Seismic risk assessment for the city of Girona, Spain

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SUMMARY:
As part of the SISPYR project (Seismic Information System for the PYRenees), a seismic risk assessment has been carried out for the city of Girona, located in the northeast of Spain. Seismic scenarios are based on a probabilistic hazard for a return period of 475 years considering two levels of soil effects characterisation: one based on the site coefficient, C, and another from a newly developed advanced level microzonation study. The seismic risk for dwelling buildings has been evaluated using the vulnerability index method. Representative structural typologies were identified and validated by local architects who helped to define their statistical distribution within the neighborhoods. Results obtained for the city show a low statistical seismic vulnerability. The majority of the building stock is expected to suffer light damages while some buildings are expected to suffer moderate to very heavy damages or even collapse. The estimated losses for these scenarios are significant.

Keywords: seismic, vulnerability, risk, Girona, site effects

1. INTRODUCTION

The city of Girona, capital of the Girona province in the northeast of Spain, is located in the confluence of four rivers. Fig. 2.1 shows the location of the municipality marked with a violet circle. The municipality has an area of 39 km^2 and a residential population of 95,674 inhabitants distributed over 9,482 dwelling buildings. According to the Spanish seismic code (NCSE-02), the seismic hazard for Girona with a return period of 500 years corresponds to a peak ground acceleration of 0.08g and an intensity of VII degrees. Recently the city has been part of the seismic risk assessment studies performed within the SISPYR (2009-2012) project (Seismic Information System for the PYRenees) (Goula et al., 2010).

This study is based on the seismic hazard assessment performed for the seismic emergency plan for Catalonia, SISMICAT (Susagna et al., 2006). Two different local hazard scenarios are considered including each one a different level of soil effects characterization. The first one, defined by Vendrell (2011), is based on the soil coefficient, C. The other one corresponds to a microzonation study developed using advanced level methodologies (Macau, 2008). With this advanced study, the soil response in Girona city has been characterized and a microzonation based on field surveys, for both H/V spectral ratios and array measurements, and numerical simulation has been performed (Macau et al., 2012).

The vulnerability of Girona's dwelling buildings has been evaluated using the vulnerability index method which defines the seismic hazard in terms of macroseismic intensity. This method, known within SISPYR as Level 1 method, is based on vulnerability indexes assigned to the typologies identified within the building stock that can be modified to include specific characteristics that influence their vulnerability. Detailed data was gathered about the characteristics of the buildings stock of Girona city. Field work around the city was carried out to identify the representative structural typologies. Local architects were consulted to validate the structural typologies identified and complete their statistical distribution depending on the year of construction, number of stories and corresponding neighborhood. All this information has been carefully organized and analyzed thanks to the GIS cartography provided by the Girona Council. The data provided was detailed enough to perform the study at the neighborhood level, so individual results are obtained for each one of the nine neighborhoods of the city.

Then, seismic risk scenarios are obtained for each of the two local hazard scenarios. The distribution of the expected damage across the city is analyzed and expected losses are calculated as uninhabitable buildings, homeless, wounded persons and mortal victims. The results from these seismic scenarios help to understand the importance of including advanced soil effects studies in this kind of assessments.

2. SEISMIC HAZARD SCENARIO

The seismic hazard considered for the risk assessment presented in this study comes from the seismic emergency plan for Catalonia, SISMICAT. This plan establishes two probabilistic seismic hazard assessments (Goula et al., 1997) with a return period of 475 years: one for rock sites (Fig. 2.1) and another one including an average soil effect for each municipality. These hazard scenarios assign to the city of Girona an intensity of VII degrees at rock sites and one of VII-VIII degrees including an average soil effect considering a 0.5 degrees intensity increment for the whole municipality.

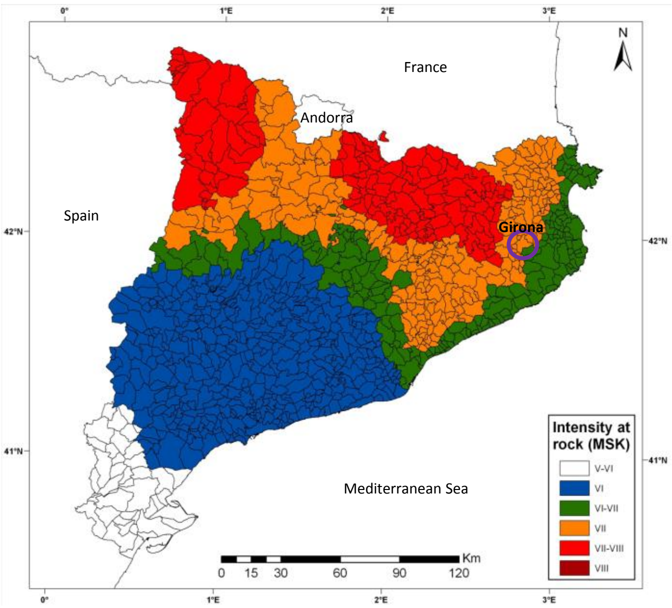

Figure 2.1. Hazard scenario at rock sites for the region of Catalonia provided in SISMICAT.

3. MICROZONATION BASED ON SOILCOEFFICIENT C

Vendrell (2011) evaluated the seismic risk for the city of Girona for the hazard scenario with soil effects by using the hazard scenario for rock and applying a more detailed evaluation of the soil effect for the municipality instead of the average used within SISMICAT. Vendrell (2011) deduced intensity increments (Fig. 3.1a) for the city of Girona from the seismic microzonation map developed by Soler et al. (2012a) in terms of the soil coefficient C, defined in the Spanish seismic normative (NCSE, 2002). The local hazard map in terms of intensity based on the SISMICAT for rock sites and including these site effects is shown in Fig. 3.1b.

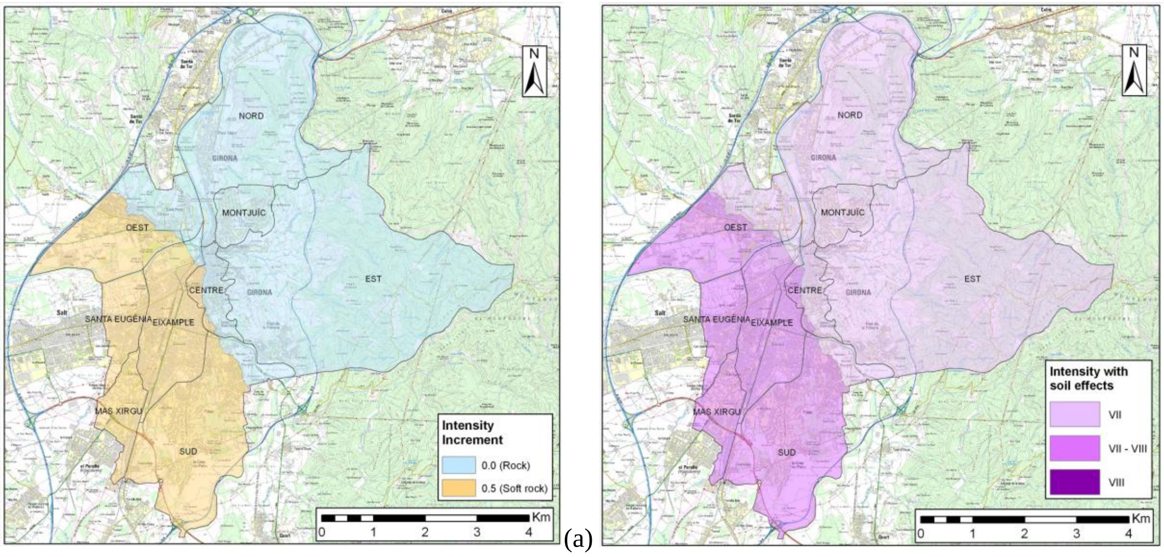

Figure 3.1. (a) Girona city microzonation map based on soil coefficient C; (b) Local hazard map for the city of Girona including the soil effects. (Vendrell, 2011).

4. ADVANCED LEVEL MICROZONACION

The city of Girona is located at the most northern part of the "La Selva" basin that was related to the opening of the SW Mediterranean Sea during the Neogene. In this area, the basin is infilled by Neogene and Quaternary unconsolidated detrital sediments with a maximum thickness of 400 meters (Benjumea et al., 2011). The deposits overlay a complex basement composed by Paleozoic metamorphic and igneous rocks; and Paleogene sedimentary rocks.

In March of 2011, seismic noise measurements were carried out in 90 different locations in the city. H/V ratios were calculated to obtain the soil's fundamental frequency in these locations. Soil fundamental frequencies ranges between 0,4 and 15,6 Hz. Lower frequencies are concentrated in the center of the basin and higher values are distributed around the rocky outcrops in the east and the north of the city.

In order to obtain shear-wave velocity profiles seismic noise array measurements were carried out in 10 sites. The surveys were conducted in sport fields and parks, were open areas suitable for seismic noise array deployment (100 m x 100 m) inside the municipality limit. Records of each seismic noise array were analyzed with the Frequency-Wave number (FK) and Spatial Autocorrelation (SPAC) methods and the inversion process (Wathelet, 2008). The processing of seismic noise data has been carried out using the GEOPSY package (http://www.geopsy.org). The most important results obtained with array technique are shown in Table 4.1.

Table 4.1. Shear-wave velocity ranges for different lithologies present in Girona.

Name of the array site	Vs (m/s)
Quaternary sediments	200-300
Upper Neogene sediments	400-500
Lower Neogene sediments	700-800
Bedrock	1500-2000

A characteristic soil column was defined for each array site from the results of seismic noise measurements and the geotechnical database of Girona (Soler et al., 2012b). This database contains information of about 1530 boreholes. 1-D equivalent linear method (ProShake, 2000) was used to obtain the transfer function and the ground motion for each soil column defined. As input motion on rock six acceleration records were selected from NERIES project accelerometric data (Network of

Research Infrastructures for European Seismology, 2006-2010) whose spectral content is similar to the response spectrum defined by Secanell et al. (2008).

Acceleration response spectra and Arias Intensity (AI) values of the different synthetic acceleration records obtained for the soil columns have been calculated. Arias Intensity and macroseismic intensity can be related from empirical observations, as for example the relation proposed by Cabañas et al. (1997) for the Mediterranean area. In this way, the intensity increment (ΔI) representative of each soil class can be obtained, using Eqn. 4.1, from the soil to rock ratio of the Arias Intensity (AI_{SOIL}/AI_{ROCK}).

$$\Delta I = 0.66\, \mathrm{Ln}\left(\frac{AI_{SOIL}}{AI_{ROCK}}\right) \tag{4.1}$$

The macroseismic intensity increment obtained for the city of Girona is shown in Fig 4.1a. The area located in the deep “La Selva” basin (in orange in the map) has a macroseismic intensity increase of +0.5. The zone with shallow sediments distributed around the rocky outcrops (red) show intensity increases of +1.0 and the rocky area (blue) presents no increase in terms of intensity. Applying these results to the hazard for rock sites from the SISMICAT the local hazard map shown in Fig. 4.1b is obtained for the municipality of Girona.

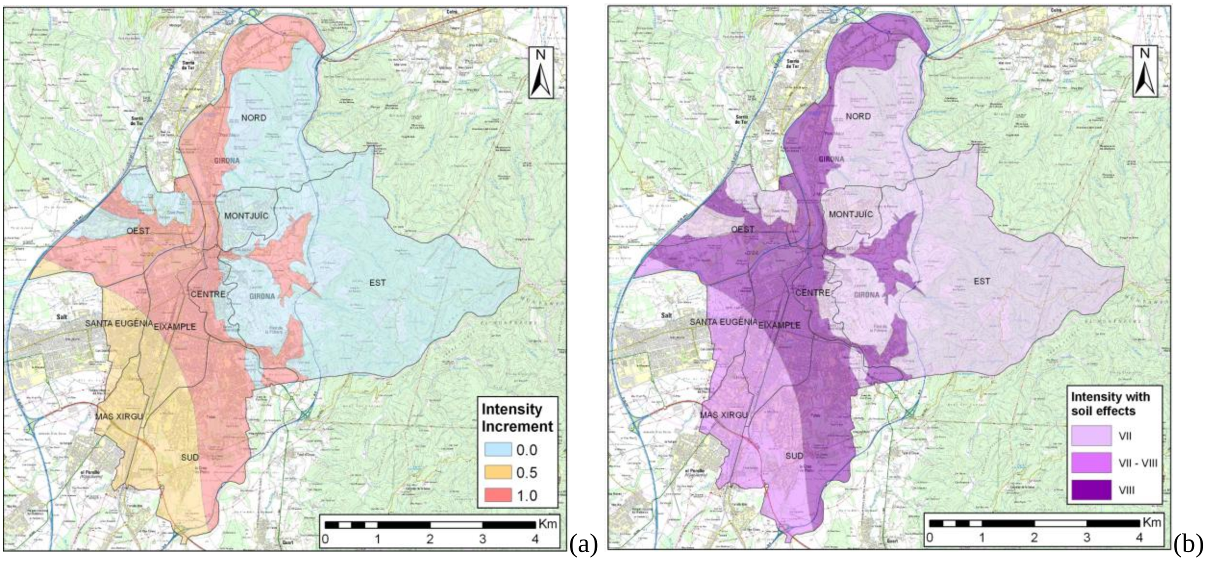

Figure 4.1. (a) Advanced level microzonation map Girona city a based on intensity increments. (Macau et al., 2012); (b) Local hazard map for the city of Girona including the soil effects obtained from the advanced method.

5. VULNERABILITY INDEX METHOD (LEVEL 1)

The Level 1 method is the vulnerability index method which is based on a statistical correlation between the macroseismic intensity and the apparent or observed damage from past earthquakes and the fact that certain structural classes tend to experience similar types of damages. This methodology has been developed over the last twenty years within the activities of the Italian National Group for Defence from Earthquakes also known as GNDT (Corsanego and Petrini, 1994). The methodology has been applied and revised through the years both to verify results and introduce improvements (Benedetti and Petrini, 1984; Bernardini, 1997; Dolce, 1997; Bernardini, 2000; Giovinazzi, 2005).

The vulnerability index method was applied within the European research project Risk-UE (Mouroux and Lebrun, 2006) in which Giovinazzi and Lagomarsino (2004) defined the range of vulnerability indices associated to 22 of the principal structural typologies present in Europe. This method allows the possibility to modify the vulnerability index as function of the characteristics of the buildings to which it is applied in order to identify specific typologies proper to a specific region. Milutinovic and Trendafiloski (2003) and Giovinazzi and Lagomarsino (2004) show the different vulnerability modifiers defined within the Risk-UE project. The applicability of the vulnerability modifiers depend on the level of detailed information available for the building stock.

The damage assessment of the vulnerability index method is calculated with a vulnerability function. Such vulnerability function relates the vulnerability index, V_I, and the intensity, I, with the mean damage grade, μ_d, which through binomial or equivalent beta functions, allows the development of a damage grade probability distribution. The vulnerability function (Eqn. 5.1) used is the one recommended by Giovinazzi and Lagomarsino (2004) for ordinary buildings.

$$\mu_d = 2.5\left[1 + \tanh\left(\frac{I + 6.25\,V_I - 13.1}{2.3}\right)\right] \quad (5.1)$$

6. VULNERABILITY OF GIRONA’S DWELLING BUILDINGS

The Level 1 vulnerability assessment requires the identification of the most representative structural typologies of the dwelling buildings. Table 6.1shows these typologies as identified by Vendrell (2011) through field work and meeting with architects experts on the construction of dwelling buildings in the city. Each typology has been associated with a corresponding typology defined in the Risk-UE project in order to assign each one a vulnerability index. The indexes for typologies M3.4T and RC2 include a regional modifier because of some differences from those in Risk-UE. M3.4T is considered to be less vulnerable than its corresponding Risk-UE typology due to the tightening of the vaults while RC2 for Girona is considered more vulnerable as shear walls are constricted to encase stairs and elevators and not used all over the structure as in the Risk-UE typology. Additional modifiers are considered for all typologies according to the number of floors, the presence of a soft story and the level of earthquake resistant design applied to the building.

Table 6.1. Representative typologies for the city of Girona and their corresponding mean vulnerability indexes.

RISK-EU Typology	Description	V_I
M1.1	Stone masonry bearing walls made of rubble stone or field stone. Wood beams except on the first floor were vaults are observed.	0.873
M1.2	Stone masonry bearing walls made of simple stone with wood beams except on the first floor were vaults are observed.	0.740
M1.3	Stone masonry bearing walls made of massive stone and wood beams.	0.616
M3.3	Unreinforced masonry bearing walls with composite steel and masonry slabs.	0.704
M3.4C	Unreinforced masonry bearing wall with masonry vaults with reinforced concrete beams or reinforced concrete slabs.	0.616
M3.4T	Unreinforced masonry bearing walls with masonry vaults tightened over the walls on all floors	0.585
RC3.2	Concrete frames with unreinforced masonry infill walls.	0.522
RC2	Reinforced concrete columns with solid or lightened slabs. In Girona, concrete shear walls are only used around stairs and elevators. (After 1994)	0.470
S2	Steel braced frames.	0.287
S3	Steel frame with unreinforced masonry infill walls.	0.484

Vendrell (2011) also developed a statistical distribution for these typologies as function of the year of construction, the number of floors of the buildings and their location within the neighborhoods of the municipality. The percentages of the representative typologies for each neighborhood depending on the year of construction and the number of floors was developed based on field work, the analysis of the building data provided by Girona’s Municipal Unit for Territorial Analysis (UMAT) and the expert judgment of local architects (Blazquez Guanter SLP, 2011). Fig. 6.1 shows the percentage of buildings belonging to each typology for each of the neighborhoods. As can be seen, neighborhoods Nord (B1), Oest, (B3), Est (B4), Centre (B5) and Mas Xirgú (B8) have the higher percentages of masonry structures, while Montjuïc (B2), Eixample (B6), Sant Eugènia (B7) and Sud (B9) are the ones of more recent construction and have higher percentages of reinforced concrete structures. Steel structures represent a 4% of the total building stock and correspond to high buildings mainly concentrated in the Eixample and Santa Eugènia neighborhoods.

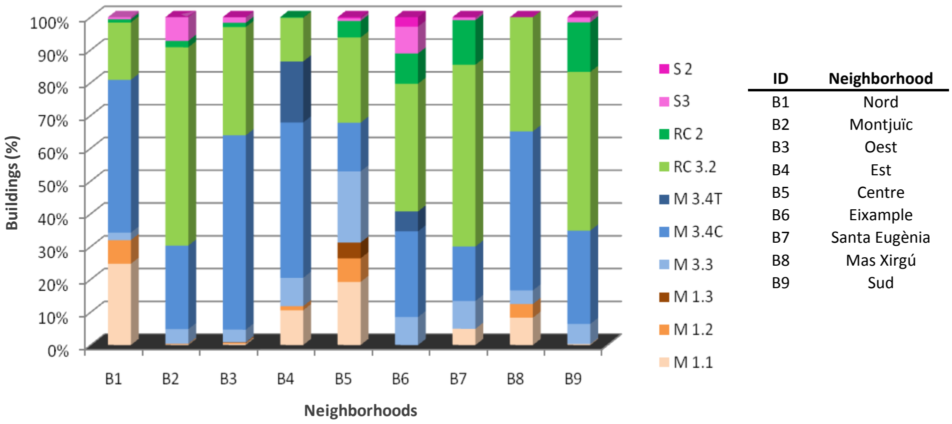

Figure 6.1. Distribution of the representative typologies for each neighborhood in Girona (Vendrell, 2011).

Based on the mean vulnerability index calculated for each neighborhood (Fig. 6.2a) the most vulnerable neighborhood is Centre with a mean vulnerability index of 0.67 and the less vulnerable of all is Montjuïc with a mean vulnerability index of 0.48. The majority of the buildings have a vulnerability index lower than 0.66 that correspond to vulnerability classes C and D from the EMS-98 scale (Grünthal, 1998). Such a vulnerability index distribution corresponds to a low seismic vulnerability strongly influenced by the fact that 49% of the buildings were constructed after 1980 (Vendrell, 2011).

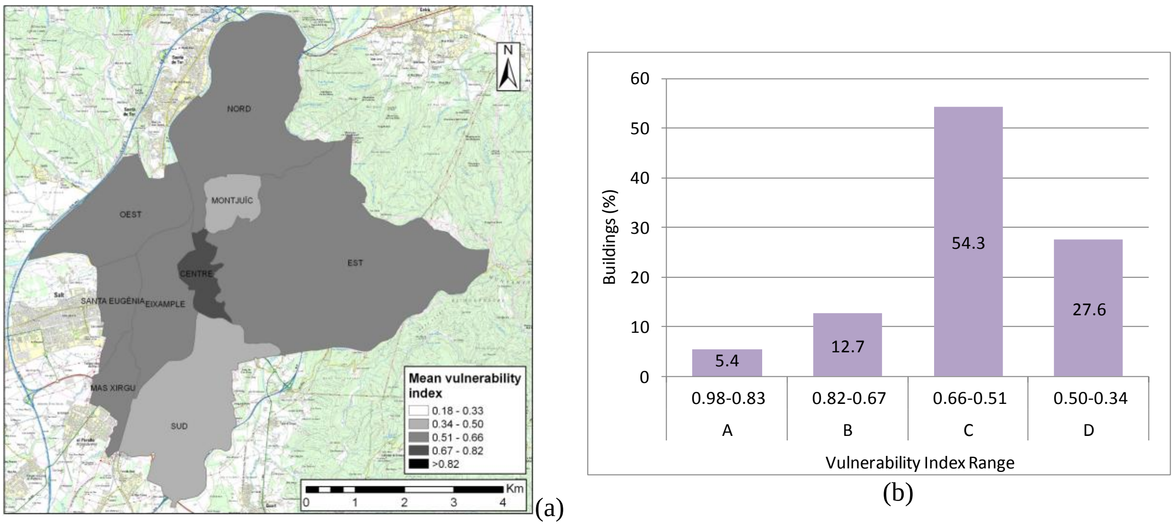

Figure 6.2. (a) Mean vulnerability index for each of the neighborhoods; (b) distribution of the vulnerability index for the whole municipality of Girona.

7. SEISMIC DAMAGE SCENARIOS

Two damage scenarios are calculated using the Level 1 vulnerability assessment. Both of them are based on the seismic hazard for rock sites from the SISMICAT but differ on the site effects considered in each one. The first Level 1 scenario includes the local hazard with the site effects obtained from microzonation in terms of coefficient C (Fig. 3.1b) and the second one considers local hazard with the site effects obtained from the advanced microzonation of the city (Fig. 4.1b). The intensities from the advanced local hazard are higher of the two local hazard scenarios. Its highest intensity (VIII degrees) affects mainly the center of the city where the concentration of older buildings and population is very important.

The mean damage grade obtained for each of the soils zones affecting the neighborhoods in each of the scenarios are shown in Fig. 7.1 for both scenarios. As can be seen the mean damage grades obtained for the scenario including advanced soil effects are higher for the center of the city.

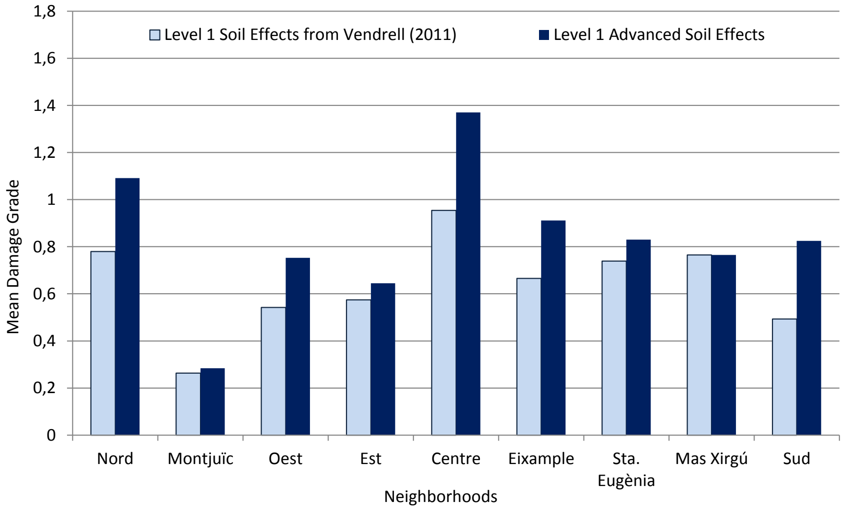

Figure 7.1. Comparison of the mean damage grade from the two Level 1 scenarios for each neighborhood.

The damage distribution for the Level 1 scenario including the soil effects based on the C soil coefficient (Fig. 7.2a) is centered on damage grade 0, so the majority of the buildings are expected to suffer no significant damages. Even the important number of buildings expected to have almost no damage, the scenario also reflects that the probability exists for some buildings to exhibit important damages. More than 1,000 buildings are associated to moderate damages (damage grade 2), more than 300 can suffer heavy to very heavy damages (damage grades 3 and 4) and even 3 buildings can be so heavily damage that can collapse due to the intensities of the scenario.

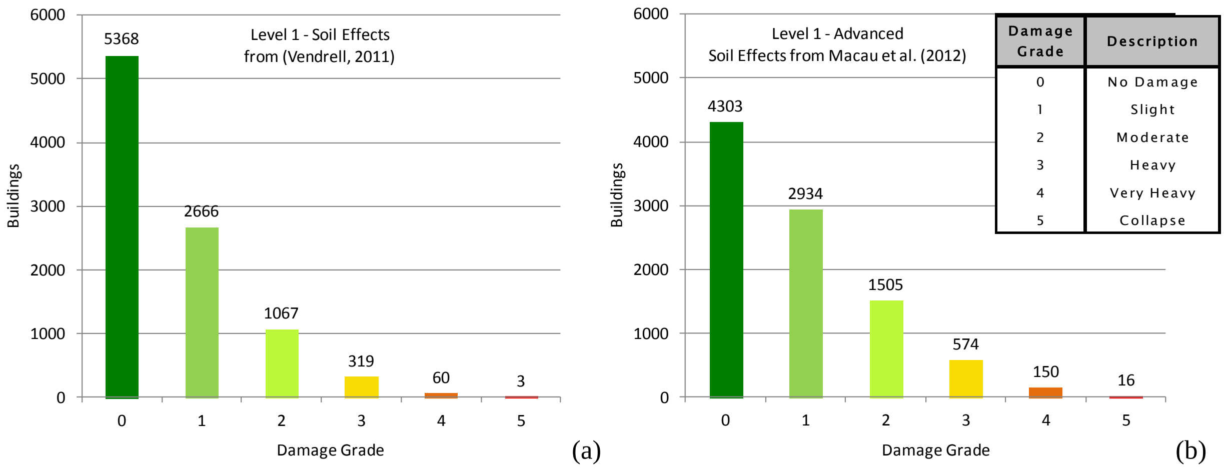

Figure 7.2. Level 1 damage grade distribution for Girona including soil effects: (a) based on C soil coefficient (Vendrell, 2011) and (b) from the advanced level microzonation.

Considering the advanced level microzonation, a more damaging scenario is obtained. Fig. 7.2b shows the damage distribution for the case scenario including the soil effects from the advanced level microzonation. This damage distribution is also centered on damage grade 0 but the number of buildings associated to this damage grade is lower while the number of buildings has increased for the other damage grades. For these soil effects 16 buildings can result so damaged as to collapse and more than 700 buildings can suffer heavy to very heavy damages (damage grades 3 and 4).

7. SEISMIC RISK ASSESSMENT

The losses associated to the scenarios considered are expressed in terms of uninhabitable buildings, number of homeless, injured and mortal victims. An estimation of those buildings that are expected to be in uninhabitable conditions was calculated from the damage distribution. Those buildings expected to undergo damage degrees 4 and 5 as well as the 50% of those associated to damage grade 3 are considered as uninhabitable. The number of expected homeless due to the scenarios is estimated based on the total number of uninhabitable buildings. The expected number of wounded persons and mortal victims are estimated as recommended by the ATC-13 (1985).

The losses results presented are those from the case scenario considering advanced microzonation as it is the scenario with higher damages. With this scenario, almost 600 buildings are expected to result uninhabitable though the entire city in comparison to the near 250 obtained considering the soil effect based on the C soil coefficient. Fig. 7.1 presents the expected number of homeless (Fig. 7.1a) and the number of wounded (Fig. 7.1b) for each of the neighborhoods of Girona. The higher numbers of both homeless and wounded are expected to concentrate on the Centre and Eixample neighborhoods. These two neighborhoods combine important factors that made them to be highly affected as important site amplification, more vulnerable buildings and a higher population than the other neighborhoods. For the whole municipality, almost 6000 homeless are expected along with more than 1000 wounded and the possibility of having more than 50 mortal victims.

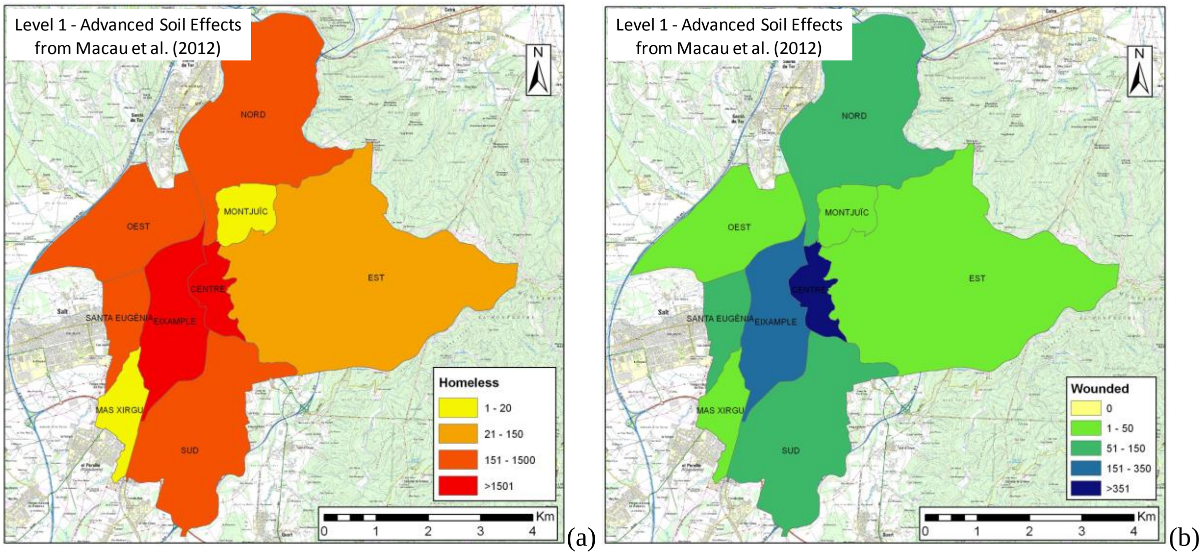

Figure 7.1. Distribution of expected number of homeless (a) and wounded (b) for the Level 1 risk scenario including soil effects from advanced level microzonation.

8. CONCLUSIONS

A seismic risk assessment has been carried out for the municipality of Girona as part of the SISPYR project. The seismic hazard is based on the intensity for rock sites recommended by the SISMICAT for the municipality. Two different local hazard scenarios has been considered: one including site effects (Vendrell, 2011) based on the C site coefficient (Soler et al., 2012a) and the other based on an advanced level microzonation performed for the city (Macau et al., 2012). The advanced level microzonation revealed the presence of 3 different zones: one rock zone, a zone with an intensity increment of 0.5 degrees and a third one with an intensity increment of 1.0 degrees. The site effects from Vendrell (2011), based on (Soler et al., 2012a) defined only two zones: one rock zone and another with an intensity increment of 0.5 degrees. In this case, the advanced level microzonation represents a great enhancement as it has revealed the presence of a third and important soft soil zone with an intensity increment of 1.0 degrees that affect a significant portion of the municipality.

The vulnerability of the building stock was evaluated using the vulnerability index method. A total of 10 structural typologies have been identified and characterized with a corresponding vulnerability index. Their statistical distribution, developed through field work and expert criteria for each one of the neighborhood of the city, allowed to estimate the vulnerability distribution of the city. Centre is the most vulnerable neighborhood. In general, the vulnerability of the city based on the vulnerability index method is estimated to be low mainly due to the abundance of recent buildings as 49% of the buildings had been built after 1980.

Seismic risk scenarios have been presented for the two local hazard scenarios considered. The worst expected damages are obtained from the local hazard based on the advanced level microzonation as it contains zones associated to an intensity increment of 1.0 degrees. For this scenario, the majority of the buildings are expected to have almost no damage but the probability of high damage grade is significant. According to these damage probabilities it can be expected that up to 16 buildings can collapse and more than 700 buildings can suffer heavy damages. Likewise, the expected losses associated to this scenario can cause almost 600 uninhabitable buildings, near 6000 homeless, more than 1000 wounded persons and about 50 mortal victims.

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