Tsunami hazards at Setubal urban area considering the 1755 Lisbon Tsunami

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Abstract

The historical accounts of the 1755 Lisbon Tsunami reveal that the earthquake, tsunami and fire caused severe damage and many fatalities. The tsunami numerical model results, which include the detailed calculation of the inundation, show the tsunami starts hitting Setubal from 40 minutes after the earthquake. There are 3 major waves, being in agreement with the historical accounts. The downtown area is inundated till Luisa Todi Av. (about 400 m inland), with inundation depths up to 0.5 m. The Port of Setubal is completely inundated with an inundation extension of about 350 m, and inundation depths up to 4 m. Although inundation depths on land are not as high as reported by the historical accounts, maximum water level at the Sado River varies between 2.4 m and 4.3 m. By using a tsunami hazard criterion, Setubal urban area has moderate hazard.

Keywords: 1755 Lisbon Tsunami, tsunami numerical model, hazard, Setubal

Palavras-chave: Tsunami de Lisboa de 1755, modelação numérica de tsunamis, perigosidade, Setúbal

1. Introduction

The November 1, 1755 earthquake occurred most probably at 10:15-10:16 UTC (Santos et al., 2011), with an estimated magnitude of 8.7 (Santos *et al.*, 2009). The following tsunami inundated the Portuguese coastline with catastrophic consequences. Santos *et al.* (2009) showed strong evidences that the tsunami source area could be located on the Gorringe Bank. More recently, Santos *et al.* (2011) concluded that Setubal would be at a critical hazard; the immediately contiguous pixels had elevated-moderated hazard. However, the model cell size of 1 minute (about 1613 m) was too coarse to include details about the Sado river. Furthermore, Santos and Koshimura (2013) compiled the tsunami parameters at the Portuguese coastline, showing there were 3 major waves and run-ups of 6 m to 17.5 m height. Since there are several accounts at Setubal, other historical accounts are translated and presented, which include more details about the tsunami inundating the studied area.

On the other hand, the urban growth verified in Setubal since 1755 has increased the exposition of people and assets to a tsunami with similar severity to the 1755 Lisbon Tsunami. Therefore, the choice of the Setubal urban area to conduct the tsunami hazards was based on a number of physical and human criteria: located at the north margin of Sado River, located inside the estuary; densely populated downtown is lower than 4m; presence of important infrastructures, such as the port of Setubal.

2. Historical accounts at Setubal

The witnesses described the tsunami with Portuguese Historical measure units. The conversion to SI is: 1 passo = 1.5m; 1 covado = 0.7 m (Oliveira, 1985).

Sousa (1928) compiled several original documents reporting the tsunami at Setubal, which are translated as: "[…] for sure more than two thousand people died. The sea entered the town with such a fury that overthrow the thick and old wall, and many buildings. It absorbed many people and moved to a distance of 500 passos [750 m] two big yates and other vessels. The alterations of the water climbed more than twenty five *covados* [17.5 m] high"; "[…] inundated for three times the land, reaching in parts the first floor of the buildings [2 stories that are about 6 m high]. The largest destruction was at Fontainhas and Troino neighborhoods. […] many people died under the ruins of the buildings and drowned on the waves, there were also fires that caused big loss."

3. Setting of the tsunami numerical model

The initial sea surface displacement is calculated based on the fault parameters proposed by Santos *et al*. (2009) with the source dimensions of 200 km by 80 km, and using the Okada (1985) formulas. The maximum vertical displacement is about 6 m, as presented on Fig.1a. Then, the non-linear shallow water equations are used, discretized with staggered leap-frog scheme (Imamura, 1995), and the numerical model is carried out on a large area (Fig1b). In order to calculate the tsunami inundation areas at Setubal, the model is then applied to a nesting of 5 domains. The domains have progressively smaller areas and finer cell size grids, and are included in the previous domain, as shown in Fig. 1b-f. In the construction of each domain several bathymetry charts are used (GEBCO, 2003, IH, 2011), and topography maps (IGeoE, 2001). This method has been applied to several tsunami studies. For example, Koshimura *et al.* (2009) calculated the inundation areas at Banda Aceh, Indonesia due to the 2004 Indian Ocean Tsunami. More recently, Santos *et al.* (2012) applied this method to Figueira da Foz, Portugal, also by considering the 1755 Lisbon Tsunami.

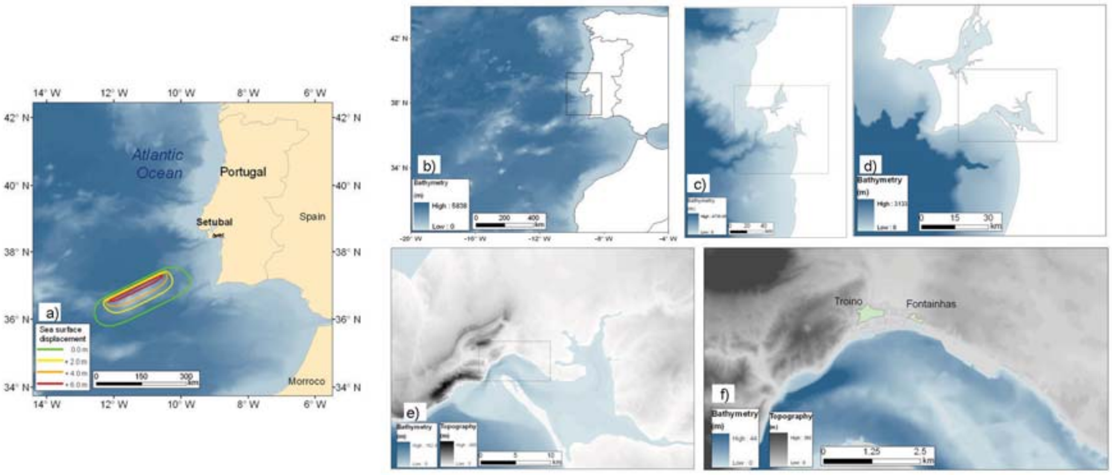

Figure 1 – a) Sea surface displacement and the location of Setubal. Nesting used to calculate the tsunami inundation at Setubal, with b) cell size of 810 m; c) cell size of 270 m; d) cell size of 90 m; e) cell size of 30 m; f) cell size of 10 m. The Troino and Fontainhas neighborhoods were the most affected by the tsunami

4. Numerical model results

The tsunami numerical model results show the first tsunami wave reaches the Sado river mouth at about 40 minutes after the earthquake and propagates upstream the Sado River. It does not cause significant inundation on the studied area. However, the second and third waves reach about 3.2 m (Fig. 2), being responsible for the inundation at the lower parts of Setubal urban area. The forth wave is not as high as the second and the third waves, but it reaches more than 2 m at the Sado River mouth and the port of Setubal. 3 major tsunami waves hit the Sado River for more than 4 hours, being in agreement with the historical accounts. As shown in Fig. 3, from 1h 40min minutes after the earthquake, the tsunami starts to inundate the lower parts of the city, which include Setubal downtown and the Port of Setubal.

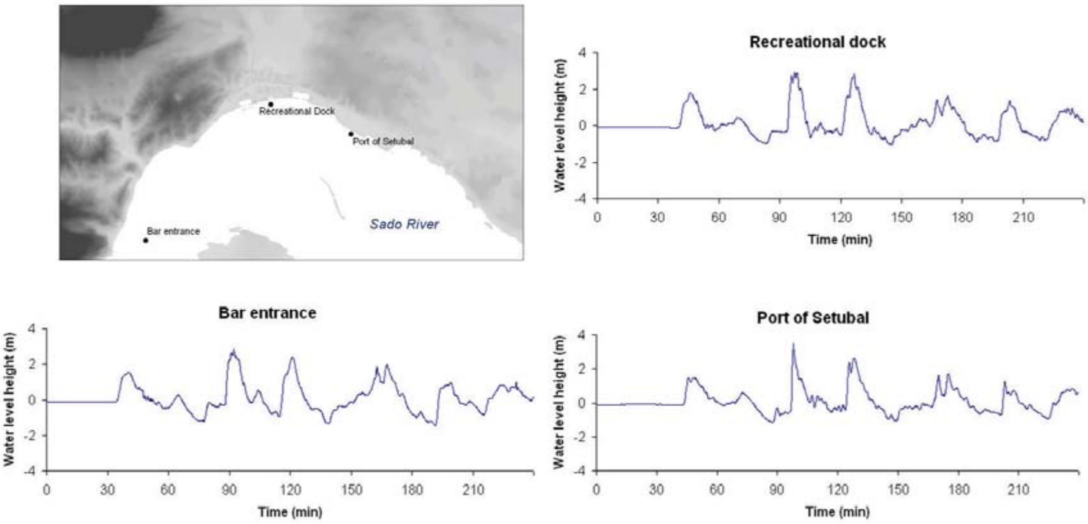

Figure 2 – Water level waveforms on the studied area

The maximum water level at the Sado River varies between 2.4 m and 4.3 m (Fig 4a). According to the Tsunami Hazard Criterion (Santos et al. 2012) these results would lead to a moderate hazard, which represent an update of the classification related to the results obtained by Santos et al., (2011). This result shows that the method presented in Fig. 1 should be taken in consideration regarding hazard classification inside estuaries, where progressive smaller cell sizes are used.

The urban growth verified in Setubal since 1755 had transformed the city's layout, by the reconstruction of the coastal neighborhoods, as well as the construction of the Luisa

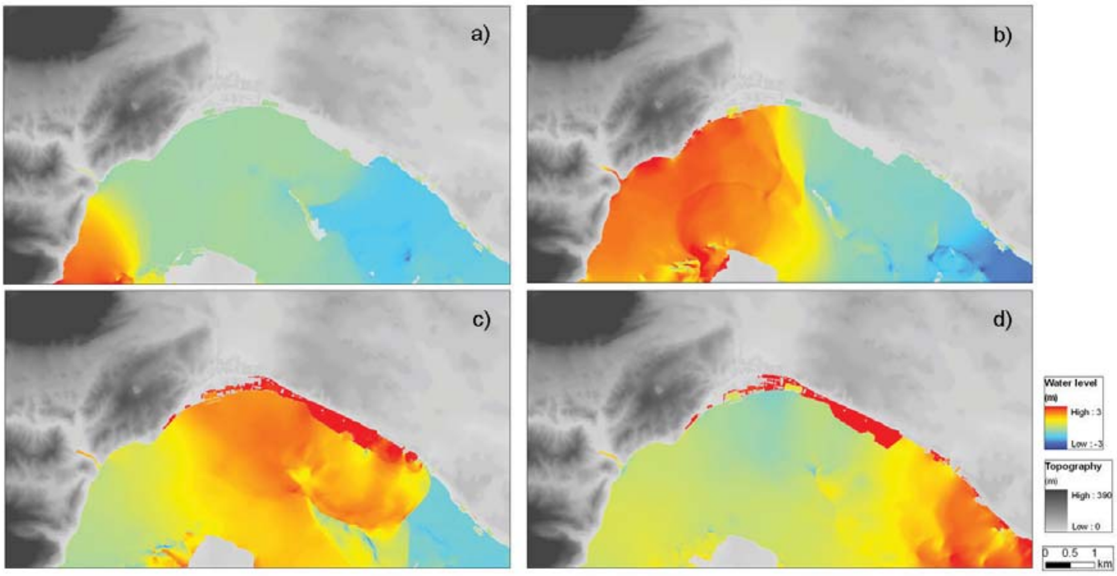

Figure 3 – Snapshots of the second tsunami wave approaching Setubal urban area, in minutes: a) 90, b) 95, c) 100, d) 105

Todi Av. and the marinas. The Fontainhas and Troino neighborhoods were severe damaged in 1755 and still exit today (Fig.4b). The downtown area is inundated till Luisa Todi Av. (about 400 m inland), with inundation depths up to 0.5 m. The Port of Setubal is completely inundated with and inundation extension of about 350 m, and inundation depths up to 4 m.

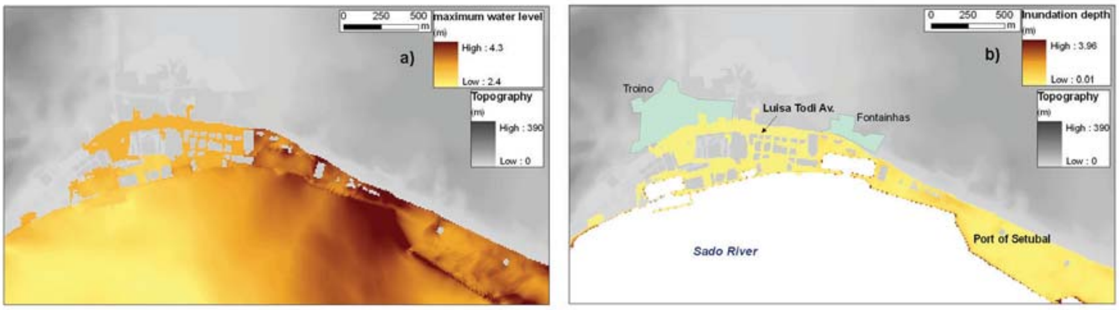

Figure 4 – Numerical model results at Setubal urban area**:** a) maximum water level; b) inundation depth

5. Conclusions

The historical accounts at Setubal have reported severe damage and many fatalities (possible more than 2000) due to earthquake, tsunami and fire. 3 major waves were also reported, with an estimated run-up varying between 6 m and 17.5 m. The tsunami reached about 750 m inland. The urban growth verified in Setubal since 1755 had transformed the city's layout, by the reconstruction of the coastal neighborhoods, as well as the construction of the Luisa Todi Av. and the marinas.

The tsunami numerical modeling of the 1755 Lisbon Tsunami carried out at Setubal urban area shows there are 3 major waves, being in agreement with the historical accounts. The downtown area is inundated till Luisa Todi Av. (about 400 m inland), with inundation depths up to 0.5 m. The Port of Setubal is completely inundated with and inundation extension of about 350 m, and inundation depths up to 4 m. Inundation depths on land are not as high as reported by the historical accounts, nevertheless maximum water level at the Sado River varies between 2.4 m and 4.3 m (giving a moderate hazard). The tsunami waves hit the Sado River for more than 4 hours. In this study the complete validation of the historical accounts was not possible however these accounts are important to piece together the tsunami impact at Setubal. Furthermore, the tsunami numerical results obtained from this study will be the input to the building vulnerability assessment (Emidio *et al.*, 2013) on Setubal urban area.

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