Review of the 1755 Lisbon Earthquake Based on Recent Analyses of Historical Observations

C. S. Oliveira

Abstract The importance of the 1755 Lisbon earthquake is known worldwide not only among the scientific and technical communities but also in many other disciplines of human kind related to the effects and consequences of the earthquake. A re-visiting of the 1755 Lisbon earthquake is made based on the historical descriptions in what regards the multiple aspects of scientific and technological background in his smaller details as, for example, the predominant direction of shaking, the duration of the event, the anisotropy in propagation, the enormous area of perception with its direct effects along all the Iberian Peninsula and Morocco, the water movement in Scotland (seiches), the enormous tsunami that affected the Portuguese, Spanish and Morocco coast, being remarkable the waves in the other side of the Atlantic, in New Jersey. These examples illustrate that the 1755 earthquake was a unique seismologic event for which a great deal of information already exists but, on the other hand, still contains many unresolved problems.

We review the historical descriptions of several different physical phenomena, compiling available data and discussing models proposed recently in the literature, with the aim of contributing to a better characterization of the seismic source, the wave propagation, and also to the causes behind the observations in nature, in housing and population. The interpretations are supported, as much as possible, on physical evidences such as the structural characterization of simple objects and structures for which it was possible to partially recover the seismic input acting at the foundation level. The analysis of the tsunami, of several monumental structures, and especially the "Aqueduto das Águas Livres", the damage inflicted to different types of buildings, etc., represent the essential basis to place a few pieces to reconstitute the large and intriguing puzzle that the 1755 earthquake still is. Though science has already given many important clues, there are yet a large number of questions to be answered which will contribute to a full comprehension of the phenomenon and to the definition of future hazards.

C. S. Oliveira
Instituto Superior Técnico (IST), Lisbon, Portugal and Researcher ICIST/IST
e-mail: csoliv@civil.ist.utl.pt

J. Fréchet et al. (eds.), *Historical Seismology*,

Keywords Historical earthquakes · 1755 Lisbon earthquake · source mechanism · attenuation · damage · inverse problems

1 Introduction

The importance of the 1755 Lisbon earthquake is known worldwide not only among the scientific and technical communities but also among many other disciplines of human kind related to the effects and consequences of the earthquake. The 1755 earthquake was perceived in an enormous area with direct effects along all the Iberian Peninsula and Morocco, the water movement in Scotland (seiches), the enormous tsunami that affected the Portuguese, Spanish and Morocco coast, being remarkable the waves in the other side of the Atlantic, in New Jersey. This example illustrates clearly that the 1755 earthquake was a unique seismologic event for which a great deal of information already exists but, on the other hand, still contains many unresolved problems. But, on the other hand, this event was perhaps the first one in history that gathered a large amount of important data which can be used to understand many of the scientific and technical aspects related to it.

In the year when we evocate the remembrance of Jean Vogt, we want to pay our tribute to one of the individualities that most contribute to the history of seismology across Europe, bringing to the reader some new facts important to the interpretation of this historical earthquake that marks the European scientific society for many decades and centuries. It is compulsory to give continuity to the different studies that have been developed, with the intention of learning as much as possible about the phenomenon, but also to make an efficient strategy of prevention and action in the case of a tragedy of big dimensions.

Since it happened until today, many were the authors that studied the 1755 earthquake, and, in the future, a lot more will dedicate his attention to this event. Also commissions, work groups and investigation programs, etc., have been given an enormous contribution for the understanding of the phenomenon. The joining of different specialities, from seismology to the engineering seismology, through the history and sociology, etc., brought an important number of results in the search of more and better data.

Concerning only the geophysics and the seismic engineering aspects of the problem, we can refer the following authors (by chronological order) as a strong base to the study of the earthquake in Portugal, Spain and Morocco:

Moreira de Mendonça (1758), Montessus de Ballore (1906), Pereira de Sousa (1919–1932), Choffat (1904), Diniz (1910), Reid (1914), Miranda (1931), Rosas da Silva (1939), Machado (1966), França (1977 and 1978), Moreira (1979 and 1984), Rómulo de Carvalho (1987), Brazão Farinha (1990) and Campos (1998).

The 200th anniversary of the earthquake in 1955 was another occasion for using the date to launch the first modern hazard map of Portugal, *in* Simpósio sobre a Acção dos Sismos (1955), and the first modern seismic code.

In the field of historical studies, a Portuguese Commission for the Seismic Catalogue, “Comissão do Catálogo Sísmico Nacional (1980–1990)”, composed by a group of historians, sociologists, among which L. Runa, A. Freire, T. Barata, L. Braga, M. Wagner, has made considerable contributions to several aspects of the historical seismicity of Portugal including the 1755 earthquake.

Martinez-Solares (2000), Rodriguez de la Torre (1981–1993), Mezcua (1982) studied in great detail the effects of the 1755 earthquake in Spain), and Levret (1991) in Morocco.

After 1990, many contributions in the field of geophysics, seismology, tsunami science and earthquake engineering were made, namely by: M. Baptista, M. Bezzeghoud, F. Borges, E. Buforn, F. Carrilho, J. Fonseca, L. Matias, J. Mezcua, A. Paula, L. Senos, P. Terrinha, P. Teves-Costa, A. Ribeiro, A. Udias, L.M. Victor, S. Vilanova, N. Zitellini, C.S. Oliveira, J. Vieira de Lemos, J. Azevedo, etc. Among these, we should emphasize the geophysical campaigns (seismic reflection profiles), done in the transition of the oceanic to the continental shelf since 1970, which were greatly increased in the last 15 years. These were essential for the knowledge of the bottom of the ocean and of the crustal morphology, which, in association to the historical and instrumental seismicity, the tsunami studies for constraining the source mechanism and the wave propagations modelling to estimate the ground motion at different locations of the Iberian Peninsula have given a new breath to understanding this complex zone. Re-visiting the historical documents has been made by many experts to extract more reliable information by interpreting the existing descriptions under all new advancements in science and technology. In the present paper, following this line of thought, we will use a few examples to illustrate how historical descriptions can be extremely helpful to develop new understandings of a complex event of huge proportions such as this one.

The earthquake of 1755 gave origin to a wide range of contemporaneous writings, with the descriptions of the effects over the people, the houses, the monuments, the economic activities, the existing tax regulations, etc., leading to the most different interpretations. This enormous range of documents includes letters from foreigners living or travelling by Lisbon, pictures testifying the horrors of the shock, etc. After the M6.3 earthquake of 1909 in Benavente, 30 km to the NNE of Lisbon, ulterior studies about the earthquake of 1755 were retaken by different authors. Meanwhile, all the XIX century is full of literary works describing scenery where we understand many of the urban developments done in the City of Lisbon.

In the last few years, with the evocations of the 250 anniversary of 1755 earthquake, an increase of interest in the above mentioned areas, as well as the arise of studies in other areas of knowledge including paleoseismology, geography, economics, religious and political science, with contributions of experts from all over the world, has given a considerable push towards a better knowledge of 1755. This occasion was also important for the publication of other types of works related with 1755. Some are of literacy contents, romance addressing the life style at the time and describing the aftermath of the event (Chantal 2005, Quenet 2002, Tavares 2005). Others are full of historical documentation (Amador 2007, Pararas-Carayannis 1997).

It was also an opportunity to re-publish writings which were out of print or not published due to censorship. A vast bibliography was compiled by Oliveira (2005).

Another area of great interest but not dealt with in this paper is what concerns the reconstruction of the City of Lisbon. This involved a great number of discussions and developments in the most varied topics from urban planning passing by seismic resistant construction to rationalisation of construction practices.

2 Contemporaneous Information

Most of the existing information obtained at the time of the earthquake was compiled in a questionnaire with 13 questions, enquiring different aspects of the event such as how it was felt, how long the vibration last, the direction of propagation and the type of damage inflicted. Marquis of Pombal decided to promote this inquiry across the parishes of the country, using the religious authorities (Pereira de Sousa 1919–1932; Table 1).

We must sign the remarkable way how these 13 questions were elaborated (the number of victims and the ruins produced in each parish of the country), in many instances similar to the macroseismic information developed 150 years later and still used nowadays.

It is also remarkable that in Spain during the reign of Fernando VI a very similar inquiry with the same purpose was produced by the "Real Academia de la História". This inquiry was found just a few years ago and is opened to the scientific commu-

Table 1 Questionnaire sent, by order of the Marquis of Pombal, after the earthquake of 1755, to the different parishes of the country

1°	At what time did the earthquake started and how much did it last?
2°	Did you notice a bigger impulse in one side than in the other? From north to south, or, in the contrary, did you notice that ruins felt more to one side than to the other?
3°	Number of houses ruined in each parish; where there any special buildings and what is their state now?
4°	What kind of people died? Were there any nobles?
5°	Which novelties were seen in the sea, rivers or fountains?
6°	Did the tide get low or high first; how much did it grown more than normal, how many times was the flow or unusual reflux noticed; how much time took the water to get lower and how much to get higher?
7°	Were there any cleavages in the ground, what was seen there, and did any fountain came out again?
8°	What were the measures taken locally by the priest, by the soldiers and by the ministers?
9°	Were aftershocks felt? When? Which damages caused?
10°	Do you remember any other earthquake and what damages did it cause?
11°	What is the number of people in each parish, declaring when possible how many women and men?
12°	Was there any kind of lack of food?
13°	Where there any fire, for how long and what kind of damages caused?
extra	Were you victim of any ruin from the earthquake of 1755, what kind and is it already repaired?

nity (Martinez-Solares 2000). Coelho (2007), in studying the possible origins of both inquiries, classifies this accomplishment as the first scientific quantification of earthquake damage in history.

Based on the inquiries of the Marquis of Pombal and of the "Memórias Paroquiais" (Parish Memories), Pereira de Sousa (1919–1932) compiles a remarkable amount of information about the damages occurred in the construction and mainly in the monuments, developing at the same time maps of Mercalli Intensities, assigned in different geographical scales, but always with a strong connection with the geological units in which they were built. For Lisbon, Pereira de Sousa works with the map drawn by Filipe Folque in a scale of 1:10,000, identified the location of the existing monuments and classified them by damage classes.

In 1986, Oliveira tried to systematise the information about the damages occurred in the monumental constructions by the time of the earthquake. Using a wide bibliographic list, with special incidence on the work of Pereira de Sousa, he builds up a new file of information and presents a new classification of the damages. His work is supported in traditional methods of organization and registration made on cards and manual charts using the same cartographic base of Pereira de Sousa.

All this work is now under a final revision, with a transfer of treatment to modern tools of Geographical Systems of Information (GIS) to proceed to an accurate location of the monuments worked in the 1980s (San-Payo *et al.* 2005) and with the possibility to easily correlate the class and degree of damage for each structural typology with other local parameters, such as geotechnical strata, soil frequency, topography, etc.

3 Description of the Earthquake

The earthquake of 1755, better known as "Terramoto de 1755", is considered as the biggest earthquake historically known. It was strongly felt in Lisbon, Algarve, South of Spain and Morocco. Although without causing any damages, it also left signs of its occurrence in almost all Europe and in the Azores and Madeira Islands.

The seismic activity during the years that preceded the great quake of November 1st, 1755 was not intense, although references can be found to small quakes from 1750 (the day King John V died). It is interesting to note (National Archive of Torre do Tombo) that "the day before, meaning October 31st, something happened that pre-announced this catastrophe. I am referring to the fact that, during that day, the tide was delayed in more than two hours, fact that was noticed by a pilot, who, noticing the same during December 10th, shouted throughout Lisbon for people to stay out during that night because another earthquake could happen". This prophecy seemed to be accurate, and if so a good sign of immediate foreshock, as a similar observation was made on the eve of December 11th, when the earth trembled twice, violently at 4h:55 in the morning.

On November 1st 1755, Saturday, the weather was too hot for the epoch, with a temperature of 14°C and a weak wind from NE. The main shock happened at 9h:40

(the origin time of the earthquake is a matter of some controversy, with variations between 9h:30 and 10h:00, with a better possibility between 9h:35 and 9h:45) with essentially three phases, and preceded by an underground snore or simultaneous to an "underground boom that lasted the time of the vibration sounding like a far away thunder". The phases and respective durations vary from place to place, according to testimonies from the entire Iberian Peninsula. In Lisbon, the first phase, with duration of about one and a half minutes, not very violent, was followed, after a period of 1 min, by a more intense movement with duration of two and a half minutes causing serious damages. After another pause of one minute, there was a third phase, with a duration of 3 min, more violent that before. The earthquake lasted for about 9 min. The vibrations of the first phase were essentially vertical and of higher frequency than the others.

Duration of motion in other locations will be discussed later, Section 3.2.2. It is difficult to establish the direction of the movement: some say it was N–S, others, possibly in other places, indicate E–W. However, the preferential direction of the movement of SW–NE deserves some consideration, according to the fact that the downtown streets with that orientation did not suffer great damage, as houses give better support to each other in the direction of the streets axes, functioning as aggregates.

To support this interpretation two other facts should be mentioned: the reconstruction of the new City of Lisbon developed the streets with alignment of the longer axis of building blocks in the N-S direction; the small damage inflicted to the "Aqueduto das Águas Livres", as will be discussed in Section 5.1 may be not only due its good construction but also due to the predominant N–S direction of waves.

Some eyewitnesses refer that houses were wagged like carriages going in high speed on a street full of stones. Rómulo de Carvalho (1987) goes a bit far in his description stating that the movement in Lisbon starts with a "slow shake but increasing intensity. The walls of the buildings start to crack, to open crevices and soon collapse, falling on people running away through the streets." . . . "The stones of the temples vaults where Catholic mass was being prayed, the columns of the altars, the surrounding walls, etc. fall violently on people, raising dust clouds that suffocate the few survivors".

Besides the damages caused by the seismic movement (partial or total collapse of the buildings), a great fire, caused by the several fires that exploded downtown, burned during 6 days, increasing substantially the number of deaths and the material damages.

During the first 24 h, the earth trembled in an almost continuous shaking. The first aftershock, rather violent but of shorter duration, was felt around 11h:00. During the first 8 days, more than 28 aftershocks were felt, 250 aftershocks during the first 6 months and 500 aftershocks until September 1756 (Table 2). The main shocks were: 8/11/1755 at 5h:30, 15/11/1755 at 5h:00, 16/11/1755 at 3h:30 (with tsunami), 18/11/1755 early in the morning, 8/12/1755 by the end of the morning, 11/12/1755 at 4h:55 and on the 21/12/1755 at 9h:00 with two shocks of 1 min each. On 31/03/1761 another important earthquake was felt in Lisbon, an off-shore earthquake of the Portuguese coast, causing seiches and a visible tsunami.

Table 2 Main aftershocks with epicentres around Lisbon

Date	Hour	Observations
1-11-1755	10h30m	it lasted 2 minutes without damages
1-11-1755	11h	light
1-11-1755	12h	weak
1-11-1755	22h	short
2-11-1755	3h	strong
2-11-1755	21h	light
3-11-1755	7h	
4-11-1755	14h	light
5-11-1755	20h	moderate
6-11-1755	4h30m	
8-11-1755	5h30m	violent
8-11-1755	9h	strong
9-11-1755	9h30m	light
15-11-1755	5h	
16-11-1755	3h30m	very sensible
18-11-1755		
9-12-1755		violent in Lisbon
11-12-1755	5h	violent, Felt in some places of Andalusia, Extemadura and center
21-12-1755	9h	strong in Lisbon
25-11-1755	2h	
18-01-1756		
22-01-1756		
18-02-1756	morning	
01-03-1756		strong in Lisbon
07-03-1756		
11-03-1756	21h	collapse of few houses in Lisbon
24-04-1756		very strong
27-01-1756	14h15m	
30-04-1756		violent
3-07-1756		violent
10-07-1756	22h30m	strong in Lisbon
18-07-1756		strong
26-08-1756		weak
25-09-1756	14h30m	
15-01-1756		strong in Lisbon
29-10-1756	2h	strong. It caused fear in Lisbon
6-11-1756	8h15m	small in Lisbon

Two other notes worth mentioning are as follows:

- The 1755 earthquake was followed by many important earthquakes throughout Europe and also in America by the Boston earthquake Nov 18, 1755. A large event occurred in Morocco 18/19 days past the November 1st shock, causing large damage in Fez and especially in Meknez, where over 50,000 victims are accounted. This event, with epicentre in the southern edge of the Atlas, sometimes confuses the specialists which wrongly associate it with the Lisbon event.
- In Europe more than 17 events were referred in the first year post November 1755. Locations in the UK, Italy, Constantinople, were among the places

Table 3 Other events in Europe an USA in the aftermath of the 1755 earthquake (after Braga 1989)

Year	Day/Month	Hour	Location
1755	9/December		Switzerland
1756	18/February	7–8	Paris, Luxembourg
		8	Cologne, Bonn, Versailles, Brussels, Amsterdam, etc.
		9	Liége
		morning	The Hague
1756	17/August	11.30	Padova
1756	28/August	5.30	France
1757	8/February	6	Parma
1758	3/December	Night	Constantinople
1758	6/December	Afternoon	Kola (Laponia)
1759	18/March		Listoia, Toscara
1759	10/August	21.15	Bordeaux
1759	23/August	2	Cologne, Denmark
		3	Breda
1760	9/November	8	Boston, USA
1761	31/March	12	Bayona, Spain
		12.30	Cork, Ireland
		14.30	Lake Ness, Scotland
1761	1/April	13	Bordeaux
1761	20/April	13.15	Barcelona
1761	20/May	13	Rossilon
1761	10/June		Pesaro
1761	20/June	Night	Florence,Bagno, Romania
1761	9/December	20	Barnau, Siberia
1762	18/October		Roma
1763	11/July		Komore
1765	13/January		Prand, Austria

of shaking (Table 3). The most important were in Switzerland (Dec 9, 1755), Luxembourg (Feb 18, 1756) and Cologne/Denmark (Dec 23, 1759).

Interesting to note that the 1755 earthquake with the high magnitude we attribute, not only released more energy than the total of all earthquakes occurring in Europe in the first two millennium AD, but was followed during the next years by a set of important events throughout Europe.

In what concern foreshocks, besides the note already mentioned on anomalous tide behaviour, the only existing reference is the one of a small seismic movement felt in Villablino in the province of Lion in Spain (near Galiza) on October 31/1755 between 22 and 23 h or at 2 h:00 (Anonymous 1756). Some precursory phenomena of 1755 event may have take place 3–7 days before in several locations mainly in the centre-north littoral. Muddy waters, smell to sulphur, and even anomalous animal behaviour and a crack in the soil were part of those manifestations (Moreira *et al.* 1989).

But in the years prior to 1755 there were plenty of seismic activity such as in Valencia-Murcia, Spain in May 5, 1748, Madeira Island in May 31, 1748, in Africa 1751, in Belgrade in October 30, 1752, in Tunes in December, 9, 1752 and in

Comarca de Valença, Braga, northern Portugal in February 13, 1754 (*in* Biblioteca da Ajuda, quoted by Amador 2007).

Around 11h:00 in the morning of November 1st, the waves of a tsunami caused by the main shock of 9h:40 arrived in Lisbon. The Tagus waters initially run-down, dragging the boats anchored near the harbour. Then, they started to increase its level, passed over the walls of the port and invaded downtown in 300–400 yards ("Terreiro do Paço" and streets near the river banks). According to the testimony of the captain of an English vessel, the waters raised about 16 feet, three times, during 15 min. Only at 7h:00 in the morning of Sunday (November 2), the tide went back to normal.

However, as a result of the tsunami, during the first 10–12 days the tides did not have a regular course, as some times they came earlier, other times were delayed, and took 7–8 h to reach high tide and 3–4 h to reach low tide.

The impact of the tsunami of 1755 in Lisbon is described in various testimonies of that time, such the one following (in Emergency Plan for the Seismic Risk in Lisbon): "(. . .) Suddenly the sea enters the harbour with a furious inundation of water (. . .); Surpassing it ancient limits, it passed over several buildings and flooded S. Paulo quarter (. . .)" (Moreira de Mendonça 1758), "(. . .) and flood in parts with its flow and reflux the side of the waters that came out of its river bed and flooded the custom-house, the Terreiro square and the Vedoria building (. . .)". According to Baptista *et al.* (1998) downtown was flooded, being the distance of penetration of 250 m, while the "fernandine" wall (rebuilt by King Filipe I) acted as a strong barrier to the passing waters. The area between the ancient "Ribeira das Naus", the "Terreiro do Paço" and the "Jardim do Tabaco" – squares in the river banks – became totally flooded".

Another reference indicates that "the Castle of Bugio was almost covered with water in such a way that the soldiers shooted asking for help and had to withdraw to the highest part of the tower".

It is important to know the tide level by the time of the tsunami wave arrival, to take this effect into account in the progression of the waters entering Lisbon harbour. It is difficult to analyse this subject with precision because of the error introduced in the extrapolation of tide times into the past (two centuries before). However, according to the US Naval Observatory Astronomical Applications Department, from the phases of the moon, the 1st of November 1755 was two and a half days before New Moon, far away from high tides. So, the low tide was probably around noon and the high tide around 17h:45 (Azevedo 2004, personal communication). On the other hand, according to historical source, the low tide in Benavente was at noon. Based in this information, the tsunami would have arrived to the cowl of the Tagus when the waters were in strong low tide, which turns the rising of the rivers more difficult. Andrade (1992) confirms that the first wave of the tsunami reached the coast in Algarve during low tide. This information is, however, in contradiction to witnesses in Cadiz, which claim that the tsunami reached there at high tide (Campos-Romero 1989).

The tsunami was felt not only in the Portuguese coast (the harbour of Setúbal was submerged by an enormous wave; in the Algarve, the waves reached great heights) but also in the Southeast of Spain, North of Africa, Great Britain and The

Netherlands. The passage time between the "possible"[1] seismic source and Cape São Vicente is esteemed in 6–7 min and in 1 h in relation to Cadiz. In Lagos, the tsunami arrived about 15 min after the mainshock onset, and the waters first run-down, then went up 13 feet, causing great destruction mainly in the walls protecting the city. In Portimão, the waters rising 6 "braças" (fathom) drowned too many people. As referred, the biggest impact of the tsunami in the Algarve was in the bay of Lagos which could no longer accommodate big boats (greater than 45 tones) due to sediment transport and therefore the Harbour Administration has moved from Lagos to Tavira. Also the Ria de Faro suffered great changes in its coast line (Faro Beach) with significant sandy movements altering the deposition (Andrade 1992).

In Madeira and Azores Islands, the tsunami was also felt and caused great damages in the islands of Terceira (cities of Angra do Heroísmo and Praia da Vitória) and Faial (city of Horta) (Andrade *et al.* 2006).

In Creston Ferry, near Plymouth, England, the waters raised around 16h:00. Two boats that were in dry land, one and a half meters from the water were "drowned in mud" after the tsunami. It took around 8 min for the waters to get back to normal and for the boats to float again. The tsunami was also felt in the coast of America: in Antigua, 6,000 km away from Lisbon, the first wave of the tsunami arrived at 19h:30 (Lisbon time). Here, the variations of the water level were felt during two and a half hours, with the highest wave of about 3.5 m. It was also felt in Recife (Brazil) where the waves destroyed the fisherman huts.

Pararas-Carayannis (1997) mentions for tsunami heights different values and different consequences: Lisbon – run-up with 6 m height entering inland 20 m, Cascais – destruction of many boats, Peniche – many people killed, Setúbal – the water reached the 1st floor of buildings, Algarve – run-up of 30 m and many fortresses in the western portion destroyed, Lagos – the waves went over the top of City-walls (11 m) and entered the river to a distance of more than half mile carrying vessels to a great distance, Faro – not affected because of the sandy banks that protected the town, Guadalquibir – the waters reached Seville, Gibraltar – the waves reach 2 m high, Agadir – waves passed over the fortified walls of the town killing many people, Martinique – waves rose 1 m.

In summary, run-up was observed first in Gibraltar, Ceuta and Madeira; and run-down was observed first in Lisbon, Lagos (20 fathom) and Cadiz. This allows the definition of a source zone running EW to the south of Cadiz with uplifting in the northern wall.

In distances larger than 1,000 km, the seismic waves caused floods originated by seiches, the movement of the waters of the lakes, rivers and harbours, in a rhythmic way. This was observed in Switzerland, England, Scotland, Finland and Sweden. In Scotland, 2,000 km away, the waters of Lake Lamond oscillated with amplitudes of more than 60 cm during more than one and half hours. In the Dal river, north of Stockholm, 3,000 km away, these oscillations were also felt. No other earthquake in

[1] The location of seismic source in this case is simply $\sim$100 km to the west and is mentioned just as a reference.

the history caused rhythmic perturbations in the water at such large distances in a certain predominant direction of propagation (to the north). It is important to refer that only very large magnitude events, such as the Alaska 1964 Mw9.2, have caused phenomena of the same type denoting important energy at very short frequencies (<0.02 Hz).

Besides the damages caused in the area of Lisbon, which will be object of a detailed study, the earthquake was strongly felt in the south of the country. Faro was totally destroyed with a high number of death people. The same happened in other villages in the Algarve, mainly in the western part, like Lagos, Portimão, etc. The south of Spain also suffered damages but not so catastrophic.

To the North of Lisbon, the intensity was quickly attenuated; Alenquer, Torres Vedras and Óbidos were the most damaged places. Coimbra did not feel great damage[2]. However, in Corunha (Spain), 800 km away from the epicentre, some high chimneys felt down, although the population did not feel the movement. In Barcelona, 1,200 km away from the epicentral region, there are records of oscillation of lamps hanging from the ceilings of the churches. This information is extremely important in order to characterize the frequency of the vibrations at such large distances. A simple calculation shows that the seismic movement at the ground level at these sites may have reached a few centimetres for frequencies of 0.1–0.2 Hz.

The earthquake was slightly felt in the Azores Islands and curiously one of the few earthquakes felt in the islands of Flores and Corvo. This information confirms the idea that the 1755 earthquake had a radius of perceptibility of the movement of about 2,500 km.

Let's see other quotations of phenomena that should be referred:

- "On the ground, cracks were opened from where sulphuric gases came out, some closed almost immediately, others remain",
- "Light effects were seen like rays coming out of the ground".

The phenomena of leakage of sulphuric gases, accounted for in different locations, are difficult to associate to the opening of cracks caused by the passage of seismic waves on locations where geothermal springs ("Hot Baths of São Paulo" in Lisbon) already existed due to the large distances separating them from the seismic source. However, we understand that the passage of waves may somehow have instabilized a few areas already prone to these effects.

3.1 Isoseismals of the Earthquake

The way that the earthquake was felt in all the Iberian Peninsula and north of Africa has been the theme of many works published during the XXth century, among which

[2] In a document recently discovered, Calvário (1755–1764) confirms most of the information in Table 2 and adds a group of earthquakes felt in Coimbra such as 6/03/1756–6h; 11/03/1756–22–23h; 25/03/1756–2h).

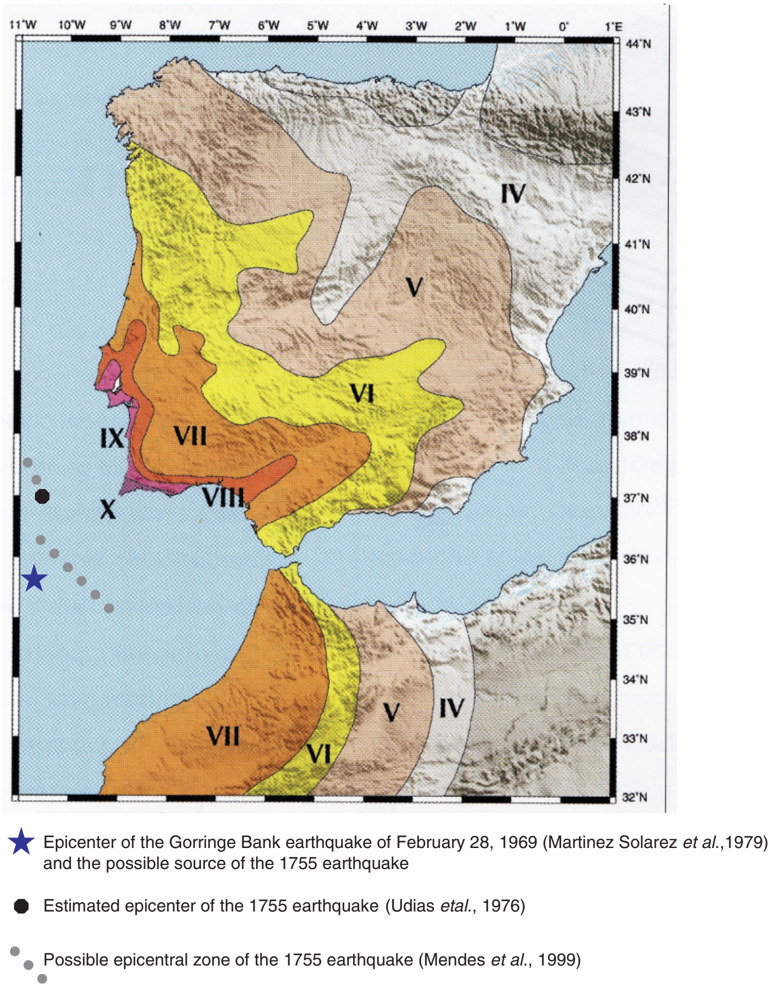
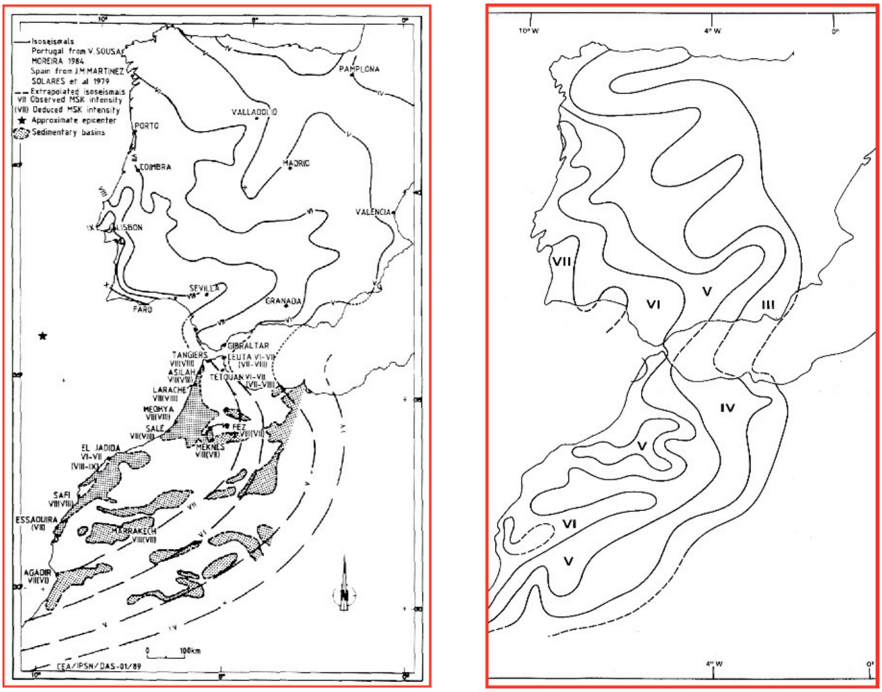


Fig. 1 Map of isoseismals (MSK Intensities) from the earthquake of November 1st 1755, with some possible localizations of the seismic source (based on Martinez Solares *et al.* (1979); Levret (1991); Moreira (1984) and Mendes *et al.* (1999)

we should mention Choffat (1904), Reid (1914), Pereira de Sousa (1919–1932), Moreira (1984) and Martinez-Solares (1979). Figures 1 and 2 summarize some of those studies, presenting the isoseismals and the possible localizations of epicentres of 1755 and of February/28/1969 event, which, until a few years ago, was considered as belonging to the same geo-morphological fault system.

The analysis of the isoseismals in Fig. 2, which joins large consensus among specialists, shows clearly that the vibrations were more intense in the south of the Mainland and in the area of Lisbon, attenuating rapidly from coastal line of the country both in the west and south. The geometric pattern of the attenuation is clearly away from the typical patterns of other earthquakes where the attenuation



(a) (b)

Fig. 2 Isoseismals of two large intra-plate events: a) 1755 (Levret 1991) and b) 1969 (Moreira, 1984). Note the similarities (the Guadalquibir valley) and dissimilarities (the southwestern Iberia) in the propagation of these two events

is more regular and concentric, emphasizing the possible role of the source mechanism, the wave attenuation anisotropy and the site effects. This latter effect is remarkably well illustrated in the positive irregularity (higher values than we could expect) in the Guadalquibir valley, showing an effect of amplification due to the presence of thick alluvial layers in that region.

In Spain, Martinez Solares (2000) was able to classify the damages occurred, distinguishing the damages in buildings of high frequency (small buildings) from the damages of buildings of lower frequency (monumental buildings), clearly prevailing the energies associated to lower frequency in areas very far from the seismic source.

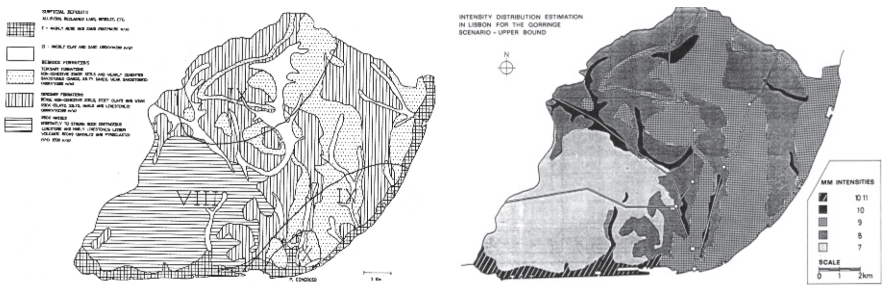
Pereira de Sousa (1919–1932) draws also the isoseismals from 1755 taking as basis of his work the geological map by assuming that the intensities should correlate well with surface geology. And he was not particularly mistaken, because that analogy exists, although it is not only the lithology of the superficial formations that contributes to the amplification of seismic waves. It is well known, and this earthquake is a clear example of that, besides the source mechanism and the wave propagation phenomenon, the type, geometry and mechanical properties of local geological strata are of most importance to characterize seismic action at a site.

Fig. 3 Main localities of Continental Portugal and Lisbon Region cited in this paper

Figure 2 was used as basis to define the outline of the seismic areas established in the Construction Regulation (RSCS 1958) promoted after the meeting of 1955 (Symposium about the action of the earthquakes 1955).

From general patterns to details for the city of Lisbon (in Fig. 3 we present the main localities mentioned throughout this paper), we find in Figs. 4 and 5 different aspects of the distribution of the damages in the interior of the city. The first Figure outlines the isoseismals according to Pereira de Sousa (1929) for the area corresponding to the entire district, overlapping once more the type of superficial geology, higher intensities being shown in the area of downtown and in the northern part of the district. Figure 5 presents in detail the most damaged areas (intensity X) corresponding to the outline of the city by that time, as well as the area of the impact of the fire (França 1978). As we can see, there is a big overlap in the outlines of the most damaged areas by shaking and by the fire, being hard to distinguish the main causes from the damages suffered. Also we can not forget the effect of the tsunami, responsible by the damages from flooding along the river.

It is important to remark that a study done in the years of 1990 (Mendes-Victor *et al.* 1994) for a scenery corresponding to the earthquake of 1755, using a simplified model to represent the effect of the surface geological layers, proposed variations of intensity (MMI) of 5 degrees, with a geographical distribution very different from the one referred by Pereira de Sousa (1929), Fig. 4(b). More recent models (Oliveira 2004), although based in more sophisticated developments than those used



(a) (b)

Fig. 4 a) Isoseismals of 1755 in the current district of Lisbon over the geological map, according to Pereira de Sousa (1929); b) Chart of intensity (Mercally Modified), done from a possible similar scenery to 1755 (scenery of Gorringe) (Mendes-Victor *et al.* 1994)

in the work of 1994, are still away from reproducing satisfactorily the damages observed. For example, the population of Belém and Pedrouços, western areas of Lisbon, reported just a small shaking, being later amazed when confronted with what had happened in Lisbon.

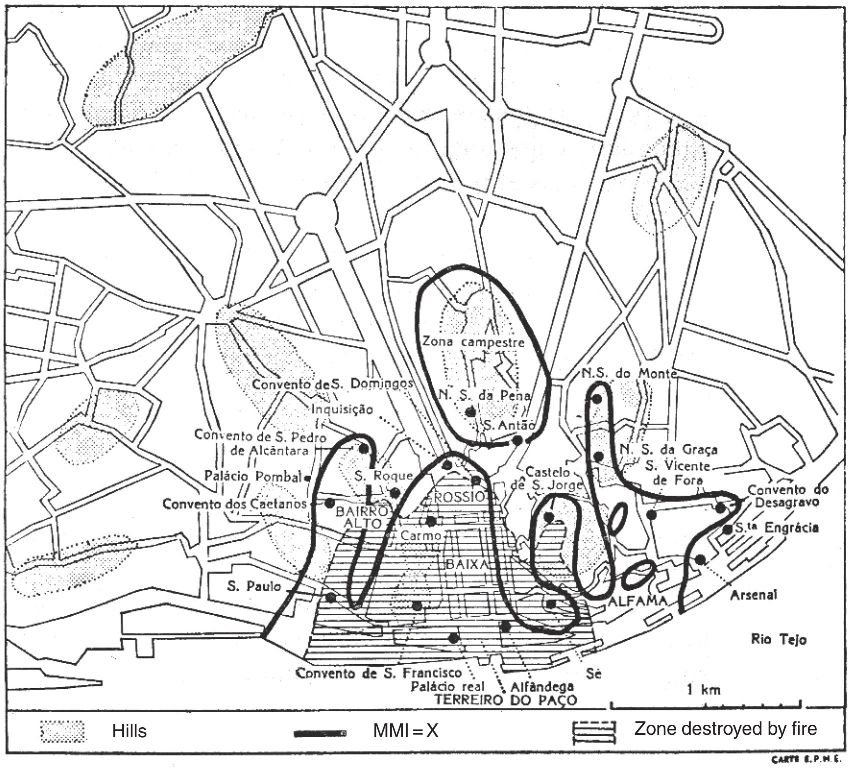


Fig. 5 Detail of the damages in the downtown Lisbon due to the vibration and fire (according to França, 1978)

The influence of the topography, of the morphology of the geological layers, the influence of three-dimensional deep geology, of the effect of important discontinuities inside the geological structures, of the three-dimensional aspects of the wave propagation, etc, are some other very important aspects that have been relegated to a second level until now. Only recently, new projects are addressing topics related to these aspects.

This theme, which is very important to determine with accuracy the effects of future earthquakes in the city of Lisbon, needs a conjugation of efforts of different areas of knowledge, including geology, seismology, geotechnical and earthquake engineering, along with the effort of analytic modulation and calibration through a careful monitoring as complete as possible. Oliveira (2004) makes the confrontation of the developed models for the city of Lisbon, using different scales of work and concluding that, although the general results are similar, the differences can be really large when seen in detail.

3.2 General Characteristics of the Earthquake

3.2.1 The Seismic Source

Based on the similarity of isoseismals and on the connection done during a long time between this earthquake and the one of February 28, 1969, the epicentral location of 1755 was placed in the region of the epicentre of 1969. Former studies placed the epicentre in different places of the Atlantic, more or less near Lisbon. Although the much research done in the last 10 years supported by studies which will be referred ahead, mainly the tsunami, the information about the crust properties, and the engineered behaviour of different structures, several source mechanisms are still disputing the origins of the 1755 earthquake (Fig. 6):

- A wide geological fault structure split in two large lengthy areas that develop in parallel to the west coast and south of Mainland Portugal (Ribeiro 2002, Zitellini *et al.* 1999).
- A phenomenon build up by two main episodes, one originated in one of the sources already described, and another located somewhere in the region of the inferior Tagus Valley (Vilanova *et al.* 2003).
- A phenomenon originated by the interaction of the Alboran Plate with the Euro-Asian Plate in a region of incipient subduction (Gutscher 2004).
- A simple model of rupture at deeper location at a "sub-horizontal" dislocation area.

These models require the use of more complex wave propagation schemes, introducing fault directivity, anisotropy elastic medium and three-dimensional (lateral heterogeneous) modelling.

The arguments put forward by the different teams working in this theme are several, and they do not take enough evidence to allow us to choose one among the

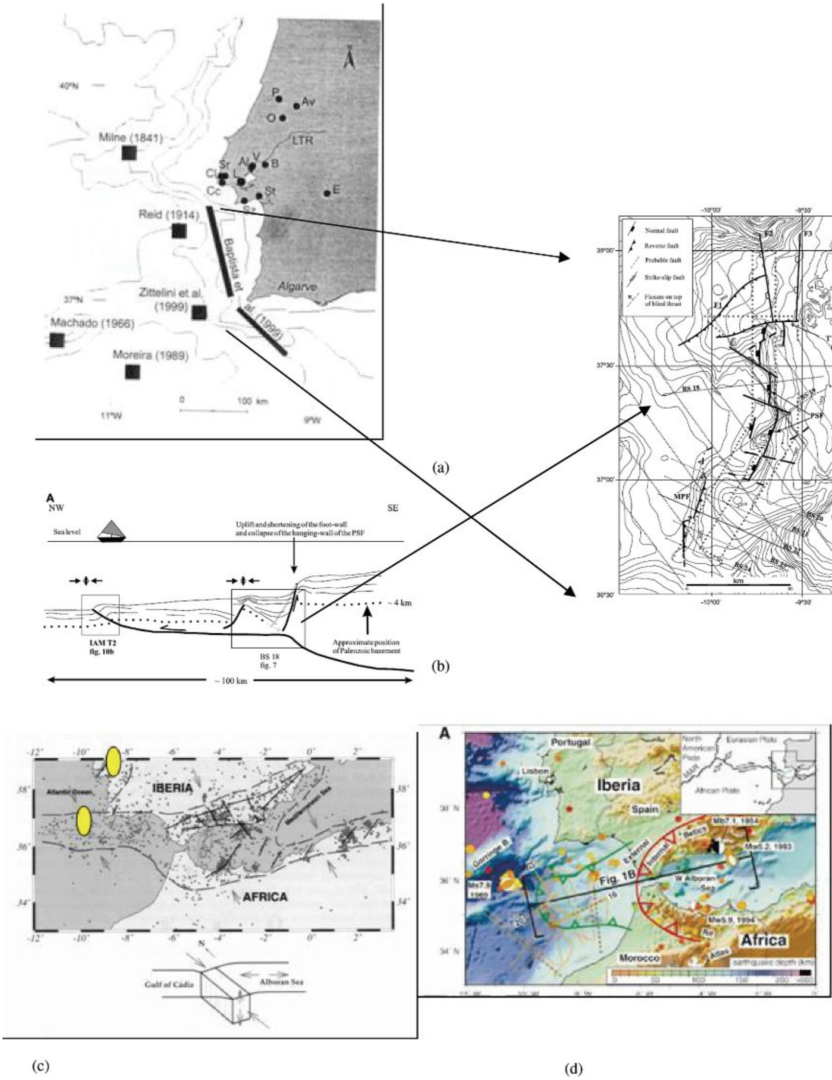


Fig. 6 Geodynamic models in contact with the Euro-Asian, African and of Alborn plates, to explain the seismic source that generated the 1755 earthquake: a) epicentres defined by several authors, along the XXth century (Zitellini *et al.*, 1999 and 2000); b) western area of the portuguese coast controled by the phenomenon of compression between the plates (Terrinha *et al.*, 2003); c) model of multiple rupture Southwest of Cape São Vicente and in the Lower Tagus Valley (Vilanova *et al.*, 2003); d) interaction of the mini Plate of Alboran with two other plates, as a possible trigger to initiate the rupture (Gutscher, 2004)

others. Even having gone forward in the information collected about such complex tectonic situation, we need more elements to clarify the models given.

In any case, the following aspects seem already irrefutable:

- The earthquake was originated in a collision area between plates, that approach each other at a low rate (5 mm/year).
- Areas of more crustal compression in the Iberian Peninsula and its surroundings are already known (Fig. 7).
- With the present information on the relative shallow depth of focal locations, the fault rupture associated to the earthquake (Mw>8.7) must extend several hundred kilometres. So, the various geological structures already identified are too small, even if they rupture in "cascade" by sympathy, to explain the amount of energy released, unless the source is deeper than presently thought or of sub-horizontal nature as Terrinha *et al.* (2003) propose. In this case, an horizontal zone involving all structural systems of Fig. 6(a) between 9° 30′–10° W and 36°–38° N, would rupture.
- The mechanism is different from the 1969 earthquake.
- The recent seismicity and even the one from the final of the XXth century, much more rigorous in the localization of the epicentres and in the definition of the source mechanisms, they do not define clearly a pattern of activity allowing a good acknowledgement of the geo-dynamic at SW of the Iberian Peninsula

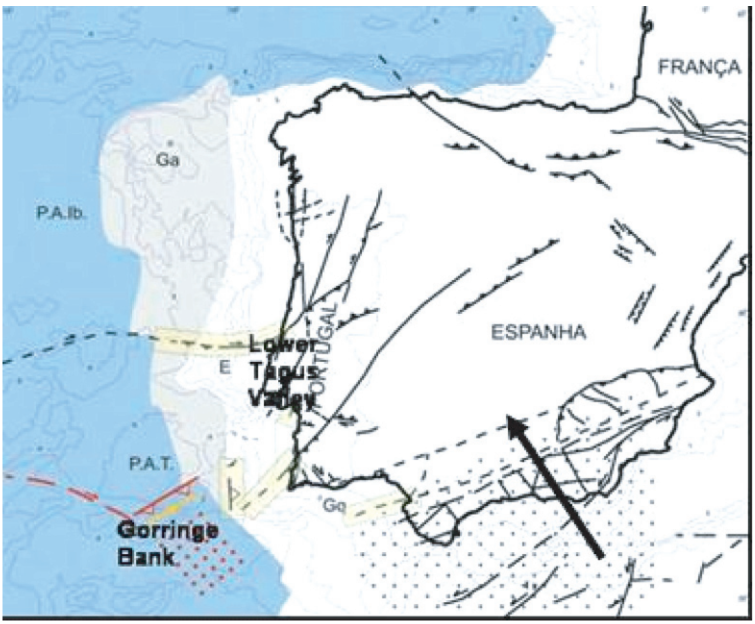


Fig. 7 Contact between the two Euro-Asian and African Plates and the main geological structures (Cabral, 1993) – the arrow indicates the predominant movement of the African Plate in relation to the Euro-Asiatic Plate

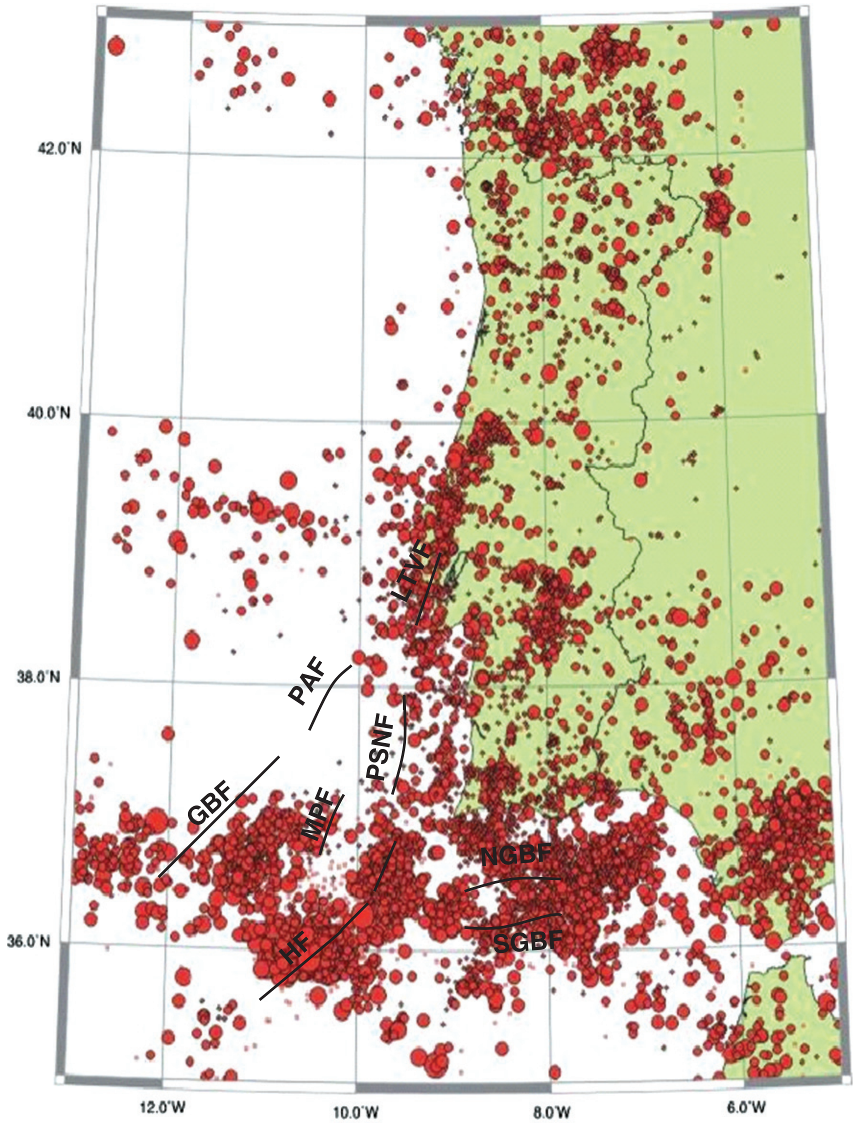


Fig. 8 Epicenters during the period of 1960-2003 (IM, 2007 and Carrilho *et al.*, 2004). MPF – Marquês de Pombal Fault System; PSNF – Pereira de Sousa Normal Fault System; GBF - Gorringe Bank Fault; PAF – Principes de Avis Fault; HF – Horseshoe Fault; NGBF – Northern Guadalquivir Bank Fault; Southern Guadalquivir Bank Fault; LTVF – Lower Tagus Valley Fault

(Fig. 8). However, we can say, for the first time, that epicentral alignments (1960–2003) in that area are becoming apparent, showing some "plausible sources" where large magnitude events may take place. Only the years to come will or will not confirm these patterns, and relate them to the 1755 seismic source.

3.2.2 The Magnitude

If it is difficult to identify a seismic source for 1755, it is no less difficult to attribute it a magnitude. Nowadays, the magnitude parameter is obtained from instrumentation which became available only a long time after the 1755 earthquake. Thus the difficulty in establishing the magnitude of historical earthquakes, for which the most accurate data is the distribution of damages or the knowledge of any simple structure that functioned as a seismograph. In this case, we should appeal to all available information of different origins, to essay an evaluation. Besides the geographical distribution of the damages, other elements of great importance are: the duration, the area of perception of the vibrations, the effects on long distances, and, finally, the comparison to other events of recent times occurred in seismo-tectonic environment similar to those of the contact of the Euro-Asian and African (Nubia) plates (Figs. 6 and 7).

The large magnitude of the 1755 earthquake is seen by the large radius of perception of its waves and the devastating effect in some regions of the coast in Portugal, Spain and Morocco. A magnitude of Mw = 8.5–8.75 has been attributed to this earthquake, presenting a rupture mechanism in the south-west region of Cape São Vicente, but it is not clear what really happened. To reach such a high magnitude in an area of collision of the plates, as referred in Section 3.2.1, it is necessary that the rupture in the plan of the fault has been rather extended, that the phenomenon has been composed by more than one single rupture, or the fault depth has been much larger than presently thought. The duration of the event was extremely long. It is hardly believed that the different phases of the vibration can correspond to the arrival of the P, S waves and the surface waves, because the time differences are too large and rupture may have been long. It seems more reasonable to think that they correspond to initial and stop phases in the rupture process. Data coming from Spanish sources confirm the great duration of felt motion, between 4 and 15 min. In Lisbon, the duration, quoted by several sources, was 6–9 min, as referred above. In Lagos, the duration did not surpass 4 or 5 min. A sound contribution to this topic can only be made after analytical simulation of different ruptures and seismic sources, to understand the effect of rupture direction, onset of the event, etc. Carvalho (2007) is presently doing a large set of experiments to analyse these effects not only in duration but also in attenuation, and the findings may contribute to clarify these mechanisms.

Based on Spanish data (Martinez-Solares 2000, Fig. 9), the correlation of duration with epicentral distance[3] is very poor: the larger durations were observed in places with epicentral distances between 300 and 500 km, decreasing for larger distances. For shorter distances the duration was smaller, as the cases of Lagos and Lisbon.

Comparing with what has happened with the earthquake of December 26th, 2004, in Sumatra Island, it is possible to review the above magnitude estimations

---

[3] The concept of epicentral distance in this case should be viewed under a great uncertainty, due to lack of knowledge of source mechanism.

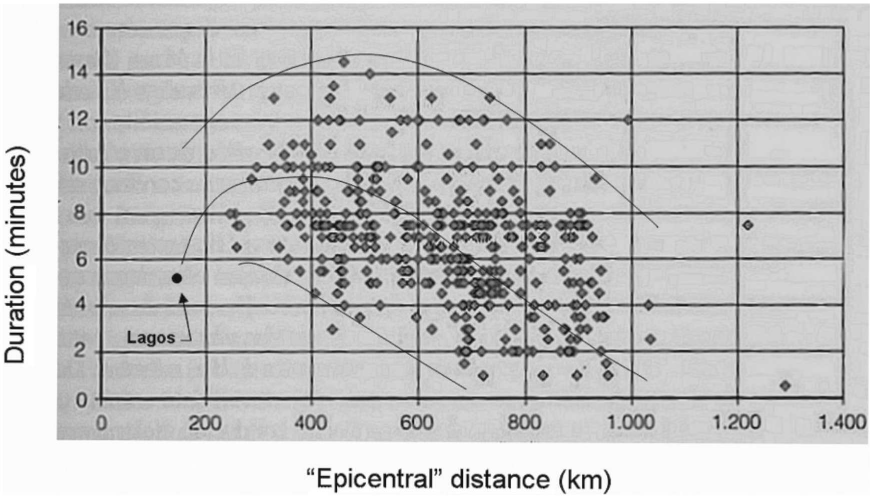


Fig. 9 Duration of vibrations as function of distance (composed after Martinez-Solares, 2000)

to higher values, in the order of Mw9 or larger. These large magnitudes have not been observed in tectonic environments of collision such as the one under study, but essentially in subduction zones. This is an important issue to be resolved in the future.

The spectrum of the vibration is different depending on the phase that is being analysed. In the first phase, the vibrations, essentially vertical and with a predominant North-South component, are of the highest frequency. The second phase and mainly the third phase are of much lower frequency.

As referred above, the seism was felt in great distances exhibiting a pattern of attenuation somewhat strange, departing significantly from the normal circular symmetry.

3.2.3 Attenuation of the Seismic Waves

The phenomenon of attenuation of the seismic waves was based on the EMS-98 intensities observations (821 points) throughout the Iberian Peninsula (Fig. 10). These points correspond to the isoseismals map of Fig. 2. The first comment is the large dispersion in existing data, due to the non-radial wave propagation pattern, as referred in Fig. 2, masked by several problems already mentioned: radiation pattern, rupture mechanism, three-dimensional propagation effects, large alluvial basins, etc. Several authors have tried to fit attenuation curves (in Teves-Costa *et al.* 2002), but the dispersion problem persists, unless those aspects are filtered out before the fitting.

The geometry of the transition ocean crust – continental crust, as well as the alluvial geological setting in large areas of the coastal and lower river estuary regions, seem to be the two most important factors in these anisotropies. Other factors

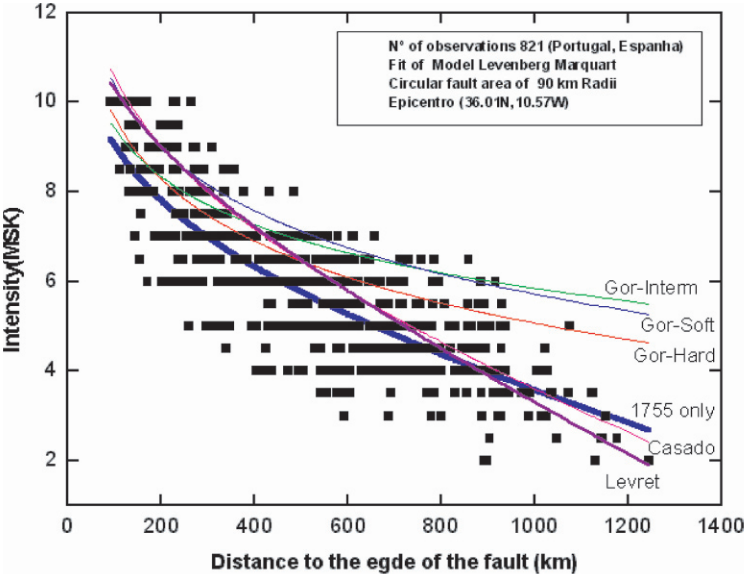


Fig. 10 Models of attenuation of the intensities seen during the seism of 1755 (Baptista *et al.*, 2001)

that might be important are the existence of "propagation channels", "orogenic barriers", etc. which were never looked upon.

Once again, we make a comparison with another earthquake, now to emphasize the existence of large dispersions (Fig. 11) for the attenuation of intensities in the 1950 earthquake of Assam, India, one of the biggest occurred in the boarder India–China (Arunachal Pradesh) (http://asc-india.org/gq/19500815_indochina.htm). Although the seismo-tectonic situations between the 1755 and this earthquake are different in several aspects, it can be noticed, by comparison of Figs. 10 and 11, that there are similarities in the general pattern of attenuation and in the dispersion of the results, with the difference that for the earthquake of Assam the closest distances to the epicentre are nearer than those in 1755. The average values for 1755 are slightly above those of the Assam earthquake, which shows a magnitude larger than Mw8.6, as referred above. The fact that the seism of Assam has a radius of perception around 1,800 km (against 2,500 km in 1755) and duration of the vibrations between 4 and 8 min (against 5–15 min in 1755) just proves this statement. Concerning the interpretation of the dispersion observed in Fig. 11, the lower line intends to represent the cases of "stiff" soils, while the upper line is a limit related with the phenomenon of soil amplification. Dispersions of this order of magnitude are observed in other earthquakes of the Portuguese catalogues (Sousa *et al.* 1992, Paula *et al.* 1996), and therefore can correspond to phenomena of amplification inherent to the complex processes of propagation and of local effects in Mainland Portugal.

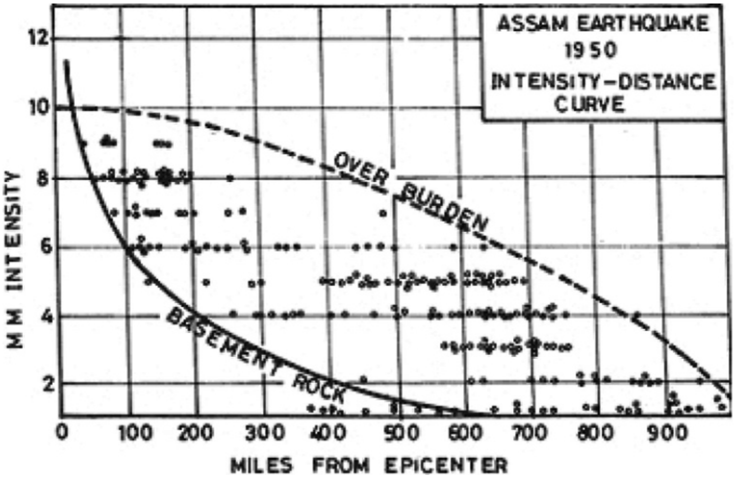


Fig. 11 The dispersion of the results is well referred in the data of the seism of 1950 in India (Mw 8.6; distance in miles)

Up to now only in subduction zones large Mw>9.0 events have been generated. However, even though occurring in a collision zone, the 1755 earthquake presents many characteristics that suggest a magnitude of that value. Certainly, due to the non existence of a single geological structure large enough to release such amount of energy, a multiple event involving more than one structure (for instance, parallel structures, rupturing in cascade) might be a possibility. Figure 8 shows alignments and gaps in the seismicity of last 50 years that fit this hypothesis.

4 Description of the City of Lisbon and Quantification of Damage

The city of Lisbon, around re-occupation (1147) fulfilled essentially the interior of the Mourish Wall with a population of about 15,000 inhabitants, organized in only seven parishes, with its main hills, roman monuments and the arm of the Tagus river spread to Rossio (Castilho 1893).

The city develops differently along the times with its own rhythms. For instance the evolution during the second half of the XIIIth century and the first half of the XIVth century was rather quick.

The urban network (Fig. 12) was composed by the open squares near the river and Rossio and the hills that surrounded downtown. More than 140 important buildings were identified in the XIIth century, and by the time of the earthquake several new buildings, some of great grandeur like the Opera House were present.

In 1755, Lisbon was organized in 43 parishes, from which the first 39 were the city itself and the other 4 correspond to the parishes of the farms that, today, belong to the City Council of Lisbon.

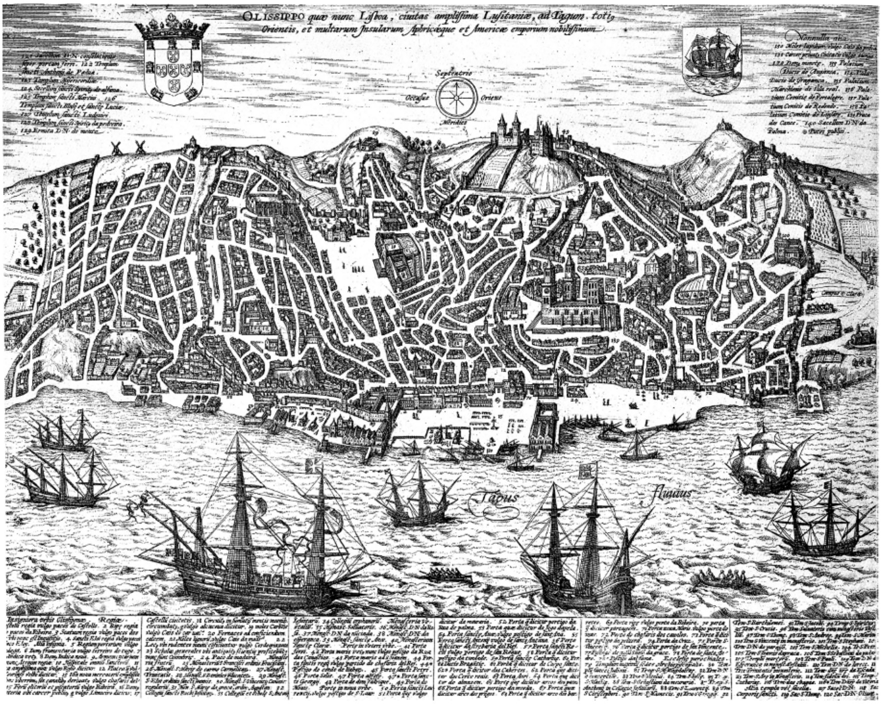


Fig. 12 Engraving Lisbon plan view at the XVIth century (G.Braunio)

4.1 Structural Characteristics of the Building Stock and Monumental Structures

Palaces and monumental structures, for its own characteristics, were classified separately from the building stock. In general, all these constructions have vertical resisting elements made of stone masonry of better or worst quality, with wooden elements forming the floors and the roof. The walls were very thick, with thickness slightly decreasing towards the higher floors. Spans between walls were rather small as well as doors and openings. Monumental constructions, usually made of good quality masonry walls, showed stone arches to sustain larger spans, especially in the ground floor, like the archways in Rossio, with 25–35 arches, constituting the advanced wing of the Hospital "Todos os Santos", which was badly damaged during the earthquake. The larger churches showed peripheral walls extremely high forming "boxes" that sustained the roof in stone vaults. Depending on the dimension, the interior could present medium columns to support arches and vaults, as the construction tradition at those times would dictate. The chapels, on the other hand, were small and not so slender.

From the structural point of view the monumental buildings were classified into the following categories:

- Churches – structures of big dimensions with large open spaces and developed predominantly along one single direction – typically of rectangular shape with supporting walls on the sides and vaults with arches to sustain the ceilings and roofs. The walls are made of well-cut stone masonry in the exterior with widths that could reach 4–6 m at the base. The structure that sustains the roof can be in stone forming vaults or bay arches, etc., or wooden structures. To strengthen the walls, metallic ties were used in the XVIIIth century and they transmit horizontal loads from one wall to the other. All churches have bell towers of 20–30 m high, also in stone masonry, some times being part of its front, others placed sidelong.
- Convents and monasteries (cloisters) – structures with 2 or 3 floors, disposed in square, having in general, the first floor laid on abutments forming archways. The walls are on well-cut stone masonry in the exterior, preferably making the corners, with 1–2 m width, floors over wooden grounds supported in 10–15 cm over the walls. The abutments of the ground floor are built of one only stone, in slender structures, or by the overlap of several stones interconnected, in the cases of larger dimensions. The abutments of one only stone are connected in their crests by metallic ties.
- Palaces – structures for the home of noble people and/or public buildings with big with large spaces, several floors, extremely high interiors, walls on stone masonry more or less well cut, with a width of 1–2 m, with big windows and wooden floors.
- Hospitals, Hospices and Schools – buildings of quality inferior to that of palaces and with a structure mixed between a palace and a convent.
- Chapels – small churches with walls in stone masonry with no windows. They are strong and rigid structures with walls of 1 or 2 m of thickness.
- Other structures – in this category we include specific cases that present different behaviours from those referred above: (a) Military garrisons – very heavy structures, partially buried, with very thick walls. They formed the defence system of the coast of Lisbon. (b) Towers – beautiful high structures. (c) Bridges – roman type. (d) Aqueduct – bridge of big dimensions across a large valley. (e) Walls – San Jorge Castle of and Almada, and Walls "Cercas" of the City. (f) Fountains and pendulum structures.

The building stock, where most people lived, was composed by houses organized in city blocks, with 3 or 4 floors. The houses built in inclined areas could present 1 or 2 more floors at the downhill side, making 5–7 floors. The urban tissue was rather chaotic, with very narrow and winding streets, reflecting the merging of Arab culture. We can still see, today, some very well preserved samples in the district of Alfama, around the San Jorge Castle and near the river west to the "Terreiro do Paço" square. These houses have small rooms and small interstory heights, thick walls and small openings, wooden floors and stairs of one only flight. Very often they present a ground floor in stone arch supporting the walls. Façades with wooden frame in cantilever to the exterior forming a "bump" are also common. Roofs with 2 or 4 attics complete the structure.

(a)
(b)

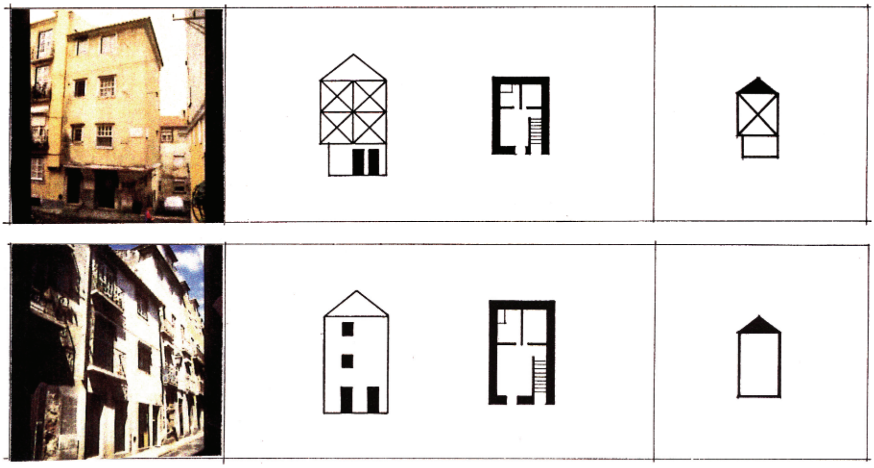


Fig. 13 Constructive typologies used before the earthquake: a) house of narrow front with an external wall forming a "bump"; b) house of narrow front with a roof of "four attics"

Figure 13 shows two examples of the typologies of the houses above described, presenting photos, elevations of the buildings and schematic cross-sections (Santos *et al.* 1993).

4.2 Quantification of Damage

Great uncertainties still do exist on the performance of building structures and monuments, extremely devastated by the earthquake, as well as on the number of victims caused by the earthquake throughout Portugal.

In relation to monuments it was possible to identify 419 in the area of the present City of Lisbon, classifying them according to the classes referred in Section 4.1. The damage inflicted by the earthquake was differentiated into 5 levels, from no damage to total collapse. Figure 14 shows the geographical distribution of those monuments in the central area of Lisbon, and Fig. 15 the damage statistics.

From Fig. 15 one can see that structures of larger dimensions suffered larger damages than small structures. This behaviour can be explained by the proximity of the frequencies of the incoming waves with the frequencies of the structures which cause a resonance phenomenon. As larger structures exhibit lower natural frequencies, the above referred behaviour supports the idea that the incoming seismic waves were with energy predominantly in the longer periods originated by sources away from Lisbon.

New studies are being made compiling all the available information on the type geometry and dimensions of the monuments, damage level sustained, and the type of soil profile underneath. The use of GIS technology is being applied to more easily establish correlations with the different parameters intervening. In this study we try to separate damage caused by the shaking from damage due to fire or even due to

(a)

(b)

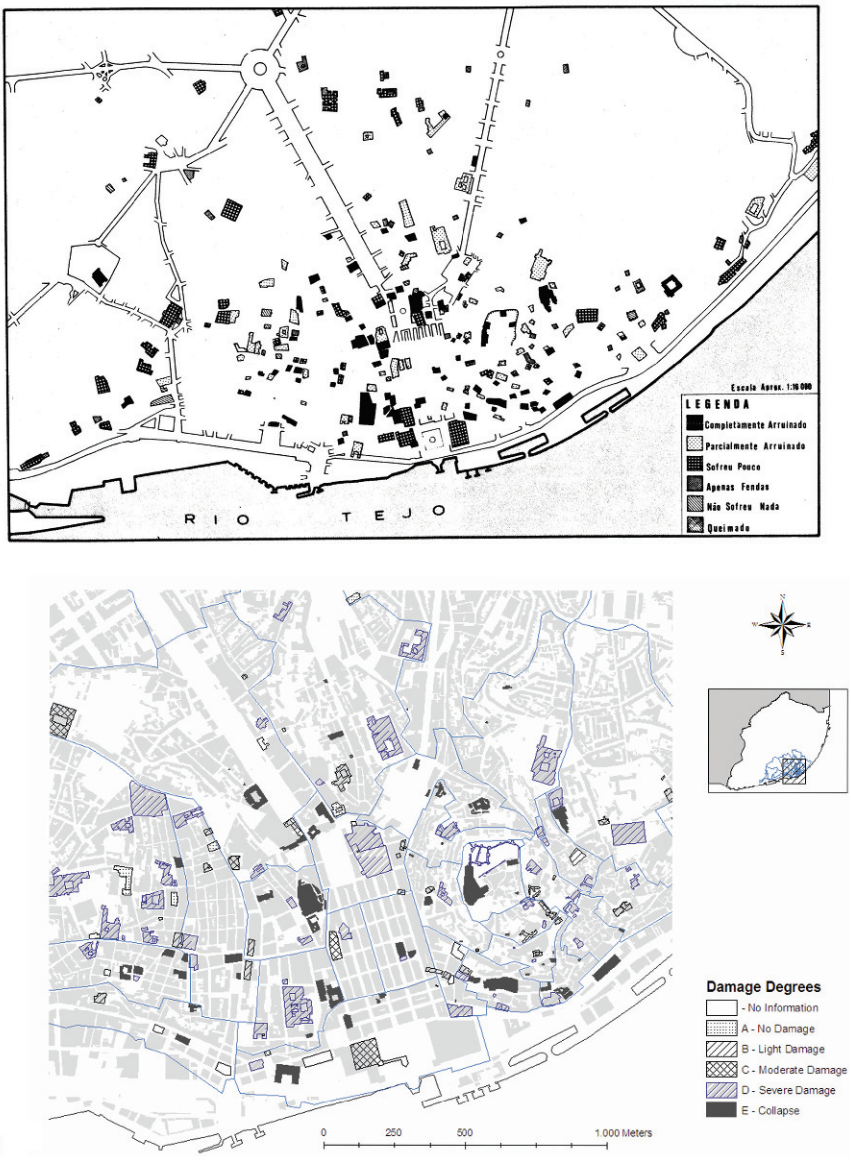


Fig. 14 Damage distribution in monuments in the City of Lisbon: a) work by Oliveira (1986); b) work by San-Payo *et al.* (2005)

the tsunami, even though, in many instances, this is quite difficult to achieve. We use engravings such as the one in Fig. 16, representing a construction having very slender walls standing alone, to analyse the cause of damage. It seems that, for this case, the fire may have destructed the roof and the shaking was not responsible for the inflicted damage.

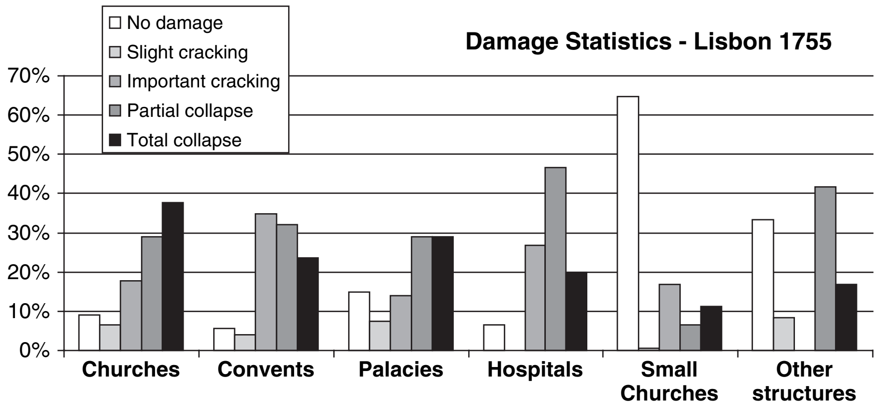


Fig. 15 Damage statistics in monuments

In relation to the housing stock, the situation is much more difficult to analyse, due to the different estimates presented by various authors. According to Pereira de Sousa (1929), confirmed in "Memórias Paroquiais", the population of Lisbon at the time was around 150,000 inhabitants with age above 7 years. The Census in 1758 indicates 34,000 apartments and 20,000 houses. Only 10–20% were in safety conditions of habitability, 60% exhibit important damage and were inhabitable, and 10–20% collapsed.

Fig. 16 Structure with slender walls without falling (Opera House or Real Theater) denoting damage caused essentially by the fire

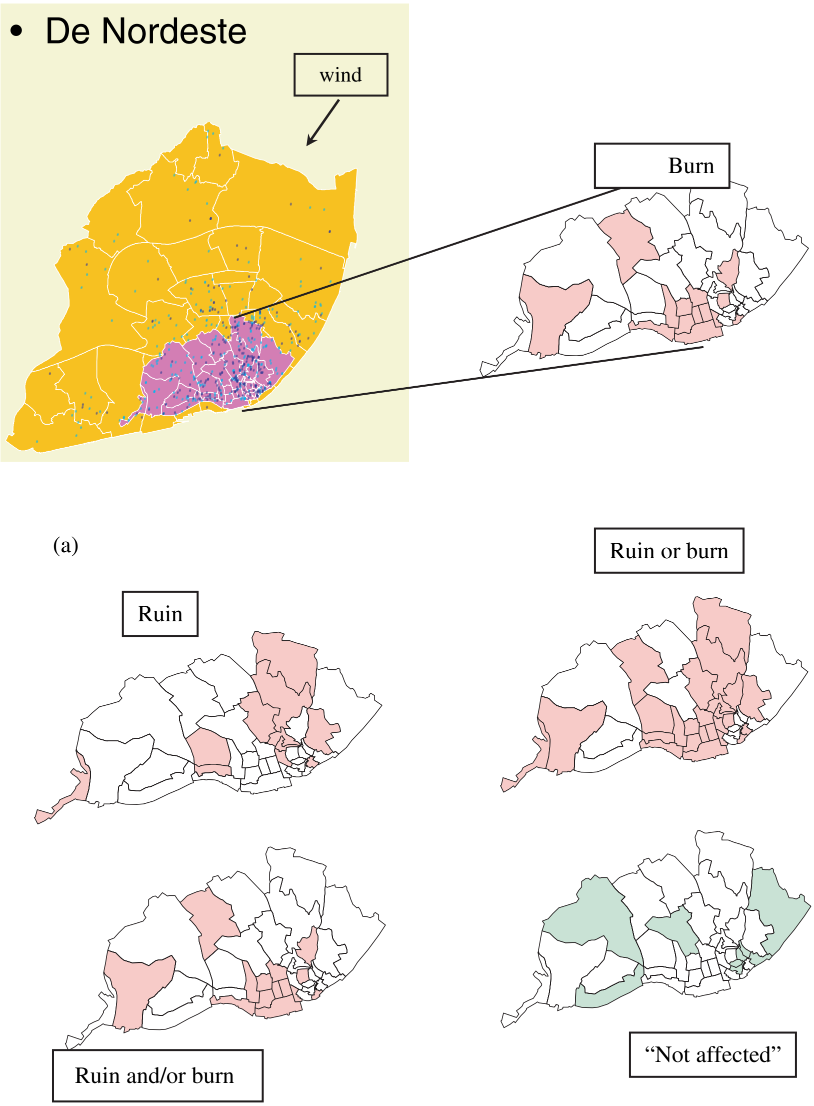


Fig. 17 Lisbon parishes more affected by shaking or fire

The fire seems to be responsible for destroying one third of the housing stock, mainly the one localized in the centre where the concentration of houses was higher. Figure 17 presents the parishes that were most affected by shaking or fire.

The estimative on the number of victims is even more uncertain. The official numbers right after the event were in the order of 5,000, a lower bound, but other sources indicate an upper bound of 30,000 death. According to the judgement of many individuals living outside the country and quoting Francisco Xavier de Oliveira (1756), the number of 30,000 victims in Lisbon seems a reasonable estimate.

However, information obtained from the population movements after the event, point to different values according to the sources. Pereira de Sousa (1914), after studying the balance of population before and after the event by parish, proposes the upper value of 8,000 deaths which correspond to around 5% of the entire population. However, he lacks information in many parishes. Pereira (2005) uses partially Pereira de Sousa data filling up many of the existing gaps supported on a more thorough research and he gets to values of the order of 30,000 deaths. This seems in better agreement if we look at the part of the housing stock damaged, from where the percent of victims should be higher, unless the collapsed houses did not kill all the population inside.

Ourselves, comparing both studies, we arrived to the following numbers:

– Prior to earthquake: Population (age < 7 years) – 147,556; Dwellings – 33,633.
– Disappeared after the earthquake: Population (age <7 years) – 31,344; Dwellings – 13,526.

These numbers need further confirmation due to the change in the administrative setting of parishes but also due to population movements to outside the Greater Area of Lisbon.

Statistics for other areas besides Lisbon are also difficult to obtain, either in Portugal, Morocco and Algeria. On the other hand, in Spain, the number of victims are of 1,200, the great majority caused by the tsunami impact in the southern coast. Only 60 were caught by the collapse of structures or fall of ornaments. 10 deaths in the Azores were due to the tsunami run-up.

To attest the tremendous work we need to perform before reducing the uncertainty bounds in this matter, the following recent findings constitute a good example of what new information can provide. Recently, in the Convent of Jesus in Lisbon, presently the Academy of Sciences, many corpses were found during excavations for maintenance procedures. It is thought that more than 1,000–2,000 victims might be there (Telles Antunes and Cardoso, 2007, personal communication). Among these victims, these investigators found corpses with signs of earthquake traumas, corpses burned by the fire that followed the earthquake, but also corpses with signs of violence practiced after the event.

This Convent was greatly damaged by the earthquake. However, the Palace of São Bento (present Assembleia da República) which is within 0.5 km and seating in the same geological setting, did not suffer much.

Detailing a little more the situation in Portugal outside Lisbon (Fig. 3, for toponym), statistics in the epoch show that in Setúbal, a village to the south of Lisbon, greatly shaken by the seismic waves with many collapsed monumental structures and suffering from the violence of the tsunami, more than 1,000 victims may have occurred and a few houses got on fire. In Santarém, to the north, very much affected with many collapses of churches and sulphur smell was spread all over the village (Pereira de Sousa 1919–1932). On the other hand, in Lagos, the village most exposed to the earthquake threat, suffering extensive damage and tsunami impact, from a population of 4,000 people housed in 900 households, only 200 died immediately and another approximately 200 were seriously injured and did not survive.

This means that the first 5% of victims were increased to 10% due to the injuries. In Lagos many large and small churches were destroyed by the strong shaking. Only one (São Sebastião) out of 5 or 6 large churches had minor damage. Also, the town walls facing the ocean and fortresses in the beach were greatly damaged.

In Oporto, 300 km to the north of Lisbon, very little damage was observed (Rosas da Silva 1939).

In Madeira Island the tower of the Cathedral (Sé) fall off to the south over the "Capela-Mor". In the Northern coast the tsunami caused first a run-down of 100 m. Then, the run-up flooded the villages of San Vicente, Ponta Delgada and Porto Moniz. There still exist some speculation on the formation of the Fajã, a place where many people may have died (Baptista, personal communication, UAveiro 2004).

Claudio da Conceição (1829) presented some complementary data worth mention. Around the so-called Greater Area of Lisbon there has been quite severe damage in locations like Sintra, Cascais, Ericeira, etc. The great Convent in Mafra did not suffer much, neither Alcobaça, even though in this one water feeding the monastery disappeared during a few days. To the north of the country the shaking was less felt. In Coimbra there were several ornamental objects that fall from their top walls. Also, the bells sound in the University tower and the river waters became very agitated. In Madrid the duration was about 8 min. The shaking was felt and in two situations the fall of the front wall in churches took place.

To the above numbers we should add the tremendous economic impact caused by the earthquake, which is also a matter of great uncertainty. Values vary from as low as 40% of the Portuguese GDP to values that can add up to 3–4 times. Twenty percentage were attributed to the losses from the collapse of the new buildings in "Terrreiro do Paço", another 20–30% to losses of stocked goods of high value, 20–30% to the housing stock, and 20% to the monumental structures in general. In a recent paper, Pereira (2005), after studying new archival and existing data concludes that direct losses from the earthquake were much lower, of the order of 40–60% of the Portuguese GDP, but the indirect consequences in the years that follow the event were major for the economical situation. "In the long-term, in spite of the terrible casualty toll and significant wealth losses, the 1755 earthquake was beneficial to the economy". In contrast, for Spain the total losses may represent as much as 20% GDP, 5% of which could be attributed to the tsunami damage (Martinez-Solares 2000).

5 Information from the Behaviour of Simple Structures: The Inverse Problem

To obtain more precise information to determine a few parameters of ground motion felt in various sites and to contribute to the establishment of the seismic source of this event in a more convincing way, we should use the most varied pieces of data. Besides the distribution of damage which is translated into the isoseismal map, the tsunami effects on the coastal areas and harbours, the behaviour of simple structures, the description of geological effects such as liquefaction, far-way effects, etc., are important points where we can gain additional information. Several of these topics were already addressed in detail. In this Section we will look into a few new topics of great importance to understand incoming ground motion, namely looking at

- The Aqueduct: “Aqueduto das Águas Livres”;
- The Corner Building: “Torreão do Terreiro do Paço”;
- The liquefaction distribution and the sinking of “Cais das Colunas”;
- The return period associated to the event from paleoseismology related to the tsunami.

5.1 The “Aqueduto das Águas Livres”

The “Aqueduto das Águas Livres” in Lisbon, a magnificent masonry structure built a few years before the earthquake, is a long structure crossing the Alcântara Valley supported by tall pillars that transform into arches. It behaved quite well during the earthquake suffering only stone block displacement in three airing towers (“Torreões”). The damaged towers were the ones positioned along the deck where the heights in relation to the valley were larger.

Many analytical and experimental studies were performed to evaluate the seismic input that generated the minor damage observed. Mathematic models were developed after determination of the mechanical properties of the materials, and were calibrated through the values of frequencies of vibration obtained with *in-situ* measurements (Fig. 18), both with ambient noise vibration (Oliveira 1986) and from records obtained during recent earthquakes (Oliveira 2005). Results indicate that Peak Ground Accelerations (PGA) at the soil level that provoke the observed damage should not have surpassed 100–150 cm/s^2. Sincraian *et al.* (1998) developed complex 2-D and 3-D non-linear models to obtain ultimate seismic loading causing the collapse of the structure, and the PGA values obtained for the longitudinal direction are above 1 g. In the transverse direction, PGA values of 0.3–0.5 g are enough to provoke the collapse of the structure.

5.2 The Corner Building: “Torreão do Terreiro do Paço”

The “Torreão do Terreiro do Paço” was a magnificent structure built just prior to the 1755 earthquake. As today, it is a massive good masonry structure (Fig. 19) founded in a soft soil of a few tens of meters. The fundamental frequency of this structure measured nowadays is on the order of 4–5 Hz. Assuming that the original structure was similar to the present one, we can say that damage to the “Torreão” was not very important. It seems that the vertical crack observed in Fig. 19 was essentially due to settlement of the foundation soil, and the part at the lower section with diagonal pattern denotes the N–S movement of incoming waves. In the adjacent cloister type

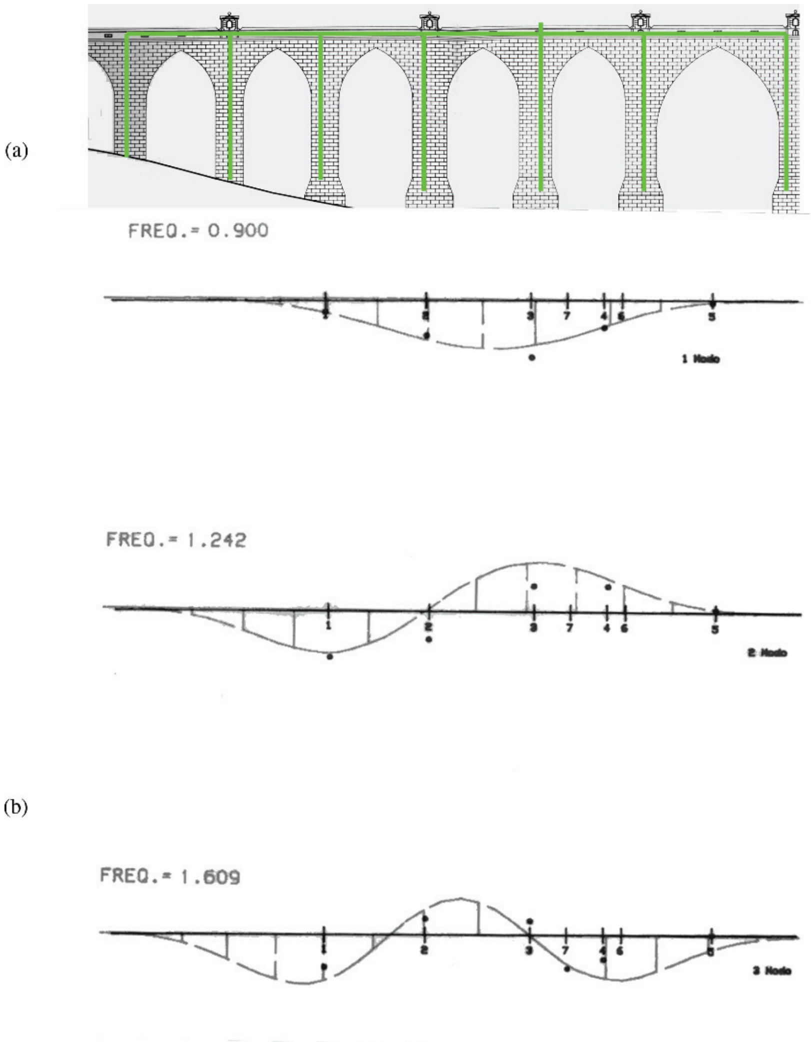
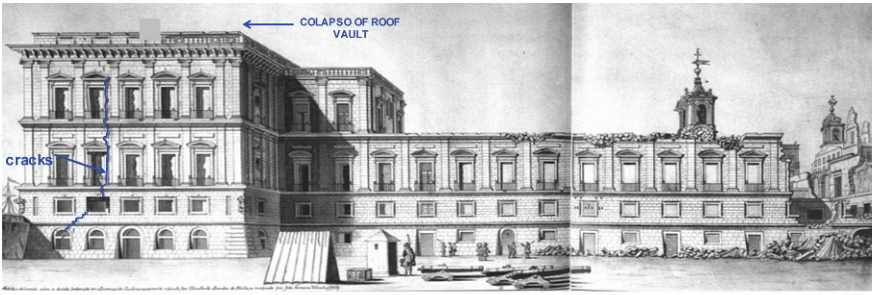


Fig. 18 Aqueduto das Águas Livres: a) 2-D model and b) *in-situ* testing to determine frequencies and modal shapes (Oliveira, 1986)

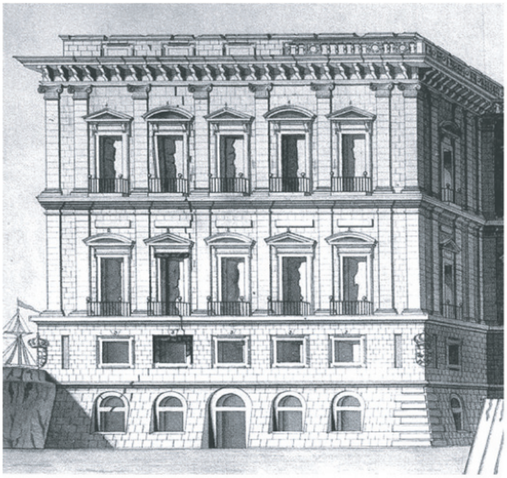
section, to the right, the soil layer is thinner, and the damage is observed at the upper floors and might be due to fire, and not so much due to shaking.

Complementary studies are being performed to clarify the behaviour of the "Torreão" by:

- Determining the structural alterations introduced in the present structure along the times in order to obtain the geometry when the earthquake occurred.
- Develop a non-linear finite element model to analyze damage and be able to foreseen what really has happened.



(a)



(b)

Fig. 19 Damage caused to the "Torreão do Terreiro do Paço" and West wing of "Terreiro do Paço": a) vertical cracking caused by strong motion and soil settlement (on the left hand side). Damage due to fire (on the right hand side). b) detail of "Torreão"

5.3 The Liquefaction Distribution and the Sinking of "Cais das Colunas"

Liquefaction observed throughout the country was another source of important information. Jorge (1994) showed locations of confirmed and probable liquefaction at sites near the coastal areas at large distances to the epicentre, denoting the large amplitude of the event, Fig. 20. According to Ambraseys (1988) only magnitudes above 9 would originate these phenomena at such large distances.

We should also add that a large number of people that run into the "Cais das Colunas", a pier built in front of the Tagus River just before the earthquake, were drowned due to its collapse. The collapse, previously attributed to tsunami waves, is now recognized as a liquefaction phenomenon with the sinking of the entire pier whose foundation was sitting on a muddy sand.

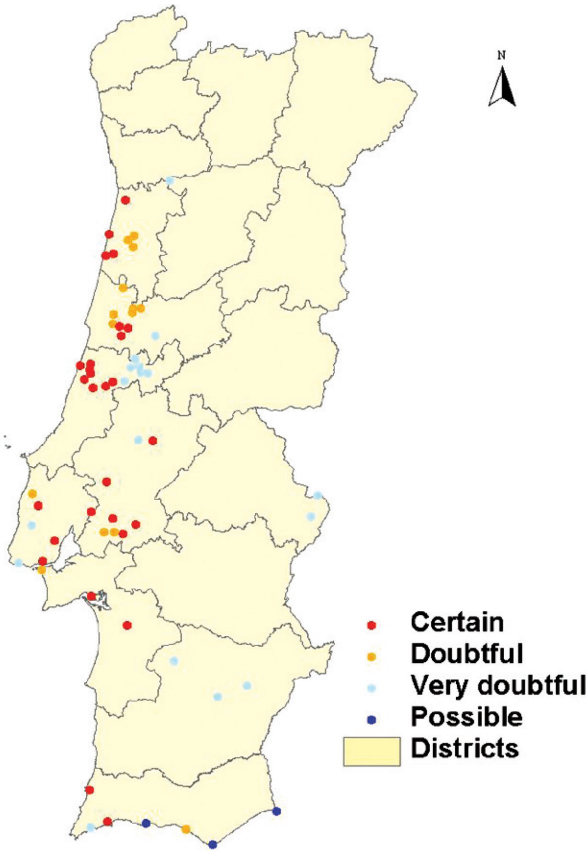


Fig. 20 Sites where liquefaction was observed (after Jorge, 1994)

5.4 The Return Period Associated to the Event from Paleoseismology Studies on Tsunamis

Paleoseismology applied to earlier tsunamis which occurred in the geological past is a new field of research which may help in identifying sites of ancient tsunami impacts and in dating the time of their occurrence. The 1755 tsunami has always called the interest of the few experts working in this topic.

Along this Section a recollection of studies is brought into discussion as the ultimate goal of estimating the return period of such an event as 1755.

Sedimentology and geomorphology evidence of the 1755 AD Lisbon tsunami includes sand, pebbles, and cobbles in the Scilly islands, UK, and in southern England (Banerjee *et al.* 2001), and on the Algarve coast in southern Portugal (Hindson *et al.* 1999, Dawson *et al.* 1995). Andrade (1992) reported the transformation of barrier islands on the Algarve coast, e.g. overwash and channels, generated by the 1755 AD tsunami. Kortekaasa and Dawson (2007) also found evidence of 1755 tsunami in other sandy beach in Algarve, Martinhal, separating the sedimentology of tsunami events from strong storm surges. 1755 Lisbon tsunami deposits have been also reported in Cadiz province, Spain (Luque *et al.* 1999).

Whelan and Kelletat (2005) observed large littoral debris and accompanying geomorphic features and they speculate about their relationship to a tsunami event at Cape of Trafalgar, located on the southern Spanish Atlantic coast, 500 km east of Gorringe Bank. Relative dating of weathering features as well as minor bioconstructive forms in the littoral zone, suggest the Lisbon tsunami of 1755 AD as the event responsible for the large deposits described. They consider that tsunami run-up or wave heights for the Cape of Trafalgar boulders of 14–16 m are conservative values.

Banerjee *et al.* (2001) also found elements for another tsunami 1,000 years ago. According to Luque *et al.* (2002) the presence of washover fan deposits on the inland margin of the Valdelagrana Spit bar, Cadiz, indicates the occurrence of a high energy marine event around 2300 cal. year BC. Historical, geomorphological, sedimentological, palaeontological and geochronological data suggest that a tsunami could have affected the area during Roman times.

In a recent study on the Aveiro lagoon, to the north of Portugal, Sarmento and Cardoso (2006) realized that the salty water flooding occurred in the Spring of 1756 may have been originated by the accumulation of water that entered the lagoon during the tsunami of 1755, together with the occlusion of the lagoon caused by the anomalous tsunami sedimentary process in the sandbank (Memórias Paroquiais, Aveiro).

New investigations on boulder deposits (>1 ton) found several west of Lisbon, and signatures of run-up to 50 m asl in vegetation scars with datings of about 200–300 years ago. This is another indication for the presence of a tsunami associated to the 1755 event. But it also gives indications of the occurrence of older tsunami, about 2400 BC and 6000 BC(?), see Scheffers and Kelletat (2005).

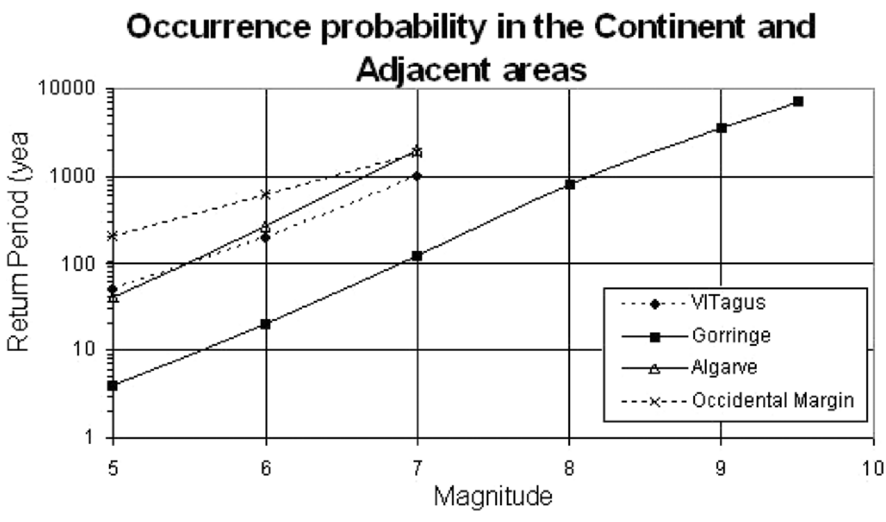


Fig. 21 Reccurrence rate for events in the most important seismic sources of Portuguese region (adapted from Rio, 1996)

All this information, together with instrumental and historical data for the Gorringe area led to the hypothesis that the Mw9 1755 earthquake may occur every 2,000–5,000 years. Figure 21 gathers all the recurrence rates for events in the most important seismic sources in the Portuguese region, including that of 1755. The above mentioned return periods seems to be in agreement with the 5 mm rate of collision between Plates and the Mw>9.

6 A Final Word

Many things have been learned in recent years using the most advanced technological tools for a better understanding of the various unknowns related to the seismic source, wave propagation, site effects, duration of ground motion, predominance of lower frequencies, etc. The damage distribution in monuments is very well known, but in the stock of housing it is still very uncertain. Much more work should be done to better clarify these aspects. This is the only way we can proceed to minimize the effects of future events of this kind. Even though this event belongs to a class of rare events with a low probability of occurrence, it may come at any time. The better we understand the better we are prepared to face it.

Acknowledgments This paper was partially supported by the Portuguese Fundação para a Ciência e a Tecnologia (FCT) under the Pluri-Annual Programme. Dr. Isabel Viseu made an overall review of the text and Mónica A. Ferreira helped in preparing the figures. The author thanks the referees for the detailed comments that helped in upgrading this text.

References

Amador F (2007) The 1755 Lisbon earthquake: collections of eighteenth-century texts. Hist. Cienc. Saude-Manguinhos. [online], vol 14, no 1 [cited 2007-06-13], pp 285–323

Ambraseys NN (1988) Engineering seismology. Earthquake Engineering and Structural Dynamics, vol 17, no 1, pp 1–105

Andrade C (1992) Tsunami generated forms in the Algarve barrier islands (South Portugal). Science of Tsunami Hazards, vol 10, no 1, pp 21–34

Andrade C, Borges P, Freitas MC (2006) Historical tsunami in the Azores archipelago (Portugal). Journal of Volcanology and Geothermal Research, vol 156, pp 172–185

Anonymous (1756) Notícia Individual que da la Academia de la Historia del Terremoto de Primero de Noviembre de 1755. Madrid (in Spanish)

Banerjee D, Murray AS and Foster JLD (2001) Scilly islands, UK: optical dating of a possible tsunami deposit from the 1755 Lisbon earthquake. Quaternary Science Reviews, vol 20, no 5–9, pp 715–718

Baptista MA, Miranda JM (2001) Atenuação da Intensidade Sísmica na Península Ibérica. Proceedings, 5° Encontro Nacional de Sismologia e Engenharia Sísmica, Ponta Delgada, pp 49–56 (in Portuguese)

Baptista MA, Miranda PMA, Miranda JM, Mendes-Victor LA (1998) Constraints on the source of the 1755 Lisbon tsunami inferred from numerical modelling of historical data on the source of 1755 Lisbon tsunami. Journal of Geodynamics, vol 25, no 2, pp 59–74

Braga ML (1989) Uma Visão Particular sobre os aspectos da Sismicidade Histórica. Algumas notícias de sismos ocorridos no Estrangeiro. In: Workshop on Historical Earthquakes in the Iberian-Maghrebian Region, Lisbon, pp I/85–I/103 (in Portuguese)

Brazão Farinha JS (1990) O Metropolitano e a Baixa de Lisboa. História, Ano XII, no 131, pp 4–31 (in Portuguese)

Cabral J (1993) Neotectónica de Portugal Continental. Tese de Doutoramento, Universidade de Lisboa (in Portuguese)

Calvário JM (1755–1764) Memória dos Tremores de Terra que se tem seguido ao formidável Terramoto do primeiro de Novembro de 1755 por Portugal. Notes. Cited by A Correia *in* A ética da Polaridade Político-Religiosa Medieval e suas Repercussões no Imaginário Sócio-Cultural Medievo. MA Thesis, Universidad Salamanca, Spain (in Portuguese)

Campos IMB (1998) O Grande Terramoto (1755). Parceria (in Portuguese)

Campos-Romero ML (1989) Epicentral Parameters of the Lisbon Earthquake Based on the Study of the Tsunami Raised. In: Workshop on Historical Earthquakes in the Iberian-Maghrebian Region, Lisbon, pp II/1–II/16

Carrilho F, Senos ML, Oliveira CS (2004) Calibração de Escalas de Magnitude Local e de Duração para Portugal Continental e Região Adjacente. 4^a Assembleia Luso-Espanhola de Geodesia e Geofísica, Figueira da Foz, pp 281–282 (in Portuguese)

Carvalho A (2007) Modelos Estocásticos para a Caracterização da Acção Sísmica em Portugal Continental. Ph.D. Thesis, Instituto Superior Técnico, Lisbon (in Portuguese)

Castilho J (1893) A Ribeira de Lisboa, descrição histórica da margem do Tejo desde a Madre de Deus até Santos-o-Velho. Lisboa (in Portuguese)

Chantal S (2005) A Vida Quotidiana em Portugal ao Tempo do Terramoto. Editora Livros do Brasil, Lisboa (in Portuguese)

Choffat P (1904) Les Tremblements de Terre de 1903 en Portugal. Boletim do Serviço Geológico de Portugal, Lisboa (in French)

Claudio da Conceição Fr (1829) Em que se dá Notícia do Terramoto do 1° de Novembro. Cap VII, Tomo XIII do Gabinete Histórico, Impressão Régia, Lisboa. (Re-edição de P. C. Domingos, Frenesi, 2005) (in Portuguese)

Coelho AG (2007) Os Inquéritos do Marquês de Pombal e de Fernando VI de Espanha sobre o Terramoto do 1° Novembro de 1755. Academia de Engenharia, Comunicação n° 2 (in Portuguese)

Dawson AG, Hindson R, Andrade C, Freitas C, Parish R, Bateman M (1995) Tsunami sedimentation associated with the Lisbon earthquake of 1 November AD 1755: Boca do Rio, Algarve, Portugal, The Holocene, vol 5, pp 209–215

Diniz JDF (1910) Contribuição para o Estudo dos Tremores de Terra em Portugal – O Abalo Sísmico de 23 de Abril de 1909. Revista de Obras Públicas e Minas, Lisboa, Tomo XLI (in Portuguese)

França JA (1977) Lisboa Pombalina e o Iluminismo. Livraria Bertrand, Lisboa (in Portuguese)

França JA (1978) A Reconstrução de Lisboa e a Arquitectura Pombalina. Instituto de Cultura Portuguesa, Lisboa (in Portuguese)

Gutscher M-A (2004) What caused the Great Lisbon earthquake. Science, vol 305, no 5688, pp 1247–1248

Hindson RA, Andrade C (1999) Sedimentation and hydrodynamic processes associated with tsunami generated by the 1755 Lisbon earthquake. Quaternary International, vol 56, no 1, pp 27–38

IM (2007) Catálogo Sísmico para Portugal. 1960–2007. Instituto de Meteorologia, Lisbon (in press)

Jorge C (1994) Zonamento do Potencial de Liquefacção. Tentativa de Aplicação a Portugal. Relatório 226/94 – NP, LNEC, 199p (in Portuguese)

Kortekaasa S, Dawson AG (2007) Distinguishing tsunami and storm deposits: an example from Martinhal, SW Portugal. Sedimentary Geology, doi:10.1016/j.sedgeo.2007.01.004

Levret A (1991) The effects of the November 1, 1755 Lisbon earthquake in Morocco. Tectonophysics, vol 193, no 1–3, pp 83–94

Luque L, Lario J, Civis JP, Silva PG, Zazo CJ, Goy JL, Dabrio CJ (2002) Sedimentary record of a tsunami during Roman times, Bay of Cadiz, Spain. Journal of Quaternary Science, vol 17, no 5–6 pp 623–631

Luque L, Zazo C, Goy JL, Dabrio CJ, Civis J, Lario J, Gómez-Ponce C (1999) Los depósitos del tsunami de Lisboa de 1755. Su registro en la Bahía de Cádiz: Flecha de Valdelagrana (Spain). In: Avances en el estudio del Cuaternario Español, Pallí Buxó L, Roqué Pau C (eds), Universitat de Girona, Girona, pp 63–66 (in Spanish)
Machado F (1966) Contribuição para o estudo do Terramoto de 1 de Novembro de 1755. Rev. Fac. Ciências de Lisboa, vol 14, pp 19–31 (in Portuguese)
Mader C (2001) Modeling the 1755 Lisbon Tsunami. Mader Consulting Co., Honolulu, Hawaii, U.S.A
Martinez Solares JM (2000) Los Efectos en España del Terremoto de Lisboa (1 de Noviembre de 1755). Monografía núm.19, IGM, Ministerio de Fomento, 756p (in Spanish)
Martinez Solares JM, Lopez Arroyo A, Mezcua J (1979) Isoseismal map of the 1755 Lisbon earthquake obtained from Spanish data. Tectonophysics, vol 56, no 3, pp 301–313
Memórias Paroquiais do Séc. XVIII, Arquivo do Distrito de Aveiro (in Portuguese)
Mendes VL, Baptista MA, Miranda JM, Miranda PMA (1999) Can hydrodynamic modelling of tsumami contribute to seismic risk assessment? Physics and Chemistry of the Earth (A), vol 24, no 2, pp 139–144
Mendes-Victor LA, Oliveira CS, Pais I, Teves-Costa P (1994) Earthquake Damage Scenarios in Lisbon for Disaster Preparedness. In: BE Tucker, M Erdik, CN Hwang (eds), Issues in urban earthquake risk. NATO ASI series E, Applied Science Volume 271, Kluwer Academic Press, Dordrecht, pp 265–289
Mezcua J (1982) Catálogo general de Isossistas de la Peninsula Iberica. Publ. Instituto Geografico Nacional, Madrid Espanha (in Spanish)
Miranda R (1931) Tremores de Terra. Ed. Silva Raposo, Coimbra, 175p (in Portuguese)
Montessus de Ballore F (1906) Les Tremblements de Terre. Géographie Séismologique. Librairie Armand Colin (in French)
Moreira VS (1979) Contribuição para o conhecimento da Sismicidade Histórica de Portugal Continental. Revista Instituto Nacional de Meteorologia e Geofísica, vol 2, no 3–4, pp 121–135, Lisboa (in Portuguese)
Moreira VS (1984) Sismicidade histórica de Portugal Continental. Revista Instituto Nacional de Meteorologia e Geofísica, Lisboa (in Portuguese)
Moreira VS, Cruz JF (1989) Review of the Historical Seismicity in the Gulf of Cadiz Area Before the 1 Nov. 1755 Earthquake – A CEC Project. In: Workshop on Historical Earthquakes in the Iberian-Maghrebian Region, Lisbon, pp I/73–I/83
Moreira de Mendonça JJ (1758) História Universal dos Terramotos que tem havido no mundo de que ha noticia, desde a sua creação até ao século presente, 255p (in Portuguese)
Oliveira CS (1986) Some quantitative measurements for calibrating historical seismicity. Proceedings of the 8th European Conference on Earthquake Engineering. Laboratório Nacional de Engenharia Civil, vol 1, pp 2.1/71–2.1/78, Lisboa
Oliveira CS (2004) The Influence of Scale on Microzonation and Impact Studies. In: Recent Advances in Earthquake Geotechnical Engineering and Microzonation, editor Atilla Ansal, Kluwer Academic Publishers, Chapter 2, pp 27–65
Oliveira CS (2005) Descrição do Terramoto de 1755, Sua Extensão, Causas e Efeitos. O Sismo. O Tsunami. O Incêndio. In: 1755, O Grande Terramoto de Lisboa, vol 1 Descrições, Editores FLAD and Público, pp 23–86, Lisbon (in Portuguese)
Oliveira, FX (1756) Discurso Patético sobre as Calamidades presentes sucedidas em Portugal. Tradução e Posfácio de JG Pires, Lisboa, 2004, Edition Frenesi (in Portuguese)
Pararas-Carayannis G (1997) The Great Lisbon Earthquake and Tsunami of 1 November 1755. (Excerpts from archives compiled in preparation of a Catalogue of Tsunamis in the Atlantic Ocean, World Data Center A – Tsunami U.S. Dept. of Commerce Environmental Science Service Administration – Coast and Geodetic Survey, May 1969.)
Paula AO, Oliveira CS (1996) Evaluation of 1947–1993 Macroseismic information in Portugal using the EMS-92 scale. Annali di Geofisica, vol XXXIX, no 5, pp 989–1003
Pereira AS (2005) The Economic Impact of the Lisbon 1755 Earthquake. (http://www.docudesk.com)
Pereira de Sousa FL (1914) Ideia Geral dos Effeitos do Megasismo de 1755 em Portugal. Tipographia do Comercio, Lisboa (in Portuguese)

Pereira de Sousa FL (1919–1932) O Terramoto do 1° de Novembro de 1755 em Portugal e um Estudo Demográfico, vol I–IV, Serviços Geológicos de Portugal (in Portuguese)
Pereira de Sousa FL (1929) Alguns Prognósticos Possíveis do Terramoto de 1755 em Portugal. Academia de Ciências de Lisboa, Boletim da Academia (in Portuguese)
Quenet G (2002) 1° Novembre 1755. La Terre Tremble à Lisbonne. In: Dix journées qui ébranlèrent le monde, L'Histoire, no 268, pp 48–49 (in French)
Reid HF (1914) The Lisbon earthquake of November 1, 1755. Bulletin of the Seismological Society of America, vol 4, no 2, pp 53–80
Ribeiro A (2002) Soft Plate and Impact Tectonics. Springer-Verlag, Berlin
Rodriguez de la Torre F (1981–1993) Efectos del Terremoto de 1 de Noviembre de 1755. Ph.D. Thesis (in Spanish)
Rómulo de Carvalho (1987) As Interpretações dadas, na época, às causas do Terramoto de 1 de Novembro de 1755. Palestra proferida na Academia das Ciências na Sessão de 29 de Outubro de 1987 (in Portuguese)
Rosas da Silva D (1939) A Cidade do Porto e o Terramoto de 1755. Publicação do Museu e Laboratório Minerológico e Geológico da Faculdade de Ciências da Universidade do Porto (in Portuguese)
RSCS (1958) Regulamento de Segurança da Construção contra os Sismos. Decreto n° 41658 de 31 de Maio (in Portuguese)
San-Payo M, Oliveira CS, Teves-Costa P, Moitinho I (2005) Contribution to the Damage Interpretation During the 1755 Lisbon Earthquake. Proceedings, International Conference on the 250 Anniversary of the 1755 Lisbon Earthquake, Lisbon, Portugal
Santos NB, Cunha RM, Alves RR, Rodeia TB (1993) A Arquitectura e os Processos Construtivos entre os Séculos XVI e Meados de XVII. Nota Técnica n° 1/93 – NDA, LNEC, Lisboa (in Portuguese)
Sarmento C, Cardoso A (2006) Testemunhos Históricos da Influência do Terramoto de 1755 na Laguna de Aveiro. Territorium, vol 13, pp 93–104 (in Portuguese)
Scheffers A, Kelletat D (2005) Tsunami relics in the coastal landscape West of Lisbon, Portugal. Science of Tsunami Hazards, vol 23, no 1, pp 3–16
Simpósio sobre a Acção dos Sismos (1955) Ordem dos Engenheiros, Lisboa (in Portuguese)
Sincraian G, Oliveira CS, Lemos JV (1998) Assessment of the Seismic Behaviour of a Stone Masonry Aqueduct Using the Discrete Element Method. Proceedings, 11th European Conference on Earthquake Engineering, Paris, CD-Rom, A.A. Balkema, Rotterdam
Sousa ML, Oliveira CS, Martins AM (1992) Compilação de Catálogos Sísmicos da Região Ibérica. Report 36/92- NDA, Laboratório Nacional de Engenharia Civil, Lisboa (in Portuguese)
Tavares R (2005) O Pequeno Livro do Grande Terramoto. Edition Tinta da China, Lisbon (in Portuguese)
Terrinha P, Pinheiro LM, Henriet J-P, Matias L, Ivanov MK, Monteiro JH, Akhmetzhanov A, Volkonskaya A, Cunha T, Shaskin P, Rovere M (2003) Tsunamigenic-seismogenic structures, neotectonics, sedimentary processes and slope instability on the southwest Portuguese margin. Marine Geology, vol 195, no 1–4, pp 55–73
Teves-Costa P, Baptista MA, Miranda JM (2002) Attenuation Models for SW Iberia – Implications on Seismic Hazard Assessment. Proceedings 12th World Conference on Earthquake Engineering, CD Rom, London
Vilanova SP, Nunes ACF, Fonseca JFBD (2003) Lisbon 1755: a case of triggered intraplate rupture? Bulletin of the Seismological Society of America, vol 93, no 5, pp 2056–2068
Whelan F, Kelletat D (2005) Boulder deposits on the Southern Spanish Atlantic Coast: possible evidence for the 1755 AD Lisbon tsunami? Science of Tsunami Hazards, vol 23, no 3, p 25
Zitellini N, Chierici F, Sartiri R, Torelli L (1999) The tectonic source of the 1755 Lisbon earthquake and tsunami. Annali di Geofisica, vol 42, no 1, pp 49–55
Zitellini N, Terrinha P, Dañobetia, J, Gracia E, Sartori R, Torelli L, Rovere M, Chierici F, Ribeiro A, Matias L, Mendes Victor L (2000) Structural Map of Offshore SW Iberia. 2ª Ass. Luso Espanhola de Geodesia e Geofísica, S03-18, pp 145–148