FRAGILITY ANALYSIS OF REINFORCED CONCRETE SCHOOL BUILDINGS USING ALTERNATIVE INTENSITY MEASURE-BASED GROUND MOTION SETS

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ABSTRACT:

Past destructive earthquakes in Turkey revealed that seismic performance of existing school buildings is inadequate as evidenced by significant damage experienced by these buildings. As a result of the unexpectedly poor performance a comprehensive study has been initiated to identify seismic vulnerabilities of existing school buildings in many parts of the country. 321 reinforced concrete (RC) school buildings located in İstanbul that were assessed in detail under the World Bank program ISMEP, had been previously assessed in Mazılıgüney et al. (2012) following various walk-down and preliminary seismic vulnerability assessment procedures. The results are compared with the ones obtained from linear detailed analysis method of Turkish Earthquake Code (TEC), and performance of the available methodologies had been comparatively tested. Fragility analyses by means of nonlinear time history analyses have been performed utilizing equivalent single-degree-of-freedom (SDOF) systems of the typical 36 school buildings (12 RC school buildings for each 3, 4 and 5 story building sets) and employing different sets of ground motion records each of which has been based on a different intensity measure (IM) as described in Kadaş and Yakut (2013). Fragility curves for 3, 4 and 5 story RC school buildings are obtained by the described procedure. Considering the drift demands at certain seismic intensity levels, the structures have been classified whether they satisfy immediate occupancy (IO) , life safety (LS) and collapse prevention (CP) performance states. Fragility curves formed by alternative IM-based ground motion sets are compared with each other to be able to investigate the effect of selected IMs on quantification of seismic risk for the selected school-building stock.

KEYWORDS: Fragility analysis, school buildings, ground motion, intensity measure.

1. INTRODUCTION

Turkey lies in one of the most seismically active regions in the world. In recent decades, earthquakes caused tens of thousands of deaths, huge amounts of economic losses and significant damage to buildings in Turkey. Recent observations after the Marmara (17 August 1999, M_w=7.4), Düzce (12 November 1999, M_w=7.2), Bingöl (1 May 2003, M_w=6.4) and Van (23 October 2011, M_w=7.2) earthquakes revealed that school buildings have been among the most severely damaged buildings. It has also been revealed that seismic performance of existing school buildings is inadequate, unfortunately, as evidenced by huge damage experienced by these buildings. Especially, the tragic collapse of the Çeltiksuyu Primary School Dormitory in Bingöl earthquake that killed 84 students and a teacher had striking evidence of how vulnerable these buildings were. Because of poor performance of school buildings in Turkey, researches focusing on determination of seismic vulnerability of these buildings have gained prominence (Kalem, 2010).

The performance of the buildings is mainly grouped into three as immediate occupancy (IO), life safety (LS) and collapse prevention (CP). In addition, the physical damage states of the buildings were also identified based on the performance levels. There are mainly four damage levels that are negligible, light, moderate and heavy. The negligible and light damage states correspond to the immediate occupancy performance level. The moderate damage state corresponds to the life safety performance level and the heavy damage level corresponds to the collapse prevention.

For school buildings, TEC requires two different performance states for two different earthquake load levels. School buildings should satisfy IO performance state for an earthquake loading having a probability of occurrence of 10 % in 50 years life time and LS for an earthquake ground motion having a probability of occurrence of 2 % in 50 years life time.

As expressed in Nielson and Pang (2011), a fragility curve, conditioned on an intensity measure (IM), represents the probability of exceedance of a prescribed damage state for a structure. This study investigates the effect of use of alternative intensity definitions in the development different ground motion sets and correspondingly, its resulting effect on derivation of fragility curves and quantified risks under a scenario event.

2. BUILDING DATABASE

Turkey is an earthquake-prone country. Strong earthquakes have led to significant damage of many school buildings in the past. Because of unexpected consequences, the government officials have initiated some projects to reduce seismic vulnerability of existing school buildings. Within this endeavor, Istanbul is given a special emphasis because of probability of a major potential earthquake in coming years. The Governorship of Istanbul has established an administrative unit to manage Istanbul Seismic Risk Mitigation and Emergency Preparedness Projects (ISMEP). This project is a significant attempt to implement essential principals of comprehensive disaster management financed by the World Bank. The main goals are to improve preparedness for a potential earthquake and retrofit or reconstruction of priority public buildings in Istanbul. ISMEP project consists of three components:

- Component A: Enhancing Emergency Preparedness
- Component B: Seismic Risk Mitigation for Priority Public Buildings
- Component C: Enforcement of Building Codes (Elgin, 2007)

A database of 321 reinforced concrete school buildings located in İstanbul that were assessed in detail under the World Bank program ISMEP has been compiled throughout this study. The general parameters of the school buildings in the database are listed in Mazılıgüney et al.(2012).

Concrete compressive strengths of existing buildings in Turkey, which need retrofit for earthquake resistance, ranges from 5 to 16 MPa and public buildings have an average concrete compressive strength of 5.86 MPa (Mazılıgüney et al., 2008). School buildings have an average concrete compressive strength of 10.22 MPa which is consistent to the building stock of Turkey, but slightly better than other public buildings.

Among the buildings employed 111, 206 and 4 of the school buildings are located in the 1st, 2nd, and 3rd earthquake zones, respectively.

Only 2 of the school buildings have an apparent building quality of “good”, while 114 of them have “average” and 205 of them have “poor” apparent building quality. Factory brick was used in 319 of the school buildings, and local brick was used in only 2 of them. 27 of the buildings are located on soil class Z1, while 261 of them

are located on site Z2, and 33 of them are located on site Z3. Pounding effect, topographic effects and the short column are the most frequently observed features for school buildings.

Detailed assessment of these buildings according to TEC revealed that 258 (80.37 %) of the school buildings in the database do not satisfy the IO performance state for an earthquake having a probability of occurrence of 10 % in 50 years and 219 (68,22 %) of them do not satisfy LS for an earthquake having a probability of occurrence of 2 % in 50 years. Number of unsatisfactory buildings for each assessment method is given below in Table 1.

Table 1. Number of unsatisfactory buildings for each assessment method.

Number of Stories (Unrestrained)	TEC EQ Zone	TEC PGA (g)	Number	Number of Unsatisfactory Buildings								
				TEC IO (%10)	TEC LS (%2)	ATC21 (FEMA154)	Sucuoğlu et al. 2003	Sucuoğlu et al. 2007	Hassan-Sozen	Özcebe et al. 2003	Yakut (with walls)	Yakut (except walls)
3	1	0,4	33	22	7	23	0	33	12	0	21	21
	2	0,3	61	53	53	32	0	61	21	0	32	30
	3	0,2	2	2	2	2	0	2	2	0	0	0
4	1	0,4	39	19	13	20	7	39	16	1	28	28
	2	0,3	90	81	75	68	0	90	44	4	51	51
	3	0,2	1	1	1	0	0	1	0	0	1	1
5	1	0,4	13	10	7	11	7	13	11	1	12	12
	2	0,3	16	15	12	14	5	16	15	3	5	5
	3	0,2	1	0	0	0	0	1	0	0	0	0

3. INTENSITY MEASURES CONSIDERED AND FORMATION OF GROUND MOTION SETS

To be able to investigate the effect of selected IMs on quantification of seismic risk for the selected school-building stock, six IMs, namely Peak Ground Acceleration-**PGA**, Peak Ground Velocity-**PGV**, Arias Intensity-**AI**, Cumulative Absolute Velocity-**CAV**, modified version of Acceleration Spectrum Intensity (defined with 0.1-2.5 s range)-**ASI*** (Yakut and Yilmaz, 2008) and Velocity Spectrum Intensity-**VSI**, were considered among several alternatives available in the literature. The reasons behind selection of this list could be shortly explained via the findings of a companion study by Kadaş and Yakut (2013); (i) ground motion prediction equations are available for most of the selected IMs, (ii) the easiness in calculation of these IMs with respect to other efficient/sufficient but more complex alternatives, (iii) some of the selected IMs, namely ASI* and VSI, possess best correlation with major engineering demand parameters and exhibit least dispersion in the results as displayed in the aforementioned study.

For each of the selected IMs, an individual ground motion (GM) record set was formed via stratified sampling from a larger ground motion database as described in detail in the companion study by Kadaş and Yakut (2013). The statistical representation of the six different GM sets, as depicted in Figure 1, shows that the record sets are skewed (i.e., less than 11 records were available at high intensities) and this fact might introduce bias into the results for high intensities. Although this observation was made at the GM set formation stage of the study, no scaling of the records were performed to obtain a uniformly distributed GM set (i.e., to achieve 11 records for each bin), as this potentially corrective attempt was out of scope of the present study.

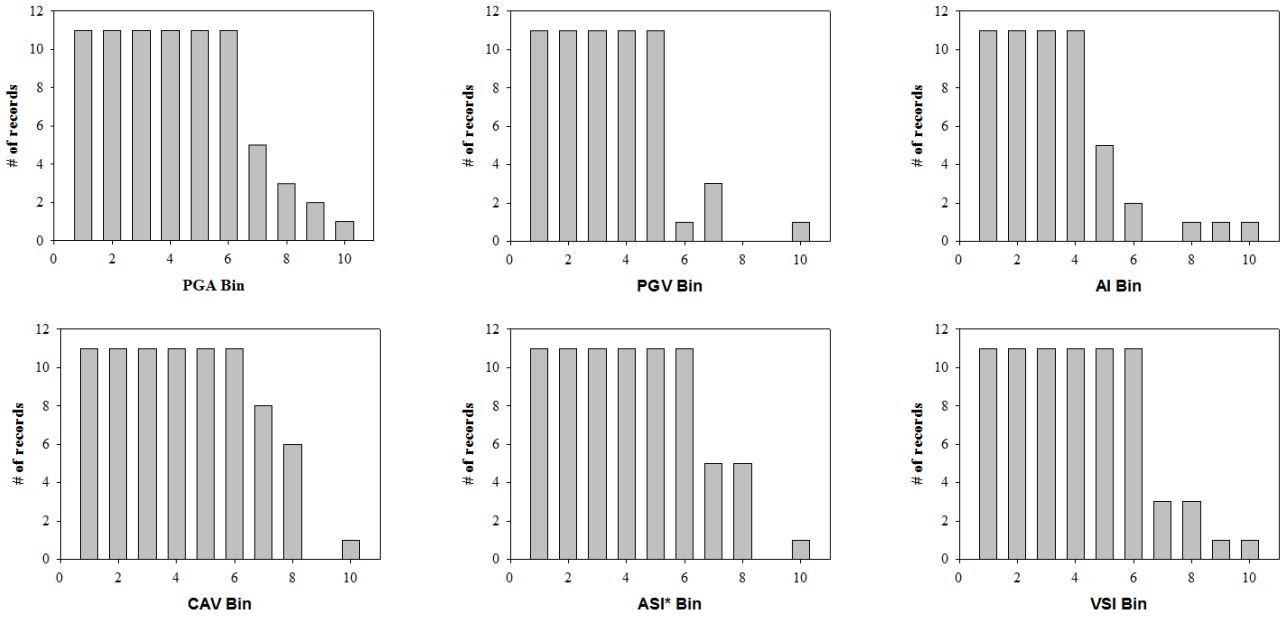

Figure 1. Histograms of alternative GM sets

4. SDOF-BASED STUDY AND DETERMINATION OF DAMAGE STATES

Three dimensional analytical models were formed for each selected 36 RC school building. 36 RC school buildings were analyzed with SAP2000 (version 14.1) in order to obtain the pushover curves in X and Y directions for each building. Pushover curves were transformed into ADRS (Acceleration Displacement Response Spectra) curves and equivalent SDOF (single degree of freedom) system parameters for each building were obtained separately, yielding totally 72 different structures. Statistics of capacity curve parameters for structures with grouped number of stories are given in Table 2.

Table 2. Statistics of Capacity Curve Parameters.

	3 story		4 story		5 story		3-4-5 story (total)	
	Mean	**Std.Dev.**	**Mean**	**Std.Dev.**	**Mean**	**Std.Dev.**	**Mean**	**Std.Dev.**
Sd_y (cm)	1,5156	1,0738	2,6527	1,2608	4,4038	3,4018	2,8574	1,9122
Sa_y (g)	1,8015	1,1344	1,1871	0,9806	0,5495	0,4668	1,1794	0,8606
Sd_u (cm)	4,4626	4,0059	8,3070	4,1571	13,3299	8,9709	8,6999	5,7113
Sa_u (g)	2,5718	1,7957	1,4444	1,2730	0,6730	0,5887	1,5631	1,2191
C_s	0,9563	0,0000	0,9563	0,0000	0,9563	0,0000	0,9563	0,0000
T_e	0,5665	0,3559	1,0803	0,4315	2,1231	1,1445	1,2567	0,6440
PF	1,2578	0,1324	1,2746	0,1302	1,4258	0,2182	1,3194	0,1603
α	0,7728	0,1082	0,7543	0,0830	0,7392	0,0707	0,7554	0,0873
γ	1,4597	0,9312	0,9196	0,7623	0,4021	0,3229	0,9271	0,6721
l	1,3956	0,2997	1,1937	0,1195	1,2095	0,1355	1,2663	0,1849
μ	3,4457	1,1640	3,1450	1,0268	3,8098	2,0505	3,4668	1,4138

(*) S_{dy}, S_{ay}, S_{du}, S_{au}, T_e stand for yield spectral displacement, yield spectral acceleration, ultimate spectral displacement, ultimate spectral acceleration and effective fundamental period, respectively.

Utilizing derived parameters for simplified models of totally 72 different cases, equivalent SDOF systems (with 5% damping ratio) were modeled in OpenSees software and nonlinear time history analyses were performed employing six different ground motion sets. Extracting maximum top drift demands from the analysis results, each structure was marked to exhibit a certain damage state under each ground motion record. While defining the damage level of the structure, following Akkar *et al.* (2005), yield spectral displacement of each structure was taken as **Immediate Occupancy (IO)** performance level, whereas ultimate spectral displacement value was taken as **Collapse Prevention (CP)** limit state. Three-quarters of the ultimate spectral displacement value was taken as **Life Safety (LS)** performance level.

5. DERIVATION OF FRAGILITY CURVES

As expressed in Nielson and Pang (2011), a fragility curve, conditioned on an IM, represents the probability of exceedance of a prescribed damage state for a structure and is generally defined with Eqn. 1:

$$F_R(C < D \mid IM) = 1 - \Phi\left(\frac{\ln(m_C) - \ln(m_D)}{\sqrt{\beta_C^2 + \beta_D^2}}\right) \tag{1}$$

The reader may refer to the aforementioned study for explicit definition of the equation presented above, but it is important to note here that the capacity uncertainty, β_C, was not included in this study to be able to investigate the effect of demand uncertainty which is mainly selected IM dependent. To derive the fragility curves for 3 limit states (IO, LS and CP) for 3-, 4- and 5-story structures, an analytical approach assuming log-normally distributed capacity and demand was followed utilizing the probit method which was codified by Baker (2013). The outcomes of this fragility function estimation study are graphically represented in Figure 2 (comparing the limit states for each IM and structure group) and Figure 3 (comparing the results in terms of number of stories for each IM and limit state definition).

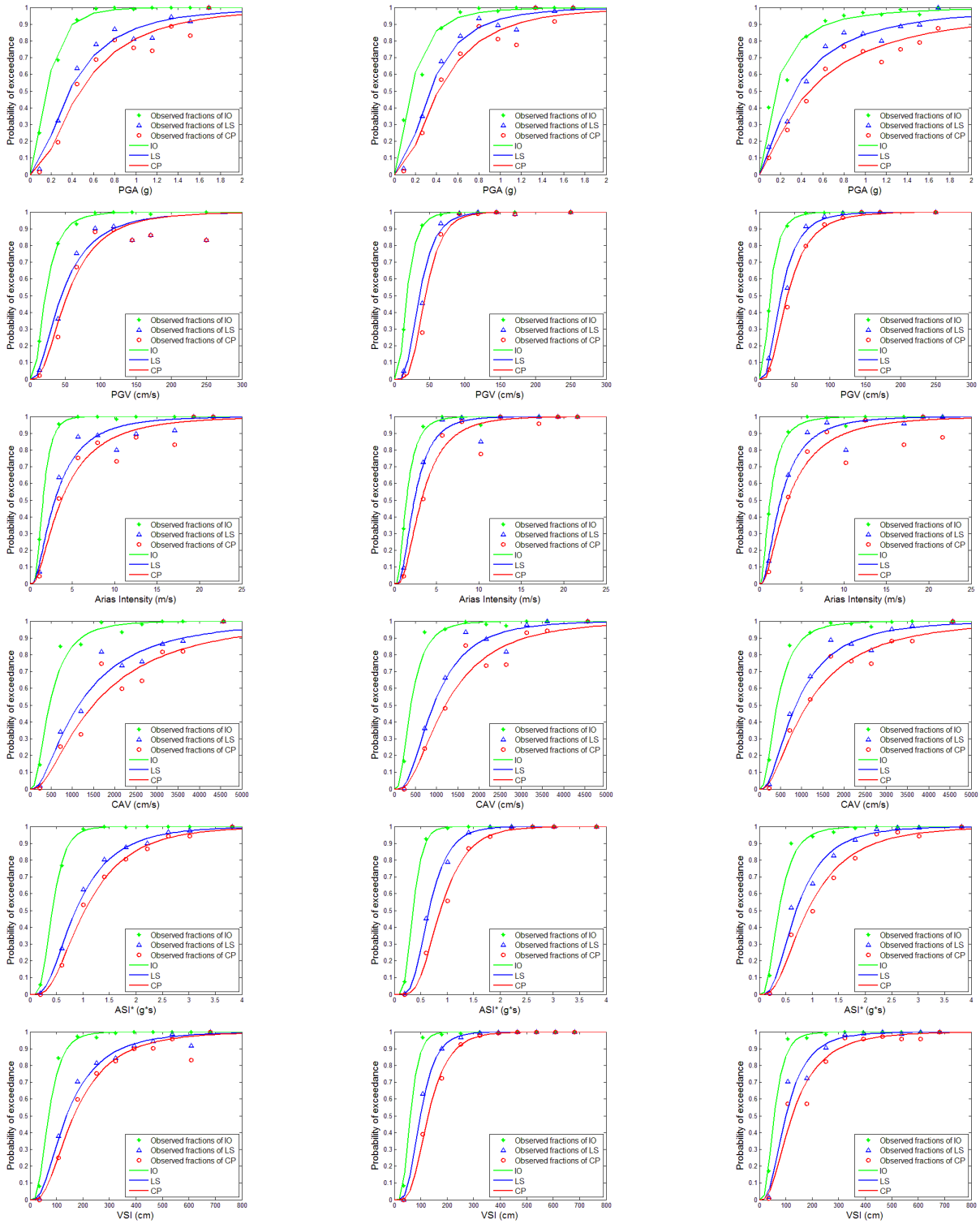

Figure 2. Fragility curves corresponding to each IM
(left panel for 3-story, middle panel for 4-story and right panel for 5-story buildings)

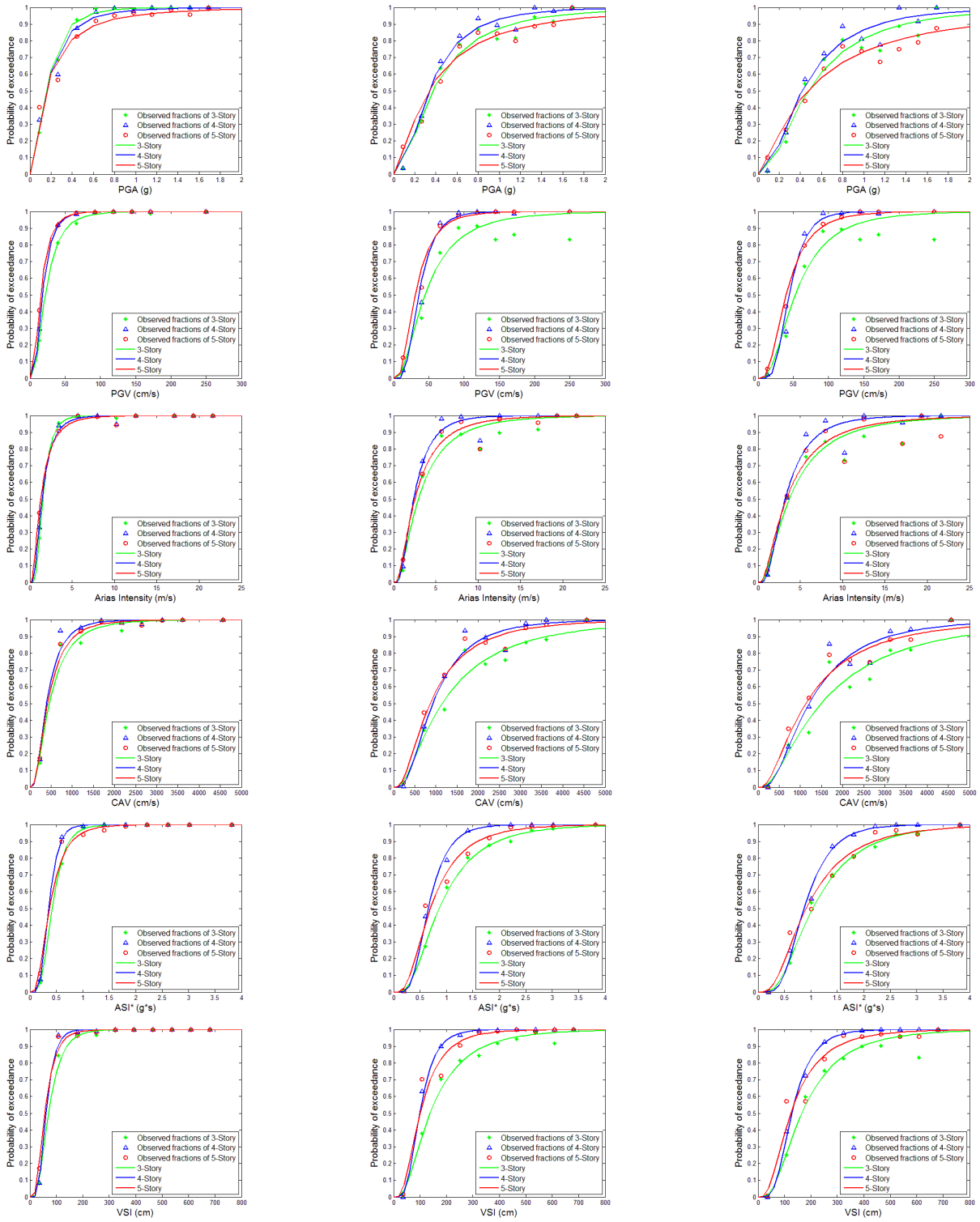

Figure 3. Comparison of fragility curves corresponding to each IM
(left panel for IO, middle panel for LS and right panel for CP limit states)

6. QUANTIFICATION OF SEISMIC RISK UNDER A SCENARIO EVENT

Comparison of fragility curves derived considering different IMs is not much meaningful without performing a seismic risk quantification study. Therefore, a scenario event was studied to show the effect of IM utilized in the formation of ground motion set and in the derivation of analytical fragility curves on the quantified risks. Assuming a scenario strike-slip earthquake event with M_w=7.5 in İstanbul (with reference to Yakut *et al.*, 2012) (along with following assumed seismological characteristics, R_{JB} (Joyner-Boore distance) = 20 km, R_{rup} (distance to rupture) = 20 km, $V_{s,30}$ (shear wave velocity)= 500 m/s considering the general site characteristics of the school-building stock and their average distance to the fault), several attenuation relationships (**for PGA**, Chiou and Youngs, 2008 (w_i=0.25 where w_i denoting the weight given to the GMPE considered), Akkar and Cagnan, 2010 (w_i=0.25), Akkar, Sandikkaya and Bommer, 2013 (w_i=0.25), Kale and Akkar, 2013 (w_i=0.25); **for PGV**, Boore and Atkinson, 2008 (w_i=0.25), Akkar and Cagnan, 2010 (w_i=0.25), Akkar, Sandikkaya and Bommer, 2013 (w_i=0.25), Kale and Akkar, 2013 (w_i=0.25); **for AI**, Travasarou *et al.*, 2003; **for CAV**, Du and Wang, 2012) were utilized to estimate the peak ground parameters for the seismic risk quantification stage of the study. The ground motion prediction equations (GMPEs) for median PGA and PGV were selected from recent studies and from well-known equations which were recommended by Kale and Akkar (2011) and considering the discussions made within Yakut *et al.* (2012). The median ASI* value was calculated using the spectral acceleration values predicted by Chiou and Youngs, 2008 (w_i=0.30), Akkar, Sandikkaya and Bommer, 2013 (w_i=0.35), Kale and Akkar, 2013 (w_i=0.35). On the other hand, the median VSI value could not be calculated, as there was no GMPE available in the literature. The median predictions for selected IMs are listed in Table 3.

Table 3. Estimations for IMs for the scenario earthquake (M_w=7.5, strike-slip)

	Median Value	**Unit**	**Remark**
PGA	0.176	g	weighted
PGV	18.780	cm/s	weighted
AI	0.823	m/s	Travasarou et al. (2003)
CAV	910.965	cm/s	Du and Wang (2012)
ASI*	0.443	g*s	weighted
VSI	-	-	-

After obtaining the median value predictions for PGA, PGV, AI, CAV and ASI*, the probability of exceedance values for limit states IO, LS and CP and for 3-, 4- and 5- story school buildings were computed using the analytically derived fragility curves and quantified risks are summarized in Table 4.

The results clearly showed that PGA-, PGV- and ASI*-based probability of exceedance values are close to each other for all of the structure groups and for all three limit states, ASI* mostly being in between PGA and PGV. On the other hand, AI and CAV yielded extreme probability of exceedance values for all cases, raising the question for problematic performance of the GMPEs used for these two IMs.

Bearing in mind the fact that these results are most probably dependent on the performance of the GMPEs employed in this study, quantification of risks through fragility curves shall be handled using GMPEs which are suitable for the seismic region the risk study focuses on.

It is also important to note here that maximum values of the IMs considered and number of records utilized or available in each bin throughout GM set formation and fragility curve development would certainly affect the outcomes of the risk study, which should be further investigated.

Table 4. Quantified risks for the scenario earthquake

	IMMEDIATE OCCUPANCY (IO)					
Story	**PGA**	**PGV**	**AI**	**CAV**	**ASI***	**VSI**
3	55.9%	40.9%	11.1%	81.8%	54.8%	-
4	55.4%	53.3%	19.3%	89.7%	71.4%	-
5	56.3%	62.0%	28.5%	86.0%	61.9%	-
	LIFE SAFETY (LS)					
Story	**PGA**	**PGV**	**AI**	**CAV**	**ASI***	**VSI**
3	19.3%	12.8%	6.1%	39.7%	14.8%	-
4	19.7%	9.2%	4.9%	48.9%	18.5%	-
5	28.6%	21.6%	8.3%	52.5%	23.8%	-
	COLLAPSE PREVENTION (CP)					
Story	**PGA**	**PGV**	**AI**	**CAV**	**ASI***	**VSI**
3	12.1%	6.4%	4.0%	29.2%	8.6%	-
4	13.8%	2.2%	2.1%	34.9%	6.7%	-
5	20.9%	11.1%	5.2%	40.3%	14.5%	-

7. CONCLUSIONS

Six IMs, namely **PGA**, **PGV**, **AI**, **CAV**, **ASI*** (Yakut and Yilmaz, 2008) and **VSI** were considered among several alternatives available in the literature to derive drift-based fragility curves for a group of typical school buildings. The fragility curves were compared with each other to be able to investigate the effect of selected IMs on quantification of seismic risk for the selected school-building stock. It can clearly be concluded that quantification of seismic risk is easily affected by selected IMs.

The results showed that PGA-, PGV- and ASI*-based probability of failure values are close to each other for all of the structure groups and for all three limit states, ASI* mostly being in between PGA and PGV. On the other hand, AI and CAV yielded extreme values for all cases, raising the question for problematic performance of the GMPEs used for these two IMs.

It can also be concluded that CAV is the most conservative and the AI is the least conservative IM to quantify the seismic risk of building stock.

Fragility curves derived by CAV based ground motion set give most proper results with TEC for the IO limit state. None of the fragility curves of alternative IM-based ground motion sets give proper results for the LS limit state case of TEC. Among the preliminary assessment procedures, only Yakut's procedure is somehow proper with only fragility curves derived by CAV based ground motion set.

The effects of selected IMs on quantification of seismic risk for the selected building stock should be checked by different building stocks and also with different alternative sets of ground motion data.

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