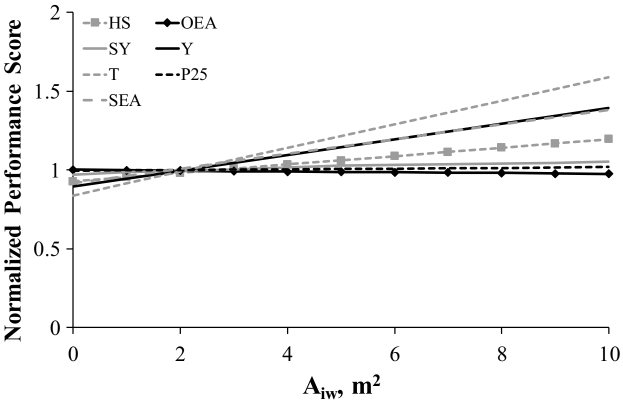


Fig. 3 Effect of infill wall area on performance score

also. Strength index is then compared with predetermined scores. Since those procedures seek the vulnerable properties of the building, having great strength index reduces its effect on performance score. In the procedure proposed by Y, infill wall area consistent with the earthquake direction is divided by the area of the ground floor and used to modify the shear capacity calculated from columns and shear walls. Y and SEA being based on almost the same procedure, ended up with the same curve assuming that infill wall area has noticeable effect on seismic performance. HS considers the area of infill walls being 10% effective in seismic resistance; therefore, their influence on performance score is less than the one in Y and SEA. Taking 15% of infill wall area to calculate the shear capacity of the critical story, the rate of increase in performance score is found to be the highest in the procedure given in *T* as shown in Fig. 3.

3.2.4 Effect of Column Area (A_{col}) on Performance Score

Figure 4 shows the effect of column area on performance score. As seen in the figure, despite the increase in performance score with the column area in all methods, in OEA, it is seen that performance score tends to decrease first, and then, it starts to increase as the column area increases. Since column area is combined with shear wall area to calculate the total area of the vertical load carrying elements, curves given in Fig. 4 has almost the same tendency as given in Fig. 2. P25, OEA and SY again consider insignificant effect of column area due to discussion made for shear wall area. Remaining procedures consider column area to increase the performance score. However, contribution of column area does not have same influence due to the assumed effectiveness of the column area consistent with the earthquake direction. For instance, although SEA, *Y* and *O* take 67% of the column area as effective, BEA increases it to 70%, T, KEA and *J* introduce further increase and assume 100% effectiveness.

As discussed in shear wall section, KEA reduces the effect of column area by modifying the procedure proposed by *T*. Although BEA increases the effect of shear wall by modifying *J*, and SEA considers shear wall being more effective than the one given in *Y*, influence of column area seems to decrease after modifications. The decrease is more pronounced in BEA, because BEA takes 70% of column area as effective although it is 100% in *J*.

3.2.5 Effect of Number of Stories on Performance Score

Increase in number of stories has negative effect on seismic performance unless the building has adequate load carrying members. SY states that damage is proportional to number of stories for the buildings investigated after 1999 Kocaeli Earthquake. Similar observation was made after 2011 Van Earthquakes (Erdil 2017). Therefore, it can be said that increase in number of stories has adverse effect on seismic performance of the existing deficient buildings. Figure 5 displays the effect of number of stories on performance score. Although all procedures assume that seismic

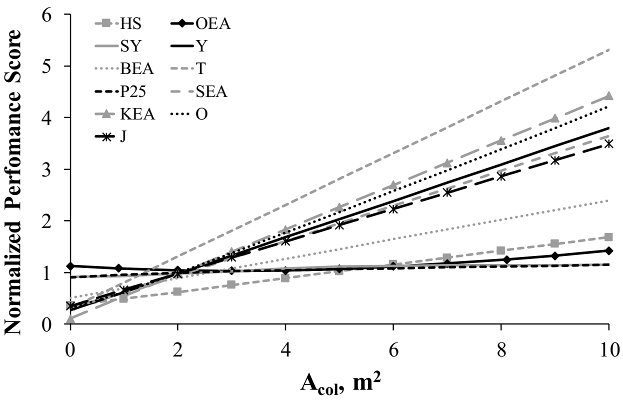


Fig. 4 Effect of column area on performance score

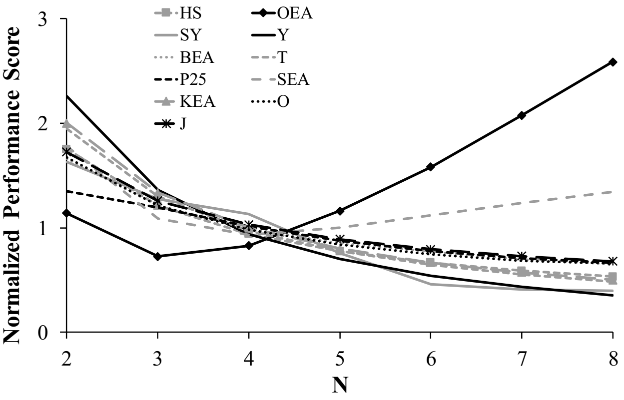


Fig. 5 Effect of number of stories on performance score

performance reduces with number of stories and the rate of decrease is almost the same, in OEA seismic performance has an increasing trend after three stories for the examined buildings in this study. The reason can be due to the cut-off equation generated using statistical analysis tools given in OEA being dependent only on number of stories. Similar trend is also visible for SEA, however, in this case a slight increase was seen after four stories. Since SEA uses the positive contribution of number of stories while calculating the shear capacity of a vertical load carrying member, as number of stories increases so the shear capacity, though a limiting value for shear capacity is also introduced.

3.3 Comparison III: Weighing Ratio of the Parameters in the Methods

Discussion given in this section focuses on the weighing ratio of the parameters used in each method. The aim is to understand which parameters have higher effects on seismic performance. In order to calculate the weighing ratio of each parameter, firstly by keeping all the parameters the same, only the concerned parameter was set to a minimum value (minimum value is picked up from the data of 192 buildings whose properties discussed in Sect. 2). Performance score of the buildings are calculated for that value assigned for that parameter, and all performance scores are summed up ending up PS_i ($i = 1$ to n; n is the number of values assigned for that parameter). Then, the value of that parameter increased, and new performance scores are calculated and summed up giving PS_{i+1}. PS_{i+1} is subtracted from PS_i to have $\Delta\mathrm{PS}_i$ (Eq. 1). $\Delta\mathrm{PS}_i$ is then divided by the number of buildings to normalize the average difference ($\Delta\mathrm{PS}_j$, Eq. 2, $j = 1$ to n; n is the number of values assigned for that parameter). This procedure is followed up to a maximum value (maximum value is taken from the data of 192 buildings discussed in Sect. 2) assigned for that parameter. Finally, effectiveness of that parameter (P_{eff}) is found from the average of all average difference values (Eq. 3).

$$\Delta\mathrm{PS}_i = \mathrm{PS}_{i+1} - \mathrm{PS}_i \tag{1}$$

$$\Delta\mathrm{PS}_j = \frac{\Delta\mathrm{PS}_i}{n_{\mathrm{total}}} \tag{2}$$

$$P_{\mathrm{eff}} = \mathrm{average}\left(\Delta\mathrm{PS}_j\right) \tag{3}$$

The parameters used in the methods are examined under ten titles in general, and the calculated weighing ratios are shown in Table 6. N, A_{c}, A_{sw} and A_{gf} seem to be the most important parameters affecting seismic performance according to most of the procedures. It is determined that the most effective parameters used in HS are number of stories, area of shear walls and ground floor. OEA and SY assume that plan irregularity and heavy overhang are the most important parameters, but it is the area of shear wall, column and ground floor according to Y, SEA, KEA and T. BEA uses A_{sw} as the most influential parameter; however, KEA considers A_{col}. Procedures developed on the same base seem to give importance to almost the same parameters; for example, since BEA is the modified version of J, they assume that the most influential parameter is A_{sw} when calculating the seismic performance of a building. Similarly, SEA modified the procedure in Y; therefore, they ended up with almost the same result stating that A_{sw}, A_{col} and A_{gf} are most effective parameters.

Examining the concerned procedures as whole, the average weighing ratios for all parameters are also calculated as given in the last column in Table 6. It is seen that the most effective structural parameter is the area of shear wall with a weighing ratio of 17%. Following that, column area and ground floor area seem to be the most important parameters considered in the procedures. According to the authors, plan irregularity is the most influential architectural parameter (12.8%) affecting the seismic performance of a building. After that, soft/weak story seems to be significant. Although concrete strength is important in RC buildings, it is one of

Table 6 Weighing ratios of the parameters in the methods, %

	HS	OEA	SY	Y	BEA	T	P25	SEA	KEA	O	J	Average[a]
A_{sw}	28.1	8.6	2.5	19.6	40.8	27.1	5.1	36.0	13.9	18.2	31.2	17.0
A_{c}	14.1	2.4	2.1	19.6	12.1	27.1	4.9	26.6	31.2	22.4	19.5	13.4
A_{gf}	33.4	6.2	3.5	19.5	15.2	16.8	12.1	22.7	21.3	13.6	14.0	13.1
Plan irregularity		31.3	20.4	2.8	11.1						13.6	12.8
N	21.6	18.9	19.2	17.7	10.7	13.1	22.8	5.7	18.1	9.7	10.8	12.4
Soft/weak story		15.4	25.4	10.7	4.7	2.8	14.8		3.7	22.5	6.5	9.6
Heavy overhang		17.1	19.4	1.6			2.9					8.3
Torsion			5.4	3.1		4.5	30.8		6.0	11.2		8.2
f_{c}			1.5	2.5	5.4	4.6	6.1	5.3	5.9	2.5	4.3	3.4
A_{iw}	2.8	0.1	0.8	2.8		4.1	0.5	3.7				1.7

[a] Converted to %

the least important structural parameters with a weighing factor of 3.4% as seen in Table 6.

3.4 Comparison IV: The Success Rate in Predicting the Vulnerability Level

The main objective of the Tier 2 evaluation procedures in the literature is to determine the extent of damages that will occur in existing buildings under possible earthquakes. Most of the procedures do not define the damage levels as low-medium-heavy-collapse but on the contrary, vulnerability was emphasized considering building performance score. Although OEA is based on immediate occupancy and life safety performance levels, *O* and *J* use several seismic risk levels depending on the performance score. Remaining eight procedures use a predetermined cut-off value to distinguish vulnerable ones from the safe ones. Since seismic performance scores and damage classifications are different in each procedure, it is necessary to find a common denominator to make a reasonable comparison.

In this study, two seismic vulnerability levels are considered depending on the seismic performance of the buildings: Undamaged-lightly damaged-moderately damaged buildings are considered as buildings with low risk of damage (Low-R) and severely damaged-collapsed buildings are classified as buildings with high risk of damage (High-R). This distinction is based on whether the building can be occupied after an earthquake. As it is known, undamaged buildings can be used immediately after an earthquake, lightly damaged buildings can be used after proper repair and renovation, while moderately damaged buildings can be utilized after being strengthened. In other words, in case of these three damage states, the building can be occupied after an earthquake. On the contrary, severely damaged buildings and collapsed buildings cannot be used after an earthquake. Therefore, these buildings are considered as buildings with high risk of damage.

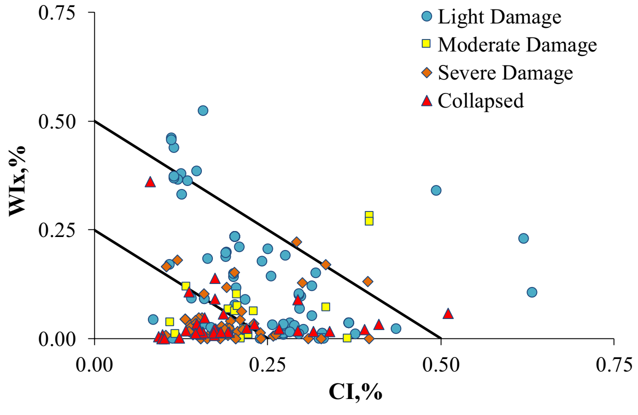
A total of 192 buildings are evaluated considering the 11 procedures, and for each procedure, the correct damage estimates for Low-R buildings and High-R buildings are assessed separately, and finally, overall prediction percentage is calculated as summarized in Table 7. Considering the overall success in predicting the damage levels, it can be seen from the table that best estimate is made by SY with 79.2% and BEA, *T*, P25 and SEA have also attained more than 70% success. SY updating their walk-down procedure by introducing strength index and redundancy level become more successful in predicting seismic vulnerability of buildings although they use predetermined scores for the structural and architectural parameters. Since BEA modified the procedure given in *J* considering the Turkish database, and the buildings investigated herein have close properties as considered in BEA, the prediction level is high as compared to *J*. Modification in *Y* by SEA seem to be successful in predicting the overall damage, as the estimate rate is 72.4% in SEA, but it is 64.1% in *Y*. Although KEA eliminated infill wall area in the procedure given in *T*, they ended up less overall success rate as compared to T. HS using only four parameters seem to have reasonable prediction as opposed to OEA who developed a statistical based approach. This indicates that statistical based methods need further investigation as stated by Yakut (2014).

It should be kept in mind that overall estimate should not be the only criteria to comment on the success of a procedure. The Low-R and High-R estimates should also be separately evaluated in order to make a fair comment. As seen from *J*, it is found that the procedure evaluated all the High-R buildings successfully, i.e., success rate is 100%. Does this mean that this procedure can 100% predict all buildings' seismic performance? The answer is no, because it is not that successful in predicting the Low-R buildings. In this case, the success rate is only 29.6%. Therefore, after commenting on overall success, here success rates for Low-R and High-R are also examined. It is viewed from the table that, although *J*, *O*, *Y* and KEA have great success in predicting High-R buildings, they are not that successful in Low-R buildings. The reason can be attributed to the high cut-off or limiting value which distinguishes Low-R from High-R buildings. On the other hand, OEA has low cut-off values resulted in higher success in Low-R but less success in High-R buildings. Besides having higher overall prediction level, SY, BEA, *T*, P25 and SEA have also reasonable estimate in High-R and Low-R buildings. The difference in each risk level is not too much, and it can be said that those procedures are more successful than the remaining seven procedures.

Figures 6, 7, 8, 9, 10, 11, 12, 13, 14 and 15 give estimates of the procedures for each investigated building. Results of each procedure are discussed separately. In all figures, collapsed buildings are illustrated by red triangles, severely damaged buildings are shown by orange diamonds,

Table 7 Correct damage state prediction ratio of the procedures, %

Damage state	Number of bldg.	SY	BEA	*T*	P25	SEA	HS	*J*	*Y*	KEA	*O*	OEA
Low-R	98	83.7	70.4	79.6	71.4	62.2	80.6	29.6	36.7	38.8	29.6	72.4
High-R	94	74.5	81.9	71.3	79.8	83.0	53.2	100	91.5	88.3	97.9	9.6
All	192	79.2	76.0	75.5	75.5	72.4	67.2	64.1	63.5	63.0	63.0	41.7



(a) x-direction **(b)** y-direction

Fig. 6 Results of the HS procedure

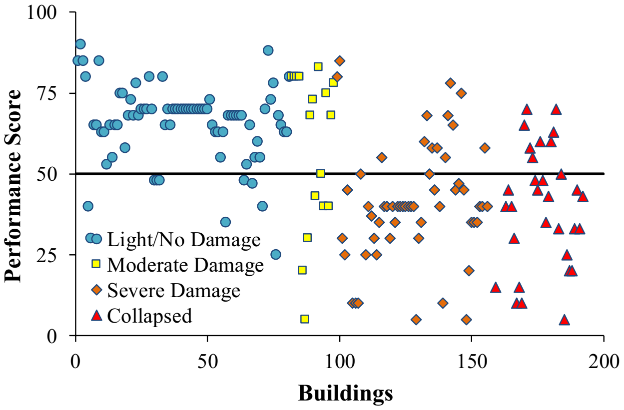
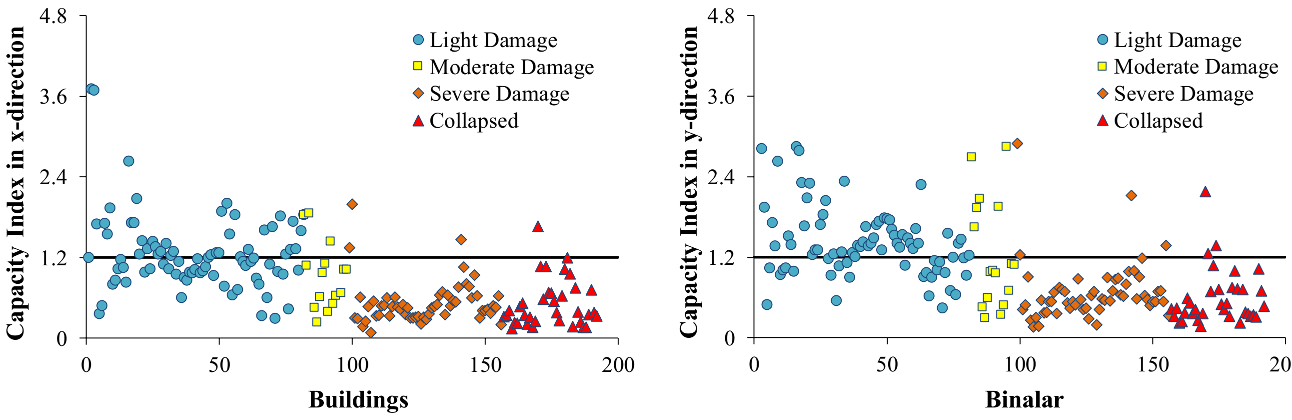


Fig. 7 Results of the SY procedure

moderately damaged buildings are demonstrated by yellow rectangles and finally blue circles used for lightly damaged buildings.

HS evaluates buildings considering each earthquake direction separately as shown in Fig. 6. In the figures, CI stands for column index and WI represents the wall index. In HS, it is assumed that CI = 0.25% and WI = 0.25% distinguish Low-R buildings from High-R buildings. As can be seen from Fig. 6, majority of the High-R buildings have very low wall ratios. For such less parameter, the procedure is found to be more successful.

SY updated their walk-down procedure by introducing redundancy level and strength index which takes load carrying structural members into account. After assigning predetermined scores for each structural and architectural parameters, a final performance score is attained, and that final score is compared with a cut-off value of 50 as shown



(a) x-direction **(b)** y-direction

Fig. 8 Results of the procedure defined in *Y*

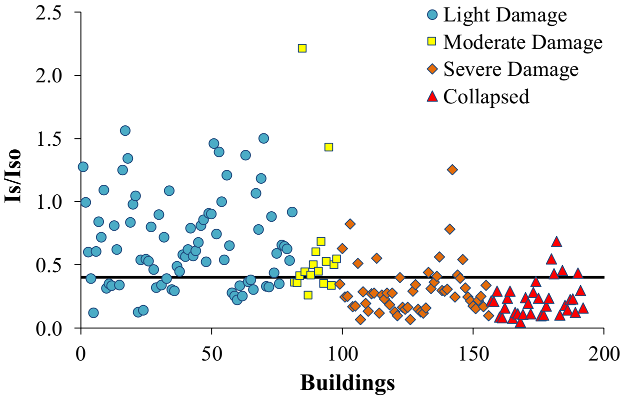


Fig. 9 Results of the procedure proposed by BEA

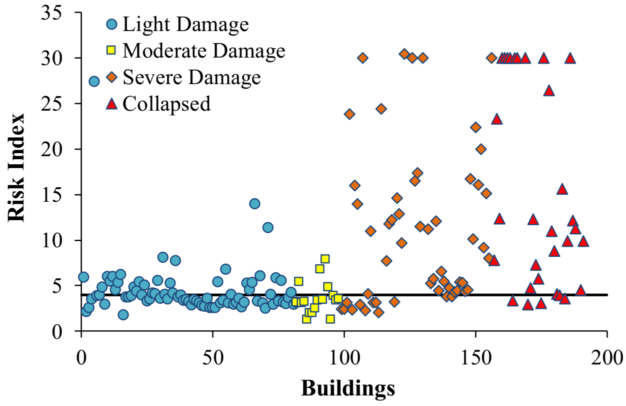


Fig. 12 Results of SEA procedure

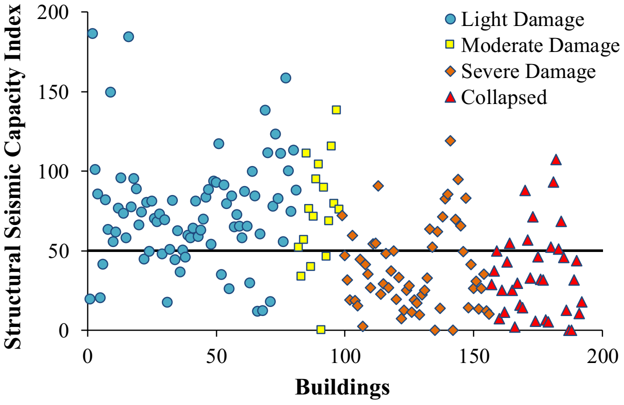


Fig. 10 Results of the procedure given in *T*

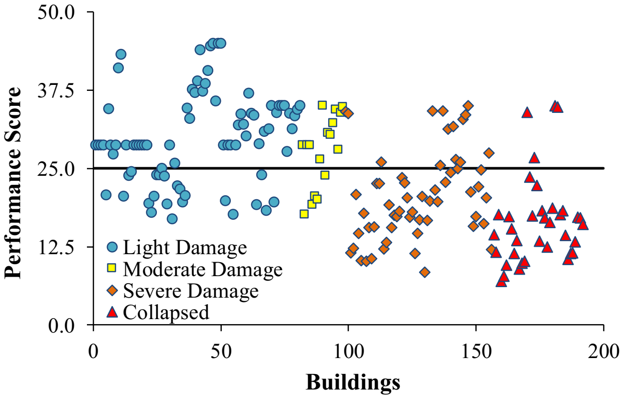


Fig. 11 Results of P25 procedure

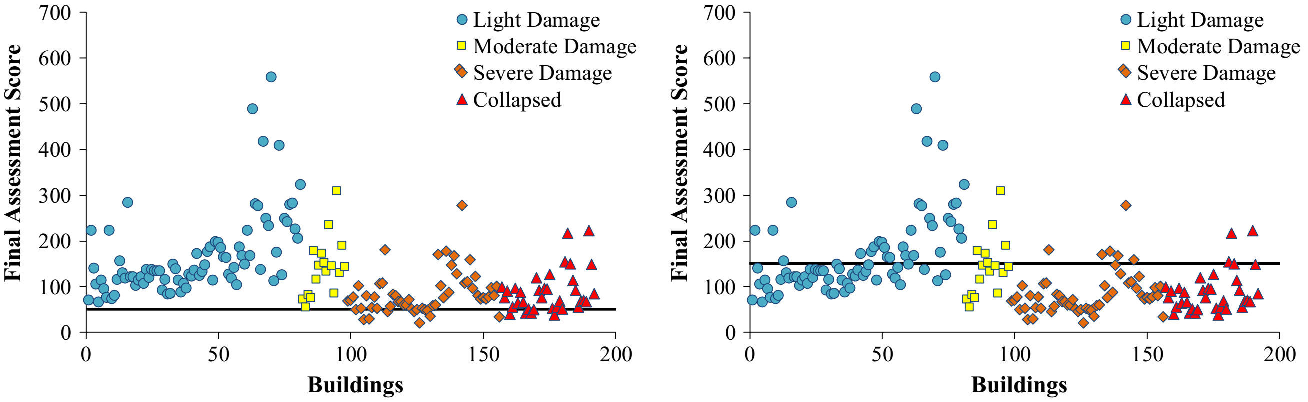
in Fig. 7. It is seen that the cut-off value of 50 is successful in separating Low-R buildings from High-R buildings.

The evaluations for *Y* were also made for both x- and y-directions as shown in Fig. 8. The procedure defined in *Y* is based on shear capacities of vertical load carrying members, and the calculated seismic performance score is compared with a cut-off value of 1.2. This cut-off value has been tested in this study with 192 buildings, and it was found that the cut-off value is high for such vulnerable buildings and reducing it to 1.0 the prediction percentage will increase from 63.5 to 74%.

BEA, as previously noted, modified the procedure given in *J* using the Turkish buildings database. Considering local soil conditions, structural and architectural parameters, performance index and reference index are calculated. The ratio of these indexes gives the performance score of a building whose seismic performance is evaluated by comparing the obtained score with a cut-off value of 0.4. It is seen from the Fig. 9 that the procedure is successful in distinguishing Low-R buildings from High-R buildings with the defined cut-off value.

The procedure defined by *T* is called DURTES, and it is also shear capacity vs. demand-based procedure. Using vertical load carrying members, shear capacity of the critical story is calculated and then modified considering the architectural parameters. With the estimated base shear demand, seismic performance of the building (called structural seismic capacity index) is assessed as illustrated in Fig. 10. Like the previous procedures, *T* also uses a cut-off value given as 50 to identify Low-R and High-R buildings. It is seen from the figure that the procedure can be evaluated as successful since the cut-off value seems to make a reasonable separation.

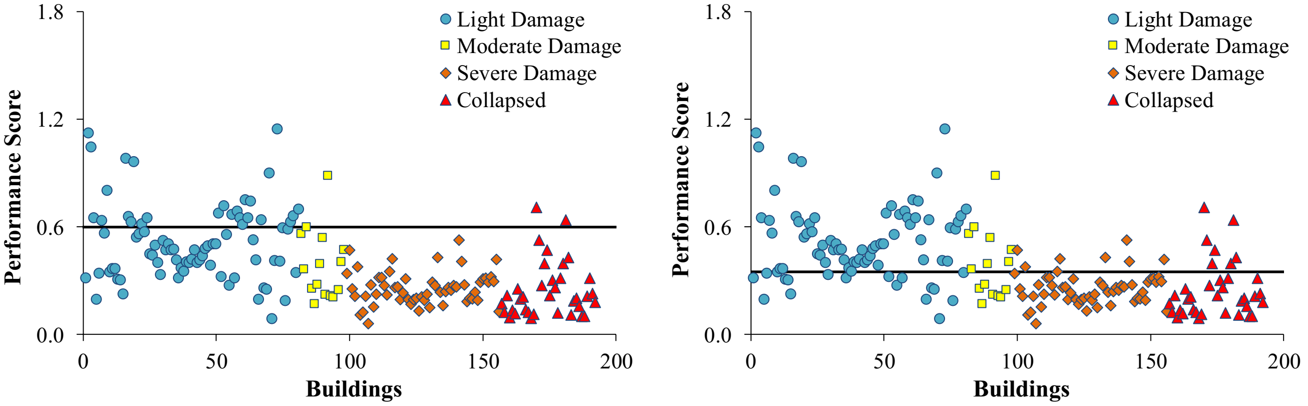
Figure 11 shows the results of P25. In this method, the cut-off value is determined as 25 and it is stated that buildings having performance score below this value will be evaluated as High-R buildings. The method has been tested with 192 buildings, and it is observed that the procedure is not so successful in predicting Low-R buildings. The main disadvantage of this method is that the predetermined scores are more dominant than the capacities, thus affecting the buildings' performance score. It is believed that with some



(a) Cut-off value is 50

(b) Cut-off value is 150

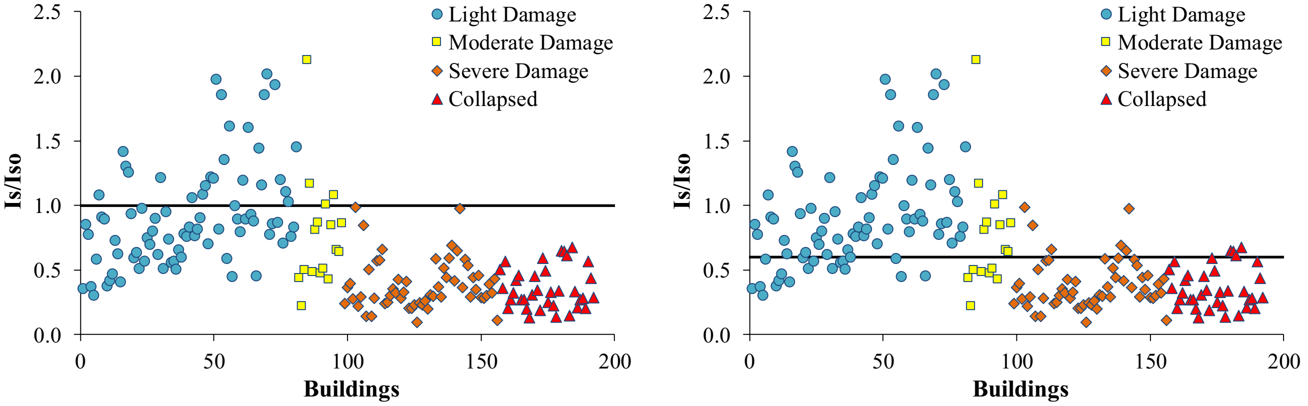
Fig. 13 Results of KEA procedure



(a) Cut-off value is 0.6

(b) Cut-off value is 0.35

Fig. 14 Results of the procedure proposed by *O*



(a) Cut-off value is 1.0

(b) Cut-off value is 0.6

Fig. 15 Results of the procedure given in *J* revision (especially for soil properties) in predetermined scores, the percentage of correct estimate will increase.

Results of the procedure proposed in SEA are depicted in Fig. 12. SEA eliminates the effect of architectural properties and introduces the effect of axial load on shear capacity of vertical load carrying members in the procedure defined by *Y*. The risk index is then calculated from the shear capacities and base shear demands and then compared with a cut-off value of 4. In this case, the higher the risk index, the vulnerable the building be. As it is seen from the figure, the risk index calculated for severely damaged and collapsed buildings are relatively high. Therefore, it can be concluded that although the procedure is not so successful in predicting the vulnerability level of Low-R buildings, it is quite successful in determining High-R buildings.

Figure 13 shows the results of the procedure given in KEA. This procedure is the modified version of DURTES which is proposed by *T*. KEA states that if the final assessment score is below 50, the building has high risk, if it is between 50 and 150, then the risk is moderate, buildings having final assessment score higher than 150 are not vulnerable. Considering the 192 buildings in this study, with a cut-off value of 50, 114 buildings' vulnerability levels are predicted correctly (Fig. 13a); however, if the cut-off value increases to 150, the correct estimate increases to 121 buildings (Fig. 13a). It is obvious that cut-off values are sensitive to the properties of buildings. For example, if the cut-off value is equal to 100, then 151 buildings' vulnerability level can be predicted correctly meaning that the success rate will increase to 78.6%.

Results of seismic performances calculated using the procedure defined in *O* are given in Fig. 14. In Fig. 14a, the cut-off value is taken as 0.6, as suggested in the article. With that cut-off value, it can be seen that the majority of the buildings are below the cut-off value meaning that most of the buildings have high seismic risk which is not correct for the investigated 192 buildings. Since the procedure was developed considering the building quality in Japan, it may not be applicable for Turkey due to the differences in design and construction practices. Therefore, in order to use a procedure that was developed for a specific country, some modifications are inevitable to have a higher success rate in predicting seismic risks. For example, without modifying the general algorithm, if the cut-off value is reduced to 0.35, the correct estimate rate increases to 79.2% as shown in Fig. 14b.

As for the last procedure presented in J, results are illustrated in Fig. 15. Figure 15a shows the seismic performance results of the buildings according to the original cut-off value defined as 1.0. As can be seen from this figure, most of the buildings are in the High-R region. The reason discussed in previous paragraph for *O* is also valid for *J*. Again, with a simple approach, the estimated percentage of damage levels increases from 64.1 to 81.3% when the cut-off value is reduced to 0.6 (Fig. 15b).

4 Conclusions

Eleven preliminary seismic vulnerability analysis procedures were examined considering the properties of 192 buildings, and comparisons were made in terms of number of parameters used in the procedures, effect of parameters on seismic performance, weighing factors of each parameter and success in estimating the damage level. Nine of the procedures were developed considering Turkish database; HS, OEA, SY, *Y*, BEA, *T*, P25, SEA, KEA, and two of them constructed using Japan database: *O* and *J*.

It is found that all procedures need different number of parameters to comment on seismic vulnerability of RC buildings. HS requires the least number of parameters, i.e., four parameters, whereas P25 utilizes 22 parameters. The remaining procedures have 10–17 parameters. Since almost all procedures implicitly or explicitly need the shear capacity and base shear demand, area of the columns and shear walls seem to be the main parameters because only those parameters were used in all procedures.

Nine procedures (except HS and OEA) used concrete strength directly in calculations. From all procedures, it can be seen that performance scores increase with the increase in the concrete strength. However, the rate of increase is different. For example, in *T*, KEA and BEA methods, concrete strength is linearly proportional to the performance score, whereas in P25, *O*, *Y* and SEA, there exists a nonlinear relationship, i.e., as concrete strength increases the rate of its effect on performance score decreases.

All methods take into account the shear wall area when calculating performance scores. It is observed that, as shear wall area increases, performance scores increase also in almost all methods except SY and P25 because of the predetermined scores assigned to that information. It is found that modifying the procedure in *T*, KEA reduces the effect of shear walls; updating the parameters in *J* according to the buildings quality in Turkey, BEA increases the effect of shear walls; eliminating some architectural parameters in *Y*, SEA also increases the effect of shear wall. Although like shear walls, columns are also vertical load carrying members, their contribution does not have same influence due to the assumed effectiveness of the column area consistent with the earthquake direction.

Increase in number of stories has negative effect on seismic performance unless the building has adequate load carrying members. Although all procedures assume that seismic performance reduces with number of stories and the rate of decrease is almost the same, in OEA seismic performance has an increasing trend after three stories for the examined buildings in this study.

N, A_{col}, A_{sw} and A_{gf} seem to be the most important parameters affecting seismic performance according to most of the procedures. Procedures developed on the same base seem to give importance to almost the same parameters. Examining the concerned procedures as whole, it is seen that the most effective structural parameter is the area of shear wall with a weighing ratio of 17%. Following that, column area and ground floor area seem to be the most important parameters considered in the procedures. According to the authors, plan irregularity is the most influential architectural parameter (12.8%) affecting the seismic performance of a building. Although concrete strength is important in RC buildings, it is one of the least important structural parameters with a weighing factor of 3.4%.

Considering the overall success in predicting the damage levels, it is found that best estimate is made by SY with 79.2% and BEA, *T*, P25 and SEA have also attained more than 70% success. SY updating their walk-down procedure by introducing strength index and redundancy level becomes more successful in predicting seismic vulnerability of buildings although they use predetermined scores for the structural and architectural parameters. Since BEA modified the procedure given in *J* considering the Turkish database, the prediction level is high as compared to *J*. Modification in *Y* by SEA seem to be successful in predicting the overall damage. Although KEA eliminated infill wall area in the procedure given in *T*, they ended up less overall success rate as compared to *T*. HS using only four parameters seem to have reasonable prediction as opposed to OEA who developed a statistical based approach.

Although *J*, *O*, Y and KEA have great success in predicting High-R buildings, they are not that successful in Low-R buildings. The reason can be attributed to the high cut-off or limiting value. On the other hand, OEA has low cut-off values resulted in higher success in Low-R but less success in High-R buildings. Besides having higher overall prediction level, SY, BEA, T, P25 and SEA have also reasonable estimate in High-R and Low-R buildings. The difference in each risk level is not too much, and it can be said that those procedures are more successful than the remaining seven procedures.

The cut-off value for some procedures is sensitive to the data of the examined buildings. For example, reducing the cut-off value in *Y* from 1.2 to 1, the one in *O* from 0.6 to 0.35 and the value in *J* from 1.0 to 0.6, higher rate of success can be attained.

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