SEISMIC RISK EVALUATION IN BARCELONA, SPAIN

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SUMMARY

Barcelona (Spain), is a city located in the northeastern part of the Iberian Peninsula. About 1,600,000 inhabitants leave in the second more important city of Spain, and during the last 10 years a great number of improvements have been performed in the city. On May 15, 1995 a small earthquake (M≈4.6) occurred in the Mediterranean offshore of Catalonian and shaked the city (MSK intensity IV) producing an unusual reaction of the population: the telephones of civil protection and mass media were collapsed. In order to design a seismic emergency plan scientific and civil institutions are working together to evaluate the seismic risk of the city. Seismic hazard, soil response and building vulnerability have been analyzed. Preliminary studies on lifelines and special buildings also have been performed. All the collected information is being implemented in a Geographic Information System (GIS) to obtain damage scenarios for the city.

We summarize the most important results achieved. Concerning the basic seismic hazard, the maximum intensity likely felt in Barcelona is about VII (MSK); the return period for this intensity is 1,000 years. The May 15, 1995 earthquake, recorded 70 km far from Barcelona has been used to obtain synthesized accelerograms for M=6.0 by using empirical Green's functions. Concerning the site effects, both empirical and analytical approaches have been applied to for microzonation purposes; the geological and geotechnical information has been compiled and the predominant periods of the soils have been obtained by using the Nakamura's method. He predominant periods range from 0.06 s, found in outcrop Paleozoic domains to a maximum value of 2.1 s found in Besos river deltoid areas. The available geotechnical columns have been used to obtain the soil response (amplification & periods). As a result of these studies specific design spectra have been proposed three main soil types which summarize the geological and geotechnical characteristics of the urban soils of Barcelona. Concerning the building vulnerability, the Italian method has been used. We obtained vulnerability index maps and damage scenarios for the urban area of Barcelona and for VI, VII and VII MSK intensities. Preliminary work performed about special buildings and lifelines are also presented.

INTRODUCTION

Robert Mallet was the first who performed a systematic and scientific treatment of the damage caused by the famous Neapolitan earthquake of 1857. Since then, many authors proposed intensity scales describing the damage grades produced by earthquakes in the buildings, soils and population. At the end of the last century and during the 20^{th} a great transformation of the society has became. Great amounts of people coming from poor areas in to more developed ones has produced an anomalous, fast and chaotic growth of the cities. The infrastructures needed by these great urban societies increase, day by day, the enormous value cumulated in these cities which normally are located in deep valleys near rivers. When an earthquake shakes a modern city it results a great damage and losses that increases with the complexity of the actual urban societies. We have many examples of the actual capacity of seismic events to cause natural disasters. One of the most recent is

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Armenia, 1999 in Colombia). The purpose of seismic risk studies is the knowledge of the value exposure in order to prevent and diminish the damage caused by probable earthquakes in one area. The main topics involved in seismic risk studies are as follows: hazard, vulnerability and value at cost. Seismic hazard estimates the probability of occurrence of a seismic event. Vulnerability evaluates the ability of goods to resist the dynamics actions caused by earthquakes. The value at cost is the economic estimation of the losses caused by a seismic crisis. It involves a great complexity with parameters related to buildings, infrastructures, civil protection services, security, health, education, work, organization of the society, economic system, lifelines, buildings with special functions, and also the interaction of all these and others, often virtual structures, between them.

On May 15, 1995 a small earthquake (magnitude 4.6) occurred in the Mediterranean coast of Catalonian, shaking Barcelona with a MSK intensity of IV. The inhabitants had an unusual reaction to a so small seismic event. Most of then noted the shake and the phones of civil protection and mass media collapsed. Civil authorities were then worried about what had happened if a stronger earthquake had occurred and decided to know more about the seismic risk of the city and to design a seismic emergency plan. Since then civil authorities and scientific institutions work together in the evaluation of the seismic risk of the city. In this work we present the most important results achieved on seismic hazard and soil response, building vulnerability, special building and lifelines. Ongoing studies in the improvement of the used methodologies and on the estimation of nonlinear effects of the soils and on the integration of all the information on a GIS system are also presented.

After a short description of the city the results on basic seismic hazard determination, soil microzonation and vulnerability of the main typologies of buildings will be presented. Finally, special building analysis, lifelines and ongoing work on other related topics will be also outlined.

BARCELONA THE CITY

The first human signals in Barcelona are aged 2,500 years, but the Romans arrived Barcelona 218 years before Jesus Christ. The historical evolution of Barcelona includes the following periods: pre-roman, Roman (218 BX, 250 AX), Christian (250-717), Arab (718-803), Carolinian (803-1000), Comptal (1000-1200), Barcelona head of Catalonia (1200-1516), Barcelona of the Austrians (1516-1714), and Barcelona of the Bourbons (1714-1868).

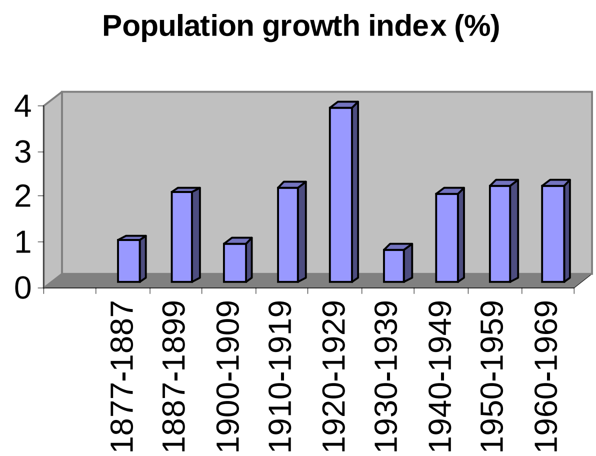


Figure 1. Growth of the population of Barcelona in the period between 1877 and 1970.

At the end of the Roman period the city had between 10,000 and 12,000 inhabitants and at the end of the 4th century, Barcelona was a fortified town with a very big wall 8 m high, 3.65 m width and more than 1,122 m long. The surface covered by the city was about 10,50 Ha. At the beginning of the 11th century Barcelona had about 20,000 inhabitants and occupied about 80 Ha. Four centuries later Barcelona had about 115,000 inhabitants and in 1850, 175,000 people were leaving there. But the way towards the great Barcelona began in 1868 by adding small towns, which are their actual districts. The census of 1,900 counted more than 500,000

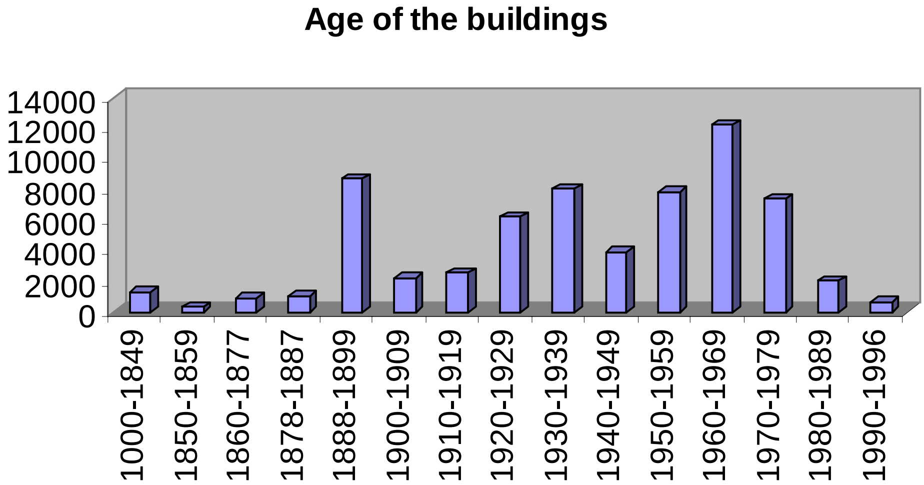


Figure 2. Number of buildings constructed during the actual millenium.

Between 1910 and 1930 the population grow from 587.411 to 1,005,565 people. The strong decay of the growth index in the 1930-1940 decade was due to the civil war of Spain. Today Barcelona is the second bigger city in Spain.

Barcelona is located in the northeastern part of the Iberian Peninsula near the Mediterranean Sea. Their geographical coordinates are 2º 4' 42," East longitude and 41º 17' 49" North latitude. Downtown altitude is 12.5 m (Pl. Santa Jaime). Barcelona has a population of 1.514.588 habitants and it is divided into 10 districts. The Table 2 presents the actual distribution of the population.

Table 1: People distribution between the 10 districts of the city. Surface and density of population are also indicated. The data are referred to January 1999 (Barcelona city guide, 1999).

DISTRICT NAME	POPULATION (Hab.)	SURFACE (Km^2)	DENSITY (Hab/Km^2)
Ciutat Vella	85.817	4,31	19.911
Eixample	249.002	7,47	33.334
Sants-Montjuic	167.877	20,87	8.044
Les Corts	82.896	5,98	13.862
Sarria-Sant Gervasi	131.237	20,01	6.559
Gracia	116.037	4,15	27.968
Horta-Guinardo	169.237	11,92	14.198
Nou Barris	169.814	8,00	21,227
Sant Andreu	136.331	6,53	20.878
Sant Marti	206.340	9,83	20.991
Total	**1.514.588**	**99,07**	**15.288**

SEISMIC HAZARD

Barcelona is located in Catalonia, a low to moderate region of NE Spain bordering on France and the Mediterranean Sea. The city is on the Mediterranean coast occupying the pediment of the Paleozoic Catalonian coastal ranges and is located between two rivers: the Llobregat river at the western and the Besos river at the eastern part. The Tibidabo-Collserola Mountains, about 500m high border its northern part and the Mediterranean Sea limits its southern part. Seismic hazard is composed of the combined effects of the base hazard and the local hazard. Local hazard is affected by topography and all geological and geotechnical features. In this section we summarize the main results about base hazard and local or site effects.

Base seismic hazard

The expected seismic MSK intensity in Barcelona for a 500 years return period is about VI-VII (Secanell 1999). The corresponding PGA level is about 0.03 and 0.07 g. This values are very similar but slowly greater than the proposed ones in the Spanish seismic code (NCSE-94, 1995). These two intensity grades were chosen by the city civil protection service to estimate damage scenarios.

Geology

Two main geomorphologic units compose the soils of the city: the mountain relieves and the plain. The mountains are Paleozoic and Tertiary materials that outcrop in the north (Tibidabo Paleozoic Mountain) and in the SE (Montjuich Tertiary Mountain). The Barcelona plain, where most of the city was built, is also setup by two main units separated by a 20-30 m high scarp: the pediment plain and deltaic deposits of the rivers. The pediment plain is composed of old consolidated quaternary soils called "*tricycle"* composed by red clays, eolian muds and rounded gravels. Some anthropic soils exist in several areas of the city, mainly in the southern beaches. The Figure 2 summarizes the main types of soils of Barcelona.

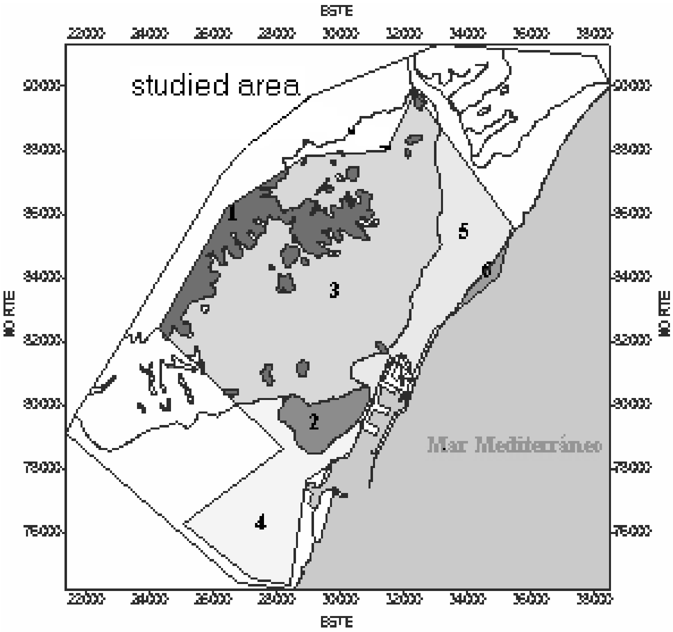


Figure 3. Main soils of Barcelona: 1. -Tibidabo-Collserola (Paleozoic slates and granites) 2. - Montjuïc (Tertiary marls, sands and conglomerates). 3. - Tricycle deposits (Pleistocene). 4. Llobregat delta (Holocene sands and silts). 5. Besós delta (Holocene sands and silts). 6. Anthropic soils. (Modified from Losan, 1978)

Empirical soil response analyses

Microtremor measurements were performed at 204 selected points sampling all the geological features of the urban area of Barcelona. Each data at every point had a 180 s time history with 100 samples/s. The Nakamura's method (horizontal to vertical spectral ratios) was applied to the collected data. 15 s time windows 25% overlapped were used. The predominant periods obtained in the Paleozoic outcrops were quite homogeneous with an average value of about 0.06 s. On the Tricycle soils we obtained a wide period range. This fact probably is caused by changes in the thickness of the sedimentary layers and by creeks coming to the Mediterranean Sea from the mountains. The thickness average is about 20 m and range from zero to a maximum value of 50 m. The periods obtained range between 0.10 and 0.30 s in high slope zones but periods up to 0.70 s were obtained in most of the plain. In the Besós area we obtained predominant periods greater than 0.5 s, with a maximum value of 2.1s. Close to the river periods between 0.50 and 0.83 s were found while periods between 1.0 and 2.1 s were obtained in the remaining areas where also some periods ranging between 0.67 and 0.91 s can be seen. The predominant periods found in the Tertiary outcrop range between 0.09 and 0.91 s; this wide interval can be due to the fact that in this zone there were many quarries, which were filled with materials of quite different qualities. Finally very stable values in the range 0.72-0.77 s were obtained in the 19 measurements realized in the Llobregat deltaic area. The Figure 4 summarizes these results.

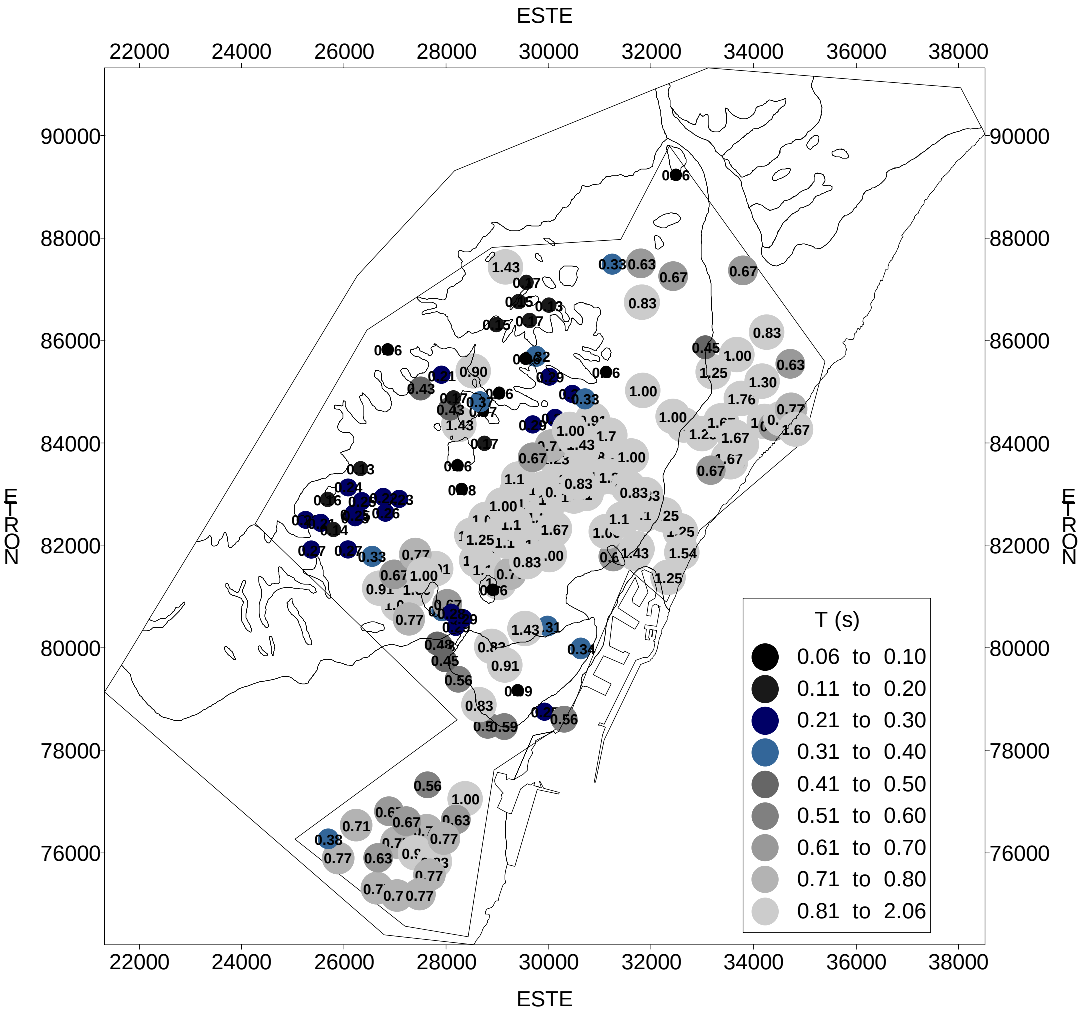


Figure 4. Natural periods of the soils of Barcelona obtained by using the Nakamura's method.

Seismic zonation

Cid (1998) collected information about 70 geotechnical columns corresponding to 70 mechanical holes, estimated the corresponding dynamic parameters and applied a linear equivalent method (Idriss and Sun, 1992) to estimate the dynamic response of the soils. Comparison of the predominant periods obtained by using the Nakamura's method and the numerical simulations leads reasonably good agreements. He was able to classify the soils of the city in four main zones proposing a design spectrum for each zone. The seismic zones are 0. Paleozoic outcrop, 1. Deltaic areas, 2. Tricycle zone with high sediments (near the deltaic areas) 3. Tricycle zone with low depth sediments (near the Paleozoic outcrop. Taking as reference site the transfer function obtained for the Paleozoic outcrop (zone 0) he obtained the following characteristics for the design spectra: zone I. Maximum amplification of about 2.5 times at a period of 0.4 s, zone II. Maximum amplification of about 2.5 times at a period of 0.2 s. Zone III. Maximum amplification of about 2.25 times at a period of 0.2 s. This amplification in zone III decays for lower frequencies.

SEISMIC VULNERABILITY AND EXPECTED DAMAGE

We used several approaches to evaluate the seismic vulnerability of buildings of Barcelona. The simplest one is to use the well-known MSK intensity scale classification of buildings. The distribution of typologies A, B and C has been estimated from the age of the buildings. The Figure 5 summarizes the 10 districts of the city with the distribution of types of buildings. Class A means rubble stone, field stone, adobe (earth break), class B means massive stone, non reinforced brick or concrete blocks, non reinforced brick with reinforced concrete floors and reinforced brick (confined masonry) some types of wooden buildings are also included in this class. Metallic structures and reinforced concrete buildings are included in Class C.

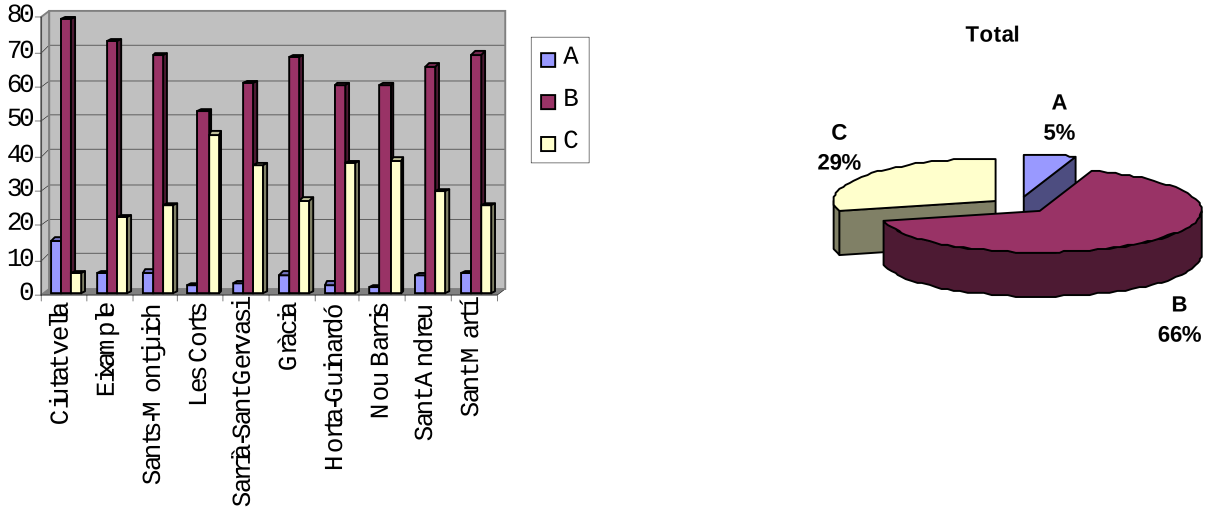


Figure 5. Vulnerability classes of the buildings for the 10 districts of Barcelona and for the complete city. (See explanations in the text).

The damage expected for a seismic event of intensity VII is computed from the damage grades described in the MSK scale. The Figure 5 presents the % of buildings with a damage grade of 4 or 5 plus the 50% of buildings with a damage grade of 3, which are described as destruction (4), collapse (5) or strongly damaged.

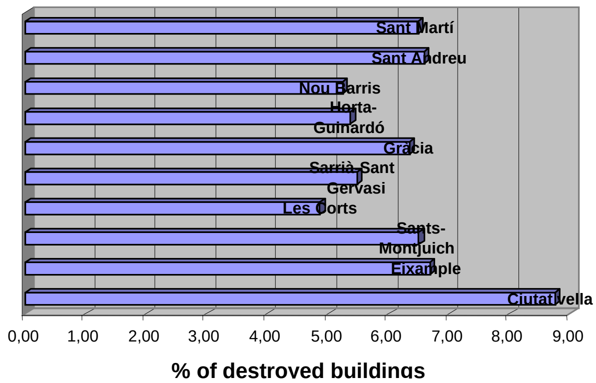


Figure 6. % Destroyed buildings for the 10 districts of Barcelona. Modified from Chávez (1998)

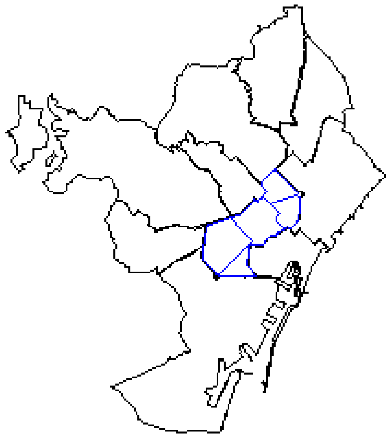
From these results it is easy to infer damage to the population. Chávez (1998) also studies the vulnerability and damage for several intensity grades by using the EMS-92 European Macroseismic scale obtaining similar results. Mañà (1997) proposed a specific vulnerability scale for the buildings of Barcelona and also a special damage grades for intensities between VI and VII MSK. Vulnerability classes B and C are subdivided in three special categories attending to the typical features of the buildings of the city.

Finally the vulnerability index and damage Italian method was calibrated for Spanish buildings by analyzing the damage produced by recent earthquakes in the southern part of Spain. Then the obtained vulnerability-damage curves have been applied to the urban area of Barcelona.

CONCLUSIONS AND ONGOING WORK

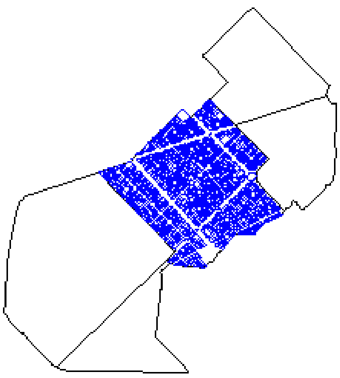
The main conclusions are as follows:

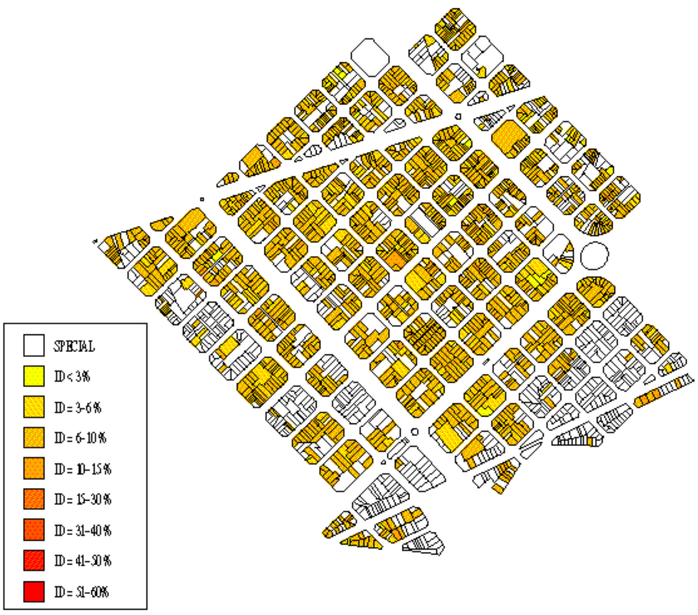
- The seismic risk of Barcelona is low; for an intensity VII earthquake, very low structural damage may be expected, nevertheless significant non-structural damage can occur. When analyzing the VIII seismic intensity case, considerable structural damage is expected.



a) Urban area of Barcelona
Blue line borders the Eixample district.

b) Vulnerability index map for the "dreta de l'Eixample" quarter in the Eixample district.





c) *"Eixample"* district

d) Damage map for the "Dreta de l'Eixample quarter in the Eixample district. Damage is % (reparation/reposition).

Figure 7: Example of vulnerability and damage maps for massonry buildings in a quarter of the city, Blancked areas correspond to special or not masonry buildings. Maps are for VII MSK intensity.

- The methodology applied may be used to analyze the seismic risk of other Spanish cities located in areas with higher seismicity
- The damage scenarios obtained in these works will be used to design a seismic emergency plan.
- The vulnerability index method permits to identify the damage in an individual building, when the data basis used is complete and accurate. The major problem to use this method is the quality of the available information.

Additional work is being realized on special buildings and lifelines. Preliminary results obtained by applying vulnerability index and damage curves to special buildings indicate that: most of the special buildings (64%) are reinforced concrete framed buildings; this typology shows a bad behavior for relatively high intensities. A VIII intensity event would strongly damage (between 40 and 80%) about 24% of them From the application of ATC vulnerability damage curves to the life lines we have been able to detect zones where moderate damage would be caused by VII intensity earthquakes.

ACKNOWLEDGEMENTS

This study has been supported, in part by the CICYT (project Number AMB98-0558) and the DGICYT project N. PB96-0139-C04-03. The Civil Engineering School of the Technical University of Catalina (ETSECCPB) and the Civil Protection Service of the City gave additional support.

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