An approach for identification of areas with higher expected damage and definition of priority levels for prevention plans in Murcia Province (SE Spain)

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ABSTRACT The Murcia Region is one of the most active zones in Spain, where three earthquakes took place in 1999, 2002 and 2005. In spite of their low magnitudes (M_w 4.8), these earthquakes caused important damage, the last one reaching an EMS-98 intensity of VII. After that event, the RISMUR project started, aimed at providing a general picture of the seismic risk, which allows us to identify zones requiring a more detailed analysis of where prevention plans should be prioritized. A multidisciplinary study, starting with the seismic hazard assessment, which follows the Probabilistic Seismic Hazard Assessment methodology has been carried out at a regional scale. The expected ground motion (rock sites), for a return period of 475 years, has been characterized in terms of *PGA* and spectral ordinates and the corresponding maps have been drawn. In addition, a regional geotechnical study has been done and a classification of eight types of soils has been proposed, with the corresponding amplification factors. The combination of previous maps and factors, gives a new hazard map which already includes local effects. In parallel, a vulnerability assessment of the Murcian building stock is carried out, based fundamentally on the age of construction and following the EMS-98 criteria. Taking into account the expected ground motions and building vulnerabilities, the distribution of expected damage is estimated by the application of probability damage matrixes. A suite of maps representing seismic risk in terms of damage parameters for the entire region and from which we can identify the locations with higher expected damage have been obtained. We use the Coulomb stress transfer map of the region as additional criteria for defining priority areas where detailed studies should be performed. This gives information about the zones with stress load due to the previous seismicity and where new events could be triggered. The superposition of this map with the active faults of the region and the locations with higher expected damage allows us to establish a four-level priority ranking where future local-scale analyses should be made.

1. Introduction and objectives

The objective of the RISMUR project is to evaluate the potential damage for the expected ground motion with 475 years of return period. The results will allow us to establish a relative index of risk in the different locations and to identify those areas where the expected physical losses are higher, due to the motions with exceedance probability of 10 % in 50 years. With this aim, we try to discover the zones that require a more detailed analysis where, in a second phase, specific damage scenarios for particular earthquakes are defined with a deterministic approach or by deaggregation analysis. The study is made at a regional scale, covering all the province (11,317 km^2) and the vulnerability and damage are evaluated at each location entity following the EMS-98 scale (Grünthal, 1998) criteria.

The study is part of the emergency plan of the Civil Protection, which was activated after the occurrence of three earthquakes in the last 8 years: the 1999 Mula, 2002 SW Bullas, and 2005 La Paca earthquakes. Yet these events had moderate magnitudes (M_w~4.8), they produced significant alarm in the population and damage to structures, reaching maximum EMS-98 intensities of VII.

2. General planning of the study

The general study is planned from a multidisciplinary perspective, with a modular structure which integrates results of the following phases:

Seismic Hazard Assessment. A probabilistic seismic hazard analysis (PSHA) has been carried out in order to obtain the probabilistic ground motion for a 475-year return period. In a first step, hazard maps for *PGA* and spectral accelerations (*SAs*) for *T*= 0.1, 0.2, 0.5, 1, and 2 s have been drawn at rock sites. Secondly, a regional geotechnical classification has been proposed and amplification factors have been assigned to each class. These factors have been applied to the ground motion parameters previously estimated at rock sites and new hazard maps including local effects have been obtained, which give the input motion for inclusion in the risk analysis.

Vulnerability analysis. An approach has been proposed for vulnerability assessment based on the study of the temporal evolution for the different building typologies. From this analysis, the vulnerability class is assigned as function of the year of construction for each building, which is the only available and reliable data for the entire building stock.

Seismic risk assessment in terms of expected damage. A database and GIS with information of the strong motion parameters and the vulnerability distribution previously obtained for each location have been built. From that, the damage distribution for each class of vulnerability is estimated, through the application of damage probability matrixes (DPMs), considering the ground motion levels and vulnerability distributions previously determined.

Identification of zones with highest risk. Finally, the interpretation of the results allows us to identify those locations where the risk (in terms of expected damage) is higher. We introduce a complementary priority criterion for defining locations where addressing future, more detailed analyses. This is based in the Coulomb stress transfer map of the zone, which highlights the areas with positive stress load resulting from the past seismicity and where triggering mechanisms are more probable. Fig. 1 shows the general outline of the study. Each phase is described in the following sections.

3. Development of the risk analysis

3.1. Seismic hazard assessment

Due to possible earthquakes in the Murcia Province and surrounding areas, we consider the expected ground motion for a 475-year return period as seismic input for the risk estimation. The

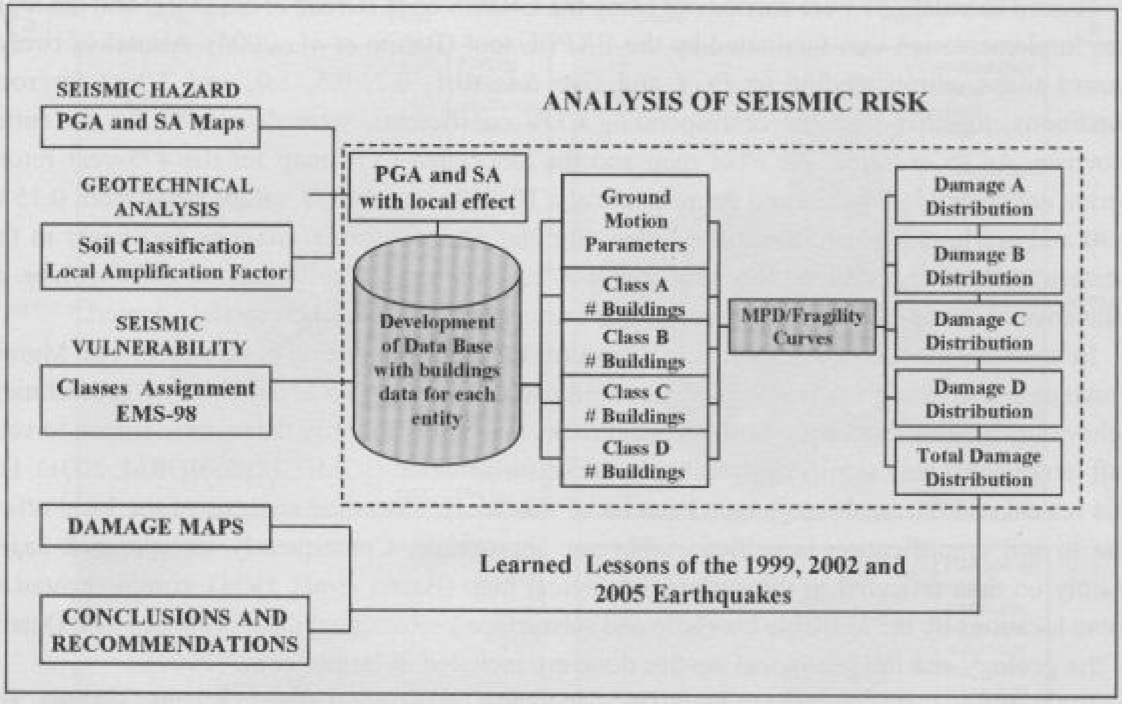

Fig. 1 - General planning of the study.

region under study has a very complex geology, integrated by soils with very different seismic behaviour. Hence, the soil effect has an important role in ground motion characterization.

In a first step a seismic hazard analysis at rock sites has been carried out. The analysis follows the PSHA methodology, including a logic tree with two nodes for capturing epistemic uncertainties related to seismic zoning and ground-motion models. Details of this study are described in Benito *et al.* (2006).

Three different seismic zonings have been considered in the first node of the logic tree: the one used to produce the official seismic hazard map adopted in the current Spanish Seismic Building Code (NCSE-02, 2002), the model developed by López Casado *et al.* (1995) and the one of García-Mayordomo (2005).

Only a few studies regarding attenuation that provide strong ground-motion relationships using local data are available (e.g., Martín Bourgón *et al.*, 1996; Cabañas *et al.*, 1999; Cantavella *et al.*, 2004). These data belong to earthquakes with magnitudes lower than 5.1 in all cases and hence they are not suitable for probabilistic hazard calculations. Thus, a selection of models derived from other regions has been necessary. Two main criteria are considered for that selection: models derived from data of regions with similar tectonic context and models statistically reliable for small-magnitude earthquakes (M_w<5.0) because these events are frequent and have an important contribution to the hazard in the area under study. Then, the strong motion models of Ambraseys *et al.* (1996), Sabetta and Pugliese (1996), and Berge-Thierry *et al.* (2003) have been chosen for our analysis.

Hazard calculations were carried out using the CRISIS code (Ordaz *et al.*, 2001) and the logic tree implementation was facilitated by the EXPEL tool (Benito *et al.*, 2004). A total of twelve hazard maps, corresponding to *PGA* and five *SAs* (0.1, 0.2, 0.5, 1.0, and 2.0 s) for rock conditions, together with the corresponding COV coefficients, were developed for the entire province. As an example, the *PGA* map and the associated COV map for the 475-year return period are shown in Figs. 2a and 2c, respectively. The associated COV values range from 0.15 to 0.30 and are higher north, towards Murcia city and east, towards Cartagena and lower in the western part of the region. We interpret this asymmetrical distribution of COV values as indicative of the epistemic uncertainty on the basic seismic zonification model adopted.

In a second step, a geotechnical classification for the study region is proposed. The Murcia Province presents a great lithological variability which leads to an assemblage of geotechnical behaviours ranging from very hard, compact rocks that hardly amplify the seismic signal, to very soft terrains that may significantly enhance the seismic motion (IGME, 1995; BORM, 2001). For this reason and due to the regional character of this study, a detailed analysis of the local effect due to soil amplification is neither viable nor appropriate. Consequently, an approach based mainly on data reflected in the surface geological map (Baena *et al.*, 1994), complemented in some locations by the available borehole and subsurface geotechnical data, is carried out. Details of the geology and the geological studies done are included in Benito *et al.* (2007).

Eight different soil classes are identified depending on their response to seismic shaking. For the most recent materials (Quaternary rocks), that present a very different consistency, it is necessary to make a more detailed division than that recommended in the Spanish Building Code NCSE-02, which only considers four soil classes. The internationally accepted criteria and classifications of Borcherdt (1994) are used for this purpose. Fig. 2b shows the geotechnical classification map for the Murcia Region, at a scale 1:200,000.

Subsequently, the possible amplification of seismic motion by each type of soil is studied following the methods originally proposed by Borcherdt (1994) and adopted in the 2003 NEHRP Provisions, used widely in these types of analyses. The factors included in Borcherdt (1994), NEHRP (2003), EUROCODE-98 (1998) and NCSE-02 (2002) are compared and an average of all of these is considered in this study for *PGA* and *SA* of T=0.1, 0.2, 0.5, and 1 s.

Finally, the combination of seismic hazard maps at rock sites (as that of Fig. 2a) with the geotechnical classification map (Fig. 2b) and amplification factors results in new maps of ground motion parameters, including soils effects (Fig. 2d). Fig. 2d shows the hazard map for *PGA* on soil conditions. As a summary of the results, maximum expected ground motions including the corresponding soil amplification for the 475-year return period are found along some river valleys (including Murcia city), with PGA_{475} > 0.25 g, SA_{475}(0.2s) > 0.75 g, and SA_{475}(1.0s) > 0.25 g.

3.2. Vulnerability of buildings

A database for the Murcia Region was initially generated, with the necessary data of buildings and location to assign the vulnerability and evaluate damage. The original data comes from the following sources: National Statistical Institute (INE), National Geographic Institute (IGN) and the Civil Protection of the Murcia Region and correspond to 1059 location entities.

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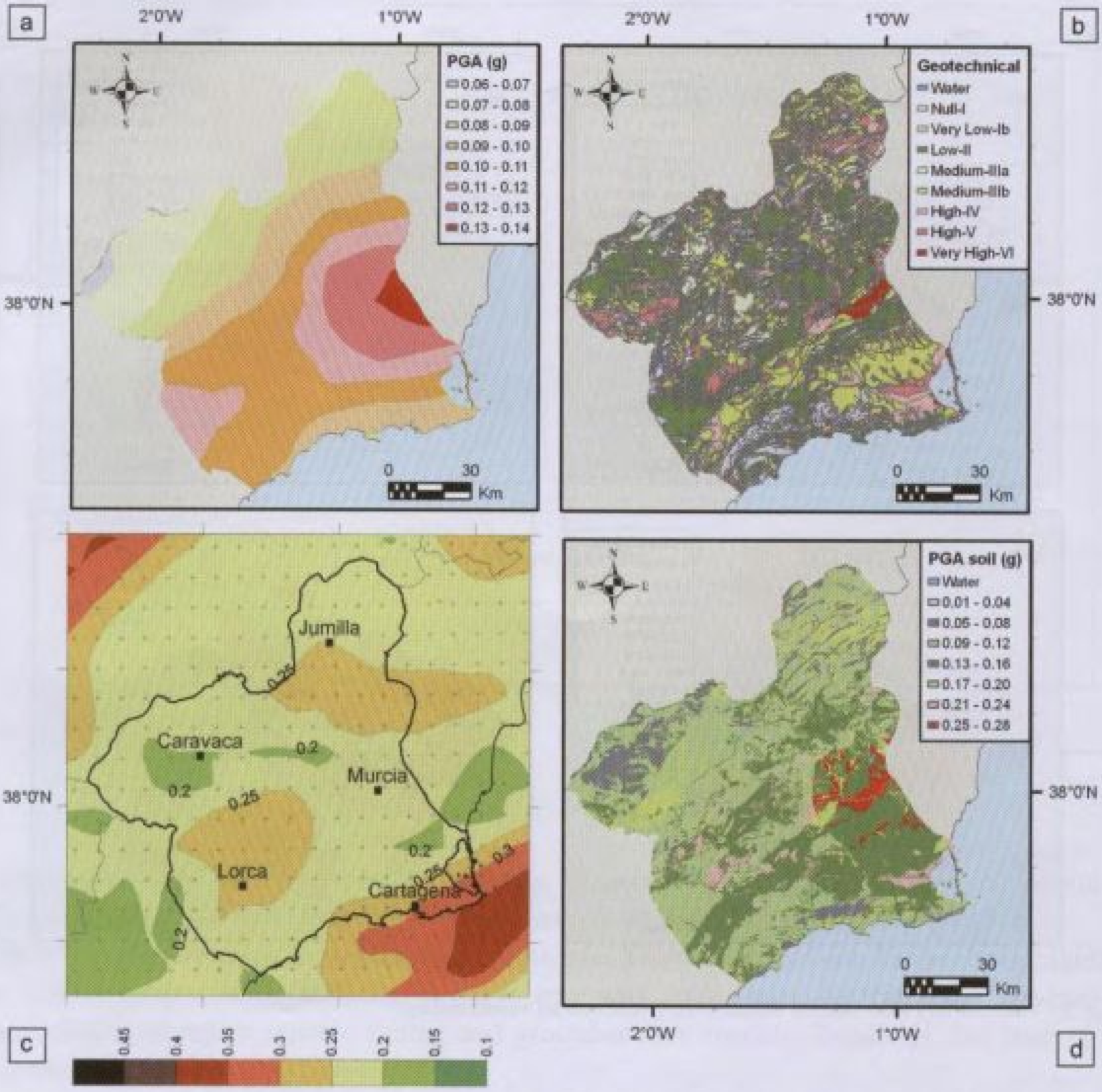

Fig. 2 - a) Expected *PGA* on rock condition for the 475-year return period. b) Qualitative soil response (site amplification) to seismic shaking. c) Coefficient of variation of expected *PGA* on rock condition for the 475-year return period. d) Expected *PGA* for the 475-year return period including local effect.

both rural and urban edification. A visual inspection of all the buildings of the region goes beyond the scope of this study since this phase is also implemented at a regional scale. Unfortunately, the information regarding construction types, vital for any vulnerability assessment, has not been collected by the original sources, so a methodology was developed to determine vulnerability types through the building's age, a detail which is collected for residential buildings, or 95.64% of the total building stock. At first it was necessary to classify the region's building types in terms of the EMS-98 vulnerability grades, that were determined through on-site building inspections and analyses throughout the province. Once this was achieved, a second

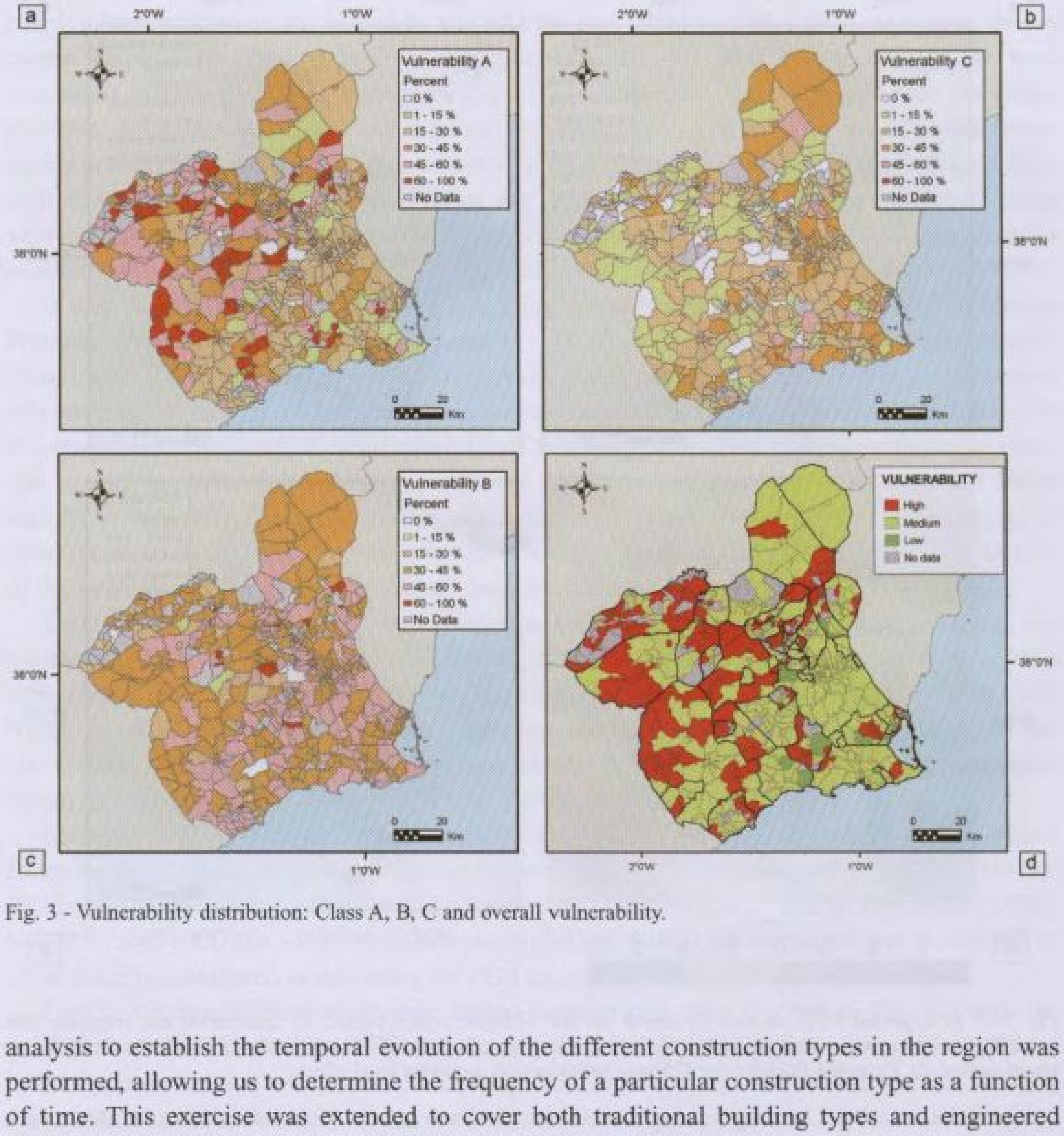

Fig. 3 - Vulnerability distribution: Class A, B, C and overall vulnerability.

analysis to establish the temporal evolution of the different construction types in the region was performed, allowing us to determine the frequency of a particular construction type as a function of time. This exercise was extended to cover both traditional building types and engineered structures performing after renewals of the national earthquake codes.

As a result, we estimate a probable or plausible vulnerability class, according to the date of the building. The successive renovations of the building codes give an indication of the starting date for the less vulnerable classes.

A slight difference is observed in the evolution of typologies for rural and urban environments. The introduction of less vulnerable classes in rural areas occurs later than in urban areas, and affects small towns and disseminated buildings. With this in mind, we propose two tables, labelled "rural" and "urban", with the probability for each class assigned as a function of the construction year (Tables 1a and 1b). These tables are applied to the data of each location, thus obtainig the number of buildings that probably belong to each vulnerability class. In

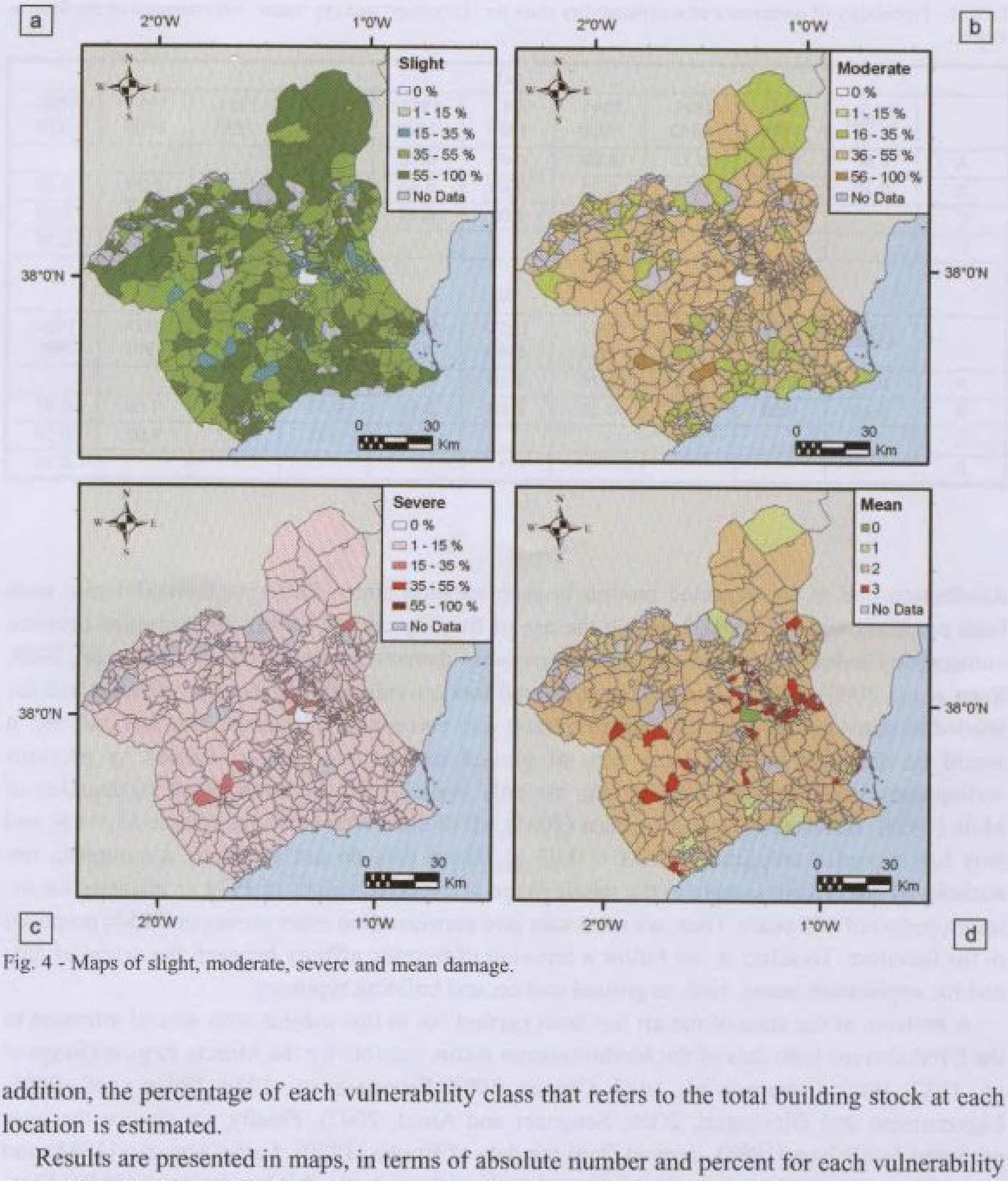

Fig. 4 - Maps of slight, moderate, severe and mean damage.

addition, the percentage of each vulnerability class that refers to the total building stock at each location is estimated.

Results are presented in maps, in terms of absolute number and percent for each vulnerability class. Figs. 3a, 3b and 3c show the percentage for classes A, B, and C, which are dominant in the region. Finally, a global classification has been made, differentiating locations with high, medium and low vulnerability, according to the following criterion: percentage of A $\geq 45\%$, percentage of A+ percentage of B $\geq 50\%$ and percentage of C $\geq 40\%$, respectively. Fig. 3d shows the global vulnerability distribution following this classification.

3.3. Risk assessment: estimation of expected damage

Once the vulnerability class is assigned to our building stock, we estimate the damage

Table 1 - Probability of occurrence of a vulnerability class for (a) "urban" and (b) "rural" environments of the Murcia Region.

(a)										
	<1900	1901-1920	1921-1940	1941-1950	1951-1960	1961-1970	1971-1980	1981-1990	1991-1995	1996-2001
A	0.80	0.72	0.72	0.69	0.46	0.18	0.05			
B	0.20	0.28	0.28	0.28	0.49	0.38	0.40	0.38	0.28	0.18
C				0.03	0.05	0.44	0.55	0.57	0.62	0.69
D								0.05	0.10	0.13

(b)										
	<1900	1901-1920	1921-1940	1941-1950	1951-1960	1961-1970	1971-1980	1981-1990	1991-1995	1996-2001
A	0.80	0.72	0.72	0.70	0.50	0.20	0.10			
B	0.20	0.28	0.28	0.30	0.50	0.65	0.55	0.53	0.38	0.31
C						0.15	0.35	0.47	0.62	0.59
D										0.10

distribution due to the expected motion in each location entity. Different methodologies have been proposed with this goal, based in the use of fragility curves, DPMs, relationships between vulnerability index and damage parameters, capacity-demand spectrum, etc. (Barbat *et al.*, 2006; Roca *et al.*, 2006). All of them represent ground motion-vulnerability-damage relations and are needed to translate the expected ground motion into percentage of damage. For this purpose, it would be desirable to have local data of ground motion and damage caused by previous earthquakes. However, such kind of data are only available for the three recent earthquakes of Mula (1999), Bullas (2002), and La Paca (2005), all of them with small magnitude $M_w \sim 4.8$, and very low recorded amplitudes ($PGA < 0.02$ g). These data do not configure a complete, nor statistically significant sample in the whole range of expected values of *PGA* or intensity for the return period of 475 years. Then, we must take into consideration other curves or DPMs proposed in the literature. To select it, we follow a criterion of tectonic affinity between the origin of data and the application zones, both in ground motion and building typology.

A revision of the state of the art has been carried out in this subject with special attention to the DPM derived with data of the Mediterranean Basin, suitable for the Murcia Region (Braga *et al.*, 1982, 1985; Coburn *et al.*, 1987; Chávez, 1998; Sabetta *et al.*, 1998; Dolce *et al.*, 2006; Lagomarsino and Giovinazzi, 2006; Sengezer and Ansal, 2007). Finally, we choose the ones proposed by Chávez (1998), derived from the data of Irpinia (1980), Lazio-Abruzzo (1984) and some Catalonian earthquakes which we used in the risk study for this last region (SISMICAT).

The quantification of damage is done following the EMS-98 scale criteria (Grünthal, 1998). The application of the selected DPM over the strong motion and vulnerability data of each location allows us to estimate the damage distribution, i. e. the number of buildings that will probably suffer each damage degree for each vulnerability class. In addition, we combine damage degrees into three levels: slight (D0 plus D1), moderate (D2 plus D3) and severe (D4 plus D5) and we also obtain the mean damage at each location.

The total damage distribution, independent of the vulnerability class, has been also evaluated.

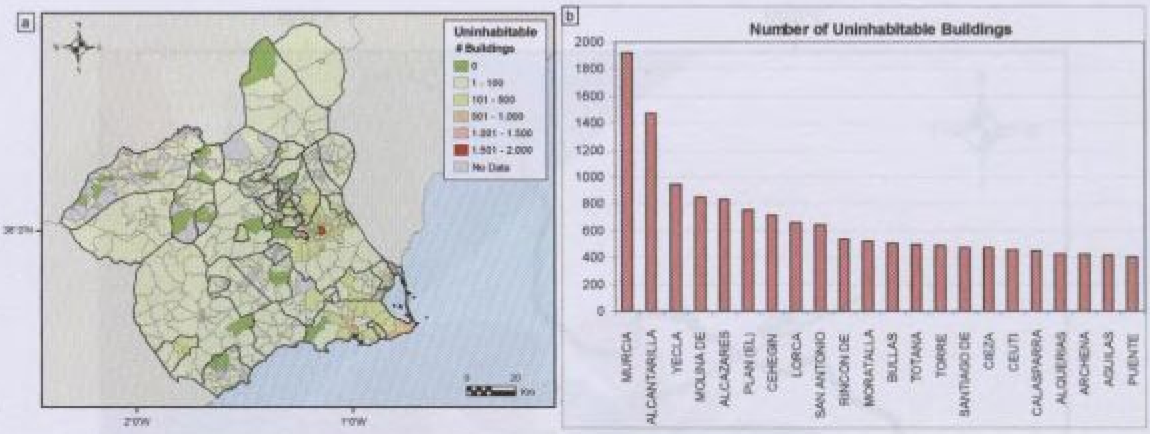

Fig. 5 - Map of number of expected uninhabitable dwellings (a) and histogram with locations having a larger amount of uninhabitable dwellings (b).

Fig. 4 shows the maps corresponding to slight, moderate, severe and mean damage. Finally, we estimated the number of uninhabitable buildings at each location (Fig. 5a), following the approximation proposed by Coburn and Spence (1992):

No. Uninhabitable bldgs = Number D5 + Number D4 + 50 % Number D3.

4. Discussion of results: identification of areas with higher expected damage and definition of priority criteria for detailed analysis

The maps related to total damage have been analyzed, in order to identify the towns with higher expected damage. We consider that the number of uninhabitable buildings and the number of buildings with severe damage are adequate indexes to establish net damage. Fig. 5b shows the histograms with the number of uninhabitable buildings for the twenty towns where this number is higher, and where damage can be expected higher.

Although it is not usual in risk studies, we have introduced a Coulomb Failure Stress map as a complementary criterion to define priority levels for the identification of zones where detailed analyses and mitigation plans are addressed.

4.1. Coulomb Failure Stress as complementary criteria

The dynamic and static changes in the state of stress produced by earthquakes may advance or retard the failure of faults in the region (Harris, 1998). The stress drop on a fault plane due to the occurrence of an earthquake produces an increase of effective shear stress around the rupture area (Chinnery, 1963). Variations in static stresses lower than 1 bar are able to induce the reactivation of nearby faults that are close to failure, either as aftershock activity or as larger earthquakes. This phenomenon has been described as a triggering process (King *et al.*, 1994). It has also been observed that the triggering process may also involve changes of seismicity rate in a certain zone, increasing or decreasing for several months after a main shock (Simpson and

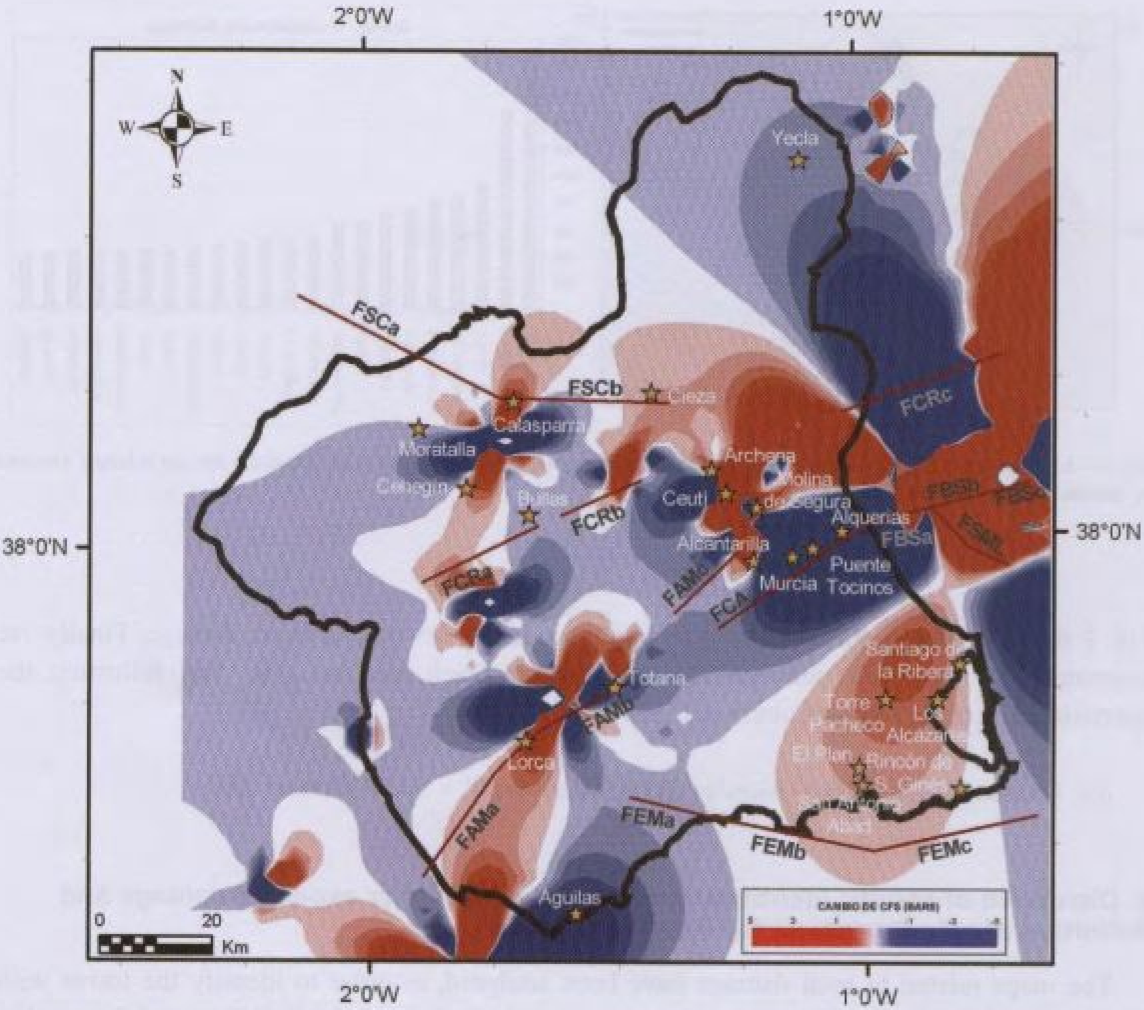

Fig. 6 - Coulomb stress transfer map of the Murcia Region. Red and blue areas refer to positive and negative stress changes, respectively. Stars indicate locations with a larger estimated amount of uninhabitable buildings and red lines stand for active faults.

Reasenberg, 1994).

In the present study, we made an estimation of the static stress change produced by the earthquakes with M_w> 4.0 and/or intensity (MSK > VII) that occurred in the Murcia Region and surrounding areas in the last 500 years. The rupture parameters and fault plane orientations were obtained from geological maps and damage descriptions in the case of historical events, and from focal mechanisms in the case of instrumental events. In both cases, the rupture area and the slip size are calculated with the empirical relations of Wells and Coppersmith (1994).

The static Coulomb stress change ΔCFS was calculated in an elastic half-space using the Okada (1992) equations with a shear modulus of $33.2\times10^{10} Nm^{-2}$, a Poisson ratio of 0.25 and an apparent friction coefficient of 0.4 that is an acceptable value according to Deng and Sykes (1997). Positive values of ΔCFS promote fault rupture, while negative values inhibit activity. For a detailed discussion of the method see Harris (1998).

4.2. Results and criteria for defining priority levels

In Fig. 6 we present the map of stress change (at 5 km depth) calculated on planes well oriented under the stress field active in the area (compressive, with SH_{max} orientation of N150°). The principal stress changes are related to historical events. In spite of the uncertainty of rupture parameters for these events, the model gives us a good idea about the magnitude and spatial distribution of stress transfer.

The knowledge of this distribution is especially interesting in areas with low strain rate where long term stress recovery after a big earthquake is slower than in very active areas, such as the Murcia Province. This means that bigger historical earthquakes that occurred during the last 500 years may influence the seismicity even now.

The map gives information about the areas with stress load where the probability of new events increases. Considering that this information may be useful to establish prioritized areas where detailed analyses must be performed, we have superposed this map on the map of the main active faults in the region and the location of the towns with higher expected damage. The following criteria have been established to define four priority levels over the towns previously identified:

Priority 1: towns located in a stress-loaded area and in the vicinity of active faults;
Priority 2: towns located in a stress-loaded area and far from active faults;
Priority 3: towns located in a stress-unloaded area and in the vicinity of active faults;
Priority 4: towns located in a stress-unloaded area and far from active faults.

5. Summary and conclusions

A seismic risk study covering the Murcia Province (SE Spain) in the frame of the RISMUR project is presented. The risk has been represented in terms of expected damage for the ground motion with a return period of 475 years, in order to identify the most damaging areas.

As a global result, we can establish the towns where the expected net damage is higher, expressed as a larger number of uninhabitable dwellings and a larger number of buildings with severe damage.

In an experimental way, a Coulomb Failure Stress change map has been introduced as a complementary criterion to define priority levels for the identification of zones where detailed analyses and emergency plans are performed. The map gives information about the areas with stress load where the probability of new events increases. The superposition of this map with the main active faults and the results of the seismic risk analysis allows us to establish four priority levels over the towns with higher damage: faults in the vicinity and located in stress-loaded lobes, no faults in the vicinity and located in stress-loaded lobes, faults nearby and located in stress-unloaded lobe and no faults in the vicinity and located in stress-unloaded lobes. Taking into account these results we will define, particular damage scenarios in a second phase.

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