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BUILDING VULNERABILITY AND SEISMIC RISK ASSESSMENT FOR İZMİR, TURKEY

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ABSTRACT

Izmir, the third largest city in Turkey, is located in a tectonically active area with significant earthquakes in the past. The latest destructive event has occurred in 1778 and it is assumed that significant amount of stress is accumulated along the various faults in the area since then. It is therefore crucial to assess the seismic risk in Izmir and estimate the extent of the expected building damage in case of a large scenario earthquake along the Izmir fault that crosses the city. In addition to the fact that an active fault crosses the city, a large proportion of the metropolitan area, especially the northern section of the Izmir Bay, is exposed to local site effects due to the soft sediments associated with the Gediz river delta system. This, combined with a very dense building stock and poor construction practices, makes the city prone to a high level of risk. Consequently, any attempt in quantifying the seismic risk in terms of the extent of the building damage will be useful to local authorities in urban planning and risk mitigation measures.

Seismic risk assessment is conducted for Izmir based on a worst case scenario earthquake occurring along the Izmir fault. The input ground motion is estimated using hybrid kinematic simulations of an extended fault rupture (Bjerrum et al., 2013). The various building categories are identified and mapped through satellite images combined with ground surveys in the city. Furthermore in order to assess the building response, 22 selected buildings representing the different building typologies are measured using the H/V spectral ratio technique on ambient vibrations. The results show systematic variations between the different building categories. The results are used not only in obtaining the predominant frequencies for these buildings but also to test the importance of including building response parameters in seismic risk analysis. Seismic risk analysis is performed using the software SELENA (Molina et al., 2010).

INTRODUCTION

İzmir, the third largest city in Turkey with a population of over 3.7 million, is located on the west coast of Turkey surrounded and underlain by several active faults (Emre et al. 2005). Previous GPS studies have confirmed a westward migration of the Anatolian microplate, with rotation of western Anatolia in the area around İzmir (e.g. McClusky et al. 2000; Nyst and Thatcher 2004). This migration and rotation result in reactivation of faults along the west coast of Turkey and İzmir is of this reason

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exposed to significant seismic hazard. The city has historically experienced strong ground shaking due to earthquakes. The latest large earthquake in the area was in 1778, following two events separated in time by approximately 50 years. In 1688 an earthquake of M=6.8 caused 5000 casualties, while the 1778 earthquake had an estimated death toll of 200 and the associated macroseismic intensities in İzmir have been estimated to up to MMI = X for these events (Ambraseys and Finkel 1995; Papazachos and Papazachou 1997; Papazachos et al. 1997). Low seismic activity in the last 240 years, and the results of a local GPS study focusing on the local tectonic deformation around İzmir (Aktuğ and Kılıçoğlu 2006) indicate that stresses are building up across the faults in the area (Figure 1).

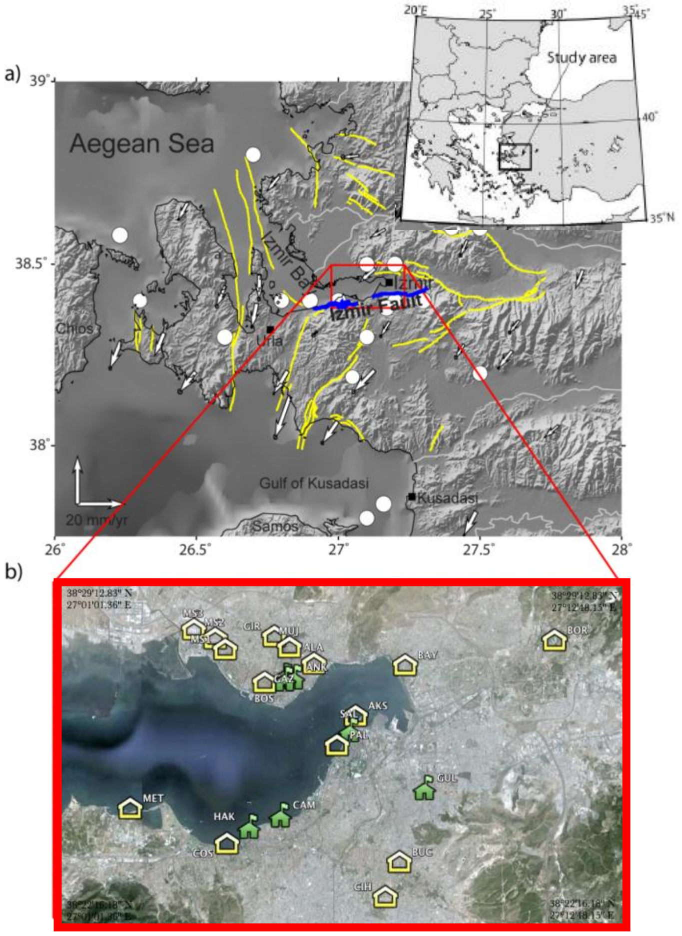

Figure 1. a) Map of the İzmir and surroundings. The faults mapped by MTA (Emre et al., 2005) are shown as yellow lines, İzmir fault is marked with blue. The historic events in the area are indicated as white circles (Ambraseys and Finkel, 1995; Papazachos and Papazachou, 1997; Papazachos et al., 1997) and the GPS velocity field from Aktuğ and Kılıçoğlu (2006) is shown as white arrows. b) Map showing the locations of the 22 buildings investigated in this study. Schools are shown in green whereas other buildings are shown in yellow. Map prepared in Google Earth © .

İzmir is located directly above a normal fault of approximately 40 km length, potentially capable of generating a Mw=6.9 earthquake (Wells and Coppersmith 1997). In addition, large parts of the metropolitan area are underlain by soft sedimentary deposits, especially on the northern (Karşıyaka) and eastern (Bornova) parts of the İzmir Bay. Previously both probabilistic and deterministic (based on ground motion simulations) seismic hazard analyses have been conducted for the area around İzmir. Expected ground motions of 0.4 g for a 475 year return period were predicted, while earthquake rupture scenarios predicted ground motions on bedrock level exceeding 750 cm/s^2 in the center of the city (MMI, 2000; Bjerrum 2007; Bjerrum and Atakan 2008; Deniz et al. 2010; Bjerrum et al., 2013). Figure 2 shows the average peak ground motions (in PGA and PGV) from the study of Bjerrum et al. (2013).

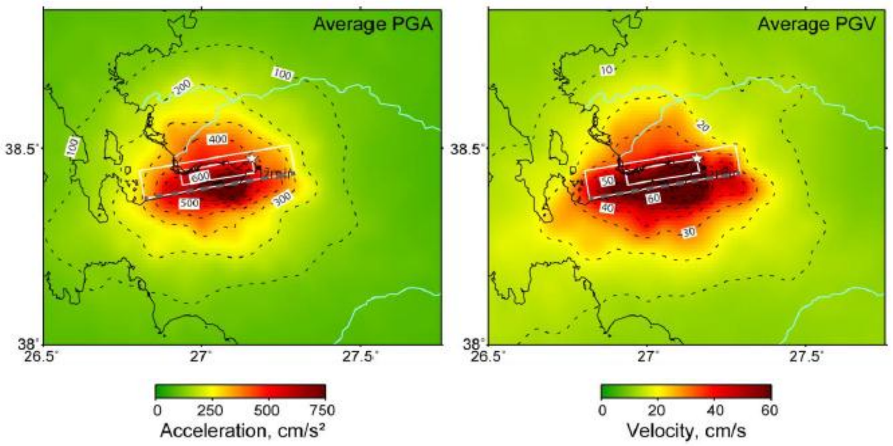

Figure 2. Spatial distribution of average ground motion of PGA (left) and PGV (right) from ground motion simulations (modified from Bjerrum et al., 2013). The surface projection of the ruptured fault plane and asperity are shown as white rectangles, the surface trace is marked with a thick stippled line. The nucleation point is shown as a white star.

Over 50% of the general building stock in Izmir consists of reinforced concrete (RC), frame buildings with unreinforced brick masonry in-fill walls (EERI, 2007). In addition, the majority of the buildings in Turkey are not build according to the design codes, and neither do they provide good-enough quality of reinforcement of concrete (Sezen et al., 2003; Korkmaz et al., 2009). Two previous seismic vulnerability and risk studies were conducted in Izmir. The Metropolitan Municipality of Izmir (MMI) (2000), calculated the city's socio-economic losses due to a future earthquake. They used a capacity spectrum method with input from seismic hazard (ground motion) and a building inventory of more than 200,000 buildings classified in structural types and ages. This study finds that most of the damage is expected to be related to RC frame buildings with more than six storeys. Less economic loss is estimated to be related to masonry buildings. Korkmaz et al. (2009) studied five typical RC buildings in Izmir and they their expected earthquake performance. All buildings were designed according to the 1975 Turkish Building Code. In this study different approaches are used to assess the vulnerability of the selected buildings. The results indicate that the RC building face risk of poor performance during a possible future earthquake. If Izmir were to experience ground motions similar to the 1999 Düzce earthquake, the city's building stock would be heavily damaged and collapses would be expected.

The response of a building during an earthquake depends on the input ground motion and the dynamic characteristics of the building itself. The dynamic response of a building is dependent on the building's fundamental frequency, damping coefficient and modal shape, which in turn is dependent on the building's structural system, material of the structural system, mass distribution, geometry, non-structural elements, type of foundation, aging, etc (Oliveira et al., 2006).

The objective of this study is to identify the building topologies and areas that are most at risk in Izmir. The first part of the study focuses on assessing the fundamental frequencies of different building categories in Izmir, both to test if the H/V microtremor method is a reliable tool to assess the fundamental frequency of a building, but also to address the complexity of the single building response, compared to the general building categorization, as applied in seismic vulnerability and loss computation tools. The second part of the study focuses on the vulnerability and risk of the city's general building stock. This is done by creating a building inventory for Izmir, which is used in the vulnerability and risk assessment in the loss computation tool SELENA (Molina et al., 2010).

H/V FOR BUILDING RESPONSE ANALYSIS

The H/V microtremor method as proposed by Nakamura (1989) has been widely used in assessing the fundamental frequency of soils in order to assess the possibility of site amplification during an earthquake. Different studies have demonstrated that the H/V technique gives good estimates of resonance frequencies of soils (Mucciarelli and Gallipoli, 2004). The technique has thus primarily been used to assess the fundamental frequency of sediment layers, but the technique has in recent years also been used to assess the fundamental frequencies of buildings. According to Gallipoli et al (2004), H/V microtremor measurements give a good estimation of the fundamental frequency of a building. In this study, we investigate the fundamental frequencies for 19 buildings of RC frame (11 residential buildings, six schools, two municipality buildings, one University building and one hotel (Figure 1b)), using the HV microtremor measurements. The survey was conducted during the spring of 2010 in the metropolitan area of Izmir. The results are compared to different period-height relationships obtained by both analytical and empirical methods

The same principles used for sediment layers are used in the case of determining the fundamental frequency of a building. The theory is that by taking one measurement at the top of the building, and calculating the ratio between the amplitude for the Fourier spectra of horizontal and vertical components; the H/V spectrum will show a pronounced peak centered at the fundamental frequency of the building. Dependent on the height and complexity of the building, the peak might not always be clear. For both complex and lower building the peak might be difficult to identify, whereas for tall buildings, the peak will be more pronounced (Gallipoli et al., 2010). Herak (2009), claims that even though the H/V microtremor method can assess trustworthy fundamental frequencies for some buildings, one should be skeptic to the results obtained if the soil amplification at the site is significant; this can lead to a false identification of the buildings response, because the free field (outside) measurements may contaminate the building response.

Measurements were conducted using a Sara SR04 seismic digitizer with three 4.5 Hz geophones. The measurements were collected with a sampling at a rate of 100 Hz and recorded in SEISLOG (Utheim and Havskov, 2002). To study the recorded signals SEISAN (Havskov and Ottemöller, 2008) was used. Processing of the collected data was done with the software GEOPSY (Wathelet, 2011). H/V spectral ratios were calculated using a window length of 25 s with no overlap and tapered with a 5% cosine function. A Konno and Ohmachi smoothing with a smoothing constant of 40 was used without filtering (Konno and Ohmachi 1995). Anti-triggering was set with a minimum STA/LTA of 0.2 and maximum STA/LTA of 2.5, where the time windows of the STA and LTA were set to 1 s and 30 s, respectively.

ANALYSES AND RESULTS FROM H/V MEASUREMENTS

In general it was found that the fundamental frequency of the buildings decreases with increasing height (i.e. number of stories). This is a confirmation of a well-established fact, but at the same time, this also confirms that the H/V microtremor method is able to identify this trend. It is also seen that the measurements taken at the top floors show a more pronounced peak than the measurements taken at the 1st floors. This is also in agreement with what is expected. Furthermore, the amplification factor increases for the measurements taken at a higher building level. The 21 examined buildings had a variation of 3 to 20 stories and the corresponding fundamental frequencies obtained vary between 5.9 Hz (lowest building) to 1.0 Hz (highest building). A summary of the results from the H/V microtremor measurements is presented in Table 1.

Table 1. Summary of the results from the H/V measurements on 19 selected buildings.

No. of stories	No. of buildings	Fundamental frequency range (Hz)	Average fundamental frequency (Hz)
3	1	5.9	5.9
4	5	4.4-5.7	5.3
5	3	3.2-5.	4.1
7	2	2.4-2.8	2.6
8	1	3.1	3.1
9	2	2.3-2.4	2.4
10	2	1.7-2.1	1.9
18	2	1.3-1.5	1.4
20	1	1.0	1.0

As an example we show the H/V curves obtained at Gültepe Elementary School, located in the eastern part of the city. The H/V spectra are shown in Figure 3. From the H/V ratio measured at the top floor, there is a clear peak at around 6 Hz. The free field measurement shows a peak at around 0.8-1 Hz. This peak is also present in the H/V curves at the 1st floor and at the top floor.

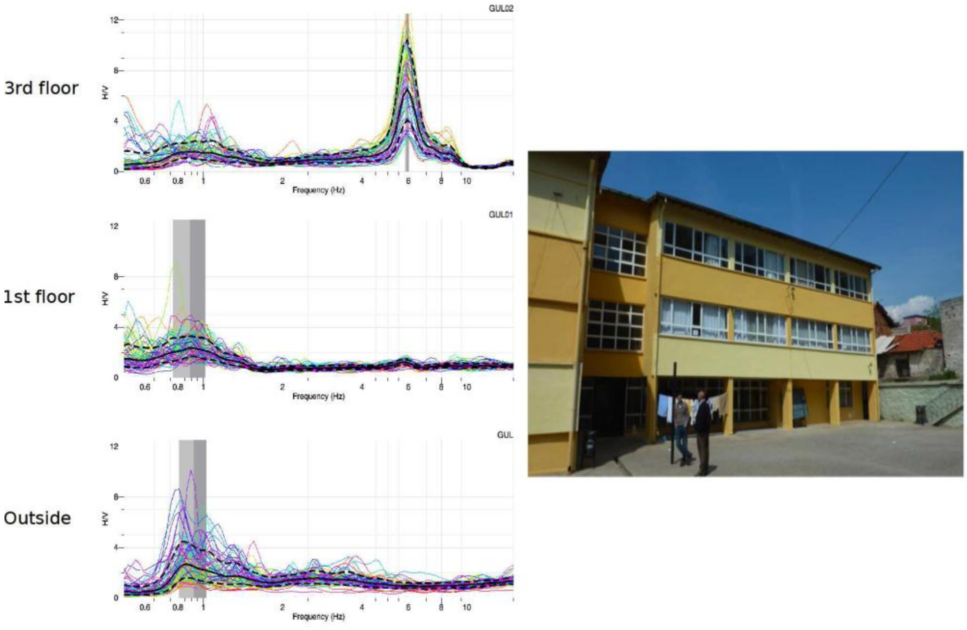

Figure 3. H/V curves obtained from the measurements at Gültepe Elementary School (eastern part of Izmir). Tthe black curve represents the H/V ratio, geometrically averaged over all colored individual H/V curves, and the two dashed, black curves represent the standard deviation. The grey area represents the averaged peak frequency and its standard deviation. The frequency value is found in the middle of the grey area.

The fundamental frequencies assessed from the H/V microtremor measurements are compared to empirical period-height relationships in order to test if the H/V microtremor results are reliable. In doing so, one story is assumed to be equivalent to 3 m. The results are compared to the relationship from Eurocode 8 (CEN, 2004), Crowley and Pinho (2004), Gallipoli et al. (2010) and Navarro et al. (2002). The comparisons with the different period-height relationships are presented in Table 2. It is seen that the fundamental frequencies from this study are not comparable to the fundamental frequencies obtained by Crowley and Pinho (2004). The measured results from the higher buildings are comparable to the empirical results from Eurocode 8, whereas the frequencies for the lower buildings are not comparable. In general best fit is observed between the measured frequencies from H/V and the two empirical relations from Gallipoli et al., (2010), and Navarro et al., (2002).

Table 2. Comparison of the fundamental frequency obtained by H/V microtremor measurements with Eurocode 8, Crowley and Pinho (2004), Gallipoli et al. (2010) and the results obtained by Navarro et al. (2002).

Number of stories	Average measured fundamental frequency (Hz)	Average empirical fundamental frequency (Hz)			
		Eurocode 8	Crowley and Pinho, 2004	Gallipoli et al., 2010	Navarro et al., 2002
3	5.9	2.57	1.11	6.90	6.80
4	5.3	2.07	0.83	5.20	5.10
5	4.1	1.75	0.67	4.17	4.08
7	2.6	1.36	0.47	2.98	2.92
8	3.1	1.23	0.42	2.60	2.55
9	2.4	1.13	0.37	2.31	2.27
10	1.9	1.04	0.33	2.08	2.05
18	1.4	Not available	0.19	1.16	1.13
20	1.0	Not available	0.17	1.04	1.02

BUILDING INVENTORY IN IZMIR

Building inventory in Izmir is determined using sattelite images as provided by the Google Earth©, combined with a detailed field survey in three selected areas that are shown in Figure 4 below. These are Mavisehir, Karsiyaka and Konak. Prior to the field survey, these three different areas were studied in Google Earth where the assumed height/number of stories for each building was estimated. The height of the buildings was estimated according to the HAZUS methodology, which divide the buildings into three different categories, according to their height:

- 1-3 floors (low-rise)
- 4-7 floors (mid-rise)
- 8+ floors (high-rise)

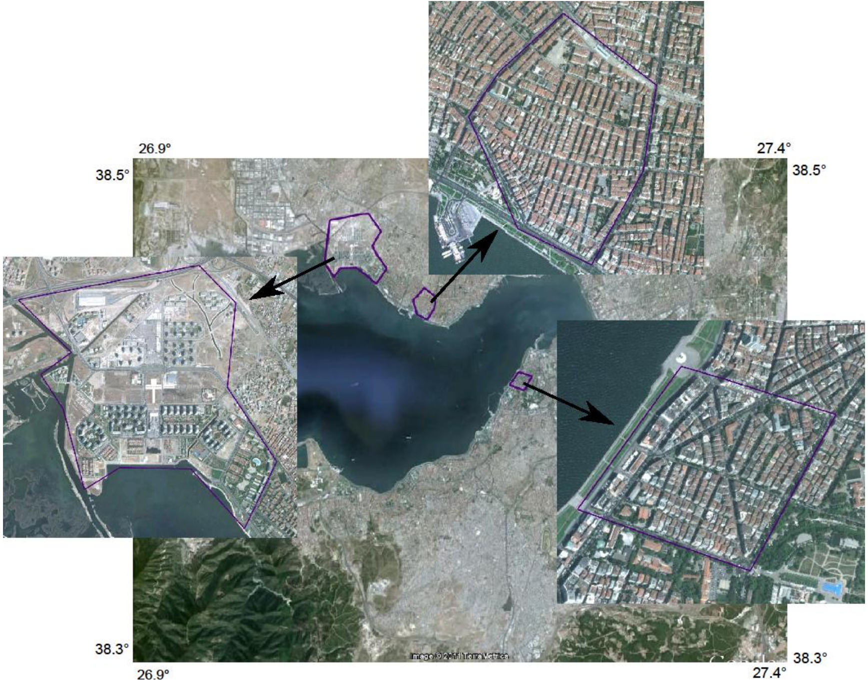

Figure 4. A map of the three surveyed areas. Detailed maps of the areas are shown for Mavisehir (left), Karsiyaka (middle) and Konak (right). The surveyed areas are indicated with purple lines. The map is prepared in Google Earth.

The building categories are defined using the coding applied in HAZUS (FEMA, 2003). Three of the code levels have been used for Izmir: Moderate-code, low-code and pre-code (Table 3). The different code levels are applied to the buildings depending on the location of the building (if it is located in an area where the buildings are expected to have good or poor seismic behavior) as well as depending on the age of the building. In order to separate “brick/block unreinforced masonry” structures with timber floors from “brick/block unreinforced masonry” structures with concrete floors, low-code is used for “brick/block unreinforced masonry w/timber floors” and pre-code is used for “brick/block unreinforced masonry w/concrete floors”. This is because timber, in general, is a more ductile and light weight material compared to concrete, and therefore, a higher code level has been chosen for structures with timber floors.

In Table 3 a distinction is made between buildings built before and after 1975. The year 1975 was chosen because this was the year a new building code was introduced in Turkey (the predecessor to the 1997 Turkish building code). It is therefore assumed that the buildings built after 1975 are of higher quality than the ones built before this threshold. In addition, there is also a distinction between buildings built before and after 2002. This threshold was chosen because in July 2001, a new legislation regarding the quality control of constructions was introduced in Turkey.

Table 3. Seismic code levels used for buildings of different age and buildings located in different areas of the city (depending on the expected quality of the buildings).

	AREAS WHERE GOOD SEISMIC BUILDING BEHAVIOR IS EXPECTED	AREAS WHERE POOR SEISMIC BUILDING BEHAVIOR IS EXPECTED
Pre-code	Built before 1975	Built before 1975 and between 1975-2002
Low-code	Built between 1975-2002	Built after 2002
Moderate-code	Built after 2002	None
High-code	None	None

In the following (Tables 4 and 5), various structural types as adopted from HAZUS (FEMA, 2003) and PAGER database (Jaiswal and Wald, 2008) and their relation to the existing seismic codes in Turkey are shown.

Table 4. The different code levels used for areas where good seismic building behavior is expected.

STRUCTURE TYPE, HAZUS	STRUCTURE TYPE, PAGER	SEISMIC DESIGN CODE	
C2H	R/C shear walls	1975-2002	Low-code
C3L	R/C frames with masonry infill	Before 1975	Pre-code
		1975-2002	Low-code
C3M	R/C frames with masonry infill	Before 1975	Pre-code
		1975-2002	Low-code
C3H	R/C frames with masonry infill	Before 1975	Pre-code
		1975-2002	Low-code
URML	Brick/block unreinforced masonry w/timber floors	Pre 1975	Pre-code
		1975-2002	Low-code
URML	Brick/block unreinforced masonry w/concrete floors	Pre 1975	Pre-code
		1975-2002	Pre-code
URML	Weak masonry	Pre 1975	Pre-code
		1975-2002	Pre-code

Table 5.The different code levels used for areas where poor seismic building behavior is expected.

STRUCTURE TYPE, HAZUS	STRUCTURE TYPE, PAGER	SEISMIC DESIGN CODE	
C3L	R/C frames with masonry infill	Before 1975	Pre-code
		1975-2002	Pre-code
C3M	R/C frames with masonry infill	Before 1975	Pre-code
		1975-2002	Pre-code
C3H	R/C frames with masonry infill	Before 1975	Pre-code
		1975-2002	Pre-code
URML	Brick/block unreinforced masonry w/timber floors	Pre 1975	Pre-code
		1975-2002	Pre-code
URML	Brick/block unreinforced masonry w/concrete floors	Pre 1975	Pre-code
		1975-2002	Pre-code
URML	Weak masonry	Pre 1975	Pre-code
		1975-2002	Pre-code

In total the number of buildings in Izmir is estimated to be 312 258. Compared to the number of buildings stemming from the Earthquake Master Plan for Izmir (MMI, 2000), which is 217 824, the obtained number is reasonable, both according to the population growth during the last decade, and also due to the incorporation of additional areas into the Municipality of Izmir during the recent years. The summarized numbers are presented in Table 6 (total number of buildings in each building typology) and Table 7 (total percentage of buildings in each building typology).

Table 6.Total number of buildings in each building typology.

C2H LOW-CODE	C3L PRE-CODE	C3L LOW-CODE	C3M PRE-CODE	C3M LOW-CODE	C3H PRE-CODE	C3H LOW-CODE	URML PRE-CODE	URML LOW-CODE
45	71610	37066	33190	22602	7076	2893	119569	18207

Table 7.Total percentage of buildings in each building typology.

C2H LOW-CODE	C3L PRE-CODE	C3L LOW-CODE	C3M PRE-CODE	C3M LOW-CODE	C3H PRE-CODE	C3H LOW-CODE	URML PRE-CODE	URML LOW-CODE
0.01%	22.92%	11.87%	10.63%	7.24%	2.27%	0.93%	38.29%	5.83%

SEISMIC VULNERABILITY AND RISK ASSESSMENT

The metropolitan area of Izmir is divided into 42 different geo-units representing different local site conditions according to the four categories as defined by the Izmir Earthquake Master Plan (MMI, 2000), and HAZUS (FEMA, 2003). The input ground motions are based on simulated peak ground accelerations (PGA) and spectral accelerations at 0.3 and 1.0 seconds using a scenario earthquake rupturing along the Izmir Fault (Bjerrum et al., 2013). In addition to a "worst-case" scenario with a magnitude M_W=6.9 earthquake rupturing along the Izmir Fault, other scenarios with simple deterministic ground motion levels using magnitude and distance dependent variations of expected ground motions for M_W=6.0 and M_W=5.0 were also used for comparison.

All risk computations were conducted using the software SELENA (Molina et al., 2010). Capacity curves are taken form HAZUS (FEMA, 2003, Table 5.7 for the nine building structural typologies used in this study). The capacity parameters, elastic damping and the spectral displacement corresponding to the elastic limit are taken from Molina et al., (2010), whereas the Kappa values are taken from Table 5.18 in HAZUS (FEMA, 2003). Fragility curves are defined using the Table 5.9 in HAZUS (FEMA, 2003) corresponding to the median and lognormal standard deviation values for the slight, moderate, extensive and complete structural damage states.

Results for the "worst-case" scenario, as expected, indicate the highest damage percentages when compared to the other scenarios with lower magnitues (and hence lower input ground motions) (Figure 5). Common in all, however, is the relative distribution of damage in different building categories. The URML pre-code buildings suffer most damage, whereas C2H low-code buildings suffer less. Here, it should be noted that the notations used in Figure 5 for slight, moderate extensive and complete damage represent no structural damage, low structural damage, medium structural damage, serious structural damage (with a possible collapse of 5-15% of buildings in this latter category depending on the number of storeys).

The results presented in Figure 5 exhibit significant differences in computed damage between the different input scenarios. It is therefore warranted that seismic risk results obtained should be treated with care, as there are a number of uncertainties involved in the process. Due to these uncertainties, the relative distribution of damage is more interesting than the absolute values of damage as represented by the number of buildings involved in different damage categories.

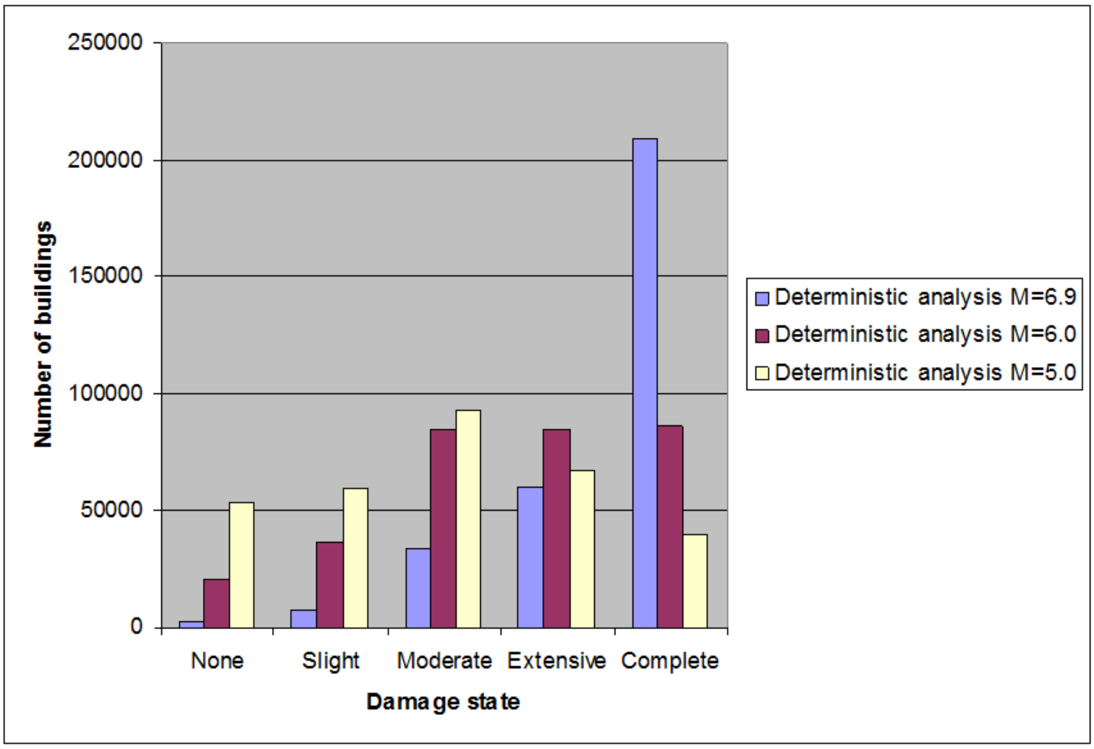

Figure 5. A comparison of three deterministic scenarios on the Izmir fault. All parameters remains the same, whereas the magnitude is decreased from $M_w = 6.9$, to $M_w = 6.0$ and $M_w = 5.0$.

DISCUSSION AND CONCLUSIONS

In this study we have computed seismic risk using the well-established methodologies as applied by HAZUS. However, the large variation in our results clearly shows that there is a need for constraining the input data. A systematic approach is needed to reduce the uncertainties in the input data used. Here it should be mentioned that the uncertainties associated with the various input data propagate through the risk computations. In the first stage, the uncertainties associated with the input ground motions, as well as the local site effects pose significant challenges in obtaining a reliable seismic risk assessment for the area in concern. More work is needed to provide additional constraints on the input ground motions. In the second stage, the uncertainties with regard to the building inventory and exposure data are equally important. However, these can be improved by a systematic survey of the metropolitan area in the future. Implementation of building specific data on seismic risk analysis methods, on the other hand, requires additional work which is beyond the scope of the current study. Here, we have only demonstrated that there is a clear potential of using more building specific data adopting microtremor measurements.

Despite the current limitations of the results obtained in this study, we can clearly conclude that even a moderate size earthquake occurring along the Izmir Fault is likely to have significant consequences in the densely populated metropolitan area of Izmir. It is therefore highly recommended that a systematic approach is used in collecting a complete building inventory data adopting an appropriate seismic risk methodology that takes into account the local conditions. Lack of destructive earthquakes in this region during the last two centuries and the fact that significant portion of the metropolitan area is underlain by soft soil conditions, combined with the dense building stock with variable quality, makes this area extremely vulnerable to future seismic hazard and risk.

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