The 1531 Lisbon earthquake and tsunami

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SUMMARY:

The 26 January 1531 earthquake heavily impacted Lisbon according to the coeval sources and archaeological remnants. The earthquake, and in particular the claimed tsunami, were not so far the subject of a quantitative study. This event is thought to be the one of the biggest in Lisbon history. The observations indicate that the water disturbance was preceded by the shock and flooding of the river banks. We present a re-appraisal of the written information and the main results of the archaeological studies. Macroseismic data is re-analysed and a new isoseismal map is presented. Finally, we investigate the water disturbance observed in the estuary to establish the occurrence of a tsunami event. Our conclusions point to the fact that a tsunami was observed along the estuary but it did not affect the city of Lisbon. This study is a contribution to the seismic and tsunami risk assessment in Lisbon.

Keywords: earthquake, tsunami, estuary, Lisbon

1. INTRODUCTION

The establishment of the scientific knowledge concerning the 1531 event has an unusual story: in the aftermath of the 1909 earthquake Osorio (1919), a Portuguese scholar, found in a Lisbon bookshop a copy of a four page letter addressing the Marquis of Tarifa (Spain) describing the large earthquake that took place in Lisbon in the year of 31. Osorio (1919) concluded that it related to a disastrous earth-quake on January, 26 1531. In a Portuguese newspaper of 5 June 1909, Brito (1909) described the discovery of an unsigned manuscript containing eyewitness descriptions of the 26th January 1531 in Lisbon area. In the compilation made by Sousa (1919) of the information related with the 1755 Lisbon earthquake, more information was recovered, because the well-known Marques Pombal inquiry, included a tenth question saying “Do you remember any previous earthquake and the damage it may have caused in each place?” (Arquivo Ministério do Reino, 1761). The answers strongly support the occurrence of the 1531 event.

Henriques et al. (1988) presented a systematic compilation of the Portuguese sources related with the 1531 earthquake and used the data to constrain the Portuguese seismic catalog. The compilation includes more than one hundred different historical sources describing the effects of the shock in the estuary between Lisbon and Santarém (see figure 1a ad 1b). Justo & Salwa (1998) made the most comprehensive geophysical study of this event, adding additional historical data from Spain. Their study focused on the earthquake effects and their relationship with the geological environment of each site. In particular, they refute the claims of significant earthquake effects far away from the NE Lisbon area, concluding that its source area should be located in the presumed Lower Tagus Fault Zone, without attributing it to a specific tectonic unit.

Several descriptions relate water agitation in the Tagus. Gil Vicente, the most famous classical Portuguese writer sent to the King John III a letter concerning philosophical implications of the earthquake explicitly refuting those that claimed for the eminent arrival of a new earthquake and tsunami one month later *“contra aqueles que deziam que logo viria outro tremor e que o mar se levantaria a vinte e cinco de Fevereiro”* (Vicente, 1562) These descriptions were written more than two hundred years before the big 1755 Lisbon earthquake and could not be biased by the 1755 tsunami.

There is an important question regarding tsunami risk in Lisbon: can an earthquake, which source is located within the Tagus Estuary generate a tsunamigenic earthquake? We review here the information available, we discuss the macroseismicity and its implications in the identification of the potential tectonic source and the estimation of the earthquake magnitude, we present numerical modeling of a possible tsunami generated inside the Estuary, and we compare the results of the modeling exercise with the historical information available.

2. THE EARTHQUAKE

The earthquake of January 26 1531 occurred between 4 and 5 am and was felt in Lisbon and along the Tagus estuary. The shock caused severe damage in the city downtown and neighbor areas, causing approximately 1000 casualties (Vogt, 1985; Justo and Salwa, 1998). Two strong foreshocks preceded the event on the 2nd and the 7th of January respectively. The waters of river Tagus flooded some places along the estuary and ships in the harbor touched the riverbed due to the movement of the water. The maximum reported MSK intensity is IX, making it one of the most severe earthquakes felt in Portugal. The approximate location of the epicentre coordinates inferred from the macroseismic field is 38.9N, 9.0W (Mezcua, 1982, LNEC, 1986).

In spite of the paucity of written coeval reports of the XVI century, a number of sources describe the event with some detail (e.g. Surius, 1567, in Babinet 1861). This is probably due to the relative importance of Lisbon as a commercial harbor in the aftermath of the first phase of the Portuguese expansion overseas. The shock caused severe damage in the city and destroyed about 1/3 of the building stock (1500 houses). If we consider the “public buildings” described by Henriques et al. (1988) which corresponded to the best building standards of the time, we conclude that the damage was particularly large in buildings located on a recent landfills most likely unconsolidated. This was the case of the Ribeira Palace and the San João da Praça Church within the old city wall (see figure 1a); Jerónimos Monastery and Belém Tower (figure 1b) built above a landfill on the northern bank suffered also structural damage but did not collapse.

The international impact of the earthquake was large: all major chroniclers like Garibay, Sandoval, Santa Maria, Barbosa and Couto describe it (in Rodriguez, 1932). Rodrigues (ca 1500-1560) then at Asilah, in Morocco, describes the event in the following way: “[...] in this kingdom of Portugal there was much work, because there was plague and earthquakes, the earth shaking and houses and buildings fall down, where many people died […] this occurred more in Lisbon and upward Tagus than anywhere else, particularly in Villa Franca, Póvoa, Castanheira, Azambuja, up to Santarém” (see geographical coordinates in Table I).

3. THE TSUNAMI

The poem by Resende (1554) describes the disaster: “[...] Morning of Tuesday/there was such a large/earthquake in Portugal/no one ever saw alike/[...]/It was also felt in the sea/The water grew with no wind/Ships touched the ground/their keels reaching the bottom/like the others were lost/all things alive”. This poem describes a phenomenon often occurring during tsunamis: the sudden withdraw of the water uncorrelated with any dramatic meteorological event. A description of a large tempest in the sea appears in some documents: “[...] several ships were swallowed by the pits of the ground and turbulent sea [...]” (Laurent Surius, 1567 translated from the lat
in Babinet, 1861); “Many ships submerged with the tempest that grew” (Codex 9857). Couto (1778) describes the sea agitation close to Lisbon downtown: “[...] in the sea the tempest was so great that destroyed and broke all ships staying in Lisbon harbor, some say that the Tagus river opened by its middle splitting its waters into a pathway and showing the sand bed”. “[…] the ships (the sailors said) seemed to go in the sky; and [then] against the rocks; and the river open by its middle and closed again” (Osório, 1919). The report found in the Codex 8009 says: “Tagus River with violent tide fluxes

and the infuriated wave agitation rose in such a way that many ships submerged and it is said that it opened in the middle of the water showing the sand of its bottom [...]". Upriver, in Vila-Franca-de-Xira (see figure 1b) the description is clear: "Sailors say that ships rose up to the heaven and struck the rocks; and, according to some sailors who were near, the waters parted and closed in the river-bed, and at Azambuja the waters withdrew in the middle and the land appeared from below: in this same river people saw the sky opening and it looked like a burning oven and they saw a big spark with a large flame; and it was close to Vila Franca" (Osório, 1919). According to by Brito (1909) "[...] caravels at sea, fishing at 40 fathom depth found themselves in dry land for three hours […]".

The description of the water disturbance associated with the earthquake includes (i) the rise of the water inundating the river bank; (ii) the retreat of the water large enough to discover significant areas of the riverbed and (iii) the observation of strong currents in the river. These observations are coherent with the existence of a large change in the Estuary seafloor, either tectonic displacement or a landslide.

4. MACROSESIMIC MODELLING

4.1 Revision of macroseismicity

The evaluation of seismic intensity values in the case of ancient earthquakes remains an open problem (see Guidoboni and Ebel, 2009, for a review). In this case, the main problems are the lack of available reports, and their poor content. Some reports describe the event by comparison with other events, while others just mention that people felt the shock. Justo & Salwa (1998) presented a seismic intensity map mainly based upon Henriques et al. (1988), with a single additional data point for Tomar (see Table I). The main limitation of this work is the fact that they give a single grade to each site.

To assign intensities in the EMS98 scale we used three intermediate classifications: intensity intervals, "equal or larger than" or "larger than in XX place", and "D" or felt "F" level (see Table I column from records. In order to translate these values in workable intensities we made a comparison with the 1909 earthquake. On the third column of table I, the known intensities for the 1909 earthquake as consigned in Choffat and Bensaude (1912) are listed. The area of greatest destruction for the 1531 earthquake looks larger than that of 1909, while the far field looks smaller.

There is no information from areas like Sevilla, Cordoba, Ciudad Real or Ciudad Rodrigo where the 1909 earthquake caused considerable alarm. Justo & Salwa (1998) intensity's determination for Trujillo, the only Spanish location available for the 1531 earthquake looks considerably larger than what is expected for 1909. This is strange assuming that we are dealing with an earthquake supposed larger than the 1909 event. From the Spanish Catalogue and references therein, we can find references and reports to earthquakes prior to 1531, or short later, in several places. Also, the chronicle of the emperor Charles V written by Sandoval, describes the earthquake but constraining it to the area of Lisbon, without any reference to a larger felt area. With this information we assign the Idef that is the value used for the isoseismal map. For the intensity evaluation we use the scale by Ramazi and Haghani (2007) for Iran. It applies to buildings similar to the buildings of the XVI century in the Iberian Peninsula. Following these authors, the damage of the Trujillo tower is assigned as 2 (crack in towers) on a building of type B. Same authors state that such damage can occur with intensity 6 (even 5). Thus, the working intensity evaluation is 6-7. Damage in Lisbon is assigned as grade VIII or IX. Also, following Ramazi and Haghani (2007), most of the damages described in Henriques et al. (1988) correspond to intensity VIII. Moreover, most damage occurs in the downtown located in an old arm of the Tagus River, where site amplifications may be important.

The destruction in the epicentral area is greater in 1531 than in 1909. This could be explained by a shallower epicentre. However, the computed depth of the 1909 event is only 10 km, and so an alternative explanation might be the overestimation of 1531 intensities by Justo & Salwa (1998).

Table 1 – Macroseismic Intensities for 26 Januray 1531 earthquake. MMI from Moreira (1984), MSK from Justo and Salwa (1998). Column 1909-04-23 states the felt intensity recorded in the 1909 Benavente Earthquake following Teves-Costa and Batlló (2010). Column I from records is the assigned intensity from the scarce available contemporary records. Column Idef is the final assigned intensity (working intensity). F means “felt”; F/D means Felt or Damaging. Longitudes and Latitudes in decimal degrees.

Location	E Lon	N Lat	MMI	MSK	I from records	Idef	1909-04-23
Alcanede	-8.822	39.416	-	8	>=7	7	-
Alcobaça	-8.976	39.548	8.5	7	>=6	7	VII
Alcáçovas	-8.154	38.392	-	7	(7-8)	7-8	-
Alcacer do Sal	-8.519	38.371	-			-	V
Alenquer	-9.006	39.056	8.5	8	8-9	8-9	VII-VIII
Almeirim	-8.627	39.208	8.5	8.5	8 (< Vila Franca)	8	VII-VIII
Alhandra	-9.007	38.930	-	6	4	4	VIII
Alverca	-9.037	38.898	-	6	4	4	VIII
Azambuja	-8.867	39.071	-	8.5	8-9	9	VIII
Batalha	-8.821	39.658	-	7	F/D	6	VII
Benavente	-8.812	38.984	9	8.5	8-9	9	X
Bombarral	-9.153	39.270	8.5	7	F/D	7	V-VI
Braga	-8.419	41.551	<2	4-8	F	4	III-IV
Cartaxo	-8.785	39.161	-	8		-	
Cantanhede	-8.589	40.352	-	7		-	
Castanheira	-8.975	38.994	9	9	8-9	8-9	IX
Coimbra	-8.416	40.213	-	7	5	5	VI-VII
Évora Monte	-7.701	38.776	8	7		-	
Guimarães	-8.296	41.443	<2	4	F	4	V
Lavradio	-9.048	38.673	-	8	F	5	-
Lisbon	-9.130	38.711	9	9	8-9	9	IV-VII
Marinha Grande	-9.051	39.707	-	-	>=6	7-8	-
Óbidos	-9.151	39.364	8	7	F/D	6	VI
Porto	-8.607	41.151	<2	4	F	4	III-V
Santarém	-8.684	39.234	8.5	9	>= 8	8-9	VII-VIII
Setubal	-8.891	38.524	8	7.5	7	7	VI-VII
Tancos	-8.388	39.451	8.5	8	< Vila Franca	8	N/A
Tomar	-8.413	39.604	-		>=6	7	V-VI
Torres Vedras	-9.260	39.091	8	6	F/D	6	VI
Trujillo	-5.878	39.457	-	7	6	6-7	-
Vila Franca	-8.991	38.951	9	8.5/9.5	(8)-9	9	VII-VIII

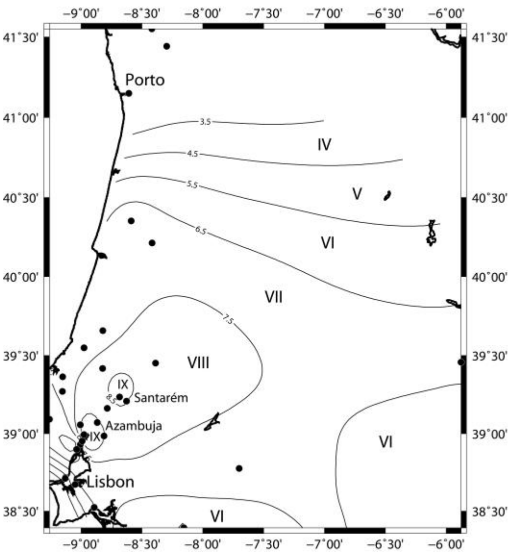

Figure 1. Isosseismal map for the 1531 earthquake

4.2 Candidate Tectonic Sources

The Lower Tagus Basin (LTB) is a complex tectonic depression overlain by a thick Cenozoic sedimentary cover that hosts the lower reach of the Tagus River, with thickness varying from some hundreds of meter to 2 km (Cabral et al., 2003). The LTB developed mainly in the Neogene as a compressive foredeep related with the inversion of the (Mesozoic) Lusitanian Basin as a consequence of NW-SE Miocene compression (Cabral et al., 2003 and references herein). Neogene-Quaternary evolution was controlled by NNE-SSW and transverse WNW-ESE faulting, generating a series of tectonic blocks, with structural highs and lows, with differential subsidence across the basin. The drainage network evolved into an entrenched fluvial system in the Quaternary following the relative lowering of the base level, once again controlled by the above fault system (Cabral et al., 2003).

Choffat and Bensaude (1910) suggest that the local historical earthquakes that impacted the city of Lisbon (e.g. 1344, 1531 and 1909) were due to a fault matching the axis of the Lower Tagus Valley. Among the three events, only the 1909 earthquake occurred in the seismological instrumental period, and so there is a well constrained moment magnitude determination (6.0 ~ 6.2, according to Teves-Costa et al., 1999, Dineva et al., 2002 and Stich et al., 2005) and a well constrained epicentral determination. Nevertheless, in spite of the recent studies conducted in the area it was not possible to determine which structure was responsible for this event (Vilanova, 2003, Cabral et al., 2003, 2004, Carvalho et al., 2005, 2006, Fonseca et al., 2011). After, 1909 the seismic activity in the area has been rather low.

If we focus in the area where the MKS intensity was close to IX the two main faults identified are the Vila-Franca-de-Xira fault and the Azambuja fault. The Vila-Franca-de-Xira fault is a NNE-SSW complex fault expressed in the field as east-verging reverse fault that places Jurassic rocks at the west over Tortonian deposits at the east. It is interpreted as Neogene inversion of a previous normal fault bounding the Lusitanian Basin with an estimated length close to 25km (Cabral et al., 2003). The Azambuja fault with the same orientation (NNE-SSW) presents a 15km long scarp and significant morphological and structural evidence of neotectonic activity. Multichannel seismic data suggest that it consists of an east verging reverse fault down to the basement with an estimated length of 20km (Cabral et al., 2004). The magnitude of the maximum credible earthquakes for these structures are 6.7 and 6.4-6.7 respectively (Cabral et al., 2003, 2004).

Among the two faults, only Vila-Franca-de-Xira fault is able to generate significant deformation in the Tagus Estuary, to be able to cause relevant water disturbance. We hypothesize that it was the source of the 1531 earthquake.

4.3 Event Magnitude

Rueda and Mezcua (2002) determined an empirical relationship between maximum intensity and moment magnitude for earthquakes in SW Iberia as $M_w = 0.96 + 0.6*Imax$. This relationship was used by Palaez et al. (2007) to assess a magnitude value to Morocco historical earthquakes. If we consider as maximum MSK intensity of IX, similar to Justo and Salwa (1998), we get M_w= 6.4. If we consider the conclusions of Cabral et al. (2003, 2004) we can consider an interval M_w= 6.4 ~ 6.6.

5. TSUNAMI MODELLING

5.1 Non-linear Shallow Water Model

The elastic deformation of the seafloor is computed using the half space homogeneous elastic approach for a planar rectangular source (Mansinha and Smylie, 1971). For modelling purposes we considered a simple rectangular geometry, defined by the coordinates (-8.828E, 39.178N; -8.908E, 38.956N), westward steeply dipping and reverse, compatible with the present regional orientation of the maximum horizontal compressive stress and the neotectonic research of Cabral et al. (2004).

The boundary conditions ensure pure wave reflection on the solid boundary (coastlines) and full wave transmission on the open boundary (open sea). The initial seawater disturbance is assumed to be equal to the co-seismic displacement produced by the dislocation at the fault, whereas the initial velocity is assumed to be identically nul. Bathymetric data were obtained from the merge of 1:25000 digital topographic maps, for the on-shore areas and the digitization of bathymetric maps for the off-shore. The grid step is 0.0025 degrees (circa 278 m northing and 219 m easting) and the calculations were made in geographical coordinates. Time step for numerical simulations was 0.2 sec.

5.2 Numerical Simulations

We performed numerical simulations of the tsunamis generated by the candidate faults discussed above. The computation time (1600 sec) is long enough to calculate the main waves in all the most relevant coastal locations along.

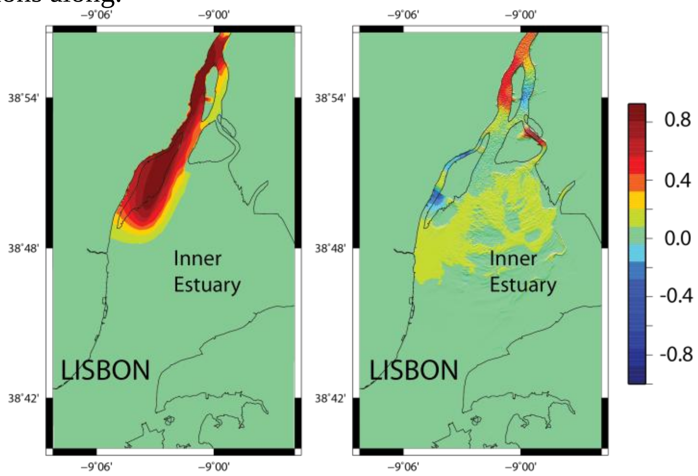

Figure 2. Initial deformation of the seafloor and wave height after 2000 time steps

The results of the simulation show that the wave generated by the elastic deformation of the seafloor propagate essentially to the west and generate significant inundation only close to Vila Franca de Xira and Alcochete and on the islets. The impact in Lisbon downtown is very small. Due to the morphological characteristics of the Estuary the seaward propagation is ineffective and the impact is concentrated in the inner estuary.

6. DISCUSSION AND CONCLUSIONS

There is controversy concerning the level of seismic hazard in Tagus Valley area (see Matias et al., 2005 and references herein). This is a consequence of two apparently contradicting facts: (i) the number of damaging historical events is large and (ii) the low level of instrumental seismicity, and the distance between the area and the Nubia-Eurasia plate boundary (circa 300 km), where the relative motion is only 4mm/y. The identification of tectonic sources in the Tagus Valley is a difficult task due to the low level of seismicity as monitored by the seismological network and to the lack of surface expressions of the major faults, buried below a thick sedimentary cover (Cabral et al., 2003). Most of the characteristics of these active structures have been inferred indirectly, from multichannel seismic made for oil prospection, or potential field data (Cabral et al., 2003, 2004, Carvalho et al., 2008).

The Lower Tagus Valley (LTV) has been the site of a significant number of large historical events, particular those of 1344, 1531 and 1909, which magnitudes have been assigned as 6.0, 7.1 and 7.6, respectively. After the 1909 event the seismicity in the area has been quite low, most of the seismicity is more related with the Lusitanian Basin than with the faults mapped or inferred by neotectonic research. The two faults studied here can generate 6-7 earthquakes and the associated coseismic deformation can affect the Tagus Estuary and generate a significant water wave.

The distinction between a tsunami like event and a storm is sometimes unclear in the texts, but the simultaneity of the earthquake definitively states the occurrence of an earthquake driven disturbance. The reports state that the Tagus divided some islands in the estuary into smaller ones; others report the occurrence of strong flux and reflux and that it was possible to see the sand on the bottom (Codex 8009). This fact is also stated by different authors later in the 18th century prior to the 1st November 1755 event, so we can believe that the information on the event was not biased by the occurrence of the great earthquake. Mendonça (1758) reports the flux of the Tagus and distinguishes between the damage observed inside and outside estuary and describes that ships were destroyed in the sea. However, there are no reports of tsunami effects along the southern Portuguese coast and the coast of Spain and we conclude that the phenomenon was probably limited to the Estuary of Tagus. The report from Couto (1778) clearly states the great damage observed in the port. Given the amount of coeval sources and the XVIII documents comparing the effects of the 1531 and 1755 events, we consider that it is an effective tsunami-like event, and we attribute it a value of IV in Iida likelihood scale.

Mendonça (1758) compares this event with the 1755 concluding that for the city of Lisbon the 1531 event was even more catastrophic if he discards significant "subversion" with the exception of a small landslide close to Lisbon castle. The eastern part of Lisbon was severely damaged and, seen the size of the city, a large amount of the building stock was destroyed. The area affected was so large that Mendonça (1758) only three years after the 1755 earthquake considered that, in proportion, the 26 January 1531 earthquake had a larger intensity: "[…] Even in the supposition that this earthquake had no subversion. It seems to me that it was greater than the one of 1755 comparing the size of the city now and what it was in those times, the ruins were bigger, as 1500 housed was a quarter of the city [...]". Mendonça analysis reinforces the conclusion that the water perturbation was not due to a landslide and we attribute it to the co-seismic deformation. In what concerns the comparison between both events, only based on the fraction of the building stock destroyed is rather limited to the impact in Lisbon and does not take into account the importance of site effects, particularly important in the weakly consolidated area close to the Tagus River in 1531.

Tsunami modeling is presented here under the assumption that the water disturbance after the 1531 earthquake was generated by the elastic deformation of the seafloor. If this is the case than the Vila Franca de Xira fault is the most probable source of both the earthquake and the tsunami. The obvious alternative explanation is a landslide triggered by the earthquake. Anyhow, seismically triggered water disturbances in the Lisbon waterfront must be considered as a potential hazard source.

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