ANNUALIZED ECONOMIC AND HUMAN EARTHQUAKE LOSSES FOR MAINLAND PORTUGAL

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ABSTRACT :

Loss seismic scenarios are important tools for civil protection emergency planning. However, effective risk mitigation strategies should not be restricted to the evaluation of a single scenario event based on probabilistic or deterministic analysis. In practice, any future event will produce significant different effects from the assumed scenario. The aim of this paper is to give a hint on the order of magnitude of the risk associated to annual seismic losses in Portuguese Continental regions. The proposed solution is to evaluate statistical central value measures to describe seismic losses. In concrete, annualized risks will be averaged over a large period of time and two single parameters (see Results and Application) are chosen to quantify social and economic impacts due to earthquakes. The results are presented in terms of average annual economic and human losses, due to earthquakes, for the 278 Portuguese Continental counties. Portuguese main provinces are ranked according to those parameters. The dependence of average annual seismic risk on predictive variables, like hazard and vulnerability, is analyzed in detail. The geographic distribution of the annualized losses leads to the conclusion that the Metropolitan Area of Lisbon (MAL) is the Portuguese region with higher losses, due to its high exposure combined with moderate hazard, whereas Algarve is the region with higher specific human losses, due to its significant seismic hazard.

KEYWORDS: Economic losses, expected annualized earthquake losses, human losses, Portugal, seismic hazard, seismic risk

1. INTRODUCTION

The main objective of this paper is to analyze Mainland Portugal seismic risk averaging all possible seismicity contributions to the region, over a large period of time (approximately 1000 years). Seismic risk is assessed at two levels of geographic disaggregation: for the 278 Mainland counties and for five large sub-regions. Five average measures of annualized losses are quantitatively estimated with the intention of (i) ranking seismic risk of the previous mention regions, and (ii) studying the influence of the variables hazard, vulnerability and exposure on risk. One should notice that, in this work, economic losses are exclusively based on building damage estimates and on related lost area repair costs. Actually, only housing stock damages were analyzed, because the only exhaustive inventory that is available at a national scale, the *Censos 2001* (INE, 2002), refers to this type of structures. This national inventory allowed the classification of the most current constructive solutions in Portuguese housing stock in typologies that share the same seismic vulnerability characteristics. So, one may advance that economic losses are strongly underestimated, because a considerable part of Portuguese build systems, exposed to seismic risk, was disregarded and because only a part of direct economic losses were included. In fact, neither some direct costs, like loss of contents, losses to lifelines, etc., nor indirect costs were estimated. Additionally, losses resulting from collateral effects of earthquakes, like fires and tsunamis, were also ignored.

2. DEFINITIONS

Most important concepts that are used in a seismic risk analysis are analogous to other environmental risks domains. Moreover, there are international standards that cover basic definitions in this domain (AS/NZS, 2004, Sandi, 1986, UNDRO, 1979). However, for the purpose of providing a more consistent, understandable and rigorous work, the main definitions here adopted are presented below:

1. *Hazard*, *H*, is «a source of potential harm» (AS/NZS, 2004) and is formally defined as the exceedance probability of a certain level of severity of the natural event, in a site, and during an exposure period of time.

2. *Elements at risk* are the elements exposed to a negative impact, direct or indirect, of the natural event.

3. *Exposure*, *E*, reflects the value of the elements at risk or may be quantified by their exposed toll.

4. *Vulnerability*, *V*, reflects the susceptibility of an element at risk being adversely affected by the natural phenomenon.

5. *Damages*, *D*, correspond to the adverse physical consequences suffered by the elements at risk originated by the natural disaster, being conditioned by a certain severity level of that event.

6. *Loss*, *L*, is «any negative consequence or adverse effect, financial or otherwise» (AS/NZS, 2004).

7. *Risk*, *R*, is «the chance of something happening that will have an impact on objectives» (AS/NZS, 2004) and is formally defined as the probability to exceed or to achieve a certain level of losses in a region and time interval. Risk depends on hazard, vulnerability and exposure. Risk may be simply measured by the expected losses to a given elements at risk over a specified time period (Coburn & Spence, 2002).

8. When expected losses are normalized by exposure we obtain the *Specific Risk*, R_S (Coburn *et al*., 1994), that is a useful measure to compare risk levels across different regions.

3. SEISMIC RISK PROBABILISTIC ANALYSIS

According to the above definitions the probabilistic analysis of seismic risk is provided by the following expression (Sousa, 2007 and Sousa *et al*., 2007):

$$P(L > l) = \int_D \int_H P(L > l \mid d)\, P(D > d \mid h)\, f_H(h)\, dh\, dd \qquad (3.1)$$

This expression is graphically illustrated in figure 3.1 for a building typology of vulnerability *v*, i.e., for a homogeneous group of elements at risk. Notice that each variable distribution is plotted with the same color in expression 3.1 and in figure 1. In the latter, seismic hazard is represented by the green distribution in the 4th quadrant of figure 3.1, seismic vulnerability by the blue distributions in the 1st and 2nd quadrants and losses by the red distributions in the 2nd and 3th quadrants of that figure.

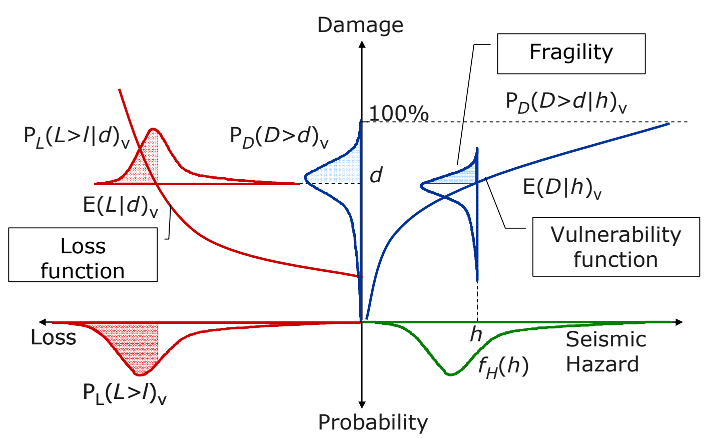

Figure 3.1 Seismic risk probabilistic modeling (adapted from Campos Costa, 2004 and Sousa, 2007)

To estimate economic losses due to physical damages in buildings an integrated impact indicator, the equivalent lost building area, was evaluated. To compute this indicator each damage state was associated to the non-dimensional variable *Damage Factor*, DF_d, defined as the ratio between a building repair cost, when it is in a certain damage state, and measured in percentage of the economic value of that typology building at the time of the earthquake (ATC, 1985). The damage ratio values purposed by SSN (1999) were used (Table 3.1):

Table 3.1 Data for beams under dynamic loading

Damage grade of EMS-98	Damage Factor DF_d [%]
1	1
2	10
3	35
4	75
5	100

In practice, the transformation of damage states by damage factors conducts to a loss index that is, in fact, an expected loss value conditioned by a seismic hazard level, $\mathrm{E}(L \mid h)$. This conditional expected loss is obtained averaging the number of buildings that belongs to a given damage state and typological class with vulnerability $V=v$, weighted by the referred damage factors (Sousa 2006):

$$\mathrm{E}(L \mid h) = Ne_T \cdot \sum_d \sum_v A_v \cdot DF_d \cdot \mathrm{P}_D(D=d \mid h) \cdot \mathrm{P}_V(V=v) \tag{3.1}$$

where:

Ne_T is the number of buildings in the studied region;

A_v is the average floor area of the buildings belonging to a typological class, with vulnerability v, in the studied region;

$\mathrm{P}_D(D=d \mid h)$ is the damage probability matrix understood as the percentages of buildings, belonging to the typological class with vulnerability v, that are in a damage state d, after suffering a seismic action with severity h;

$\mathrm{P}_V(V=v)$ is the probability that the buildings belong to a typological class with vulnerability $V=v$, and it assumed equal to the frequency of that typological classes, in the studied region.

The consideration of the average floor area of the buildings belonging to a typological class in expression 3.1 implies that exposure, E, is evaluated in terms of global habitable area in the analyzed region:

$$E = Ne_T \times \sum_v A_v \tag{3.2}$$

In this case expected economic losses are analyzed by equivalent lost area conditioned by a given level of seismic hazard. If we introduce indicative prices of construction, by square meter, exposure will be evaluated monetarily by the *Replacement Value of Building Stock, RVBS,* in the region.

As equation 3.1 converts building damages in expected losses, conditioned by a hazard level, $\mathrm{E}(L \mid h)$, the expected value of losses for a given time interval is simple given by:

$$\mathrm{E}(L) = \int_H \mathrm{E}(L \mid h)\, f_H(h)\, dh \tag{3.3}$$

When seismic hazard is evaluated by an annual exceedance probability, or by an annual frequency of exceedance, the latter expression describes the *expected Annualized Economic earthquake Losses*, referred as *AEL*.

In what concerns the other components of risk, like social losses, if, instead of buildings, we analyze the consequences of earthquakes in their inhabitants, we would obtain the *expected Annualized Human earthquake Losses*, called *AHL*, by analogy with *AEL*. Coburn & Spence (2002) model was used to evaluate human losses as a consequence of earthquakes. Nevertheless, to estimate human casualties it was assumed that most persons were indoors at the time of the earthquake, that is, only night time earthquake scenarios were contemplated, because population mobility was not considered.

In addition to absolute risk, *R*, three parameters, or risk indicators, were used to characterize specific risk, R_S: *AELR*, *AELC* e *AHLR*. The first parameter, *AELR*, the *expected Annualized Economic earthquake Losses Ratio* «represents *AEL* as a fraction of the replacement value of the local building inventory» (FEMA, 2001), whereas *AELC* expresses annualized economic losses per capita. The third parameter, *AHLR*, results from normalizing the expected annualized human earthquake losses by total resident population in the region, Np_T. Table 3.1 organizes the risk indicators used in this work.

Table 3.2 **-** Expected annualized earthquake losses parameters

Risk	Absolute	Specific
Economic	*AEL*	*AELR* and *AELC*
Human	*AHL*	*AHLR*

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4.1. Explicative variables

As seismic risk is a function of seismic hazard, vulnerability and exposure (value of building inventory and its inhabitants), they were built average indicators, of these variables in order to study their influence on expected annualized earthquake losses.

An average hazard index, denoted by *IH*, was estimated to each Portuguese county. *IH* was computed as the expected value of the random variable *H*, represented by a macroseismic intensity (EMS-98), and weighted by the probability hazard distribution for a reference time interval, τ, of 50 years, assuming that the exceedance of ground motion is independent in each year:

$$\mathrm{P}_{\tau}(H \le h) = [1 - \mathrm{P}(H > h)]^{\tau} = \left(1 - \frac{1}{RP}\right)^{\tau} \qquad (4.1)$$

where $\mathrm{P}(H > h)$ is the annual hazard distribution and *RP* is the return period.

Seismic vulnerability of the elements at risk, belonging to a given building typology, was described by the vulnerability index, varying between 0 and 1, proposed by Giovinazzi & Lagomarsino (2004) and independent of the hazard severity level. The average vulnerability of a region, $\overline{V}$, was obtained by a weighting the typology vulnerability index by the existences of the several typologies present in the region.

Exposure was described by the replacement value of building stock, *RVBS*, in the region and by the resident population, Np_T. In order to set a value for economic losses the average area of building floors, in each Census track, was multiplied by the official construction prices.

Figure 4.1, left, shows Portuguese administrative regions and right illustrates the geographic distribution, at a county level, of the variables that explain expected annualized earthquake risk. These maps shows the severe hazard level in the Southwest of the country, the high average vulnerability in the Southeast of Alentejo (Baixo Alentejo) and the important exposure in the Metropolitan regions of Lisbon and Porto.

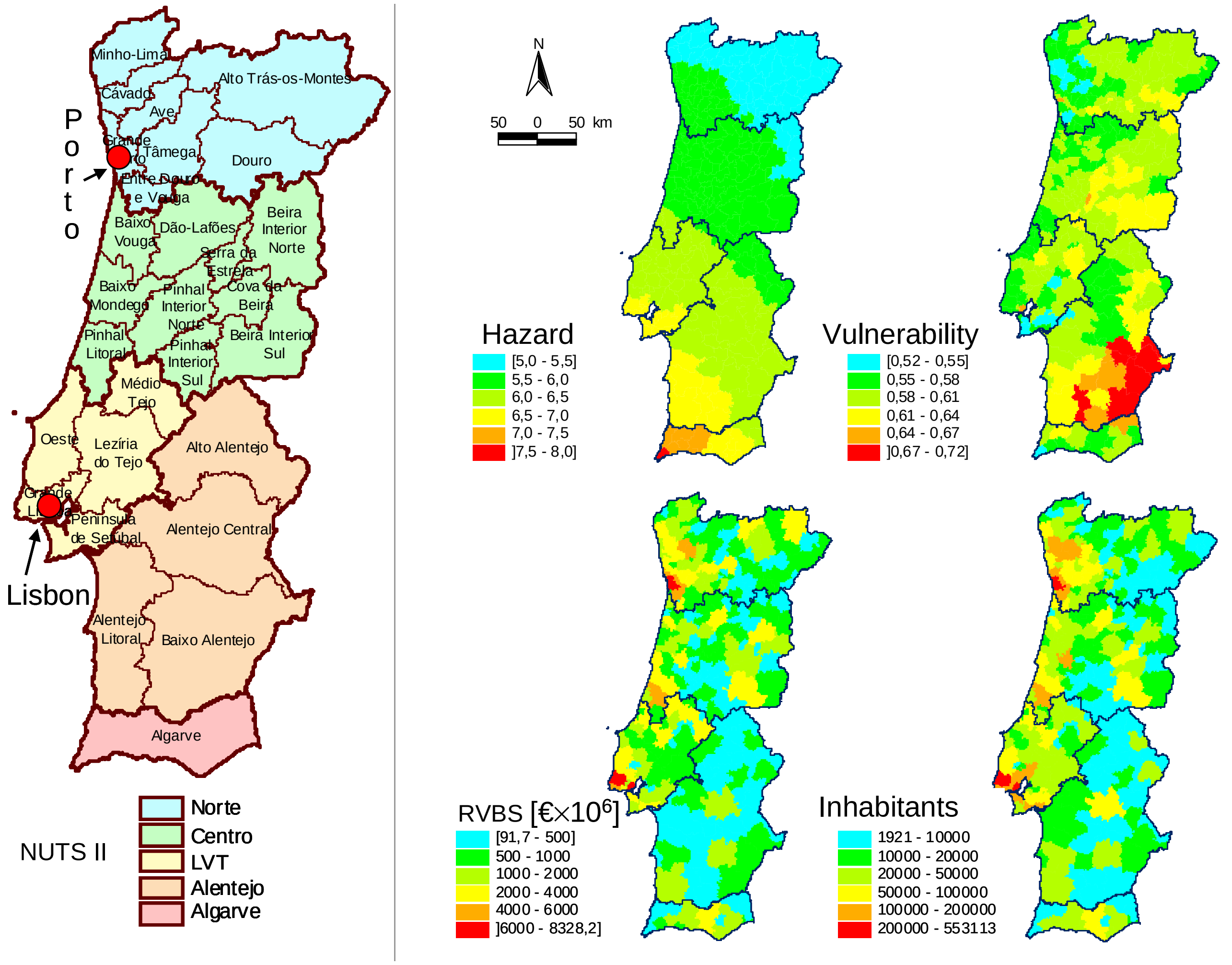

Figure 4.1 Left: Portuguese administrative regions. Right: Variables that explain seismic risk by county (adapted from Sousa, 2006)

4.2. Analysing expected annualized earthquake losses by county

Figure 4.2 presents the geographic distribution, at a county level, of the expected annualized economic earthquake losses.

Specific risk parameters, *AELR* and *AELC*, (top of figure 4.2) have high values in the South of the country, due to to the influence of high hazard and vulnerability values, whereas the geographic distribution of *AEL* (bottom of figure 4.2) evidences higher losses in Lisbon Metropolitan Area, due to the important exposure in this region and moderate hazard level.

Figure 4.3, left, exhibits the social risk parameters expressed in terms of expected number of deaths in one year, *AHL*, as a consequence of Portuguese seismicity, and figure 4.3, right, depicts this risk indicator normalized by the inhabitant's number in each county, *AHLR*. The pattern of the human losses geographic distribution is similar to the one observed in figure 4.2 referring to economic losses, more precisely, absolute risk is concentrated in Lisbon Metropolitan Area due to high exposure and moderate hazard, whereas specific risk is significant in the South of the country, due to to the influence of severe seismic hazard.

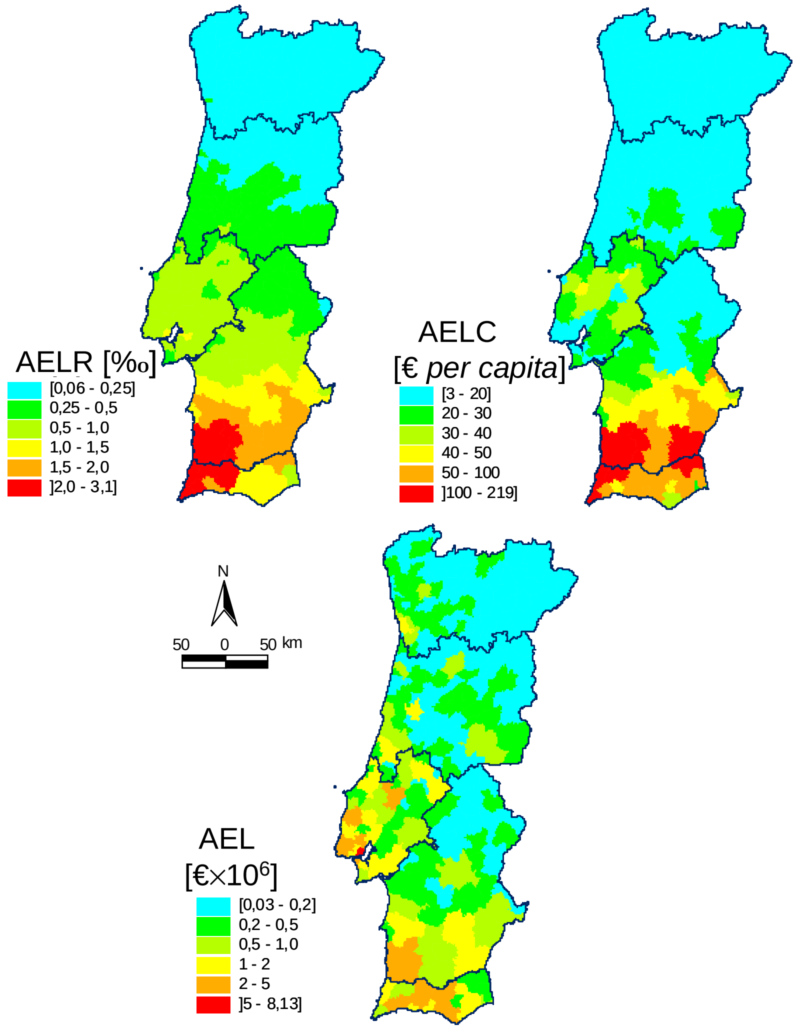

Figure 4.2 Expected annualized economic earthquake losses by county (adapted from Sousa, 2006)

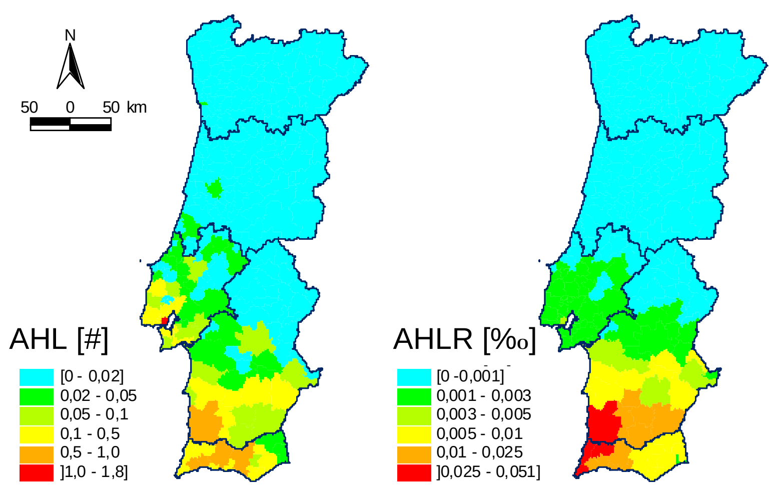

Figure 4.3 Expected annualized human earthquake losses by county (adapted from Sousa, 2006)

4.3 Cumulative expected annualized earthquake losses

When elements in risk are distributed spatially in a region, individual losses are not statistically independent and their variance may not be added without considering losses spatial correlation (EERI, 2000). However, although spatial correlation is essential to describe the global loss distribution, one may accumulate expected individual losses to obtain the region global expected annualized earthquake losses.

In table 4.1 expected annualized economic and human earthquake losses were accumulated for regions broader than counties, namely regional Census tracks (NUTS II, see figure 4.1) and Portuguese country (PT). This analysis provides a global perspective of Mainland Portugal seismic risk and allows a comparison of risk levels between regions. The same table exhibits the inventory of the elements at risk and correspondent exposure values. The higher values of the analyzed variables are bold signed.

Table 4.1 – Ranking Mainland Portugal regions by their exposure and expected annualized earthquake losses

		Norte	Centro	LVT	Alentejo	Algarve	Total PT
Exposure	Counties [#]	**86 (31%)**	78 (28%)	51 (18%)	47 (17%)	16 (6%)	278 (100%)
	Buildings [#]	**1 100 329 (37%)**	758 480 (25%)	721 868 (24%)	256 439 (9%)	160 543 (5%)	2 997 659 (100%)
	Inhabitants [#]	**3 667 602 (37%)**	1 773 498 (18%)	3 426 179 (35%)	531 520 (5%)	390 310 (4%)	9 789 109 (100%)
	Build. area [$m^2 \times 10^6$]	**247 (40%)**	141 (23%)	155 (25%)	37 (6%)	31 (5%)	611 (100%)
	RVBS [Euro $\times 10^6$]	**124 312 (40%)**	69 312 (22%)	82 530 (27%)	18 108 (6%)	15 460 (5%)	309 722 (100%)
Seismic risk parameters	*AEL* [€ $\times 10^6$]	17 (13%)	18 (14%)	**56 (42%)**	19 (14%)	24 (18%	135 (100%)
	AELR [‰]	0,14	0,27	0,68	1,06	1,54	0,44
	AELC [€ *per capita*]	5	10	16	36	**61**	14
	AHL [#]	0,2 (2%)	0,4 (3%)	**5,6 (40%)**	2,7 (19%)	5,2 (37%)	14,1 (100%)
	AHLR [‰]	0,0001	0,0002	0,0016	0,0052	**0,0133**	0,0014

From the analysis of results presented in table 4.1 it can be noted that: (i) Norte region groups 31% of Mainland counties but is responsible for 40% of the building stock replacement value, which is the higher value between the five analyzed Portuguese regions; (ii) in accordance to building inventory exposure, Norte region also concentrates high values of human elements at risk, grouping 37% of Mainland resident population. In the other hand, Alentejo and Algarve South regions represent only 5 and 4% of surveyed inhabitants in 2001 Census, respectively; (iii) in what concerns economic seismic risk the majority of losses is concentrated in Lisboa e Vale do Tejo (LVT) region. This region groups 27% of building stock replacement value, but due to its moderate hazard and higher vulnerability in Lisbon town is responsible by 42% of the global annualized economic earthquake losses (*AEL*) in Mainland Portuguese territory. Algarve region, that aggregates only 5% of building inventory exposure, due to its severe hazard level occupies the second position in terms of economic absolute earthquake losses in this territory, with 18% of losses (*AEL*); (iv) ordering the five regions by decreasing social risks, one may observe that Lisboa e Vale do Tejo is again the Portuguese region where are expected the highest annual absolute losses due to earthquakes (*AHL* = 40%), being closely followed by Algarve region (37%); regarding social relative losses (*AHLR*) Algarve region sets apart from the remaining regions, reaching a value more then double of the *AHLR* value for the second position region, i.e., Alentejo.

4. CONCLUSIONS

This study addressed direct economic and social losses in Portuguese residential building inventory and their inhabitants. Bearing in mind the assumptions and limitations of the present work one may conclude that: (i) specific earthquake risk always increases from North to South of Portuguese Mainland territory, independently of the analyzed losses being economic or social, in accordance with the increase of seismic hazard severity from North to South and with the high regional average vulnerability in Alentejo; (ii) absolute seismic risk is influenced by exposure and hazard, showing its highest values in the Metropolitan region of Lisbon; (iii) expected annualized Mainland Portugal economic earthquake losses were estimated as 0.11% of Gross Domestic Product (GDP) in 2001 (2001 was the date of the building and inhabitants Censos that was used in this work).; (iv) specific expected annualized economic earthquake losses are close to 0.04% of habitable area of the building surveyed in 2001 Censos; (v) Mainland Portugal expected annualized human earthquake losses (*AHL*) amounts to 14 deaths *per annum*.

This latter conclusion deserves some comments: this work estimated *AHL* is 20 times larger than the annualized observations in the same territory for the 20th century. In fact, in this 100 years period a total of 59 people were killed by earthquakes. Nevertheless, the average annualized observations for the last 250 years were 7 times larger than the result of the present study, mainly due to 1755 Lisbon earthquake.

Finally, we shouldn't forget, as FEMA (2001) refers, that «annualized risks averaged over many years may appear small given the wrong impression of risk due to a single event».

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