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ORIGINAL RESEARCH PAPER

The 1531 earthquake revisited: loss estimation in a historical perspective

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Abstract In this research, the 1531 earthquake is revisited. This was one of the major earthquakes that affected Portugal and, specifically, Lisbon. According to coeval sources, between 1000 and 30,000 casualties were caused in Lisbon by this tremor. This range shows the great uncertainty regarding the real effects of this Event. Analyzing the real dimension of this earthquake is the goal of this research. For that purpose, this work proposes a methodology for analyzing the destruction of historical towns. The social consequences of the quake have also been investigated. To do so, a seismic risk simulator, called SIRCO, has been used. A thorough analysis of Lisbon, prior to 1531, has been done. Firstly, the geological characterization has been included. Secondly, the building stock has been reconstructed and characterized. Next, the buildings macroseismic vulnerability index and the buildings vulnerability curves have been calculated. Finally, all this information has been gathered together in a geographical information system. The results show that the most affected areas were those located in the lower part of the city and next to the Tagus River. The simulation carried out for the 1531 Earthquake estimates 46 immediate deaths and between 158 and 397 deaths during the first week after the earthquake. The estimated total of casualties is 1000. A description of the physical and sociological losses caused by this natural event is made.

Keywords The 1531 earthquake · Seismic risk simulator · Historical seismicity · Lisbon · Sixteenth century

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1 Introduction

On the 26th of January 1531, an earthquake seriously hit Lisbon according to coeval sources and archaeological remnants (Baptista et al. 2014). The historical records show that this event caused a relevant damage in the city downtown and neighboring areas.

For this event, in terms of coeval records, Baptista et al. (2014) mentioned that the shock heavily struck downtown Lisbon and neighboring areas, causing approximately 1000 casualties (Vogt 1985; Justo and Salwa 1998). However, Bharatdwaj (2006) claimed that there were approximately 30,000 deaths. Vidal (2012) and Rossa (2002) argued that the 1531 Event was even worse than the 1755 Earthquake in terms of losses of human lives. With respect to physical losses, the records describe that the earthquake caused large destruction in the city and *damaged about one-third part of the building stock* (Miranda et al. 2012). Considering the “public buildings” labeled by Henriques et al. (1988), which corresponded to the most precise construction of that time, Miranda et al. (2012) concluded that the damage was primarily noted in buildings found in new landfills which were possibly unconsolidated. That was the case of the Ribeira Palace and the San João da Praça Church within the old city wall. There are some other written-proofs: *all palaces cracked in many places* and *many churches were ruined* (Osório 1919). An analysis of the number of damaged houses was provided by Vogt (1985), mentioning from 200 to 1500 houses. The great difference in the numbers shows the scarcity of knowledge regarding this event. In fact, today it is disputed if this event was similar to the prominent 1755 Lisbon Earthquake (Chester and Chester 2010), or to the 1344 Earthquake (Vilanova et al. 2003 and Moreira 1984) or even to the 1909 Benavente Earthquake (Moreira 1991). Determining the real dimension of the 1531 Earthquake is the goal of this research. To do so, a seismic risk simulator for Iberia called SIRCO (“SImulador de Risco sismiCO” in Portuguese) presented by Sá et al. (2016) has been used.

In this work an analysis of Lisbon in the Sixteenth century has been done. This includes the geological characterization, architectural and urban analysis, the social analysis, the dwelling characterization, the dwellings macroseismic vulnerability index, and buildings vulnerability curves. A GIS has been used for this purpose. An analysis of the coeval and the historical data of the 1531 Earthquake has been carried out. This has been focused on the earthquake itself, building stock and human losses. Finally, the social consequences of the earthquake have been analyzed.

2 Earthquake loss estimation

Earthquakes, through their devastating effects—due to ground motion, earth faulting, tectonic deformation, soil liquefaction, landslides—are a serious threat facing modern society. Seismic risk is tending to become more severe nowadays due to the increasing exposure related with the growth of urban or/and industrialized areas in earthquake-prone locations.

Lantada et al. (2010) defined “Urban seismic risk” as the convolution of hazard and vulnerability. They described the potential expected loss, which can be represented in maps, showing the expected damage of the urban area due to a specified earthquake. In a broader definition, the UNISDR (2015) defined “disaster risk “as the combination of the severity and frequency of a hazard, the numbers of people and assets exposed to the hazard, and their vulnerability to damage. Besides the diversity of possible concepts for “risk“ or "disaster risk", Earthquakes Loss Estimation Software (ELES) programs have been devised and built as "risk simulators". This software supports decision makers, planners and structural engineers in determining the seismic risk for dwellings and infrastructures. In fact, the combined used of ELES and Geographic Information Systems (GIS) has largely enhanced the output data research fields that are available for end-users.

Recent ELES can be employed within near real-time loss estimation systems by applying direct values of strong motions as inputs, in conjunction with vulnerability information. At a European level, seismic regions such as Turkey, Italy and Romania have experimented with this type of computerized solutions and had good outcomes (Dragos et al. 2015), intending to verify the level of quality of earlier estimations. Nevertheless, there is a level of inaccuracy that ELES software is certain to have, and this fact will have to be dealt with adequately (Dragos et al. 2015).

Portugal is located in the southwestern part of the Eurasian Plate, near the border of the African and North-American Plates. It is therefore subjected to offshore seismic events, having large to very large magnitudes (such as the well-known 1755 Lisbon Earthquake), and to moderate to large onshore earthquakes (Moreira 1989). This tectonic environment induces a low to moderate seismic hazard, which in countries similar to Portugal has caused considerable economic and human losses (Barata 2005).

Seismic losses of the 1531 Event have been analyzed and assessed using the SIRCO engine. This is a regional seismic risk computer simulator developed for the Portuguese Civil Protection that employs worldwide accepted methodologies which are carefully described in Sá et al. (2016). The assessment refers to the following issues: the site-dependent seismic hazard, the expected seismic response of buildings, the seismic vulnerability of structures, the seismic damage and human losses. The analysis of the spatial distribution of the existing building stock as well as the presentation of the results on expected direct seismic losses have been performed using a GIS.

A seismic risk simulator allows the study of different damage-scenarios for any virtually-generated earthquake. SIRCO uses specialized algorithms such as the Spatial Analyst (ESRI 2017a) and 3D Analyst (ESRI 2017b). Additionally, the calculation functions and the whole operation-software were elaborated or transferred (in the case of modules of calculation developed in other programming languages) to Visual Basic (Sá et al. 2016). The earthquake-parameters to be introduced in SIRCO consist of a geographical location, usually given by a pair of coordinates, a magnitude and an hour of the day.

In terms of the seismic risk model considered in this work, a deterministic approach has been chosen. Based on the estimated location of the 1531 Earthquake, the distance to the site has been computed. Given the magnitude, the distance, and the number of standard deviations for the ground motion, this has then been computed for each earthquake scenario, using a set of ground motion prediction equations that have been based on either empirical ground motions or numerical simulations of ground motions, as specified in Sá et al. (2016). The approach is "deterministic" in that single values of the parameters have been selected for each scenario (Abrahamson 2006).

3 Vulnerability characterization

In this section, the data and the resources used to study the 1531 Earthquake are presented. Firstly, the sources to obtain the geology underlying the city of Lisbon are shown. Secondly, the architecture of Sixteenth century Lisbon is described. Thirdly, a social and

Table 1 Evolution of Lisbon by Silva (1972), Rodrigues (1970) and Rodrigues (1988)

Year	City population	City dwellings
1528	± 70,000	14,014
1535	65,581	13,010
1551	112,830	17,930
1590	± 120,000	Not available
1620	128,725	26,813

demographic analysis of the city during that century has been performed and the buildings have been characterized. Next, the macroseismic vulnerability index for each dwelling type has been calculated and the buildings' vulnerability curves have been obtained. Finally, all this information has been compiled in a GIS for its use.

3.1 Demographic analysis

Silva (1972) and Rodrigues (1988) estimated Lisbon´s population then to be about 70,000 inhabitants. This was done by analyzing the information available in *Cadastro Geral do Reino*, a census work and the manuscript requested by King D. João III in 1527. This was indeed the first real census of the Portuguese population (Oliveira Marques and Alves Dias 1994). According to the same document, Lisbon had about 14,000 dwellings which gave an average population density of about five persons per dwelling (Table 1).

In social terms, the Portuguese society at the beginning of the Sixteenth century was characterized by a strong social stratification. The partition of society into orders, headed by the nobility, generated a sharp social inequality. This was differentiated between the nobility (the great, the nobles and the knights) and those who had no horse and means of war-combat, or those who exercised as a craftsman or a farmer (Saraiva 1985). Another social stratum of great importance in the society was the clergy. In fact, the clergy was considered the first order because it was the server of and mediator with God. This class had its own internal hierarchy. Therefore, immunities and its own laws that nullified the secular sphere provided it with a comfortable position in the social hierarchy (Saraiva 1985). With two dominant strata—the clergy and the nobility—it is important to stress that the survival of the vast majority of the population depended on relationships in common. That is, the successful integration of the individual depended on his/her inclusion in the corporate system. Belonging to an order or trade was a way of defending one's social and economic interests, but also a means of setting out one's status in society as a whole, which remained a tripartite system: *oratores* (those who pray), *belabores* (those who fight) and *laboratores* (those who work) (Anderson and Bellenger 2013).

Finally, a particular result of Portuguese discoveries must be mentioned. The contingent of African slaves gained a new expression, particularly in Lisbon. They constituted a workforce that replaced the ones who sailed away attracted by the enrichment provided by the exploitation of overseas territories (Fonseca et al., 2015).

3.2 Building characterization

By the time of the Renaissance, Lisbon was a large city that had developed over roughly five centuries. Nevertheless, its urban structure remained that of a medieval settlement—vast, disorganized and without a plan or proportions—except for some new

Fig. 1 Lisbon in 1520 by António de Holanda (left) and in 1572 by Braun and Hogenberg (right)

streets in the *Bairro Alto* area (Calvo 2015). Most of the streets were narrow, dirty and uncomfortable. The religious buildings were the heart of each neighborhood (Amelang 2016). According to Henriques et al. (1988), at least three factors that affected the geometry of Lisbon can be pointed out. Firstly, Lisbon has a very irregular topography which has brought about its streets being rarely straight and non-geometrically organized. Secondly, the city has a great Muslim heritage with compressed spaces between walls, compact houses, alleys, interior patios and outdoor particularities, still visible today in the districts of *Alfama* and *Mouraria*. Finally, in the lower part of the city, the buildings were constructed along rural paths that already existed, thus going outward from the old city walls.

The city of Lisbon was poorly organized, having narrow streets and alleys. This made a random blend of houses and streets with problems of circulation, hygiene and, particularly, crime at night when empty streets prevailed in the city (Amelang 2016). Nonetheless, the city blossomed with the construction of new buildings and the demolition of the oldest. Yet this rebuilding still had an irregular shape that denoted a lack of planning. There is evidence that the streets were jammed with waste dumps and that the downtown area flooded frequently, covering the streets with mud (Gschwend and Lowe 2015).

In this research, in order to recreate the Sixteenth century Lisbon building stock (largely destroyed by the 1755 Earthquake), coeval data and the following information, collected from dissimilar sources, has been used:

A. An analysis of old Lisbon paintings by António de Holanda and Braun & Hogenberg (Fig. 1).
B. A detailed model analysis of the city prior to the 1755 Earthquake, made by Gustavo Sequeira and Ticiano Violante in 1955. Today this physical model belongs to the city museum´s permanent collection (Fig. 2).
C. A web project that allows a virtual 3D tour of the 16th–18th Century *Terreiro do Paço* area (Fig. 3) (Murteira et al. 2015).
D. Scientific and scholar works published on the 250th anniversary of the 1755 Earthquake (Mendes-Victor et al. 2008).

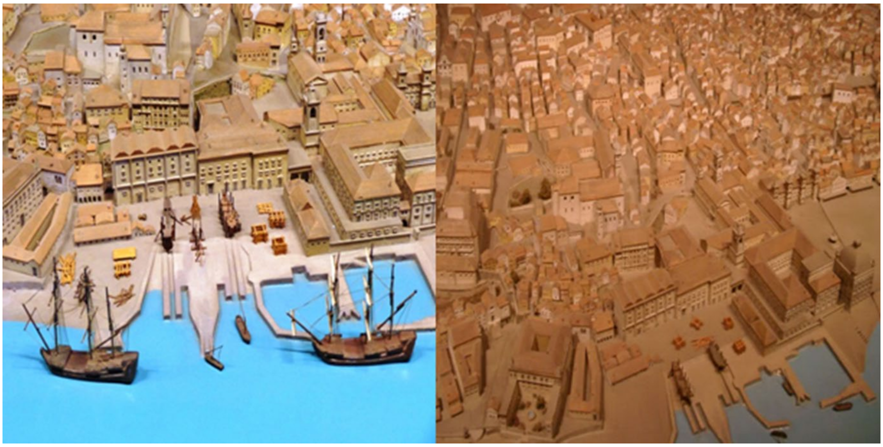

Fig. 2 City model of Lisbon before the 1755 Earthquake

Fig. 3 *Terreiro do Paço* area between the 16th and the18th Century

Gathering urban and architectural information has been essential in this analysis, allowing a confirmation cross-checked with coeval sources of the 1531 Earthquake and related building stock losses. Furthermore, it has been possible to use this information to extrapolate potential damage states. In fact, a review of the buildings' vulnerability is especially important for earthquake risk assessment. Moreover, it is particularly significant for old buildings in historic centers where this can be a relevant risk-factor. The seismic vulnerability assessment of ancient buildings must be related to isolated buildings of relevant historical and cultural importance, but also to clusters of old buildings in historical urban centers (Vicente et al. 2011).

Social segregation, as characterized above, was a mirror of the lodging typology that each social class typically occupied. Noble houses were built using massive stone with good masonry work. Clergymen's buildings would normally use brickwork or massive stone, depending on the occupant's importance in the social or in the church hierarchy. The common people's housing was made with adobe walls and wooden slabs. Only the small

Fig. 4 Lisbon landmarks location in the 16th Century (adapted from Baptista et al. 2014)

bourgeois class that thrived on commerce and trade occupied slightly better constructions. In order to qualify the 16thCentury buildings, some prior bibliography and local observations from a few existing buildings in today´s Lisbon (Fig. 4) have been used by researchers such as Santos (2006).

According to Henriques et al. (1988), in the first half of the 16th Century the predominant Lisbon buildings had two or three floors. There were three floors particularly in central areas such as near the *Alfama* or the *Sé*. There were also simple one-floor houses in the peripheral areas. The plots were generally narrow in front and wide toward the back. Moreover, the houses were relatively high, forming the type called the "gothic plot", as described by Bork (2014).

Balconies were common, the buildings advancing on the upper floors, gaining useful housing area. The law allowed using up to one-third of the area of the public street and, if two opposing buildings belonged to the same owner, a bridge could be made to connect both. This type was clearly more vulnerable to a seismic event. The wood was of good quality although not abundant. For this reason, it was primarily used in floors and roofs (Henriques et al. 1988).

The use of limestone, plentiful in this region, would be likely, but it was expensive due to its shipping costs. So, the alternative was the employing of mud walls (with/without horizontal wooden elements) and the use of adobe. Stone was reserved for noble uses (Santos 2006).

The buildings that resisted the 1531 and 1755 Events are mainly localized in the historic neighborhoods of *Alfama*, *Castelo, Mouraria* and *Bairro Alto* (Calvo 2015). The evolution of the buildings is a process that develops over time in a dynamic way and is a consequence of different factors. Accordingly, any attempt to create a typological classification is a non-rigorous process (Santos 2006). Nevertheless, buildings can first be classified by their appearance. An aggregation can be made by some characteristics into three major groups:

- *High-quality Buildings without a floor ledge* These are the ones featuring masonry walls, well cared for, at least in the paired stone corners and locking elements;
- *Low-quality Buildings without a floor ledge* These are the ones whose walls are of poor masonry, often run-down mud walls, showing large permanent deformations and, in

many cases, having a total absence of locking elements. In most cases, the walls present a considerable thickness. The decks, except for rare exceptions, present small bays and are usually wooden houses;

- *Buildings with a floor ledge* These buildings are composed of a ground floor in stone masonry and an arched floor that supports one or two floors with a wooden structure, protruding in relation to the ground floor. The exterior cladding of the walls is carried out with mixed masonry;

Additionally, other factors have also been considered:

- Existence of slant-fronted buildings (two roof water perpendicular to the façade);
- Presence of buildings having two to three floors, with deployment areas ranging from 40 to 150 m^2;
- A high density construction of the downtown and Castelo hill areas. In the periphery there is a gradual decline, as exemplified by *Bairro Alto*, where the plots are already delineated but not fully occupied;
- A comprehensive survey of religious buildings, which were singular by area, volume and even construction type, where brickwork was largely used, thereby making them massive buildings;
- Existence of buildings locked into the city walls.

All this information has been grouped together to attain the Vulnerability Index Method (hereinafter, VIM), which has been obtained from the Risk-UE Project (Mouroux et al., 2004). Contributions from other approaches (Irizarry et al. 2004; Mouroux et al. 2004; Lantada et al. 2009) have also been used to extrapolate the value of the Vulnerability Index (hereinafter, Vi) for each building class. Also, the contribution of Lagomarsino and Podesta (2004) for monumental buildings such as, for example, the Ribeira Royal Palace, the Alcaçova Royal Palace and the Hospital of Todos os Santos has been considered.

3.3 Buildings macroseismic vulnerability index

A classification table has been created using the VIM methodology. This relates the construction typology with the buildings-classification (Grünthal 1998; Lantada et al. 2009). In VIM the seismic action is expressed by the macroseismic intensity. The susceptibility of the buildings is defined by means of a Vi (Lantada et al. 2010) value which is dependent on their own conservation state. This ranges from Bad (Vi −), to Regular (Vi avg) or to Good (Vi +) (Lagomarsino and Podesta 2004). A conservation status has been attributed by analyzing the coeval records and the works that included references to the stock building age (D'Ayala et al. 1997; Santos 2006; Lantada et al. 2010), the conservation and the damage condition before and after the 1531 Earthquake and before the 1755 Event.

Concerning Table 2, the area of each reference typology has been obtained from the spatial analysis of the oldest plan available for Lisbon. This was made in 1650 by João Nunes Tinoco. This plan has an enormous value, since it is the oldest known plan of Lisbon, although the original has disappeared (Ricardo da Costa et al. 2015). It is accurate in terms of the location of the main buildings, their general usage and the delimitation of streets, and structures which already existed in 1531 and which did not undergo major changes until the 1755 Earthquake (Henriques et al. 1988). It should be noted that before the 17th Century there is only knowledge of perspective views of Lisbon.

Table 2 Vulnerability index parameters

Reference typology	Vulnerability index (Vi)	Conservation remarks	Source for Vi and conservation status (when possible)	Area (m^2)	Ductility index (Di)	Typology class
Religious/Churches Clergy	0.890	Regular (Vi avg)	Churches (Lantada et al. 2004)	79,004	3.0	A
Common—Older Neighborhoods	0.873	Bad (Vi -)	M1.1 (Grünthal 1998)	581,690	2.3	B
Noblemen/Upper Bourgeoisie	0.776	Regular (Vi avg)	M3.2 (Grünthal 1998)	104,236	2.3	C
Alcáçova Royal Palace	0.766	Bad (Vi -)	Palace (Lagomarsino and Podesta. 2004; Henriques et al.1988)	5146	2.3	D
City Walls Embedded	0.746	Bad (Vi -)	Walls (Lantada et al. 2004)	50,622	2.3	E
Common—New Neighborhoods	0.740	Regular (Vi avg)	M1.2 (Grünthal 1998)	199,283	2.3	F
Ribeira Royal Palace	0.496	Good (Vi +)	Palace (Lagomarsino and Podesta. 2004; Henriques et al. 1988)	9567	2.3	G
Hospital de Todos os Santos	0.616	Good (Vi +)	Monastery (Lagomarsino and Podesta. 2004; Henriques et al. 1988)	4578	2.3	H
Cathedral	0.736	Regular (Vi avg)	Monastery (Lantada et al. 2004)	2344	2.3	I

Table 2 also designates for each type of construction identified a most likely factor of vulnerability (Vi) along with a likely range, depending on the conservation status of the building itself (Lagomarsino and Podesta. 2004). The Vi has been usually defined ranging from −0.02 to 1.02 (Lagomarsino 2006). Nevertheless, vulnerability indices are normalized using values between 0 (least vulnerable buildings) and 1 (most vulnerable buildings). This method classifies the existing building typologies and defines their vulnerability class. For each vulnerability class, the relationship between intensity and damage is defined by using Damage Probability Matrices (DPM) (Whitman 1973).The method proposed is derived from the European Macroseismic Scale EMS-98 that implicitly contains a description of the DPM for each vulnerability class (Parodi et al. 2008). In order to describe the damage distributions (associated with each value of μD), a probabilistic distribution derived from the discretization of a beta distribution in the interval [0, 5] is adopted as recommended by the ATC 13 (1985) and stated by Oliveira et al. (2004).

$$p_\beta(x) = \frac{\Gamma(\mathrm{t})}{\Gamma(\mathrm{r})\Gamma(\mathrm{t}-\mathrm{r})} x^{r-1}(5-x)^{t-r-1} \tag{1}$$

where t and r are the distribution parameters. They are defined as a function of the average value and the variance from Eq. 2. Γ is the gamma function (Parodi et al. 2008).

$$\mathrm{t} = \frac{\upmu_\mathrm{x}\left(5-\upmu_\mathrm{x}\right)}{\sigma_\mathrm{x}^2} - 1 \tag{2}$$

$$\mathrm{r} = \mathrm{t}\,.\frac{\mu_\mathrm{x}}{5} \tag{3}$$

A discrete distribution, also dependent on the two parameters t and r, may therefore be defined in the following form (Parodi et al. 2008):

$$p(0) = p_\beta(0.5);\ p(k) = p_\beta(k+0.5) - p_\beta(k-0.5);\ p(5) = 1 - p_\beta(4.5) \tag{4}$$

where

$$p_\beta(x) = \int_0^x \frac{\Gamma(\mathrm{t})}{\Gamma(\mathrm{r})\Gamma(\mathrm{t}-\mathrm{r})} x^{r-1}(5-x)^{t-r-1} dx \tag{5}$$

The limited variation found in the values assumed by the parameter t for the numerical damage distributions taken from the EMS-98 allows one to assume a single value for t (equal to 8) as representative of the variance of all the possible damage distributions (Bernardini et al. 2007). Defining such a parameter a priori, it is thus possible to define the damage distributions exclusively through knowledge of the average value, but characterized by a variance coherent with that found from the completion of the EMS-98 matrices.

Using Microsoft Excel 2010, the parameters of the Beta distribution have been correlated with the Mean Damage grade μD. The variable will be estimated for the buildings' Vi and the corresponding seismic intensity (I) as follows (Giovinazzi and Lagomarsino 2004):

$$\mu\mathrm{D} = 2.5\left[1 + \tanh\left(\frac{1 + 6.25\mathrm{Vi} - 13.1}{\mathrm{Di}}\right)\right] \tag{6}$$

where: Vi is the vulnerability index and Di is the Ductility Index that is evaluated taking into account the building typology and its constructive features (for more details refer to Lagomarsino 2006).

Fig. 5 Vulnerability curves for the typologies of 16th Century Lisbon buildings

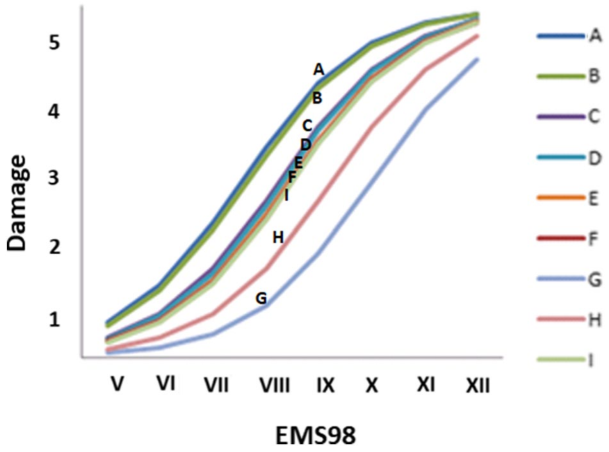

Table 3 Most likely damage level by macroseismic intensity in function of the building typology

EMS-98	A	B	C	D	E	F	G	H	I
V	D1	D1	D1	D1	D1	D1	D1	D1	D1
VI	D2	D1	D1	D1	D1	D1	D1	D1	D1
VII	D2	D2	D2	D2	D2	D2	D1	D1	D2
VIII	D3	D3	D3	D3	D3	D2	D1	D2	D2
IX	D4	D4	D4	D4	D4	D4	D2	D3	D4
X	D5	D5	D5	D5	D4	D4	D3	D4	D4
XI	D5	D5	D5	D5	D5	D5	D4	D5	D5
XII	D5	D5	D5	D5	D5	D5	D5	D5	D5

The genesis of this semi-empirical expression derives from the adjustment of the DPM values, leading to a hyperbolic function to estimate the physical damage (Vicente et al. 2010). Repeating this process for each vulnerability class and for the different intensity grades, it is possible to obtain, point by point, the likely and probable bounds of the mean damage. Linking these points, draft curves are plotted. These define the likelihood and possibility areas for each vulnerability class, as a function of the macroseismic intensity and to define a mean damage grade. The vulnerability curves obtained are called semi-empirical vulnerability functions (Belheouane and Bensaibi 2013) and are depicted in Fig. 5.

As stated above, depending on the Macroseismic intensity (I-XII), the vulnerability curves indicate the likelihood of a building typology suffering some degree of damage (from D1 to D5) when faced with an earthquake (Lantada et al. 2010). For this work, the results are shown in Table 3.

This table correlates the seismic intensity (V-XII) with the building typology (A-I, Table 2) and provides an expected damage result (D1-D5). All the information described above has been grouped together in a GIS project using ArcMap™ 10.1

Lisbon's quarters have been geo-referenced by digitalizing Tinoco´s map as shown in Fig. 6. For each block, the related information (Table 2) has been inserted into a geo-database. This has enabled the assigning of a vulnerability curve for each quarter and, consequently, a likely damage level for each seismic intensity.

Fig. 6 Detail of the digitalization of Tinoco´s Lisbon map into a shapefile

4 Hazard estimation

The seismic hazard has been characterized by a conventional deterministic approach that defines the seismic source or sources that affected the site of interest and then estimates the maximum possible earthquake magnitude for the source. The ground motion has been predicted by assuming a maximum earthquake to occur at a location that places the earthquake at the minimum possible distance from the site. This has mostly been done by utilizing an empirical attenuation relation that has been later subjected to the site effects estimation. For additional information on this software, the ground motion model adopted, the attenuation laws employed and the methodology applied for the site effects estimation, please refer to Sá et al. (2016). In this section, coeval and historical data for the 1531 event are described and compared with the data obtained by SIRCO, including the existence of possible site effects near the river banks. An intensity value has been defined for each building area using a GIS spatial analysis and, consequently, a likely damage level has been defined.

4.1 The earthquake

The 26th of January 1531, an earthquake struck between 4 and 5 a.m. It was felt in Lisbon and along the Tagus Estuary. The maximum reported MSK intensity was IX, making it one of the most severe earthquakes experienced in Portugal (Miranda et al. 2012). The approximate location of the epicenter coordinates inferred from the seismic field was 38.9N, 9.0W (Mezcua 1982; Oliveira 1986). According to Justo and Salwa (1998), the seismic event was possibly caused in the Lower Tagus Fault Zone (LTFZ). This is the same probable source of the 1344 and the1909 Earthquakes (Moreira 1991). Rueda and Mezcua (2002) determined an empirical relationship between the maximum intensity and the moment magnitude for earthquakes in south-western Iberia. A maximum MSK intensity of IX was determined for the 1531 Earthquake and a moment magnitude of 6.4 was estimated by Justo and Salwa (1998), a value slightly inferior of Mw 6.9, noted by Vilanova and Fonseca (2007), but within the interval defined by Baptista et al. (2014) of Mw 6.0–6.6.

4.2 Attenuation law

Ground motion prediction equations are an important part of seismic hazard evaluation. This hazard has to be expressed in macroseismic intensities in the case of seismic risk estimations where a relation to the damage associated with ground shaking is necessary. It should be noted that for an event with these characteristics, SIRCO uses a pool of attenuation relationships that have been tested against observed macroseismic intensities from stable continental regions (Sá et al. 2016). In this framework, two attenuation laws have been selected:

- Esteva and Rosenblueth (1964); included due to its use in the past, with practical results, in some older simulations made by the Portuguese civil protection. Furthermore, it is a law still widely used in seismic engineering (Datta 2010).

$$I\mathrm{MMI} = 8.16 + 1.45M\mathrm{w} - 2.46\ln(\mathrm{Repi}) \tag{7}$$

- Sousa and Oliveira (1996); that resulted from a work on records from macroseismic data of earthquakes registered in the Portuguese seismic catalog. Values for $\mathrm{C}_{1\ldots\mathrm{n}}$ depend on the earthquake type as defined by the EuroCode 8, National Annex for Portugal (EN 1998-1).

$$I\mathrm{MMI} = C1 + C2M\mathrm{w} + C3\ln(\mathrm{Repi}) + C4\mathrm{Repi} \tag{8}$$

4.3 Site effects

SIRCO outputs are a set of generated potential damages caused by a seismic scenario. This is the number of:

- Damaged and collapsed buildings;
- Occurrences in the public service networks;
- Dead, or wounded or even dislodged people;

This information is also provided geographically through a representation in maps of damage distribution. However, for this particular research a different approach has been made regarding geological data. At a national level, SIRCO used a geological input provided by the Portuguese geological chart on a 1:1000,000 scale (available through the OneGeology Project, Baker and Jackson 2010). Nonetheless, for a more detailed analysis, this source is somewhat inaccurate. So, in this research, a geological study set made a few years ago for the Lisbon Municipality region on a 1:10,000 scale (Almeida 1986; Almeida and Almeida 1997) has been used for estimating amplification or de-amplification phenomena due to top layer characteristics.

Seismic site effects are related to the amplification of seismic waves in superficial geological layers. The surface ground motion may be strongly amplified if the geological conditions are unfavorable, such as the ones near the shoreline of the Tagus River in Lisbon. Those consist of Holocene alluvial deposits made of unconsolidated sediments that have been deposited by running water from the Tagus River and tributary streams, filling the main valleys, and artificial deposits associated with the urban evolution, as described by Teves-Costa et al. (2012). For the estimation of this phenomenon a 1D layer model has been considered and the impedance contrast process (Le Pense et al. 2011) has been used. The impedance contrast between sediments and bedrock characterizes the soil properties.

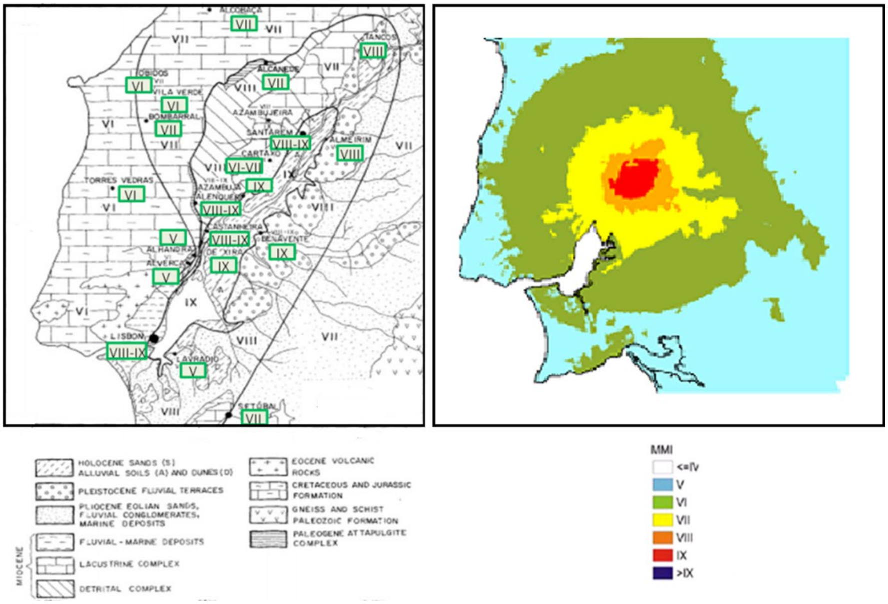

Fig. 7 1531 Isoseismal maps by Baptista et al. (2014)–left- and with SIRCO–right

The lower the impedance contrast, the softer the sediments are compared to the bedrock. It is clear that when two layers which have differing densities overlie one another, an impedance contrast exists. The trapping of seismic waves due to the impedance contrast between the bedrock and the overlying sediments is the primary cause of amplification in those sediments (Semmens 2010). This extrapolates the potential site-effects that might increase or decrease the seismic intensities estimation given by SIRCO's attenuation laws.

5 Results and risk estimation

In this section the results obtained from the simulation of the 1531 Earthquake with SIRCO are presented. Firstly, the isoseismal map and the intensity felt by the buildings are depicted. Next, the building stock losses according to the damage level have been estimated. Finally, the number of dead and injured people has been calculated. The data input for the source model was obtained from the findings of Mezcua (1982), Oliveira (1986) and Martins and Mendes Victor (1990) defining 38.9N and 8.9W as the probable epicenter. Baptista et al. (2014), using Justo and Salwa's (1998) work as a source, seconded this hypothesis by employing the Boxer method (Gasperini et al. 1999), pinpointing a similar epicenter. Simultaneously a likely moment magnitude of $M_w 6.1 \pm 0.3$ was defined for the 1531 earthquake, although a probable tsunami occurrence in the Tagus River endorses a moment magnitude nearer the upper top of this interval (Teves-Costa et al. 2017).

As a result of what has been described above, a synthetic earthquake with $M_w = 6.4$ and epicenter located at 38.9 N, 9.0 W has been simulated with SIRCO (Sá et al. 2016) and shown in Fig. 7 (right). In a qualitative framework it is possible to conclude that the latter has an isoseismal morphology similar to the one presented by Baptista et al. (2014)—Fig. 7 (left).

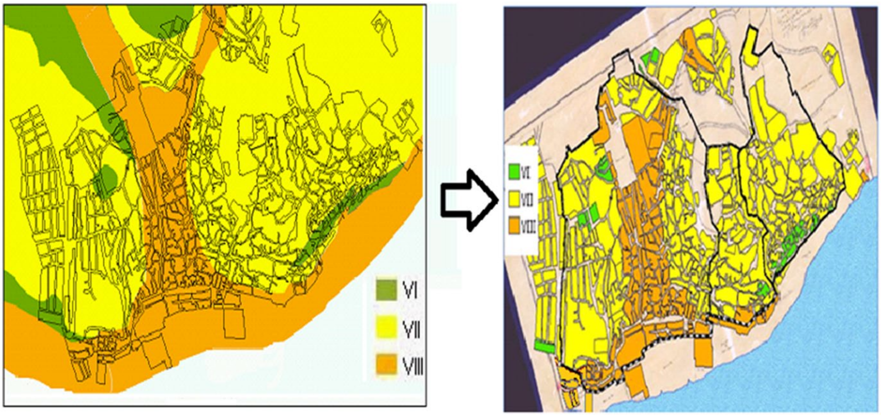

Fig. 8 Local isoseismal map (left) and the designation of intensity by each building (right)

As the present research required working at a "building level", a more detailed isoseismal map has been plotted for the city of Lisbon itself (Fig. 8). This map has also been constructed with SIRCO. It should be noted that the fine details of this map are only achievable due to the local geological survey that supports the model. This information was established by the Lisbon municipality in the early 90s when the first thorough study of the seismic risk of the City was made (Pais et al., 1996). As far as the authors have been able to scrutinize, there is no other work that presents such a detailed isoseismal map for this event. So, at this level an assessment with previous works is not possible. The analysis of the results obtained for this event visibly testifies to the occurrence of site effects phenomena, as observed in Fig. 8. The alluvial deposits that characterize this area show a positive correlation with higher intensities (VIII) when compared with the surrounding area (VI or VII).

A difficulty in this type of analysis is that aggregated spatial data (in variables such as sums or majorities) subsist at different levels of scale on the map. For example, the sum of injury incidents across a quarter cannot be directly compared to that of an entire city or a region (Soysal et al. 2012). For such a type of comparative analysis, it is proposed to normalize the results obtained from the zonal analysis in ArcGIS®—ArcMap™. Zonal analysis (ESRI 2017c) is an analysis tool in ArcMap™ under its spatial analyst extension. In a simple explanation, the zonal statistic function summarizes the values of a raster within the zones of another dataset—either raster or vector—and reports the results as a table. It is useful for several types of GIS-related analysis or studies, such as environmental monitoring, demographic studies, land management, traffic data analysis, and so on (ESRI 2016). As an input zone, the geo-referenced Lisbon quarters' shapefile represented in Fig. 6, and as an input value, the raster of the isoseismal map plotted by SIRCO, has been used by the authors. The final goal is to have a value for intensity per building as presented in the right side of Fig. 8. As the zonal tool quantifies the characteristics of the geometry of the input zones, an intensity value has been assigned to each construction of the 16th Century building stock recreation. Crossing this information with the data obtained from the vulnerability curves (Fig. 5) has resulted in a most likely value for a damage level (EMS98) by building. The zonal statistics which have been employed in this paper follow a raster-based method. Raster-based methods are widely used in environmental and geophysical studies

Table 4 SIRCO damage level (EMS98) estimation for the 1531 Event at Lisbon

EMS 98 damage level	Damage grade	Number of buildings	Percentage of total damaged buildings	Percentage of total buildings
D1	Negligible to slight	27	5.6	0.2
D2	Moderate	369	76.7	13.2
D3	Substantial to heavy	75	15.6	2.7
D4	Very heavy/pre-collapse	10	2.1	0.4
D5	Collapse	0	0.0	0.0

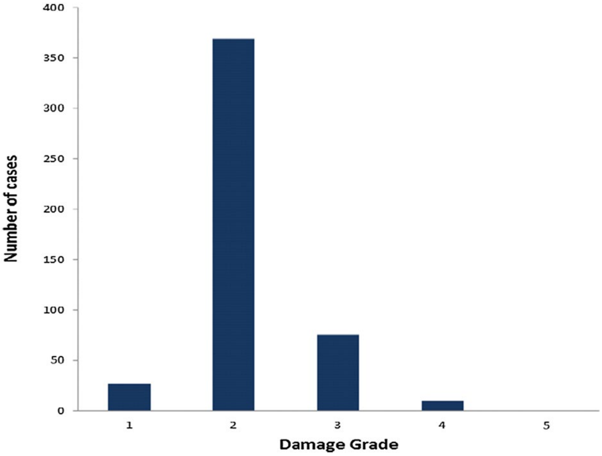

Fig. 9 Plotted distribution of the frequency and the damage grade for the 1531 Event

(Bates and De Roo 2000). For more information on zonal statistics please refer to Murayama and Estoque (2011).

5.1 Building stock losses

The analysis of the output data undoubtedly detects a prevalence (≈77%) of a “Moderate Damage”, or an EMS98 D2. This typically represents a damage grade where the houses have cracks in the walls and there are partial collapses of non-structural elements, such as parapets, balconies and chimneys. The overall allocation of the damage level can be observed in Table 4.

The allocation of the damage level is represented in Fig. 9. In the plotted function, although constructed with a small sample size (n = 5), a right-tailed pattern can be distinguished, indicating that the bulk of the values lie slightly to the left of the arithmetic mean.

Analyzing the results, it is possible to infer that the typical damage for the 1531 Event was moderate (D2). Yet, almost 18% of the buildings damaged suffered a “substantial” to “pre-collapse damage” (D3 or D4). It is in those cases that casualties tend to happen, as proposed by Coburn and Spence (2002). The value achieved by SIRCO for the total of buildings damaged has been predicted as 481. The incertitude associated with the assumptions made does not affect the scale of the numbers projected, which are consistent with those proposed by Vogt (1985), that were from 200 to 1000 damaged buildings.

Table 5 Distribution of common earthquake-driven injury typologies (adapted from Alexander 1985)

Type of injury	Rate (%)
Soft-tissue injuries	30–70
Limb fracture	10–50
Head injuries	3–10
Others	5

5.2 Human losses

Earthquake events induce a high level of mortality and morbidity due to crush injuries from falling objects (Ramirez and Peek-Asa 2005), as exemplified in Table 5. The greatest risk of injury from an earthquake is either indoors or in close proximity to buildings and other structures (Tucker et al. 2013). Furthermore, victims who have been trapped in fallen rubble for hours or possibly days run the risk of having infected wounds and gangrene (Alexander 1985; Watson et al. 2007). In terms of medical response, a study, about the 1980 Earthquake in southern Italy, concluded that from 25 to 50% of those who were injured and died slowly could have been saved if first aid had been provided (Schultz et al. 1996).

Several clinical phases of natural disasters summarize the chronological health effects.

1. Concerning injured people and survivors (Kouadio et al. 2012):
   - Phase (1), the impact phase (lasting up to 7 days), is usually the period when victims are extricated and primary treatment of disaster-related injuries is likely to be provided.
   - Phase (2), the post-impact phase (up to 4 weeks), is the period when the first waves of infectious diseases might emerge.
   - Phase (3), the recovery phase (after 4 weeks), is the period when symptoms of victims who have contracted infections with long incubation periods or those with latent-type infections may become clinically apparent. During this period, infectious diseases that are already endemic in the area, as well as newly imported ones among the community affected, may grow into an epidemic.
2. In terms of deaths (Gosselin 2005):

For the estimation of casualties SIRCO uses the injuries classification proposed by Hazus (1999):

Light injury Injuries requiring basic medical aid without requiring hospitalization.
Moderate injury Injuries requiring medical care and hospitalization, but not expected to progress into a life threatening status.
Severe injury Injuries that pose an immediate life threatening condition if not treated adequately and expeditiously. The majority of these injuries result from structural collapse and subsequent collapse or impairment of the occupants.
Dead Instantaneously killed or mortally injured.

The potential number of deaths only includes the ones that occur immediately. This number for the scenario modeled is expressed in Table 6.

Table 6 SIRCO estimation of the number of instant casualties for the 1531 Lisbon Event

Casualty type	Number of victims
Light injury	609
Moderate injury	243
Serious injury	103
Death	46

It should be noted that SIRCO and Hazus (1999) use definitions that are connected to the state of the art of medical techniques and procedures. They also consider that first rate relief efforts exist and functional health facilities are available. These conditions have a direct effect on the mortality predicted by this software. So, the statistical data for each type of injury must be adapted to 16th Century circumstances.

The public health conditions of 16th Century Lisbon were virtually inexistent, creating an advantageous situation for the thriving of infections and related diseases. This scenario was accompanied by the lack of an organized health care system. In fact, the only structured health facility for the city was the Hospital of Todos os Santos, which had a housing capability around 250 patients and limited medical staff (Silva 2015). Against a background of a pre-antibiotic era (Harriet Runcie 2015) and faced with the typical injuries caused by an earthquake (Alexander 1985; Jones et al. 1990), this framework certainly enhanced the number of deaths as a direct consequence of this event. Therefore, considering the 16th Century's poor public health conditions and a deficient relief and care system, a new factor has been introduced via a post-survival rate (ρSR) variable. The related range of values for the ρSR has been chosen by the analysis of the few statistics and little research available for several past events.[1] These include war-driven casualties due to the similarity between typical injuries sustained in historical battlefield grounds and those that are induced by an earthquake event (Gosselin 2005)—open wounds, amputations, pierced body parts, bone fractures, infections, etc. This relationship is furthermore enhanced by the fact that, throughout history, the handling of large disasters has always been conducted by the military, and that today's disaster medicine techniques and approaches derived indeed from the ones experienced in past battlefield military hospitals (Burkle and Hayden 2001).

Facing these meager health care conditions, in terms of a 1 week survival rate the variable can be estimated (see Table 7) and can be characterized by:

- For light injuries a good survival rate, only affected by the possibility of the development of some infections, or debilitation circumstances in a scenario with the presence of other diseases (80%);
- For moderate injuries a fair survival rate due to the extent of the injuries, the need of medical care and hospitalization and the risk of infection (50%);
- For serious injuries classification, typically due to crush syndrome, and other trauma (Tanaka 2012), an overall survival rate that would not exceed 20%, due to the lack of relevant medical and surgical techniques, and a binding protocol of treatment for this kind of acute injuries.

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[1] Events that occurred before the introduction of surgical listerization techniques and, later, the introduction of penicillin.

Table 7 Injuries classification, required treatments and probable survival rates for this Event

Casualties type	Treatment requirements	Estimated survival rate for the first week (ρSR)	Observations
Light injury	Injuries requiring basic medical aid without requiring hospitalization	0.75–1.00	Possible infections or communicable diseases
Moderate injury	Injuries requiring medical care and hospitalization, but not expected to progress into a life threatening status	0.50–0.75	Deficient medical techniques, danger of infection
Serious injury	Injuries that pose an immediate life threatening condition if not treated adequately and expeditiously	0.25–0.50	Deficient medical techniques Very deficient surgical techniques

Table 8 Estimation of the final values for deaths in the 1531 Lisbon Event

Deaths occurred immediately (instant scenario—as seen in Table 6)	Deaths occurred in the first week after (post-event scenario)
46	158 to 397

Considering the survival rates applied to the values showed in Table 6, it can be observed in Table 8 that the number of deaths increases by almost a factor of four for the best survival rates (1.00/0.75/0.50), or nine for the worst survival rates (0.75/0.50/0.25). Both figures increase due to deficient health and sanitation conditions and an inconsequential relief and care system existent in 16th Century Lisbon.

The application of this variable does not affect the final value for the total casualties (1001), only causing a shift within classes, due to a related mortality rate for the first week. SIRCO estimated 1001 victims for the total casualties—persons killed or injured. The incertitude associated with the assumptions made does not affect the scale of the numbers projected, which are consistent with those proposed by Vogt (1985)—around 1000 deaths.

6 Discussion

The epicenter of the 1531 event is most probably located in what is referred to as the Lower Tagus Basin. Nevertheless, its precise epicenter is not known, although several authors (Mezcua 1982; Oliveira 1986, Justo and Salwa 1998) have proposed an answer to this question. In fact, the geological conditions of the Lower Tagus Cenozoic Basin and the Lusitanian Mesozoic Basin (located to the west) are important in local amplification and site effects that mask the relationship between the location of historical events (based on seismic intensity studies) and the sources of the earthquakes (Borges et al. 2015). However, besides the location of the phenomena, it is rather important to analyze the consequential effects of this natural event.

The analysis of the isoseismal map and the intensity suffered by the buildings shows that most buildings witnessed a VII-intensity. A few buildings located to the south-east suffered an extreme IX-intensity. This can be due to the location of these constructions near to the Tagus River where the soil is softer. This confirms the existence of site effects that amplify the earthquake acceleration in those alluvial valleys (Carvalho et al. 2008), a phenomenon that was also observed in the 1755 Earthquake (Mendes-Victor et al. 1994). For the site effects assessment, the detailed isoseismal map of this event—presented in Fig. 8—has been matched with that built by Chester (2001) for the 1755 Event, represented in Fig. 10. The general observation of both maps shows a distinctive correlation between both, in terms of the intensity versus the distance to the river. The variance between both Events, in terms of absolute intensities (VIII vs. X), can be explained by different ground motions sources variables, such as distance, magnitude and different source mechanisms (Cabral et al. 2013).

Trifunac (1990) observed that the local geologic conditions play a prominent role in determining the local site amplifications, also known as site effects. From the wave propagation viewpoint, these are due to the size of the geological inhomogeneity and the distances traveled by strong motion waves. In this case, in both maps it is clear that a central strip that runs north–south of Lisbon and to the south of the city (next to the Tagus River)

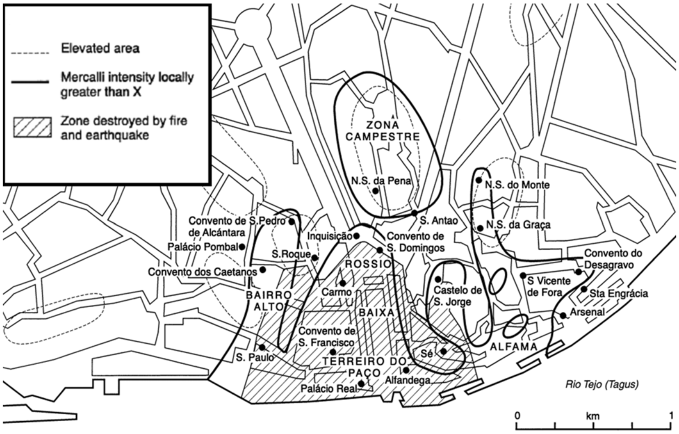

Fig. 10 Isoseismal plot for the 1755 Event (adapted from Chester 2001)

experienced the largest intensities -an outstanding VII-intensity in 1531 and X in 1755. This extent is a lower area within the city of Lisbon formed by an ancient riverbed and thus characterized by softer soil (Mendes-Victor et al. 1994). Therefore, in terms of site effects, it is reasonable to assume that this area is prone to suffer stronger ground motion accelerations. In this framework, it is also observed that a few buildings underwent a VI-intensity, most probably due to a "harder" soil less prone to local site amplifications.

Regarding the damage caused to the buildings by the Earthquake, most buildings suffered moderate or negligible to slight building damage (D1–D2). The result obtained is that 75 buildings experienced substantial to heavy damage (D3). Ten buildings became uninhabitable (D4, pre-collapse). These were probably the ones located in the new expansion landfills near the Tagus River, where the intensities felt were higher (> VIII). This caused the destruction of about 20 dwellings, considering a ratio of about 2 dwellings per building (Rodrigues 1970). The total estimated number of damaged buildings is around 480, thus causing damage to about 950 dwellings. Both numbers are consistent with the interval defined by Vogt (1985). In general, it can be stated that the damage caused to the building stock of Lisbon was moderate. These results are in concordance with Miranda et al. 2012. They stated that about one-third of the building stock was damaged. In these results, it has been estimated that 23% of the buildings suffered relevant damage. Miranda et al. 2012 also asserted that the damage was mainly noticed in buildings found in new landfills. The results show as well that the buildings which suffered most damage were those located in the lower part of Lisbon and near the Tagus River, where the soil deposits of the river are soft. Concerning the number of people who died because of the 1531 Earthquake, the simulation provides an estimation of between 500 and 1000 casualties. This number matches the text by Vogt 1985.

In a sociological framework, and as a result of reviewing some interpretations of this event, the dimension of this earthquake can also be highlighted by its historical/sociological consequences. In fact, it can be said that besides the deaths, the injured and the economic losses, the 1531 Earthquake seriously affected a part of the Portuguese society, most intensely the so-called "New Christians", as explored in Baptista et al. *(*2014). Other remarkable aspects of Portuguese history which are possibly related with this event and are worthy of further research are:

1. The king's absence from Lisbon during several years after this earthquake (1531–1537); coinciding with the monarch's keenness in making Évora the new political capital of the kingdom (Manso 1990; Rossa 2015);
2. The Holy See assent for the establishment of an inquisitorial tribunal in Portugal (December of 1531) after years of negotiations (Saraiva 1985).

This work enhances the need for the existence of earthquake historical catalogs, comprising data from the assessment of an intensity field. They supply a broad database related to seismicity, earthquake physics and seismic hazard analysis. The scientific advances in recent times have enabled seismologists to produce various types of these earthquake catalogs, which provide essential parameters to describe an earthquake—information that was used in this work to describe the 1531 Event. A good example of such a dataset can be retrieved from the Archive of Historical Earthquake Data (AHEAD) at http://www.emidius.eu/AHEAD/(Locati et al. 2014). Batló et al. (2012) also inform that several countries are working on a macroseismic intensity database. The goal of this database is to allow an easy access to earthquake listings and visualization of the geographical distribution of intensity data points through a web page without the need of installing a complex infrastructure.

Lastly, in terms of uncertainty analysis, within this study a range of uncertainties associated with hazard, vulnerability and loss modeling have been considered. Uncertainties in hazard calculations are mainly associated with earthquake occurrence—including in this case its location and magnitude—and ground motion intensity calculation, including intensity attenuation and local effects. One major factor for uncertainties is related to the errors in the selection of the attenuation relationships. In the current study, this class of uncertainties was dealt with by using a permutation for the ground motion prediction equations. The median of motion from the selected ground motion model was considered, as is characteristically done in conventional deterministic approaches for low to medium activity sources (Abrahamson 2006). Analogously, for the casualties approach, the introduction of an interval for the survival rate in the first week (ρSR) has been an approach used to minimize the uncertainties in the loss modeling. It should be mentioned that the authors are aware of possible bigger ranges and a larger variability in the existing uncertainty sources than those that have been taken into consideration in this work.

7 Conclusions

The 1531 Earthquake has been reevaluated in this research. After a thorough reconstruction of the previous situation and using a seismic risk simulator called SIRCO, the following conclusions can be drawn:

- The Lower Tagus Basin has been the site of a significant number of large historical events. Nowadays, it is considered the most probable seismogenic area for the 1531 Event.
- The damage originated by this episode can only be accessed by coeval records, helping to recreate an isoseismal map based on the intensities/phenomena observed by witnesses and recorded by writers.
- In this work, the SIRCO software was employed and a good qualitative approach to Justo and Salwa's (1998) intensities map has been achieved. The epicenter location

used has been that specified by Oliveira (1986) in his revision of the Portuguese seismic catalogue.

- This work supports the proposition that the macroseismic methodology presented by Giovinazzi and Lagomarsino (2004) and Lagomarsino (2006) can be successfully integrated into research with regards to the destruction of historical settlements and validated with the coeval records.
- In terms of human loss results, SIRCO considered that the number of casualties was projected to be around 1000 people—in a scale comparable to the one proposed by Vogt (1985).
- Considering the people that were injured, most probably about one-third died in the subsequent days. This was due to underprovided relief and limited medical capabilities. However, the final number of deaths—up to 400—is far from the 30,000 casualties considered by Bharatdwaj (2006), whose numbers should be treated as an outlier. Nevertheless, due to the high degree of uncertainties brought about, the need for further investigation and sensitivity analysis in the topic by using a post-survival rate variable in modeling losses is advisable.
- In concordance with the coeval records compiled by Henriques et al. (1988), the buildings most affected were those located in the city's downtown and next to the Tagus River. This is probably mostly due to the minor consolidation of the soil in those parts of the city (Baptista et al. 2014).
- In terms of physical losses, SIRCO considered that the number of damaged buildings was projected around 480—also on a scale similar to the one proposed by Vogt (1985).
- It can be stated that the damage caused to the building stock was moderate and not occasional as reported for the 1909 Event (Moreira 1991) or massive as in the 1755 Earthquake, which destroyed most of the city (Chester 2001). This is consistent with the notion that the Lower Tagus Basin is a seismogenic source (Morales-Esteban et al. 2010) characterized by moderate events ($Mw < 6.5$, Morales-Esteban et al. 2012) capable of generating small to moderate losses in Lisbon. Contrariwise, the Marqués de Pombal Thrust Fault and Guadalquivir Bank (MPTF/GB) combined mechanism, one of the sources proposed for the 1755 event (Chester and Chester 2010), is well able to generate larger earthquakes ($6.5 < Mw < 9.0$), albeit considering different return periods.
- The full consequences of this event are still controversial, arousing questions of its relationship with the Portuguese inquisition enactment in 1531 and the unprecedented royal court transfer to Évora from that year until 1537 as stated by Rossa (2015).
- Last but not least, this work enhances the requisite of maintaining international collaboration in assembling a database library of past seismic activity over the ages. A good example of this is the work of Batlló et al. (2012) and the Archive of Historical Earthquake Data (AHEAD) database (Locati et al. 2014) that inventories and gives access to multiple sets of information concerning each earthquake, and allows users to get comprehensive information about individual past earthquakes.

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