A seismic risk study in Málaga city's historical centre (Southern Spain)

T. Goded
Universidad Complutense de Madrid, Spain; Institute of Geological and Nuclear Sciences, New Zealand

E. Buforn
Universidad Complutense de Madrid, Spain

J. Irizarry & A. Macau
Institut Geològic de Catalunya, Spain

SUMMARY:
Málaga is located in one of the most active seismic areas in Spain, with a seismic hazard of 0.11g (500 years return period). In 1680, a large earthquake (Imax=VIII-IX) caused heavy damage to its building stock, including 36 monuments. A detailed seismic risk analysis has been carried out in the city. Site effects have been analysed using experimental and numerical techniques. A seismic microzonation has been proposed, classified in six types of soils. The results show regions with high intensity amplifications (ΔI=+1.5) corresponding to areas with heavy damage in the 1680 earthquake. Málaga's monuments have been analysed using the vulnerability index methodology. Results show a good consistency between expected and observed damage, especially for the churches typology. Deterministic and probabilistic scenarios have also been proposed for the city centre. These results may be applied for preservation and reinforcement measurements in Malaga's historical heritage.

Keywords: damage scenarios, monumental buildings, seismic microzonation, site effects, vulnerability curves

1. INTRODUCTION

The South of Spain has been affected by large earthquakes in the past, with maximum MSK (*Medvedev-Sponheuer-Karnik* scale) intensities equal or larger than VII (Fig. 1.1). According to the *Instituto Geográfico Nacional* (IGN) Data File, three events with maximum EMS-98 (*European Macroseismic Scale*, Grünthal, 1998) intensities equal or greater than VII have occurred in the Málaga region, in January 1494 (VIII), June 1581 (VII) and October 1680 (VIII-IX). These epicentres are located at less than 30km from Málaga city (Martínez Solares and Mezcua, 2002). The last large event in the area was the 1884 Arenas del Rey (Granada) earthquake (I_0=IX-X; Muñoz and Udías, 1981) located at 58km Northeast of Málaga, which caused important damage to the city of Málaga (Fig. 1.1).

The most important earthquake in the Málaga region was the one that occurred in 1680, one of the best documented Spanish shocks which affected the Southern half of Spain. This earthquake caused very heavy damage to the city of Málaga, where at least 70 people were killed and 250 injured. A thorough study of the damage caused by the 1680 event to the city of Málaga (with an estimated intensity of VIII-IX EMS-98, Goded, 2006) was carried out by Muñoz and Udías (1988) and completed with new information found in archives, libraries, etc. by Goded *et al.* (2008). From the information contained in historical documents, damage grades were estimated for 36 monuments located in the city centre. Most of these historical buildings (a total of 23) suffered severe damage (EMS-98 damage grade 4) or were completely destroyed (damage grade 5), which is an indication of the heavy damage suffered in the city.

The city of Málaga has experienced a large urbanistic development in the last thirty years, becoming in 2006 the sixth Spanish town in terms of its population, with more than 560.000 inhabitants (Instituto de Estadística de Andalucía, 2006). This fact together with its location in one of the most active seismic areas in Spain and the low seismic activity occurred in the region in the past 50 years (with maximum magnitudes less than 5.0), have motivated this work. The present study is divided in three parts. In the first part, a site effects analysis is carried out for Málaga city's historical centre (Goded, 2010; Goded *et al.*, 2011a). This site effects study represents an improvement for the city centre compared to the analyses done by Clavero and Ramos (2005) and Macau (2008) for the entire city, which was divided into four types of soils (A, B, C and D). In our study, both experimental and numerical methods have been used to obtain soil's amplifications and fundamental frequencies for the city centre, and a detailed seismic microzonation is proposed. Intensity amplifications for 27 sites in the city centre are also obtained. In the second part, the study is focused on the monuments damaged in the 1680 earthquake and still existing today (19 out of 36), and expected damage grades in a scenario similar to the 1680 event are compared to the observed damages in the past. Once the *VI* methodology has been tested for Spanish monuments by comparing expected and observed damage in the past, other monuments in the city have been added. In the third part of this study, a total of 54 historical and modern buildings in Málaga's city centre have been analysed using two seismic scenarios proposed for the city of Málaga: a deterministic scenario based on the 1680 earthquake, and a probabilistic one based on the Spanish seismic code (NCSE-02, 2002). These monuments include some essential buildings such as the City Hall (Goded, 2010; Goded *et al.*, 2011b).

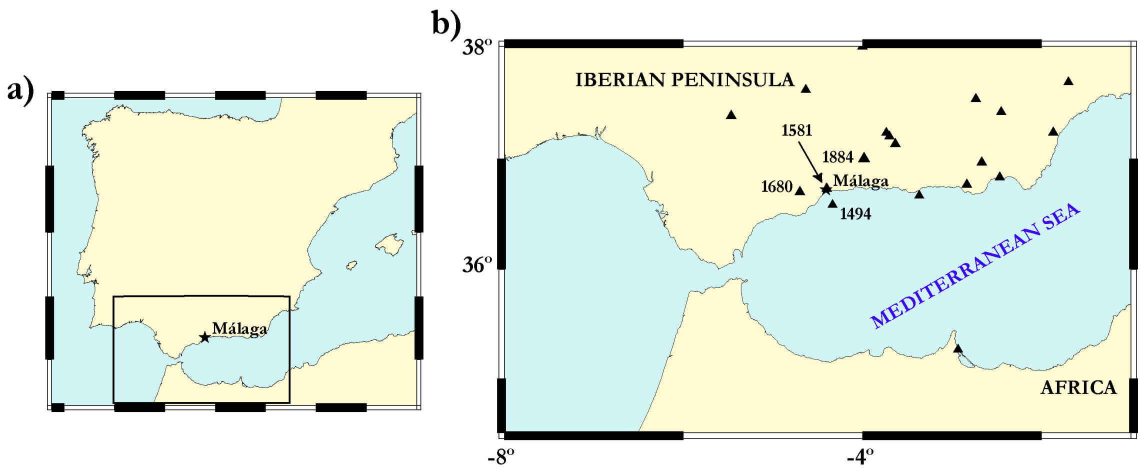

Figure 1.1. Historical seismicity (before 1950) for earthquakes with I_{max}≥VII MSK in the South of the Iberian Peninsula (IGN data file) corresponding to the marked area in figure 1a. The 1494 (I_0=VIII), 1581 (I_0=VII) and 1680 (I_0=VIII-IX) Málaga and the 1884 (I_0=IX-X) Arenas del Rey earthquake epicentres are shown. Black star indicates the location of Málaga city

2. SITE EFFECTS ANALYSIS

For the site effects study in Málaga city, two methodologies have been used: an experimental technique (horizontal over vertical ratio, or H/V, method, Nakamura, 1989) using ambient noise measurements, and a 1D numerical methodology from geotechnical data using software *ProShake* (ProShake, 2000). From the first technique, fundamental frequencies have been obtained, whereas the second methodology has been used to estimate soil transfer functions and intensity increments. *ProShake* requires an accelerogram in rock needs as an input. Due to the lack of moderate to large earthquakes (M>5.0) in this region, no strong-motion records are available for Málaga. Instead, a record from the European strong-motion database (Ambraseys *et al.*, 2000) corresponding to a m_b=5.4 earthquake in the Lazio-Abruzzo region (Italy) occurred on 7/5/1984 and scaled with the PGA for Málaga (0.11g, NCSE-02, 2002) has been used.

Intensity increments have been calculated in the numerical technique for each soil column derived from Arias intensity (Arias 1970). This parameter can be related to macroseismic intensity using empirical relationships. In this study, the relationship proposed by Cabañas *et al.* (1997) for the Mediterranean area has been used (Eqn. 2.1):

$$\ln(AI) = 1.5 I_L (MSK) - 6.42 \quad (2.1)$$

where AI is Arias intensity in cm/s and I_L is the local macroseismic intensity in MSK scale.

In June 2005, a microtremor measurements field survey was carried out in 74 sites along six profiles in Málaga city, 27 of them corresponding to sites in the city centre. A 5-second triaxial Lennartz seismometer and a Cityshark acquisition system were used. Ambient noise was acquired during 5 min using a sampling frequency of 100 Hz. The results obtained show fundamental frequencies ranging between above 5.0 Hz at the East, corresponding to rock sites, and 1.0 Hz at both banks of the *Guadalmedina* river (Western part of the city centre), corresponding to an area with sedimentary materials. An intermediate area is clearly distinguished between the Eastern bank of the river and the rock sites with frequencies around 2.0 Hz.

In the numerical methodology, the geotechnical data to obtain the soil transfer functions has been provided by LIDYCCE (*Laboratorio del Instituto de Investigación, Desarrollo y Control de Calidad en la Edificación, S.L.*), obtained from 400 drills carried out in the city. To characterize the soil columns in the city centre, 48 drillings corresponding to 34 soil columns have been analysed.

A microzonation of the city centre in six types of soils has been obtained from the analysis of all the parameters and methodologies (experimental and numerical) involved. The main features of each region are shown in table 2.1. These parameters belong to columns selected as representative of each subregion proposed. The fundamental frequencies belonging to the closest noise measurement to each of the columns can also be seen in table 2.1, showing the good consistency obtained with both experimental and numerical techniques.

Table 2.1. Fundamental frequencies, soil amplification factors and intensity increments for the 6 subregions proposed in Málaga's city centre microzonation

Region	**fo (Hz)**	**fo (Hz) (closest noise measurement)**	**Soil amplification factor**	**ΔI**
A	> 5.0	> 5.0	---	+0.0
B1	4.0	4.0	6.5	+1.0
B2	2.0	2.0	5.6	+1.5
B3	1.0	1.2	6.3	+1.0
B4	1.0	1.0	3.8	+0.5
C	0.9	0.9	3.8	+0.5

In this study, new subregions have been defined that were not identified in the Clavero and Ramos (2005) study. Although zones A and C have remained as a unique area, B zone has been divided into four regions clearly distinguished and called B1, B2, B3 and B4 (no sites corresponding to D zone were analysed in this study). This differentiation in region B is based on the wide range of the different results obtained: fundamental frequencies (0.8 Hz to 4.2 Hz), soil amplification factors (3.7 to 6.8) and intensity increments (+0.3 to +1.6). The proposed B1, B2 and B3 subregions are characterized by high soil amplifications. These subregions represent transition zones between region A (with rock on the surface), and region B4, classified as region B by Clavero and Ramos (2005), and representative of the Western part of the city. The lower depth of sedimentary layers in B1-B3 regions turns out into high shear velocity contrasts between the bedrock and the surface, and consequently, in high soil amplifications. These subregions remain the most vulnerable regions in Málaga region, especially region B2, with intensity increments of +1.5.

In Fig. 2.1, the soil transfer functions belonging to the representative columns in regions B1, B2, B3, B4 and C are shown. The fundamental frequencies belonging to the closest noise measurement to each of the columns are also drawn.

The comparison between the proposed microzonation and the monuments' observed damage due to the 1680 Málaga earthquake is shown in Fig. 2.2. It is observed that B2 is the region with the largest amount of monuments and where the highest percentage of buildings with damage grades 4 and 5 (EMS-98 scale) was located. Moreover, three out of the five monuments with damage grade 5 in the 1680 earthquake belong to region B2. Two main conclusions can be derived from this result: the fact that site effects were already noticed in the past, and the good consistency between the microzonation proposed and the observed damage.

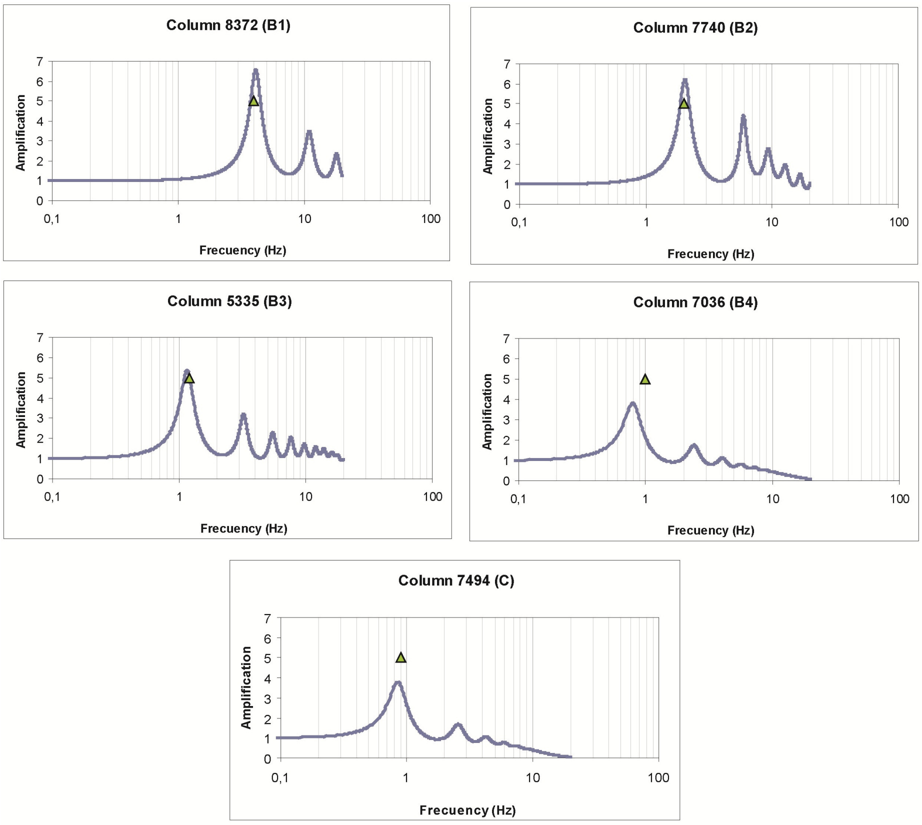

Figure 2.1. 1D site effects numerical method applied to Málaga's city centre: examples of soil transfer functions using numerical simulation (*ProShake*) corresponding to representative columns of regions B1, B2, B3, B4 and C. Triangles correspond to H/V ratios belonging to the closest noise measurement to each column. Amplification values for the H/V ratios are not representative and have been pictured at a standard value of 5 (references correspond to the study by Goded, 2010)

3. VULNERABILITY OF MÁLAGA'S MONUMENTS

The vulnerability index (*VI*) methodology is based on the fact that certain building classes with the same mechanical behaviours and loading patterns usually exhibit the same kind of damage pattern during an earthquake. In this way, buildings can be classified in different types and vulnerability functions can be developed for each of them based on observed damage patterns. The *VI* methodology as used in this paper was proposed by Lagomarsino *et al*. (2003) within the European Risk-UE project (Mouroux and Le Brun, 2006) for historical and monumental buildings. It consists on a macroseismic approach where the seismic hazard is defined by the macroseismic intensity. The technique is based on the use of vulnerability curves which correlate the post seismic damage grade or condition of the building to the intensity suffered, using a discrete probabilistic distribution. The vulnerability function to obtain the mean damage grade μ_d recommended by Lagomarsino (2006) for monumental buildings was proposed by Sandi and Floricel (1994) as a vulnerability curve representation, and was used by Lagomarsino and Giovinazzi (2006) for ordinary buildings (Eqn. 3.1):

$$\mu_d = 2.5\left[1 + \tanh\left(\frac{I + 6.25V_I - 13.1}{\phi}\right)\right] \tag{3.1}$$

where μ_d is the mean damage grade, I the macroseismic intensity, V_I the vulnerability index of the building and ϕ represents the slope of the vulnerability curve.

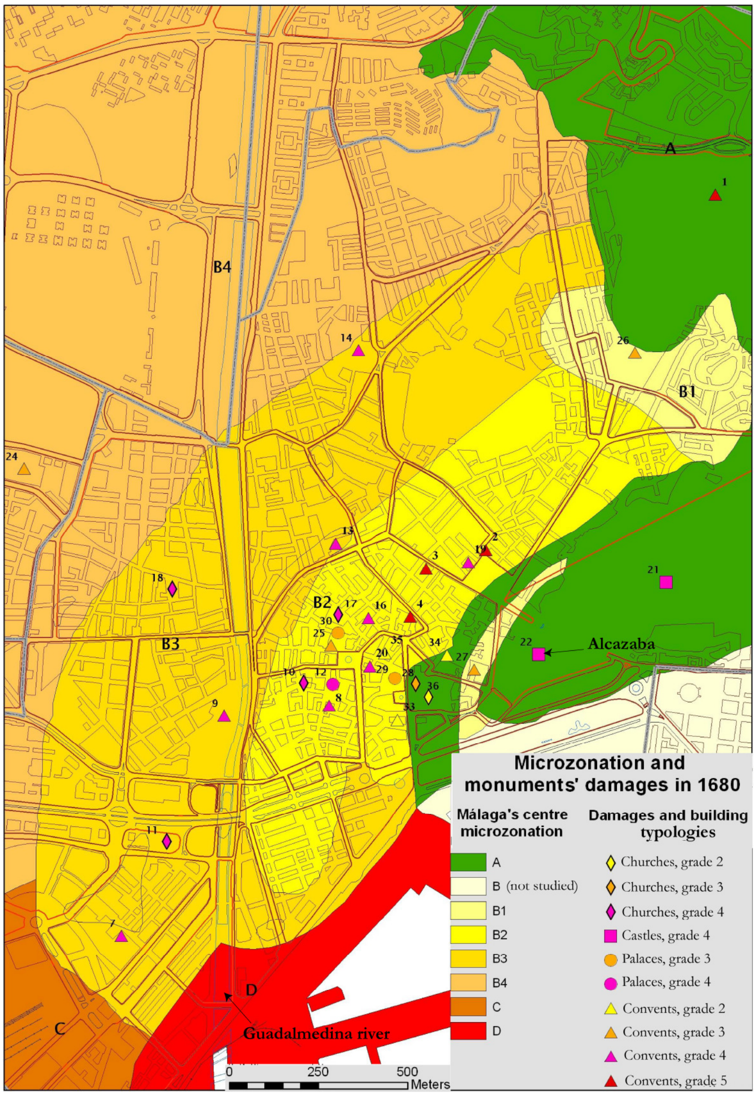

Figure 2.2. Monumental buildings' damage grades for the 1680 earthquake together with the seismic microzonation proposed for Málaga's historical centre. Monuments' colours correspond to damage grades (EMS-98 scale), and symbols to the different building typologies (building references from Goded *et al.*, 2008)

The seismic behaviour characterization for each building type, and thus the vulnerability index values, were obtained by Lagomarsino (2006) from a statistical analysis of the seismic damage to Italian monuments observed during the past 30 years, especially after the Friuli (1976) and Umbria-Marche (1996, 1997) earthquakes. The vulnerability index for each building is obtained by the sum of two components: a vulnerability index due to its type and some vulnerability index modifiers that depend on the state of the monument.

For the first part of the vulnerability study, the *VI* method has been used to analyse the 19 monuments damaged in Málaga city due to the 1680 event and still existing today. According to their type, the vulnerability analysis includes 12 churches, 3 convents, 2 castles and 2 palaces. In order to obtain the vulnerability index modifiers for each of the buildings, detailed information has been compiled from architectural guides and architectural studies of specific monuments (García González *et al.,* 1987; Ayala, 1999; Rodríguez Marín, 2000; Candau *et al.,* 2005). Expert judgement (architect Ricardo García, personal communication) has also been used in order to validate each of the parameters. Site effects are considered by adding the intensity amplification of each subzone (obtained from the site effects study in section 2) to the intensity assigned to the city due to the 1680 earthquake (VIII-IX, Goded *et al*., 2008).

Table 3.1 shows the main features of the 19 monuments studied, including the subzone to which they correspond and the intensity corresponding to its location. This intensity corresponds to the one assigned in 1680 event (Goded, 2006) together with the intensity increments derived from the site effects analysis (section 2). From the comparison between the expected damage grades obtained from the (*VI* methodology) and the observed damages, we observe a good consistency between both, especially for the church type. For the two castles analysed in this study there is a three damage grade difference between expected (1) and observed (4) damage grades (table 3.1). It seems these two castles do not fit the castle type within the *VI* methodology, being more vulnerable than the typical castle considered in the methodology. These Málaga castles are very antique buildings (from the XIth century) from the Muslim period, which are not represented in the Italian castles analysed during the *VI* method development, and could explain the misfit observed. In such sense, a type of Muslim castle could perhaps be added to the methodology when applied to monuments from Southern Spain, where there is a considerable amount of this type of buildings.

Table 3.1. Monuments damaged in the 1680 earthquake and still existing today. Main features and comparison between expected and observed damage grades. (References correspond to Fig. 2.2)

Ref.	**Monument**	**Present type[1]**	**Subzone[2]**	**Intensity[2]**	**Damage grade in 1680[3]**	**Most probable mean expected damage grade**
7	Church of the Carmelitas Descalzos Monastery	C	B3	8.5	4	4
9	Church of the Santo Domingo Monastery	C	B3	8.5	4	4
10	San Juan Church	C	B2	9.0	4	4
11	San Pedro en los Percheles Church	C	B3	8.5	4	4
12	Church of the ancient Clérigos Menores' School	C	B2	9.0	4	4
14	Church of the Capuchinos Monastery	C	B3	8.5	4	4
17	Santos Mártires Church	C	B2	9.0	4	4
18	San Pablo Church	C	B3	8.5	4	3
21	Gibralfaro Castle	CA	A	7.5	4	1
22	Alcazaba	CA	A	7.5	4	1
24	Ángeles Trinitarios Calzados Monastery	M	B4	8.0	3	2
25	Church of the ancient Compañía de Jesús Monastery	C	B2	9.0	3	5
26	Church of the Nuestra Señora de la Victoria Monastery	C	B1	8.5	3	3
27	Recoletas Bernardas del Císter Monastery	M	B1	8.5	3	3
28	Sagrario Church	C	A	7.5	3	3
29	Episcopal House	P	B2	9.0	3	2
30	Seminal School	P	B2	9.0	3	2
34	San Agustín Monastery	M	A	7.5	2	1
36	Cathedral	C	A	7.5	2	3

[1]Types: C: church; M: convent/monastery; P: palace; CA: castle
[2]According to the site effects study by Goded (2010); [3]According to Goded *et al.* (2008)

4. SEISMIC SCENARIOS

To obtain damage scenarios (third part of this study), 35 monuments have been added to the 19 previously studied. As selection criteria for both seismic scenarios, the chosen monuments are those from the city's heritage built before 1850, adding some important buildings built after that year such as the City Hall or the Central Bank, and include two historical-artistic monuments of national interest and one of provincial interest. The great majority of the historical buildings (43 out of 54) were built between the XVIth and the XIXth century. According to its types, most of the buildings (29 out of 54) correspond to palaces. Two monasteries and two churches have been added to the ones analysed in section 3. Three new types have been included: two theatres, one chapel and one tower.

For the deterministic scenario based on the 1680 earthquake, the starting point is the expected intensities' map obtained by Irizarry *et al*. (2007) using Sponheuer (1960) attenuation law from the intensity values assigned by Goded (2006) to several towns in Southern Spain. For Málaga's city centre, the expected intensity within this scenario would be of VIII (EMS-98). When the intensity amplifications due to site effects are considered (section 2), the final intensity map for this scenario shows EMS-98 intensity values of IX-X surrounded by an area of intensity IX near *Guadalmedina* river. The lowest value (intensity VIII) is located at the Eastern part of the city centre, where the *Alcazaba* castle stands (Fig. 2.2). According to the deterministic scenario, 22 monuments would suffer intensity IX-X, which include *San Juan* and *Santos Mártires* churches (Fig. 2.2, refs. 10 and 17, respectively), the Cervantes theatre (ref. 39), the Consulate House (ref. 43), the Municipal Archive (ref. 56) or the Central Bank (ref. 59). The 15 monuments with intensity IX include *San Pedro* church (ref. 11) and *San Telmo* Tower (ref. 65). Finally, 6 and 11 buildings could suffer intensities VIII-IX and VIII, respectively. The ones with the lower expected intensity (VIII) correspond, for example, to the Bank of Spain (ref. 51), the City Hall (ref. 52) and the Roman theatre (ref. 69), all of them located on rock sites (A region, Fig. 2.2, table 2.1).

The monuments' distribution according to its mean damage grade (Fig. 4.1a) shows that 68% of the monuments analysed would expect damage grades between 3 and 4 considering the mean vulnerability index, whereas 88% would suffer damage between 4 and 5 if the upper vulnerability index is considered. The mean damage probability distribution (Fig. 4.1b) show low probabilities of collapse for most of the monuments. Nevertheless, there is a 40-50% probability of suffering complete destruction in 13% of the monuments studied. For the upper damage probabilities, there is an 80-90% probability of collapse for 16% of the monuments.

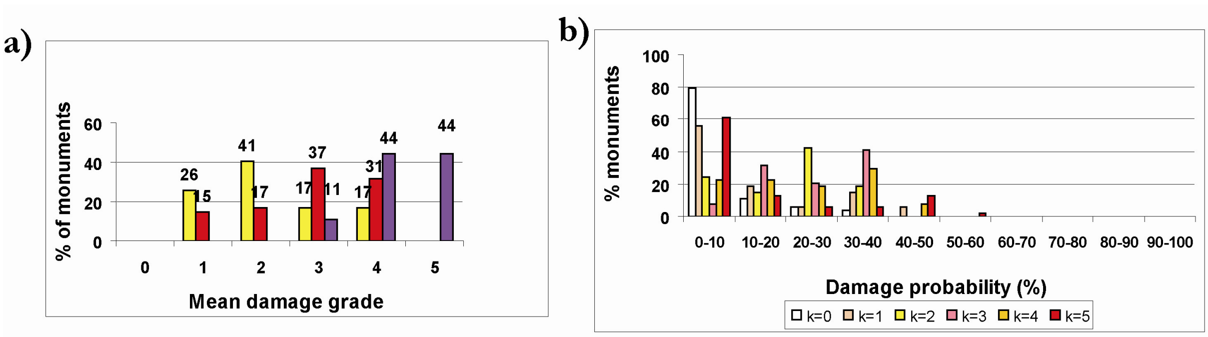

Figure 4.1. Deterministic scenario based on the 1680 earthquake. **a**: Lower (yellow), medium (red) and upper (purple) mean damage grades distribution; **b**: Mean damage probability distribution

The probabilistic scenario is based on the Spanish Seismic Code (NCSE-02, 2002) that establishes a seismic hazard in Málaga of 0.11g for a 500 years return period corresponding to an intensity of VII-VIII degrees (Dirección General de Protección Civil, 1997). Once intensity amplifications for each subzone are applied, the final intensities are half a grade lower for every region than for the deterministic scenario. The highest intensity for the probabilistic scenario is IX while it was IX-X for the deterministic scenario, so less damage can be expected. In this case, the *San Juan* church could experience an intensity of IX instead of IX-X, and the City Hall could suffer an intensity of VII-VIII instead of VIII.

The percentage of monuments with expected mean damage grades between 1 and 4 (Fig. 4.2a) is very similar, between 20% and 30%, and collapse is not expected for any of the monuments. When upper values are considered, 54% of the buildings are expected to suffer very heavy damage (k=4), and 26% could collapse (k=5). As expected, damage results are lower than for the deterministic scenario, with less monuments associated to a damage grade 5 (from 44% to 26%) and more associated to a damage grade 4 (from 44% to 54%). When probabilities are considered (Fig. 4.2b), the majority of the historical buildings would expect very low probabilities of suffering damage grades 4 or 5 (p_k<10%, where p_k is the expected damage probability for damage grade k). Nevertheless, around 15% of the monuments could suffer these damage grades with a 30-50% probability. For the upper damage probabilities, there is a 70-80% probability of collapse for 16% of the monuments.

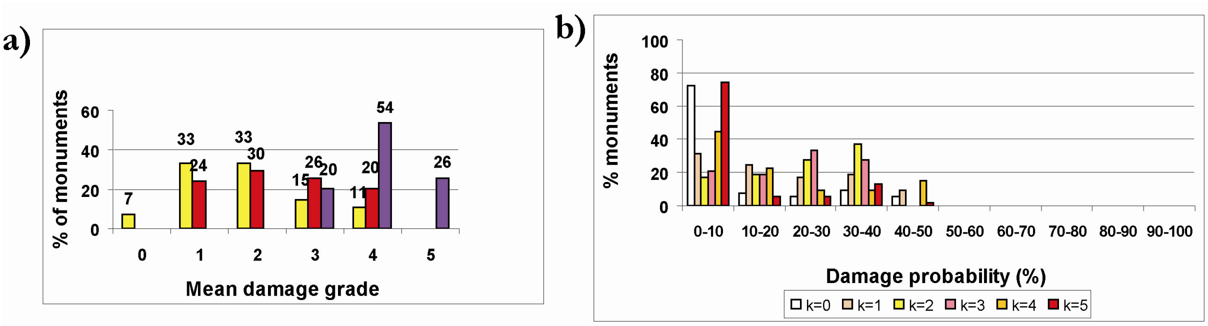

Figure 4.2. Probabilistic scenario based on the Spanish seismic code NCSE-02. **a**: Lower (yellow), medium (red) and upper (purple) mean damage grades distribution; **b**: Mean damage probability distribution

The 12 monuments with the highest mean damage probabilities have also been analysed for both seismic scenarios. Of these 12 buildings, 10 correspond to churches. The other two correspond to a chapel (ref. 54) and a tower (ref. 65). These results are not surprising, as these monuments belong to the most vulnerable types (with the highest vulnerability index values). A building corresponding to one of these types only needs to have high vulnerability modifiers (depending on its condition and geometry) and/or high intensity amplifications (depending on its location) to become one of the monuments at higher risk in the city.

5. CONCLUSIONS

Site effects in the 1680 shock have only been explained when a detailed city centre microzonation has been proposed and region B has been subdivided into regions B1, B2, B3 and B4. These subregions corresponding to the historical city centre have never been proposed before, being one of the improvements from previous studies in the city. They belong to transition zones between the rock at the East (where the *Alcazaba* stands) and the sedimentary soils near the *Guadalmedina* river, at the West, with high shear wave velocity contrasts between the bedrock and the surface. These regions, with high intensity increments (+1.0 to +1.5), correspond to the areas where the highest damage to monuments took place in the 1680 earthquake. All of these results confirm that, although broad microzonation studies are the first step for a seismic risk study in a certain area, detailed microzonations in small areas are essential to obtain realistic damage estimations.

Spanish monuments seem to fit reasonably well with Italian historical buildings, so it could be possible to apply the *VI* methodology in future studies to other cities in the South of Spain. The 1680 earthquake has been described as a *potentially destructive* event by Irizarry *et al*. (2007), who studied the vulnerability of ordinary buildings for the city of Málaga and developed loss estimations for the same deterministic and probabilistic scenarios proposed in this work. The present study corroborates the heavy damage an earthquake such as the one occurred in 1680 can cause to the city, with a mean expected loss of the 13% of the city's historical monuments with a 40-50% probability of collapse.

According to the vulnerability index results, the churches, chapel and tower studied have proved to be the most vulnerable buildings. It is highly recommended to take the necessary measures to avoid the possible future seismic damage for these monuments.

It must be taken into account that the monuments studied are not only buildings belonging to the city's cultural heritage, but also other essential buildings in the city such as the City Hall, the Central Bank or the University's main building. For these monumental buildings, good performance during an earthquake is vital for emergency planning. Considering the deterministic scenario, the most probable mean damage grades correspond to light damage for the University's main building, moderate damage to the City Hall and heavy damage to the Central Bank. These results highlight the importance of this kind of studies to avoid complications due to damage suffered by essential buildings during an earthquake.

It would be convenient to study in detail the damage suffered by Spanish monuments and historical buildings during past earthquakes. This would allow applying the vulnerability index methodology considering national monumental types. Finally, the generation of a catalogue with all the Spanish monuments with its location, type, past seismic damage, rebuilding processes involved, etc. is highly recommended. No catalogues of this kind exist for the present except for some countries, such as Italy or Portugal (Sousa, 2003; Lagomarsino and Podestà, 2004). Efforts should focus on the generation of such databases, which would be enormously helpful to correlate vulnerability, seismicity and soil types in order to evaluate the seismic risk of the national monuments. Its preparation is essential for the vulnerability analyses of this kind of buildings, a crucial task before taking actions for the preservation of our historical, artistic and cultural heritage against upcoming earthquakes.

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