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KnowRISK

Know your city, Reduce seISmic risK through non-structural elements

Prevention and preparedness projects in civil protection and marine pollution. Prevention Priorities

Deliverable Report

Deliverable B3 – Mapping the risk (RiskMAP)

Task B – RiskMAP

Deliverable/Task Leader: IST, EERC, INGV

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Project co-funded by the European Commission – Civil Protection Financial Instrument		
Dissemination Level		
PU	Public	x
PP	Restricted to other programme participants (including the Commission Services)	
RE	Restricted to a group specified by the consortium (including the Commission Services)	
CO	Confidential, only for members of the consortium (including the Commission Services)	

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LIST OF SYMBOLS AND ABBREVIATIONS

DS	Damage state
GMPE	Ground motion prediction equation
GMT	Greenwich mean time
ICI	Iceland Catastrophe Insurance
IM	Intensity measure
LN	Lognormal distribution
Mw	Moment magnitude
PGA	Peak ground acceleration
SISZ	South Iceland Seismic Zone

1. DESCRIPTION OF THE DELIVERABLE

1.1 INTRODUCTION

This report is the deliverable for the B3 task within the EU Project KnowRisk, Know your city reduce seismic risk through non-structural elements. Action B3 focuses on producing risk maps, integrated into Geographic Information Systems (GIS) to be used as supporting tools in risk communication activities.

Damage of non-structural elements of buildings (i.e. partitions, ceilings, cladding, electrical and mechanical systems and furniture) is known to cause injuries, losses, business interruption, and limit the functionality of critical facilities, such as hospitals and schools, causing a significant impact on earthquake resilience. For almost all building occupancy types, at least 70% of the total cost is invested in non-structural elements. Most of the non-structural elements are vulnerable to a relatively low level of ground shaking. The seismic risk for a particular non-structural element is governed by a variety of factors, including the regional seismicity, proximity to an active fault, local soil condition, dynamic characteristics of the building structure and non-structural elements, their bracing and anchorage to the structure and the location of the non-structural element within the structure (FEMA 74, 2005).

Risks maps are often designed and visualised in a way which cannot be easily understood by laypersons and/or not suitable for the respective needs of public authorities in risk zones and operational management. Provide simple and easily understood guidelines for local government entities, fire departments and general public to conduct risk assessment of their community, is one of the main objectives of RiskMAP's.

Risk maps that depict the extent of non-structural damage grades 2 and 3 expected after an earthquake event, can provide basic information to be used effectively for community risk assessment and planning.

Risk maps can be an useful tool in identifying and addressing risk as part of emergency preparedness and disaster risk reduction.

1.2 METHODOLOGY FOR IMPROVING RISK MAPS

1.2.1. Introduction

In methodological terms, this action will be pursued on the basis of a selection of pilot-areas in the case study areas of the three participating countries.

The pilot-areas have been analysed in detail (macro and micro scale), namely the earthquake ground motion and building data (Census or other). Furthermore, for each country detailed seismic scenarios have been presented in Action B1. In pilot areas where there might be a deficiency of hazard or vulnerability data, discussion on the best representation to illustrate non-structural damage will be pursued.

1.2.2. Which contents should be included in Risk MAP's for which user-group?

For a target-oriented communication, the contents of earthquake risk maps need to be adjusted to the end-user needs, since different end-user groups have different requirements on the contents of earthquake risk maps (Figure 1).

Strategic planners require maps that show where areas of high risk are, i.e. where there is a need for risk mitigation efforts.

Emergency managers need easy accessible maps in case of emergency to have quick access to information on affected areas, people to be evacuated, critical infrastructure to be protected, evacuation routes etc.

The *General public* requires easily understandable and accessible maps, but with a lower complexity of information, including only the most crucial information: buildings and roads in the area and which of them will be affected in case of a specific event. In case of emergency evacuation routes, shelter and assembly points should be included.

	Strategic planners	Emergency planners	General public
Information density/complexity	High	High, but quick access to information	Low, Quickly and easily understandable
Hazard	maximum acceleration reference, Probabilities,..	maximum acceleration reference, Probabilities,..	High - Low
Consequences/Risk	• Event specific damage, also annual average damages (for economic appraisals) • Economic, social, cultural and environmental risks • Critical infrastructure	• Number of people at risk (to be evacuated) • Critical infrastructure (to be protected or evacuated): hospitals, schools, energy & water supply, traffic infrastructure	• Buildings (affected) • Roads (affected)
Additional information	Optional	Symbols Text	Symbols (self-explanatory) Text Information on evacuation routes and assembly points should be included in the maps in order to show people quickly how to behave in case of emergency

Figure 1. Recommendation for RiskMAP's contents.

As shown in Figure 1, a map should rather be easy accessible, not overloaded with information and high in contrast with regard to the choice of colours.

According to Gaspar-Escribano (2011), the use of colour instead of size is preferable for the understanding of the seismological message. The colour scheme selection must follow the natural human perception, where variations in colour grey-value or lightness, light and dark shades of just one selected hue (e.g., shades of blue) are perceived as hierarchically ordered. The legend should be sufficiently large, with a limited number of information (not more than five discrete classes).

As an example, Figure 2 shows a seismic hazard map expressed in terms of maximum acceleration reference value at the surface. As these are the parameters used to regulate earthquake-resistant design of structures, it is important to make these parameters available to professional users. However, these hazard parameters have no meaningful content for a lay (public are not familiar with the concept of return periods or exceedance probabilities), it may be convenient to reorganize hazard results in a simple scale (such as high/medium/low hazard).

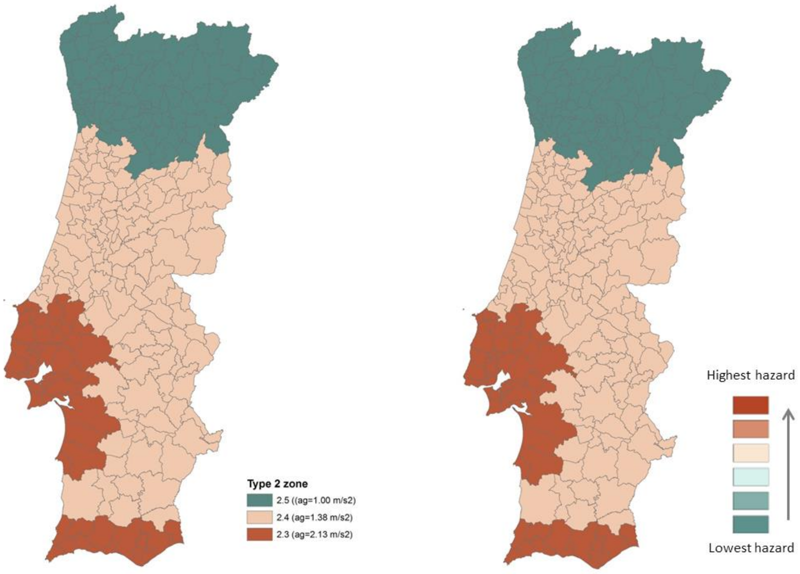

Figure 2 - Portuguese seismic hazard map. Left: professionals users; right: unprofessional users.

2. RISKMAP FOR LISBON PILOT AREA

After collecting the data for the analyses, the Alvalade parish was chosen as a target area, in which it was possible to retrieve high quality data.

It seems to be important to mention that there is not an ideal map, even for the different user groups.

The following minimum requirements should be met when risk maps have to be compiled:

- identify where people live with respect to the recognised hazard/risk;

- identify important public buildings like schools and municipal buildings;

- it is useful to have a small scale map that shows street names, building footprints in order to avoid questions like "where on this map is my home?"

- text within the maps can enhance the transmission of important information (ex: street names)

It is important to include the community, the schools in the pilot areas during the process, with workshops, surveys, to test and improve maps. In fact this is one of the aims of Task E2 (participatory risk communication).

Concerning graphic representation and arrangement for risk maps, an idealised map for Lisbon pilot area could look like Figure 3 and **Error! Reference source not found.**. In these maps we have included not only the building damage but also additional information/recommendations ("What should I do?"). It is important to test them, assess the preferences of map-readers, and make adjustments in order to raising people's awareness and motivation for taking actions to mitigate the impacts of hazards.

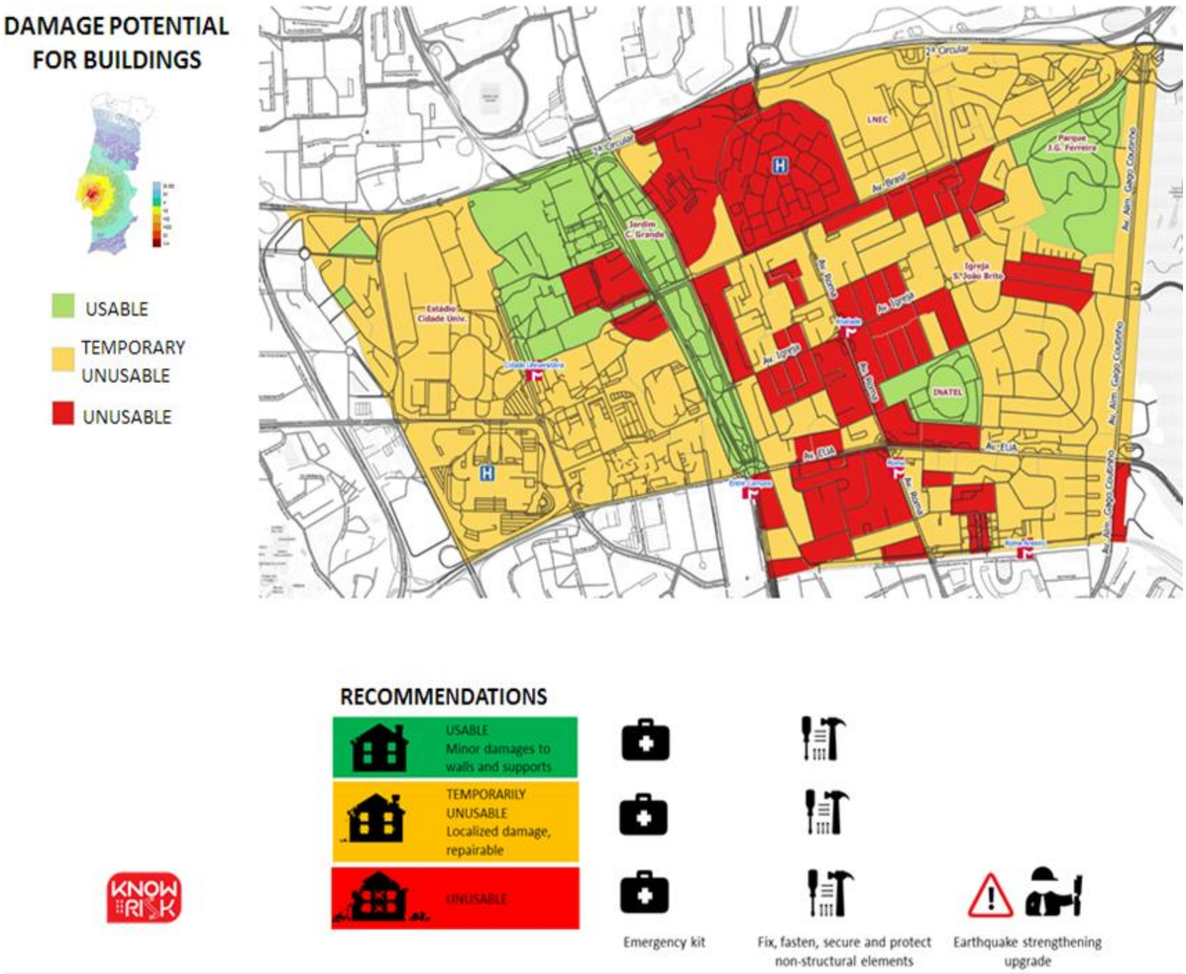

Figure 3 -. Expected pattern of building damage by block for an EC8 (Type II) scenario and recommendations to reduce damage for the Alvalade pilot area. Estimates are based on the likelihood of damage in each of three states: slight (D1), moderate (D2-D3) and extensive (D4-D5). Map patterns reflect the most likely state of damage for a given block.

A participatory approach can improve the content and design of maps by highlighting features that are particularly useful to laypersons (Reed, 2008). Future improvements can be done, and two or three test maps can bdeveloped and test them and validate the content of maps with different stakeholders. These stakeholders could be students, local residents, decision makers and professsionals from emergency management. The second set of maps can show the same detail of Figure 3 but additionally may include: information on the affected population and emergency management information.

3. RISKMAP FOR MT. ETNA PILOT AREA

3.1 INTRODUCTION

The Mt. Etna area is highly urbanized, with many villages located all around the volcano at different altitudes up to 700 m a.s.l. In particular, the southern and eastern flanks are the most populated areas, where the villages are very close to each other. Moreover, a dense network of roads, power lines and methane pipelines connects the villages. The study area covers part of the south-eastern flank of the volcano, over an area of approximately 510 square kilometers, and includes 28 municipalities (Table 1) with a total population of about 400,000 inhabitants.

Table 1- Municipalities in the Mt. Etna study area.

ISTAT code	Municipality
19087001	Aci Bonaccorsi
19087002	Aci Castello
19087003	Aci Catena
19087004	Acireale
19087005	Aci S. Antonio
19087010	Calatabiano
19087012	Camporotondo Etneo
19087016	Fiumefreddo di Sicilia
19087017	Giarre
19087019	Gravina di Catania
19087023	Mascali
19087024	Mascalucia
19087026	Milo
19087031	Nicolosi
19087034	Pedara
19087035	Piedimonte Etneo
19087039	Riposto
19087041	S. Giovanni la Punta
19087042	S. Gregorio di Catania

ISTAT code	Municipality
19087044	S. Pietro Clarenza
19087045	S. Agata li Battiati
19087046	S. Alfio
19087048	S. Venerina
19087050	Trecastagni
19087051	Tremestieri Etneo
19087052	Valverde
19087053	Viagrande
19087055	Zafferana Etnea

3.2 VULNERABILITY OF RESIDENTIAL BUILDINGS

To carry out a vulnerability analysis on a regional scale, the size of the building stock can be inferred from the data collected during the Italian census, when correctly adapted for the purpose of the vulnerability evaluation to the whole Italian territory (Meroni et al. 1999; Meroni et al. 2000).

The Italian National Institute of Statistics (ISTAT) census data on residential buildings, disaggregated by census sections, has been used as a survey of the exposed elements at seismic risk, as already prepared during the past UPStrat-MAFA project. The data are grouped according to the census sections, and the vulnerability indices were evaluated using the approach proposed by Lagomarsino and Giovinazzi (2006), Giovinazzi and Lagomarsino (2001) and Bernardini et al. (2007). Census data are a primary source to assess residential building vulnerability over large areas. They provide uniform cover of the whole country; however, the information they provide only makes it possible to estimate the total number of buildings and their total volume; it provides poor classification, in terms of age and a few typological parameters. The ISTAT data on residential buildings allows the definition of the frequencies of groups of homogenous structures, with respect to a number of typological parameters: vertical structures, age of construction, number of storeys, state of maintenance, and state of aggregation with adjacent buildings (see Table 2). The census which has been taken into consideration is that one of 1991, being the data of 2001 and 2011 unusable. Strict legal rules on confidentiality of information, in force of 1996, impose data providing in the aggregate form only, with no chance to intersect multiple independent variables at least at municipality level. This limitation does not allow an information crossing on the typological characteristics, critical in the procedure for seismic vulnerability evaluation. During these first months of the project the 1991 census data (ISTAT, 1991) have been updated, by upgrading all the necessary information for vulnerability assessments and comparing the same census variables in the following surveys. In this way it was possible to extrapolate the same categories of information reported by the 1991 census, but updated at the most recent survey (2011).

These data gave an estimate of the number of buildings and the volume of the constructed space for each municipality and for each section of the census. As this information is not directly provided in the published data, it was necessary to infer the data from the available records. To calculate the number of buildings present in the census section that were not available from the census statistics (drawn up on the basis of individual homes, and not the entire buildings), information was taken from the ISTAT "No. of flats per building" statistics: a class by class listing of the number of homes in each building in which a given home is located. The calculation of the number of buildings in the census section was then made using the corresponding mean values for each class, adding together the fractions of buildings surveyed.

Furthermore, to calculate the volume of the buildings present in the census section, information was inferred from details of the surface area of the flat, suitably adjusted so as to include any portions of buildings that were not accounted for in the census form, which considered residential buildings only. To this end, the 'Surface Area' total was multiplied by a correction factor that took into account the number of non-residential and rural flats. The figure thus produced was then multiplied by the average height of homes (3 meters), a figure not considered by ISTAT.

ISTAT was also a direct source of information that helped to divide the sum total of buildings into classes according to the breakdown given in table 1.2. This information was grouped both according to census section and by municipality, depending on the geographical scale required by the analysis being carried out.

The sub-division of buildings according to level of maintenance was based indirectly on ISTAT data. Although the level of maintenance of a building is widely known to affect its behavior under seismic conditions, ISTAT data does not, unfortunately, provide such information. An analysis of data collected from the vulnerability charts revealed how the presence of efficient installations is systematically associated with lower vulnerability indices than those with sub-standard installations. It was therefore decided to take the presence of efficient systems as an indirect measurement of the state of maintenance of the building, and a further breakdown of the data into two classes was made on the basis of information concerning aspects of installations included in the ISTAT data. The sections of the census form considered were: "Drinking Water Systems", "Plumbing Systems", "Drainage Systems", "Connections to the Sewage System", "Bathtub and/or Shower Installations", "Domestic Hot Water Supply" and "Fixed Heating Installations".

Finally, for each typological class in the census section or municipality, the percentage of the total number of buildings, the percentage of the total surface area, and the percentage of the resident population at the time of the census were calculated. The collected data were stored in ArcGIS shapefile, where the database contains not only the municipal boundaries and/or census sections, but also the ISTAT data file in the format of a DBF file that can be collated with the shapefile.

Table 2 - Typological classes of buildings identified from the ISTAT data.

Structural typology	Building age	Number of floors	Structural context	Level of maintenance
Masonry buildings	age < 1919	1 or 2 floors	Isolated buildings	Good
Reinforced Concrete buildings	1919 ≤ age ≤ 1945	3, 4 or 5 floors	Block of buildings	Low
Soft storey buildings	1946 ≤ age ≤ 1960	6 or more floors		
Other typologies	1961 ≤ age ≤ 1971			
	1972 ≤ age ≤ 1981			
	age > 1981			

3.3 MODEL FOR EMS VULNERABILITY CLASSIFICATIONS OF ISTAT CENSUS DATA

The ISTAT data allow to classify buildings into vulnerability classes (A to F) of the EMS scale by assigning a score of vulnerability. The classification procedure is consistent with a vulnerability assessment at national scale (Meroni et al., 2000) calibrated on more than 28,000 detailed GNDT vulnerability forms (Benedetti and Petrini, 1984) collected all over the Italian territory. In that work, referring to the municipalities in which were available the GNDT Ist and IInd level forms, the average vulnerability indices are evaluated for homogenous groups of buildings based on the census variables of the ISTAT data. For example, for masonry buildings it is possible to evaluate the variation of the vulnerability index for each class of age construction, number of floors, structural context and level of maintenance.

The following describes the method of deterministic classification of groups of buildings defined on the 1991 ISTAT data; this proposal takes an additional parameter, namely takes into account the possible date of seismic classification of the territory. This parameter is consistent with the criteria suggested by the EMS scale, which introduced classes D, E, F for buildings constructed with criteria (progressively more severe) of anti-seismic protection. This is primarily important for R.C. buildings, but certainly not negligible even for masonry buildings.

This proposal (Bernardini et al., 2008) is defined on five parameters, specified in Table 3 for each of the five types of vertical structures provided by the 1991 ISTAT data.

Table 3 - Parameters for classifications of the 1991 ISTAT data (from Bernardini et al., 2008).

k (type)	**1** **soft storey**	**2** **R.C.**	**3** **masonry**	**4** **other**	**5** **unknown**
$I_v{}^1{}_1$ (k)	50	45	60	55	52
Delta_i (k)	-20	-20	-25	-20	-22
Delta_j (k)	-10	-15	-15	-15	-15
Manut (k)	-10	-10	-10	-10	-10
Classif (k)	-10	-20	-10	-10	-15

The indices *i* and *j* of the second and third rows (Table 3) refer respectively to the *i* ranges of the construction age (or total retrofitting) of the buildings, and to the *j* typological factors specified in Table 4.

The Delta parameters (Table 3) are the total variations, linearly distributed with the respective indices, starting from the I_v value of the worst case (for $i = j = 1$) and reported, for each *k*, in the first row. In particular, the values in the first row are the mean values of the I_v indices for the type *k* of an aggregated building, built before 1919, and, in any case before the seismic classification of the territory, with the number of floors 3 (> 4 floors) and in a low state of maintenance.

The factors *Manut* and *Classif* specify the reductions of I_v to be applied respectively if:

- the group of buildings is declared in a good state of maintenance (in year 1991);
- the group of buildings was built after the date of the seismic classification of the territory.

Therefore, the mean of I_v index for each group of buildings is defined by the relation:

$$I_v(i, j, k) = I_v{}^1{}_1\,(k) + \mathit{Delta\_i}\,(k) * (i-1)/5 + \mathit{Delta\_j}\,(k) * (j-1)/5 + \mathit{Manut}\,(k) + \mathit{Classif}\,(k)$$

The last decrease is applicable for ages of construction $i > i_c$, where i_c is the age range in which the seismic classification of the territory was in-forced. For example, if the municipality was classified in 1979, it is reasonable to assume $i_c = 5$; if it was ranked in 1972 it is preferable to assume $i_c = 4$.

Therefore, the classification into vulnerability classes of the EMS scale is evaluated according to the criteria specified in Table 5.

The index I_v thus defined assumes numerical values in the following ranges:

- [0, 50] for buildings with soft storey (class B to D);
- [0, 60] for masonry buildings (class A to D);
- [-20, 45] for R.C. buildings (Class B to E).

This result seems substantially in accordance with the definitions contained in the EMS scale.

Table 4 - Influence of the age of construction and the typological factors (from Bernardini et al., 2008).

I	Range of age of constructions	*j*	Typological factors	
			Aggregations	**Numbers of storeys**
1	< 1919	1	2 (yes)	3 (>4)
2	1919-1945	2	2 (yes)	2 (3-4)
3	1946-1961	3	1 (no)	3 (>4)
4	1962-1971	4	2 (yes)	1 (1-2)
5	1972-1981	5	1 (no)	2 (3-4)
5,4	1982-1984	6	1 (no)	1 (1-2)
6	1984-1991			

Table 5 - Criterion of classification in the EMS-98 vulnerability classes (from Bernardini et al. 2008).

EMS98 Class	A	B	C	D	E	F
I_V (mean)	$50< I_V$	$30< I_V \leq 50$	$10< I_V \leq 30$	$-10< I_V \leq 10$	$-30< I_V \leq -10$	$I_V \leq -30$

3.4 UPDATED ESTIMATE OF THE EXPOSED ELEMENTS

The final result of the previous analysis was the classification of residential buildings on 6 vulnerability classes of the EMS98 scale (A to F) (Grünthal, 1998). This distribution, expressed at municipality level, was subsequently updated, taking into account the evolution of the census variables that can be derived from 1991 ISTAT data that has been collected during the census 2001 and 2011. The changes found after the 1991 census are such as to require the updating of the vulnerability classification of residential buildings based on its evolution over the past 20 years, bypassing the restrictions imposed by the new data supplied in aggregated way only.

The evolution of the settlements on the territory has been studied in particular through the following census variables existent in the last three ISTAT censuses:

1. the surface of the housing area occupied by at least one resident person (*Sup*),
2. the number of residential buildings (*Ed*),
3. the number of components of the families living in residential buildings (*Res*).

For this purpose it was necessary to perform an alignment of the municipal and provincial administrative reference, which over the past 20 years has involved the studied territory. It also noted an important change in the geometry representing the administrative limits of the census sections released by ISTAT in the year 2001. Due to these changes and different texture of the census sections, it has been impossible to compare data at this geographical level, thus limiting the analysis at the municipal scale. It then proceeded to identify the evolution of the individual census variables expressed at the municipal level. Applying these percentages of increase or reduction on the overall values allows to redistributing such variations on the vulnerability distributions derived from the 1991 ISTAT data only and obtaining their projection to the year 2011.

The increasing trend on residential buildings has been affected on the distribution in vulnerable classes. It is assumed that the increase or decrease of buildings detected by ISTAT on the territory is ruled by the principle of conservation buildings on better conditions from the point of view of vulnerability, with the phasing out of buildings in worse conditions from the point of view of seismic performance.

A key role in this process is played from any seismic classification of the individual municipalities: if so, the new buildings will be in class D, E and F only, otherwise, in the absence of anti-seismic regulations, we could still find also in the class C.

Using the census variable *Sup*, *Ed* and *Res* collected in the years 1991 and 2011, it was calculated the difference Δ. If, for example, the number of buildings in the year 2011 was lower than that of 1991 (i.e. $\Delta Ed < 0$), it has been supposed that the number of buildings decreased in the classes with greater vulnerability (A to C), assuming that the buildings have been abandoned or replaced. The total decrease is equal to the difference recorded which, by convention, it is distributed on the three classes of vulnerabilities. If, conversely, the number of buildings is increased, there are two cases: (i) the increase is distributed evenly on the four lower vulnerability classes (C to F) if the municipality has maintained the same level of seismic classification; otherwise,)ii) if the municipality has increased its level of seismic classification, it was hypothesized to have new buildings in the safer classes (D to F) and the total increase will be split on the three less vulnerable classes only.

As set out above it can be summarized by the following rules:

• Δ (*Sup* / *Ed* / *Res*) <0 → Δ (*Sup* / *Ed* / *Res*) / 3 * A / B / C (*Sup* / *Ed* / *Res*);

• Δ (*Sup* / *Ed* / *Res*) > 0 → Δ (*Sup* / *Ed* / *Res*) / 4 * C / D / E / F (*Sup* / *Ed* / *Res*)

if the municipality is not classified in the seismic zones;

• Δ (*Sup* / *Ed* / *Res*) > 0 → Δ (*Sup* / *Ed* / *Res*) / 3 * D / E / F (*Sup* / *Ed* / *Res*)

if the municipality is classified in the seismic zones.

Following the results of the analysis just presented, it is proceeded with the assignment of the vulnerability classes, from A to F, according to the methodology described by Bernardini et al. (2008).

Faced with a tiny increase in the amount of built-up environment (about 12% over the entire study area), we have obtained a different distribution in the classes of vulnerabilities with an increase in the lower vulnerability classes (D, E). Figure 4 shows the distribution in classes of vulnerability for buildings estimated using data ISTAT 1991 and its update to the values at the year 2011. This updated distribution clearly shows an increase of lower vulnerability buildings, in classes D and E. A smaller decrease can be noted in the most vulnerable classes also, from A to C. This overall pattern describes a generalized decrease in the building's vulnerability in the last 20 years in the studied area.

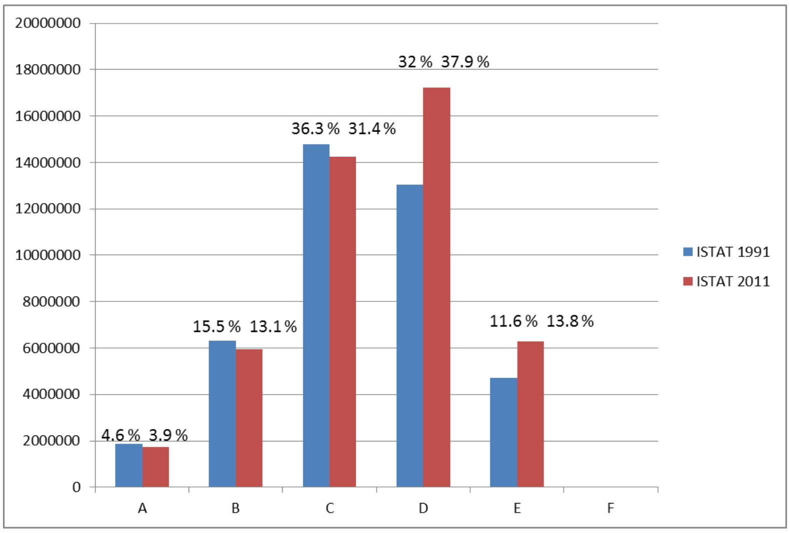

Figure 4 - Vulnerability distribution of residential buildings into the classes A to F in the Etna region. Built volumes (m^3) refer to the 1991 ISTAT census data and their updating at the year 2011. For a better precision, they are also reported with their percentage values.

The last elaboration is the weighted sum of the volumes in each vulnerability classes multiplied by the average score of each vulnerability class. In this way it has been obtained an average vulnerability index for each census sections of the municipality in the zone of analysis, ranging from 0 to 1. The adopted numerical scores of the index are relate to the central values of the vulnerability classes ranges (from A to F) deducted from Bernardini et al. (2007:

$$V_{index} = (V_A{*}0.88 + V_B{*}0.72 + V_C{*}0.56 + V_D{*}0.4 + V_E{*}0.24 + V_F{*}0.08) / V_{TOT}$$

where V_A ... V_F are respectively the residential built-up volumes in A to F classes.

The geographical distribution of the mean vulnerability index for residential buildings evaluated in each census section, is shown in Figure 5, obtained from the 1991 ISTAT data (left map) and from its update at the year 2011 (right map).

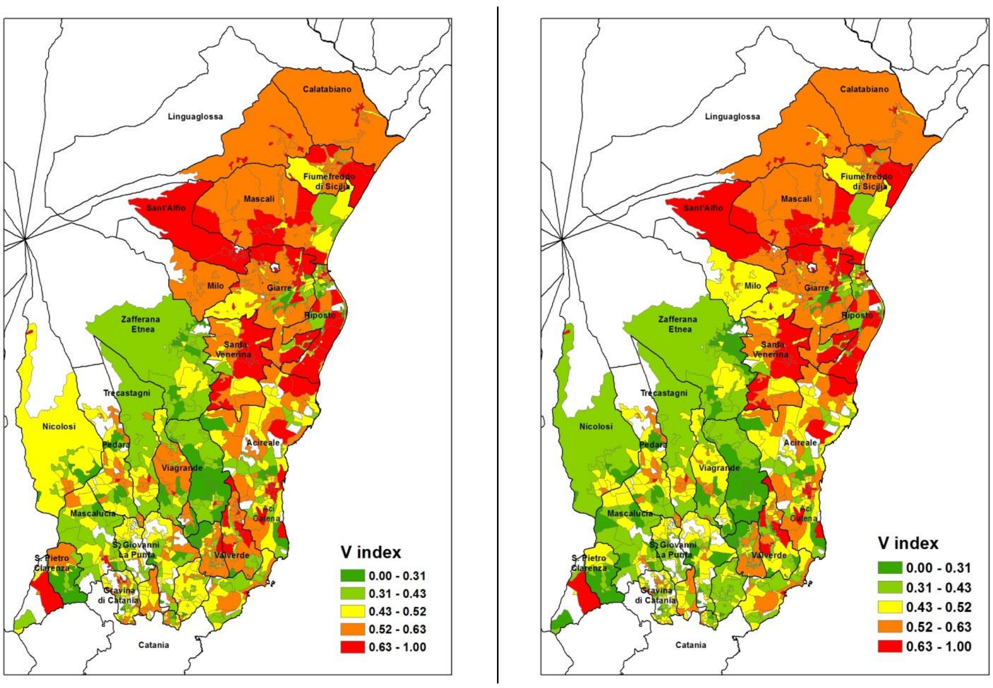

Figure 5 - Mean vulnerability index calculated for each census sections of the municipality in the zone under study (Mt. Etna) updated at the year 1991 (left) and the year 2011 (right).

3.5 MODEL FOR SEISMIC DAMAGE ASSESSMENT

The study of the seismic risk of an urban region follows two main steps: (i) exposure geo-referenced inventory and vulnerability classification of assets at risk; and (ii) vulnerability characterization according to damage models.

In this project, damage models are selected in agreement with the macroseismic evaluation of the seismic hazard provided in previous actions B1 and B.2, so a macroseismic method for the vulnerability assessment of buildings has been adopted.

The damage model proposed by Giovinazzi and Lagomarsino (2006) and revised in Bernardini et al. (2007), was successfully applied in previous Portuguese and Italian seismic risk studies (Sousa, 2006, 2008; D'Amico, 2016). This model classifies the building stock according to the vulnerability table of the European Macroseismic Scale (EMS), and predicts damage distributions, conditioned by an intensity level, for each damage grade of the scale.

According to this model, the seismic vulnerability of the elements at risk that belongs to any given building typology (i.e., buildings with a similar behavior during an earthquake) is described by a probable vulnerability index, which varies between 0 and 1, and is independent from the hazard severity level.

The authors estimated an expected damage grade, μ_D, for a building typology according to the following equations (Bernardini et al., 2007):

$$\mu_D = 2.5 + 3\tanh\left(\frac{I + 6.25V_I - 12.7}{3}\right) \times f(V_I, I) \tag{1}$$

with f (V_I , I) defined as:

$$f(V, I) = \begin{cases} e^{\left(\frac{V}{2}\times(I-7)\right)}, & I \le 7 \\ 1, & I > 7 \end{cases} \tag{2}$$

and where μ_D is the mean damage grade (grade 1, slight; grade 2, moderate; grade 3, heavy; grade 4, very heavy; and grade 5, collapse) of D, the random variable damage, I is the intensity and V_I is the vulnerability index. Fragility curves, $\mathrm{P}(D > d \mid I)$ are further modelled according to a beta distribution, with a probability density function given by:

$$p_{\beta}(d) = \frac{\Gamma(q)}{\Gamma(p)\cdot\Gamma(q-p)}\cdot\frac{(d-a)^{p-1}\cdot(b-d)^{q-p-1}}{(b-a)^{q-1}} \qquad a \le d \le b \tag{3}$$

in which, $\Gamma(\cdot)$ is the gamma function, *a, b, p* and *q* are the parameters of the Beta distribution, where the authors assumed *a* = 0, *b* = 6, *q* = 8 and *q* is given by:

$$p = q\cdot(0.007\cdot\mu_D^3 - 0.0525\cdot\mu_D^2 + 0.2875\cdot\mu_D) \tag{4}$$

Thus, using Equations 1 to 4, the fragility curves to be used in modelling damage due to the occurrence of a macroseismic intensity *I* can be completely defined:

$$P(D > d \mid I) = 1 - P_{\beta|I}(d) \tag{5}$$

3.6 RISK MAPS EVALUATION

The Italian case study comprises the Etna area, which was studied in the past UPStrat-MAFA project (Grant Agreement N° 23031/2011/613486/SUB/A5). The lower eastern flank of the volcano has been considered because of the high degree of risk arising by the dense urbanization – 28 municipalities in this area, with a total population of about 400,000 inhabitants – and the presence of relevant infrastructure and lifelines.

The information on vulnerability is an element that together with shaking ground-motion parameters, has been used for the identification of risk. The study of the seismic vulnerability of an urban region follows two main steps: (i) the exposure geo-referenced inventory and the vulnerability classification of assets at risk; (ii) the vulnerability characterization according to damage models.

Finally, by means of the macroseismic damage model previously described, a classification of the building stock from the related vulnerability, was made. According to the physical structures exposed to the earthquake impact, it can be organized in different estimated levels of damage severity classified in 5 growing levels. The results point out on the grade D2 (moderate damage) and the grade D3 (substantial to heavy damage) of the EMS scale where non-structural damages are concentrated.

Moreover, the possibilities of expanding data are being explored. Other vulnerability data available from past studies of the Etna earthquakes are in the collecting phase. This information includes the forms for post-earthquake damage and safety assessment and short term countermeasures (AeDES form) (Baggio et al., 2002) filled after the recent moderate earthquakes in the Etna area. The AeDES forms survey permits to assess the structural damages of buildings after an earthquake. Information about the building position, classification, material, structural typology, damage of the seismic event and previous damages are object of this form. From the analysis of this data we will try to extrapolate information about the relation between structural and non-structural damage on residential buildings.

4.RISKMAP FOR ICELAND PILOT AREA

4.1 INTRODUCTION

Seismic risk for a given region reflects the probability of some kind of damage due to seismic hazard in the area. The risk can be related to expected number of fatalities or injured people, damage of buildings, bridges, roads, power plants or other types of civil structures and infrastructure. It can also be associated to potential economic, social and environmental consequences due to hazardous events. In general, everything in a modern society that is exposed to earthquake hazard is at risk from earthquakes.

Identifying and mapping the seismic risk is necessary to be able to determinate mitigation programs, making decisions and creating a task list to reduce risk. Risk maps can be constructed for some given exposure time, for instance for one year or 50 years etc. This can be termed as probabilistic risk map. Alternatively, they can be created to show risk for some specified earthquake events, which can be called a scenario risk maps. In fact, in order to make a probabilistic risk map one has to be able to compute risk from different seismic events.

In this report the focus will be on seismic risk of Icelandic residential buildings located in the South Iceland Seismic Zone (SISZ). Evaluated fragility curves based on loss data from three recent major earthquakes in Iceland (Bessason & Bjarnason, 2016) will be used to construct scenario risk maps for the main building typologies in the area. The split of the loss in both structural and non-structural damage will be considered. The scenario will be the two equal size (Mw6.5) South Icelandic earthquakes of June 2000 which struck with four-day interval and with internal fault distance of approximately 15 km. The same methodology can be used to construct risk maps for other scenarios.

4.2 FRAGILITY CURVES

Fragility curves provide the probability of exceeding specified damage state for a given earthquake intensity. Fragility curves can be evaluated by analytical methods, based on observed loss data or by some combination of this. Other methods based on expert opinion also exist. The fragility curves used in this report to create the risk maps are based on detailed building-by-building loss data for residential buildings from three recent earthquakes in 2000 and 2008 in the South Iceland seismic zone. Almost 9,500 buildings were affected. The database is complete in the sense that it includes all low rise residential buildings in the affected area both damaged and undamaged (Bessason and Bjarnason, 2016). Other vulnerability studies so far using data from recent South Iceland earthquake have all been restricted to low-rise residential buildings (Bessason et al. 2012, 2014; Rupakhety et al., 2016).

4.2.1. The South Iceland earthquakes of June 2000 and May 2008

In June 2000, two major earthquakes struck the South Iceland Seismic Zone (Figure 6). The first earthquake (M_w 6.5), struck on June 17, 2000, 15:41 (GMT). The earthquake was a right-lateral strike-slip earthquake, with fault striking in the north–south direction and an approximate focal depth of 6.3 km. Subsurface fault mapping based on the micro-earthquakes showed an approximately 12.5 km-long and 10 km deep vertical fault rupture (N7_A) (Vogfjörd et al., 2013). The highest recorded PGA was 0.64 g, 5.7 km from the fault. The second earthquake (M_w 6.5) struck on June 21, 2000, at 00:52 (GMT). This earthquake was also a right-lateral strike-slip earthquake, with the fault striking in the north–south direction (N1_A) and with an approximate focal depth of 5.3 km. Subsurface fault mapping based on the micro-earthquakes showed an approximately 16.5 km-long and 7-9 km deep almost vertical fault rupture (Vogfjörd et al., 2013). The highest recorded PGA was 0.84 g at 3.1 km distance from the fault.

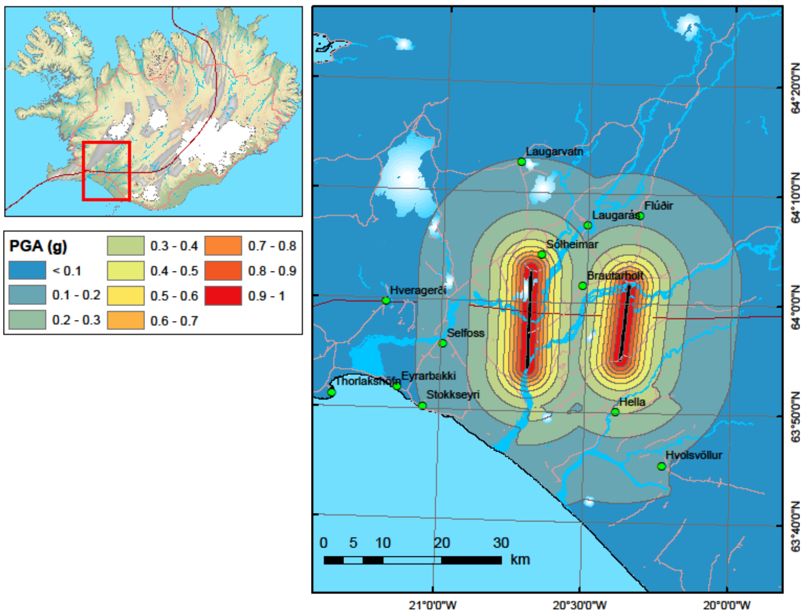

Figure 6 - Scenario hazard map based on PGA for the two South Iceland earthquakes: 17 June (right fault) and 21 June 2000 (left fault).

In addition to these two main earthquakes, there were some after-shocks in the area. All of them, however, were of magnitude less than M_L 4.5 except one which was M_L 5.0. It can be concluded that the effect of after-shocks on damage were minimal and can be ignored.

In May 2008, an earthquake caused by slip in two separate faults occurred in the western part of SISZ (Figure 6). The first slip was in the eastern fault and the wave propagation from it triggered a slip in the western fault about one second later. A macroseismic epicentre has been determined at 63.98°N and 21.13°W, at 15:45 (GMT) (Halldórsson and Sigbjörnsson, 2009). This earthquake was a right-lateral strike-slip earthquake, with fault striking in the north-south direction. The magnitude of the combined events was estimated as M_w 6.3.

4.3 PROPERTY DATABASE

In Iceland all buildings are registered in an official database which contains detailed information about the type of use, date of construction, number of storeys, building material, and geographical location. In addition, it includes valuation, both for taxation and reconstruction insurance purposes usually termed replacement value (Icelandic Property Registers). The property database does not list structural bearing systems nor soil conditions at construction sites.

4.4 BUILDING TYPOLOGY CLASSES

The South Iceland Seismic zone is basically agricultural land with many farms and a few small villages and service centres. The vast majority of residential buildings are low-rise (1-3 stories) single apartment blocks or town houses and only in a few exceptional cases can taller buildings be found. The number of timber houses is similar to the number of concrete houses.

In evaluation of the fragility curves used in this report the sample buildings were classified in five different typologies (Bessason and Bjarnason, 2016). Two typologies were defined for RC buildings, one for those built before 1980 and before implementation of seismic codes (pre-1980) and one for those designed by seismic codes (post-1980). Similarly, two typology classes were used for timber structures, pre-1980 and post-1980, and finally one for buildings made of hollow pumice blocks which can be considered as brick buildings. Nearly all the pumice buildings were built before 1980. The older low-rise buildings (pre-1980) are generally well-built despite not being seismically designed and the new seismic code (Eurocode 8) does not in fact request advanced seismic design for the low rise buildings to fulfil the code requirements. The new code, however, mandated minimum reinforcement of structural walls. Furthermore, about the time that the codes were implemented (~1980) concrete strength was increased in RC structures in Iceland to increase their weathering resistance. Finally, in recent year finish of foundations has improved.

4.5 LOSS DATA

Natural catastrophe insurance of buildings is mandatory in Iceland and is administrated by the Iceland Catastrophe Insurance (ICI) fund. Therefore, after catastrophic events like large earthquakes, the repair and replacement cost for every damaged building is estimated by trained assessors in order to settle the individual insurance claims.

After the earthquakes in 2000, the loss assessment work started right after the second event and in 2008 it also started only a few days later. The assessment work procedure was as follows:

1. A property owner reported damage to his local insurance company, which informed ICI;

2. Assessors who worked in pairs prepared for the assessment work by familiarizing themselves with technical drawings and other related information about the damaged property;

3. Assessors performed a first inspection of the property, all building damage was documented, marked on drawings and photos taken;

4. Assessors prepared a damage assessment report. The reports included a description of the damage and a cost estimate for the repairs. The repair cost estimate was the basis for compensation to the owner and used along with the replacement value to compute the damage ratio of each property in this study.

After the two June 2000 events the assessed damage was divided into five subcategories of structural and non-structural damage (Table 6). The damage data after the 2008 earthquake were classified in more detail in ten subcategories and then further divided into 4 to 8 items. In total, the damage was broken down under a total of 62 headings. The details of the damage data after the 2008 earthquake were used to map the main statistics of the damage in Bessason et al. (2012). The ten subcategories used in the damage mapping after the 2008 earthquakes can be combined and reduced to the same and identical subclasses as were used after the 2000 events in order to make comparison.

Table 6 - Subcategories of damage used in the survey after the 2000 earthquakes.

Category	No.	Subcategory
Structural damage	1	Excavation, foundations and bottom slab
	2	Interior and exterior supporting structure (walls, columns, beams, roofs)
Non-structural damage	3	Interior finishing work (partition walls, mortar, suspended ceilings, cladding)
	4	Interior fixtures, paintwork, flooring, wall tiles, windows, doors, etc.
	5	Plumbing (cold water, hot water and sewer pipes), radiators, electrical installations

4.6 INTENSITY MEASURE

In evaluation of the fragility curves PGA was used as intensity measure (IM). The affected buildings were all low-rise and shear walls dominate the seismic lateral resisting system. They are therefore stiff with a low natural period, which justifies the use of PGA as IM. PGA (m/s^2) at each site was estimated by using a ground motion prediction equation (GMPE) given by Rupakhety and Sigbjörnsson (2009):

$$\log_{10}(PGA) = -1.038 + 0.387 \cdot \mathrm{M_w} - 1.159 \cdot \log_{10}\left(\sqrt{\mathrm{H}^2 + 2.6^2}\right) + 0.123 \cdot S + 0.287 \cdot P \tag{1}$$

where H (km) is the shortest horizontal distance from the site to the surface of the fault trace; S is a site factor which takes the value 0 for rock sites and 1 for stiff soil sites; and P is an error/scatter term which follows a standard normal distribution, i.e. $P \in N(0,1)$. Most of the strong motion data used to calibrate the parameters in Eq.(1) were taken from significant Icelandic earthquakes but they were also augmented by records from continental Europe and the Middle East. Both the horizontal components were used from each station and the equation refers to rock sites. The main characteristic of the GMPE given by Eq.(1) is that it predicts a relatively high PGA in the near fault area whilst the attenuation with distance is more than generally found with a GMPE of similar form (see for instance Ambrayses et al.,1996). The GMPE can be used to compute scenario hazard map for the two South Iceland earthqukes of June 2000 (Figure 6). The contours tend to stretch out in the south where large plains of alluvial sediments can be found along the coast.

4.7 DAMAGE STATES

The detailed loss data after the South Iceland earthquakes of June 2000 and May 2008 gave the possibility to compute the damage factor (DF) for every building:

$$DF = \frac{\text{Estimated repair cost}}{\text{Replacement value}} \qquad (2)$$

The damage states used to construct the fragility functions presented in Bessason and Bjarnason (2016) could therefore be related to the damage factor instead of only verbal description (none, slightly, moderate etc.). Damage states defined by Dolce et al. (2006) were used for the construction of the fragility curves (Table 7).

Table 7 - Definition of damage states for fragility curves.

Damage state	Range of damage factor	Description of damage
DS0	0%	No damage
DS1	>0 – 5%	Slight
DS2	>5 – 20%	Moderate
DS3	>20 – 50%	Substantial to heavy
DS4	>50%	Very heavy to total

4.8 EVALUATED FRAGILITY CURVES

Lognormal distribution (LN) was used as functional form for the fragility curves. A methodology presented by Shinozuka et al. (2000), based on maximum likelihood method, was applied to estimate the two LN parameters. In Bessason and Bjarnason (2008), LN fragility curves were first fitted to each building typology class, each damage state, and each earthquake (17 June 2000, 21 June 2000 and 29 May 2008). For the 17 June 2000 earthquakes only loss data from buildings located east of the fault were used and for the 21 June 2000 earthquakes only loss data from buildings located west of the fault were used in evaluation of the fragility curves (Figure 6). Buildings located between the faults were dropped because there one can expect accumulated effect from both events. Comparison of the fragility curves from this showed some different characteristics in all three events. But in the final step data from the three events was combined and fragility curves evaluated for each building typology class (Table 8).

Table 8 - Estimated mean value (μ) and standard deviation (σ) for the fragility curves based on lognormal assumption and the approach of Shinozuka et al. (2000).

	Pre-1980 RC		Post-1980 RC		Pre-1980 Timber		Post-1980 Timber		Pumice	
Damage states	μ	σ	μ	σ	μ	σ	μ	σ	μ	σ
No damage	0.381	0.334	0.514	0.466	0.708	0.927	0.700	0.853	0.413	0.423
Slight	0.957	1.09	3.73	6.85	2.89	6.24	5.42	14.4	0.988	1.320
Moderate	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	12.8	50.7
Substantial									NaN	NaN

From these values the parameters of the lognormal distribution, LN(α,β), can be computed as:

$$\alpha = \log\left(\frac{\mu^2}{\sqrt{\sigma^2+\mu^2}}\right) \tag{3}$$

$$\beta = \sqrt{\log\left(\frac{\sigma^2}{\mu^2}+1\right)} \tag{4}$$

As an example, fragility curves for damage states D0 and D1 for pre-1980 and post-1980 RC buildings are shown in Figure 7. The curves for D2 and D3 are below probability 0.1 (Bessason and Bjarnason, 2016).

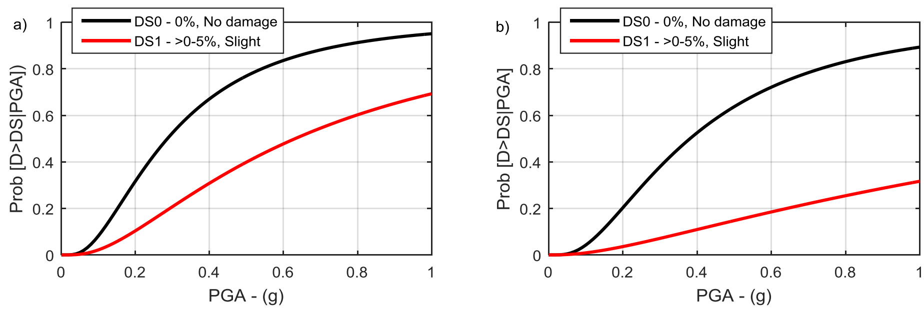

Figure 7 - Fragility curves. Left: pre-1980 RC buildings; right: post-1980 RC buildings (Bessason and Bjarnason, 2016).

4.9 RISK MAPS

By combining the fragility curves defined by the LN model with the parameters defined in Table 8 and the computed PGA for the two South Iceland earthquakes of June 2000 (Figure 6), it is now possible to compute scenario risk maps for these two events and all the five building classes defined previously. As an example, the risk maps for pre-1980 RC buildings show that in the village of Selfoss the probability of exceeding DS0 (no damage) is in the range 0.10-0.20 (Figure 8 left), whilst the probability of exceeding DS1 is less than 0.05 (Figure 8 right). The maps show that the newer building typologies (post-1980) perform better than the older ones. Although not shown by the maps, the probability of exceeding DS2 is less than 0.10 everywhere in the affected area except for the pumice buildings (Bessason and Bjarnason, 2016).

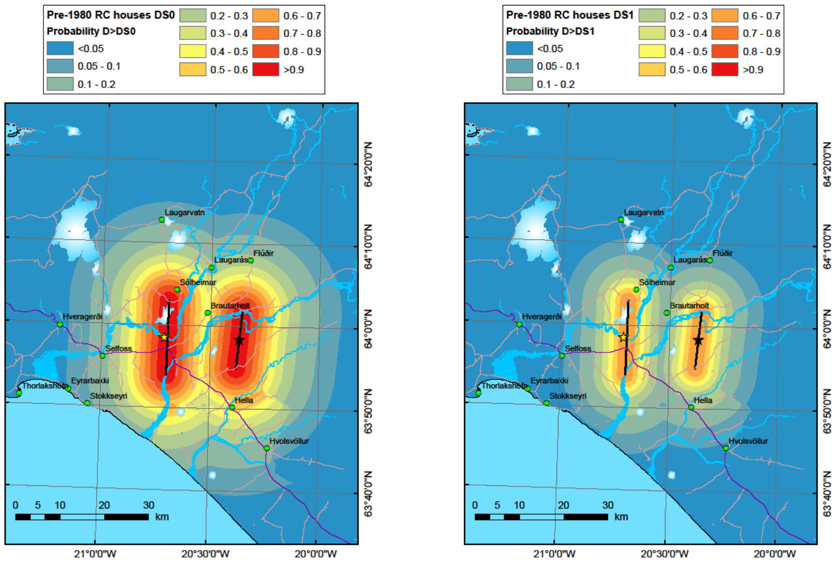

Figure 8 - Scenario risk maps for reinforced concrete buildings built before 1980. Left: probability that Damage State will exceed DS0; right: probability that Damage State will exceed DS1.

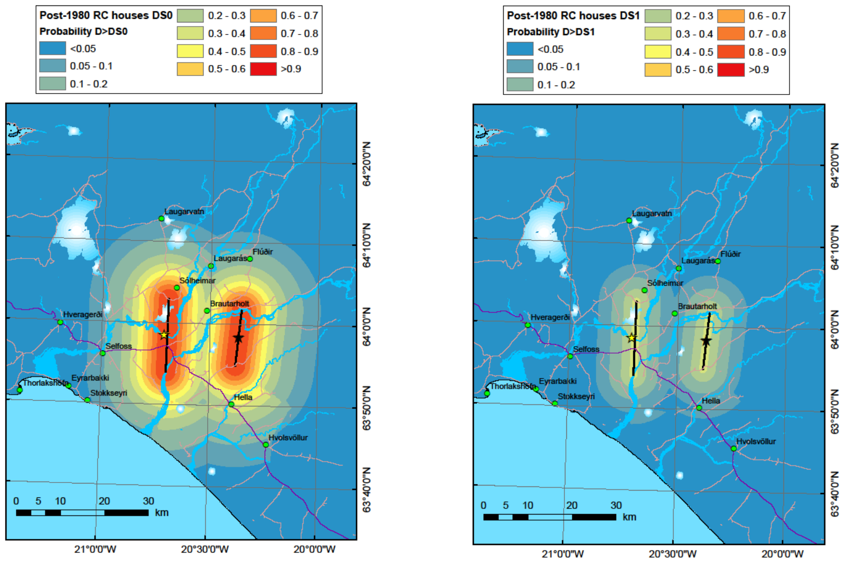

Figure 9 - Scenario risk maps for reinforced concrete buildings built after 1980. Left: probability that Damage State will exceed DS0; right: probability that Damage State will exceed DS1.

One weakness of the maps are that they do not take into account that in the area located between the two faults of the June 17th and June 21st events, there will be accumulated loss caused by strong ground motion contribution from both the earthquakes. This phenomena needs further investigations.

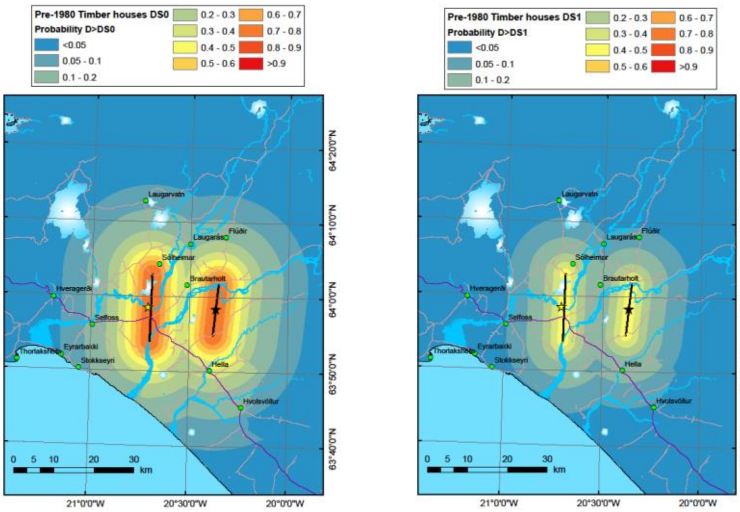

Figure 10 - Scenario risk maps for timber buildings built before 1980. Left: probability that Damage State will exceed DS0; right: probability that Damage State will exceed DS1.

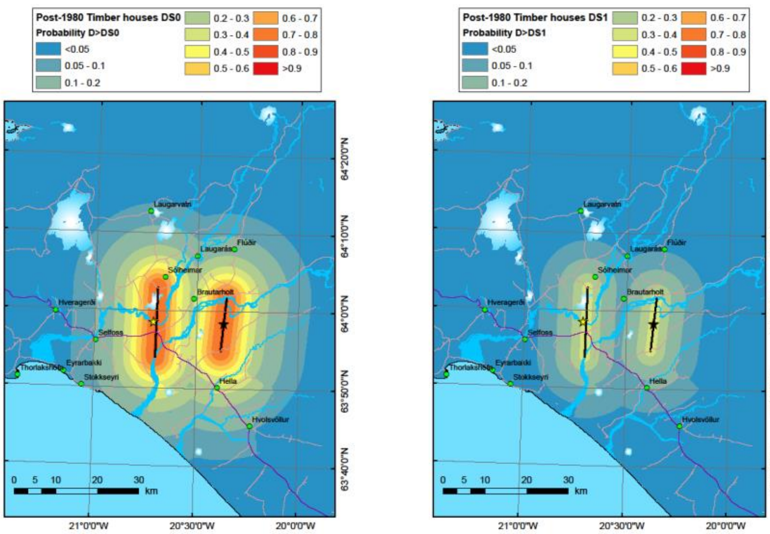

Figure 11 - Scenario risk maps for timber buildings built after 1980. Left: probability that Damage State will exceed DS0; right: probability that Damage State will exceed DS1.

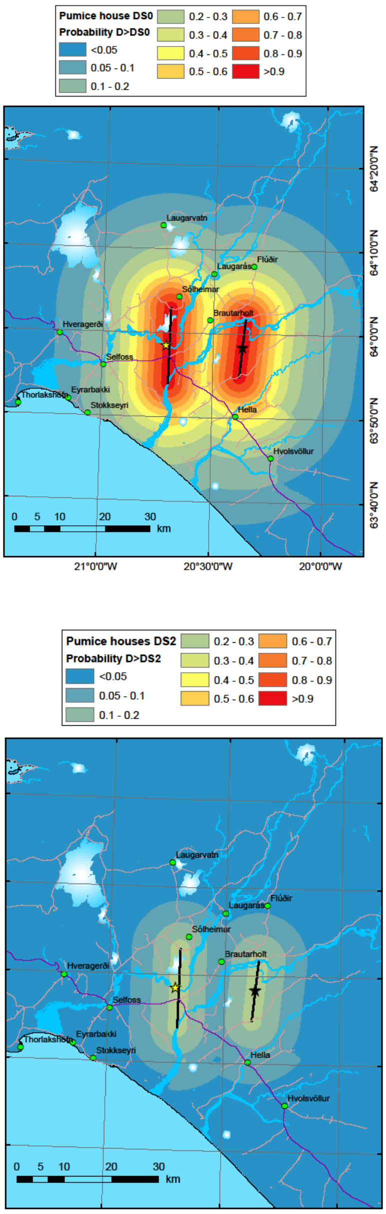

Figure 12 - Scenario risk maps for pumice buildings built. Top left: probability that Damage State will exceed DS0; top right: probability that Damage State will exceed DS1; bottom left: probability that Damage State will exceed DS2.

The risk maps only give information about total loss. Fragility curves or vulnerability models for the non-structural loss alone have not yet been developed. However, studies of the loss data from the three South Iceland earthquakes have shown that most of the losses are related to non-structural loss (Bessason et al., 2014; Bessason and Bjanason, 2016). In those studies the loss data were divided between five subclasses of structural and non-structural damage (Table 6). The observed loss for each damaged building was split proportionally among the subcategories such that the total sum was 100%. From this it was possible to find average proportional value for each subclass for a given earthquake and a given building typology. Only damaged buildings contributed to the results and buildings at all distances (all PGA levels) were assembled (Figure 13). Column 4 is the highest in all cases and reflects that non-structural damage of interior fixtures, paintwork, flooring, wall tiles, windows and doors contributed most to the overall damage in each case. Column number 2 is overall the second highest. It is related to structural damage of interior and exterior supporting structures (walls, columns, beams, roofs). By summing columns 1 and 2 it can be seen that structural damage was on average less than 40% in all cases except for the old timber buildings in the 17 June 2000 earthquakes. Overall the structural damage was more significant in the two June 2000 earthquakes (M_w 6.5) than in the May 2008 earthquake (M_w 6.3).

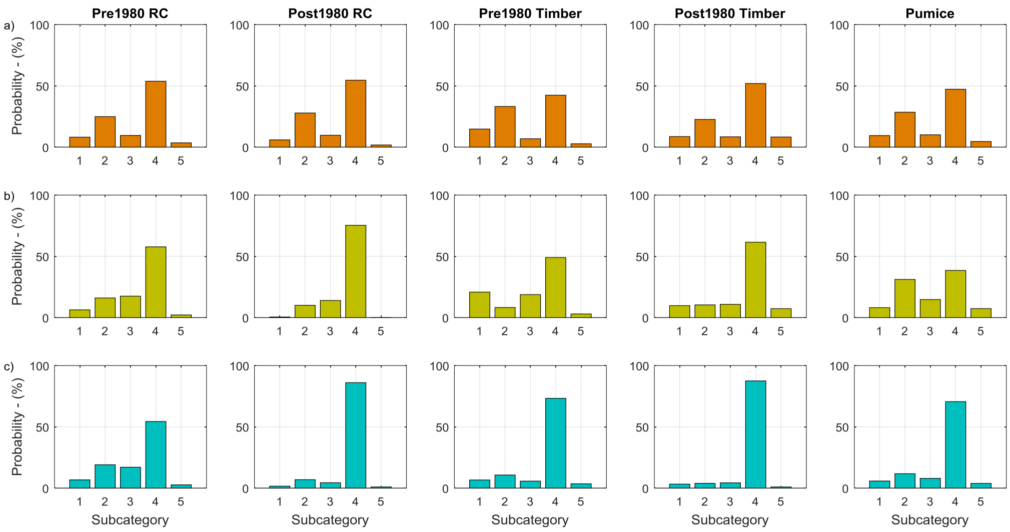

Figure 13 - Classification of damage data in five subcategories (Table 6) for five building typology classes. Top: 17 June; middle: 21 June 2000 M_w 6.5 earthquake bottom: 29 May 2008 M_w 6.3 earthquake.

4.10 CONCLUSIONS

Fragility curves based on loss data from three recent earthquakes (M_w 6.5, M_w 6.5 and M_w 6.3) in South Iceland have been used to construct risk maps for five low-rise residential building typologies which dominate the residential building stock in the area. A number of information and conclusions can be drawn from the maps and damage data from these three events:

- No residential buildings collapsed in these three earthquakes and no people were killed or badly injured.

- The probability of exceeding damage state DS2 (5-20% loss) in the near-fault area as well as at greater distances was less than 0.10 for four of the building typologies, i.e. for pre-1980 RC, post-1980, pre-1980 timber and post-1980 timber buildings, even. It was only for the hollow block pumice buildings (brick buildings) that it was higher.

- Newer building typologies (post-1980) built after the implementation of seismic codes performed better than older building typologies.

- Number of buildings was undamaged although located in the near-fault areas.

- Non-structural damage dominated the overall damage for all building typologies and all the three earthquakes.

The main findings from recent earthquakes in South Iceland are quite encouraging and indicate that low-rise residential buildings in seismic zones in Iceland behave satisfactorily in earthquakes of magnitudes 6.5 or less. However, larger earthquakes can be expected in Iceland and extrapolation of fragility functions and vulnerability relationships based on loss data from lower magnitudes to higher is risky. A combination of analytical methods and empirical methods maybe required.

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