Tsunami risk assessment at Figueira da Foz, Portugal

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SUMMARY:
The November 1st 1755 Earthquake and Tsunami were responsible for the worst natural disaster known to have occurred in Portugal, causing a high number of casualties and severe damage. Tsunami numerical simulation results that include the detailed calculation of the inundation areas at Figueira da Foz produced a maximum water level of 8m, and a local amplification at the Figueira da Foz beach. On the other hand, the numerical simulation results show that a tsunami scenario similar to the 1755 event could inundate the area up to 10 km upstream the Mondego River. By using a criterion to assess the tsunami hazard, the area has a tsunami inundation hazard between low and moderate. If the spurs and sand dunes remain intact during a tsunami event, less than 0.68 % of the resident population is at risk. However, if these structures are completely destroyed the affected population is up to 4.6%.

Keywords: 1755 tsunami, tsunami numerical model, tsunami risk

1. INTRODUCTION

On the 1st November 1755 the Portuguese coast was inundated by a tsunami with catastrophic consequences. Despite the importance of this event, there are still doubts about the characteristics of this historical event. These doubts are even more surprising, knowing that today the repetition of an event with similar severity would have much worse consequences. The most important physical feature about this tsunami is to identify the location of the tsunami source area. However, the research carried out by Santos et al., 2009 showed strong evidences that the source could be located in the Gorringe Bank (see Fig 2.1 for location). In addition, at Figueira da Foz coastal zone the historical witness' account reported an unusually high tsunami run-up of 36 m (for ex., Santos et al., 2011). Furthermore, the results of the tsunami propagation numerical simulation obtained by Santos et al., 2009 and Santos et al., 2011 confirmed that Figueira da Foz had indeed an unexpected high run-up, when the tsunami maximum water level is compared with the results obtained for the entire Portuguese coastline.

The urban growth verified in Figueira da Foz since 1755 has increased the exposition of people and assets to a tsunami with similar severity. Therefore, the choice of Figueira da Foz to conduct the tsunami risk assessment was based on a number of physical and human criteria that included: (i) it has a very large town center located at a very low altitude; (ii) it is facing WSW; (iii) it has a wide beach reaching 500m width in its southern end that is strongly conditioned by the presence of two artificial spurs in the Mondego river mouth; (iv) it suffers a high fluctuation of population between the winter and summer months and between working days and weekends; and (v) there is an industrial zone connected to an important harbor.

There are many definitions of risk. In this study the concept of risk is "the expected number of lives lost, persons injured, damage to property and disruption of economic activities due to a particular natural phenomenon, and consequently the product of specific risk and elements at risk.", whereas the specific risk is "the expected degree of loss due to a particular natural phenomenon and as a function of both, natural hazard and vulnerability" (Tiedemann, 1992).

Thus, the first objective of this study is to calculate the tsunami inundation areas at Figueira da Foz, by considering the 1755 Lisbon Tsunami. Santos et al., 2011 proposed a criterion to quantify the tsunami hazard, and this method will be followed in this study. Then, the population data (INE, 2011) at Figueira da Foz will be considered, combined with the tsunami hazard map, in order to conduct the tsunami risk assessment.

2. SETTING CONDITIONS OF THE TSUNAMI NUMERICAL MODEL

2.1 tsunami source area

Since this study is based on the 1755 tsunami which is an historical event, there are many uncertainties. One issue that has been a topic of discussions is the location of the tsunami source area. The seismotectonic offshore Portugal is quite complex since there are several bathymetry structures, as shown in Fig. 2.1. The largest structure is the Gorringe Bank which has 200 km length by 80 km width. There have been several proposals for the tsunami source area, all of them with positive and negative points. Santos et al. (2009) compiled these proposals, mostly located at the Pereira de Sousa Scarp, Marques de Pombal Scarp, Guadalquivir Bank. That study showed very strong evidence that it could be located on the Gorringe Bank. The authors validated the tsunami numerical model with both historical accounts and geological records, namely the presence of turbidites near the Gorringe Bank (Thomson and Weaver, 1994, Lebreiro et al., 1997). In addition, seismic intensity modeling (Grandin et al., 2007) also supported the source model at the Gorringe Bank. Therefore, in this study, the 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 2.1.

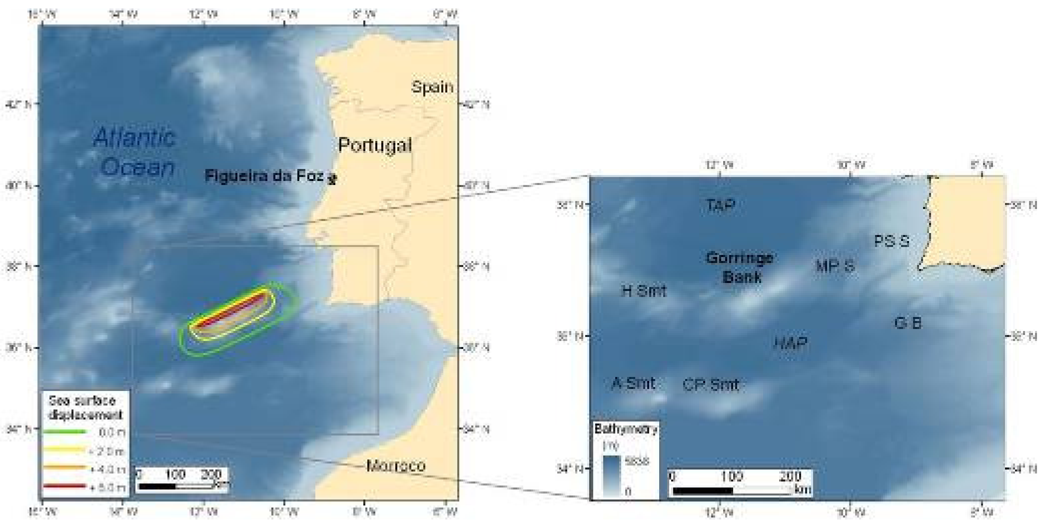

Figure 2.1. Sea surface displacement (left) and bathymetry structures offshore Portugal (right), where the most evident is the Gorringe Bank. Abreviations by alphabetic order are A Smt: Ampere Seamount, CP Smt: Coral Patch Seamount, G B: Guadalquivir Bank, *HAP*: Horseshoe Abyssal Plain, H Smt: Hirondelle Seamount, M PS: Marques de Pombal Scarp, PS S: Pereira de Sousa Scarp, *TAP*: Tagus Abyssal Plain.

2.2. Nesting

In order to calculate the tsunami inundation areas at Figueira da Foz, the non-linear shallow water equations are used, discretized with staggered leap-frog scheme (Imamura, 1995). They are 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. 2.2. The first domain is the widest and has a cell size of 2025 m. Then, domains 2 and 3 have cell sizes of 675 and 225 m, respectively. Finally, domains 4 and 5 have cell sizes of 75 m and 25 m, and show the details of the coastal zones and topography. In the construction of each region several bathymetry charts are used (GEBCO, 2003, IH, 2010, 2011), and topography maps (IGeoE, 2000, 2001a, 2001b, 2001c, 2001d, 2002a, 2002b, 2002c). This method has been applied to several tsunami studies. For example, Koshimura at al. (2009) calculated the inundation areas at Banda Aceh, Indonesia due to the 2004 Indian Ocean Tsunami.

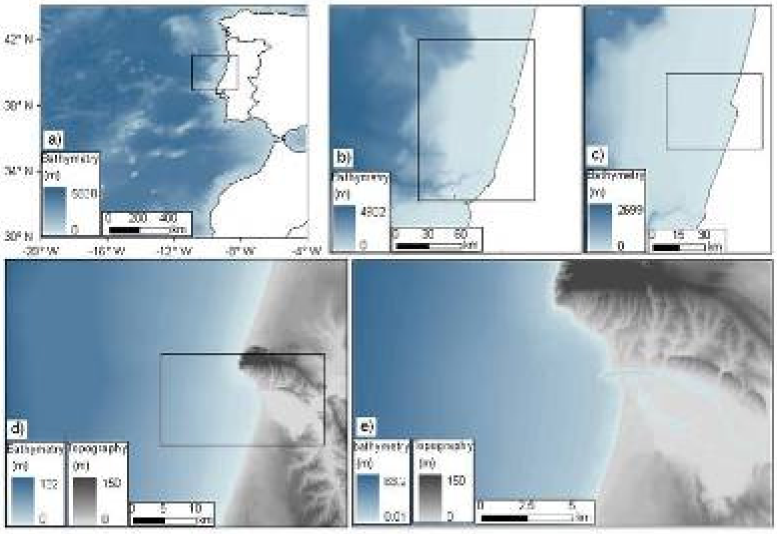

Figure 2.2. Nesting used to calculate the tsunami inundation at Figueira da Foz: a) cell size of 2025 m; b) cell size of 675 m; c) cell size of 225 m; d) cell size of 75 m; e) cell size of 25 m.

The studied area is focused at Figueira da Foz. The area is limited by the Mondego Cape and the Costa de Lavos, as presented in Fig. 2.3. The figure also shows a zoom where is possible to point out some local places. The Figueira da Foz beach is located in front of the city, is a wide beach reaching 500m width in its southern end. At the river mouth of the Mondego River there are 2 large man-made spurs, and other infra-structures that help in the protection of the harbor, which provides an important support to local industries and fishery. These structures also provide 2 small beaches (one located on the north margin of the river, and the other on the south margin of the river, at Cabedelo) with calm waters, being very popular during summer and hot days. From Cabedelo to Costa de Lavos there is a continuous stretch of small beaches limited inland by poorly preserved sandy dunes. All the beaches are very popular during the summer and hot days. The most densely populated areas are on Figueira da Foz city in the north margin of the Mondego River and between Gala and Cova in the south. The study area also includes salt marshes and agricultural activity mostly related with rice paddies.

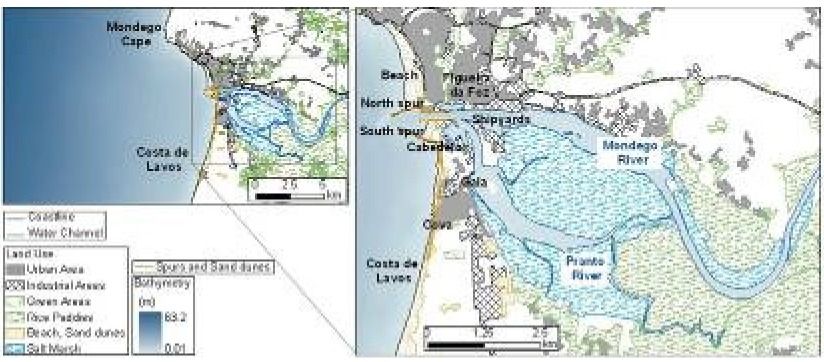

Figure 2.3: Framework of the Figueira da Foz area.

3. NUMERICAL MODEL RESULTS

The first tsunami wave takes more than 1 hour after the earthquake started to reach Figueira da Foz.

The tsunami wave front of the first wave has a direction North-south, as shown in Fig. 3.1. It arrives first at Mondego Cape, at about 68 minutes, with 4 m high. Costa de Lavos is hit at 69 minutes after the earthquake with 2.3 m high. Then it continues to propagate into the land, hitting the Figueira da Foz coastline at about 70 minutes, with an initially 2 m high, and at 73 minutes with 5 m.

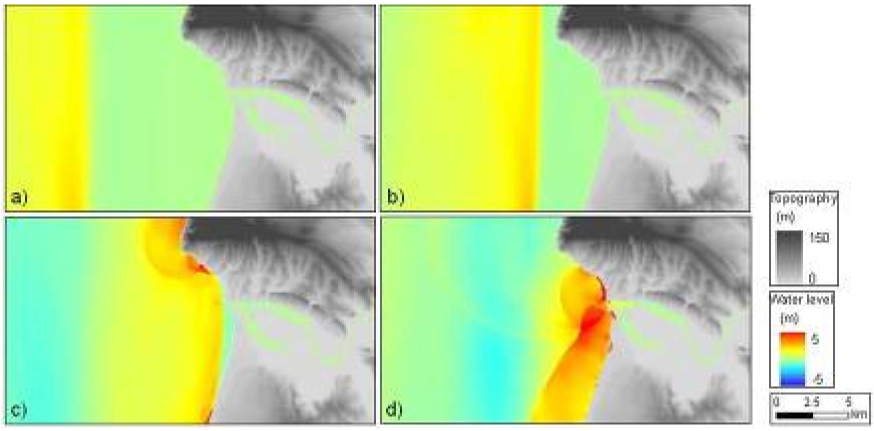

Figure 3.1. Snapshots of tsunami approaching Figueira da Foz, in minutes: a) 60, b) 65, c) 70, d) 75.

The tsunami penetrates about 10 km upstream the Mondego River, inundating its margins, as presented in Fig. 3.2. From the analysis of Fig. 3.2 it can be concluded that the north and south spurs of the Mondego River are effective in the reduction of the tsunami maximum water level, since the Figueira da Foz city is not affected. The low land areas of the salt marshes are inundated about 100 m inland, except the area in front of Gala where the maximum inland penetration is about 300 m. The existence of a small agricultural channel on the salt marshes provides a channel for the tsunami path. The maximum tsunami penetration on the salt marshes is about 1,500 m. The tsunami also reaches the rice paddies through the Pranto River. In addition, sand dunes are a natural barrier that protects the Cova-Gala urban areas from the tsunami.

The maximum water level is 8.12 m at the south of the south spur inundating most of the Cabedelo area, including the harbor and its surrounding industrial zone (see Fig 2.3 for place location). Another dangerous place is the Figueira da Foz beach, where the maximum water level reaches 7.69 m. However, all the beaches are hit with waves reaching about 6 m high. These results are in agreement with the 1755 historical report at Figueira da Foz, where it was described a local amplification at the beaches. Although the maximum water level is much lower than the 36 m reported (Santos et al., 2011), the numerical model results show a qualitative local amplification at the beaches. The objective of this study is not to validate the historical report however the results presented in Fig. 3.2 provide important clues about the tsunami behavior on the area. For this reason, future studies focused on the historical accounts at Figueira da Foz should be conducted in order to validate the historical accounts.

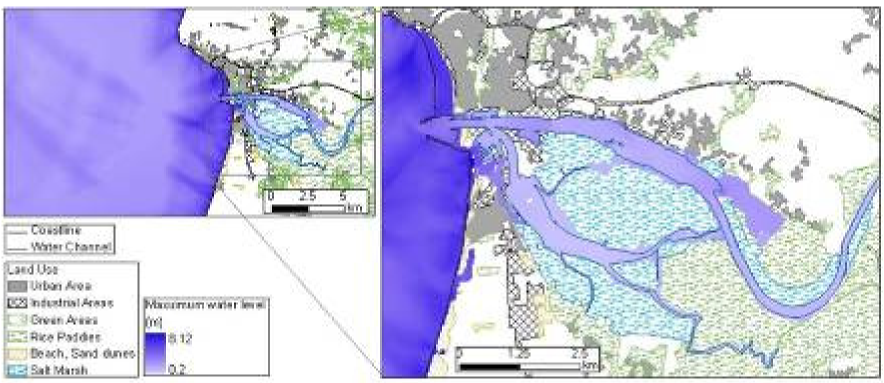

Figure 3.2. Maximum water level at Figueira da Foz.

4. TSUNAMI HAZARD ASSESSMENT

4.1 Normal topography

According to the Criterion for Tsunami Hazard Assessment (Santos et al., 2011) the tsunami hazard at Figueira da Foz will be classified based on tsunami travel times, combined with the tsunami inundation high, as presented in Fig. 4.1. First, it is necessary to consider the susceptibility for the tsunami inundation. It has 5 classes, ranging from low, if the inundation depth is less than 2 m, to critical if the inundation depth is higher than 15m. Second, the susceptibility for tsunami travel time is low if the first wave arrives later than 50 minutes after the earthquake and critical if the first wave arrives within 20 minutes. Finally, the susceptibilities are crossed at the tsunami hazard matrix, and the tsunami inundation hazard is obtained. This method will be used to obtain the tsunami inundation hazard at Figueira da Foz.

Criterion for Tsunami Hazard Assessment

Water level high (m)	Classification	Travel time (min)	Classification
0 - 2	Low	0 - 20	Critical
2 - 5	Moderate	20 – 30	High
5 – 10	High - moderate	30 – 40	High - moderate
10 – 15	High	40 - 50	Moderate
More than 15	Critical	More than 50	Low

Tsunami Hazard Matrix

T. Time \ W. Level high	Low	Moderate	High - moderate	High	Critical
Critical	High - moderate	High	High	Critical	Critical
High	High - moderate	High - moderate	High	High	Critical
High - moderate	Moderate	High - moderate	High - moderate	High	High
Moderate	Moderate	Moderate	High - moderate	High - moderate	High
Low	Low	Moderate	Moderate	High - moderate	High - moderate

Figure 4.1. Tsunami hazard matrix obtained from the combination between travel times and water level high (Santos et al., 2011).

From the above Criterion, the susceptibility for tsunami inundation varies between low and high-moderate, as presented in Fig 4.2a. On the other hand, the susceptibility for tsunami travel time is low, since the fist wave arrives after 50 minutes, as presented in Fig. 3.1 and discussed in the previous section. Consequently, the tsunami hazard at Figueira da Foz is classified from low to moderate, as shown in Fig 4.2b. The low hazard zone corresponds to about 4.7 km^2 of area in the low category, and the moderate hazard is about 0.69 km^2.

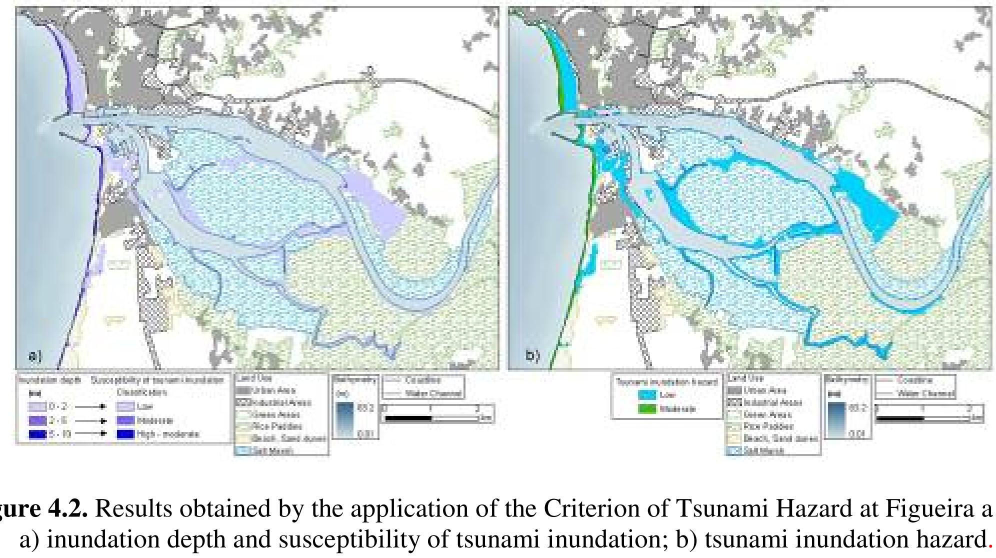

Figure 4.2. Results obtained by the application of the Criterion of Tsunami Hazard at Figueira a Foz: a) inundation depth and susceptibility of tsunami inundation; b) tsunami inundation hazard.

4.2 Worst case scenario

On the March 11, 2011 a magnitude 9.0 earthquake occurred offshore the Pacific side of the Japanese coast. It generated a tsunami that inundated most of the Tohoku region causing about 20,000 casualties and severe damage (for ex. Santos, 2011). The Japanese coastline is very well protected with concrete breakwaters however some collapsed due to the tsunami. At MinamiSanriku (NHK Sendai, 2012) the breakwaters disappeared almost completely. On the other hand, the sand beach at the Lake Torinoumi in Watari was washed away by the tsunami (CNN, 2011). In addition, subsidence caused by the earthquake was observed on several areas. For example, at Ishinomaki, Miyagi District subsidence reached almost 1 m. Another observed phenomenon was liquefaction: at Urayasu, Chiba District the ground level changed almost 20 cm, although the area is located more than 300 km from the epicenter. Consequently, the lessons from the 2011 Great East Japan Tsunami that will be extrapolated to the tsunami scenario at Figueira da Foz are: (i) man-made coastline protections, such as concrete breakwaters, reduce the tsunami impact but they may not offer a perfect protection; (ii) sand dunes are natural barriers that are also effective in the reduction of the tsunami impact, however they are unstable structures that may collapse; and (iii) earthquake secondary effects like liquefaction and subsidence are not completely predictable and it is possible that these phenomena occur even on locations far from the epicenter, causing the coastline protection to be somewhat compromised.

Therefore, although Fig. 3.2 and Fig. 4.2 show that spurs at the Mondego River mouth and sand dunes on the Cova-Gala and Costa de Lavos are effective to reduce the tsunami hazard reduction, it is not possible to know whether or not these barriers would stand. In addition, there are evidences that show weaknesses in these protective structures: (i) spurs are not made from concrete. They are basically clusters of large stones. From 1994 to 2011 the protective structures were partially destroyed in 5 storm events in the zone of Costa de Lavos and Cova-Gala. As it is shown in Fig 4.3 some of these structures are currently collapsing. (ii) sandy dunes are already in danger of collapsing due to coastal erosion. During the 60's the erosion rate measured in Costa de Lavos and Cova-Gala ranged from 5 to 7 meters/year (INAG, 1998). In addition, the coastal sandy dunes barrier was partially collapsed for two times in the last 18 years due to storm surge. Therefore, it will be considered the worst case scenario by removing the breakwaters and sandy dunes from the numerical model input data, shown in Fig 2.3. This procedure will simulate the total collapse of the structures, without offering any resistance to the tsunami path.

Figure 4.3: Photos taken during the field survey on April 2012: a) scattering of stone blocks of the south spur (shown in red) at Cabedelo; b) spur at Cova shows already some damage on its top, delimited by the blue line.

Figure 4.4 shows the maximum water level obtained by not considering the spurs and sandy dunes. The tsunami penetrates about 10 km upstream the Mondego River, inundating its margins, as presented in Fig. 4.4. This is a similar situation like the one presented in Fig. 3.2. Without the spurs, the tsunami inundates most of the low land areas of Figueira da Foz city, which include the margins of the Mondego River, the marina and one garden. The maximum inland penetration is 175 m. The tsunami inundates the low land areas of the salt marshes. It crosses the entire area on 2 different places, which have extensions of about 2 km. In addition it inundates almost entirely the Cabedelo area including the beach, harbor and shipyards. This last infra-structure was not affected in the normal topography scenario, shown in fig. 3.2. The tsunami also reaches the rice paddies through the Pranto

River. On the other hand, without the sand dunes to protect the urban areas of Cova-Gala, this area is completely inundated by the tsunami. The maximum water level is 8.03 m at the Figueira da Foz beach.

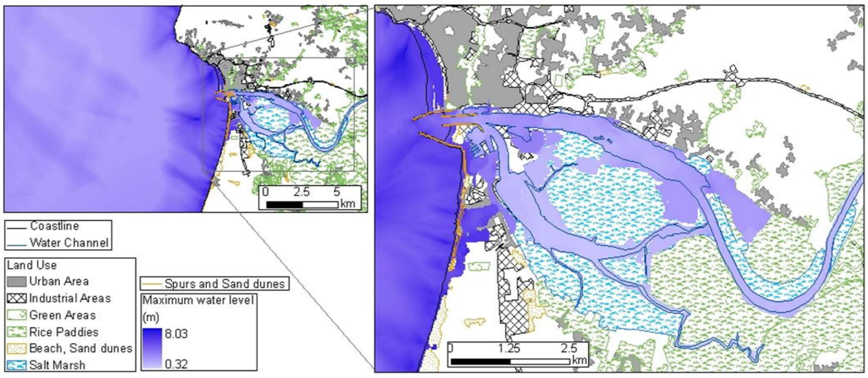

Figure 4.4. Maximum water level at Figueira da Foz, obtained by removing the spurs and sandy dunes.

From the above mentioned Criterion for Tsunami Hazard Assessment, the susceptibility for tsunami inundation varies between low and high-moderate, as presented in Fig 4.5a. The susceptibility for tsunami travel time is low, since the fist wave arrives after 50 minutes, as presented in Fig. 3.1. Consequently, the tsunami hazard at Figueira da Foz is classified between low and moderate, as shown in Fig 4.5b. This corresponds to about 6.86 km^2 of area in the low hazard class. Therefore, this approach leads to an increase in 2.16 km^2 (46%) in area in the low tsunami inundation hazard when compared with the normal topography scenario. The area in the moderate hazard class is 0.92 km^2 which corresponds to an increase of 0.23 km^2 (23%).

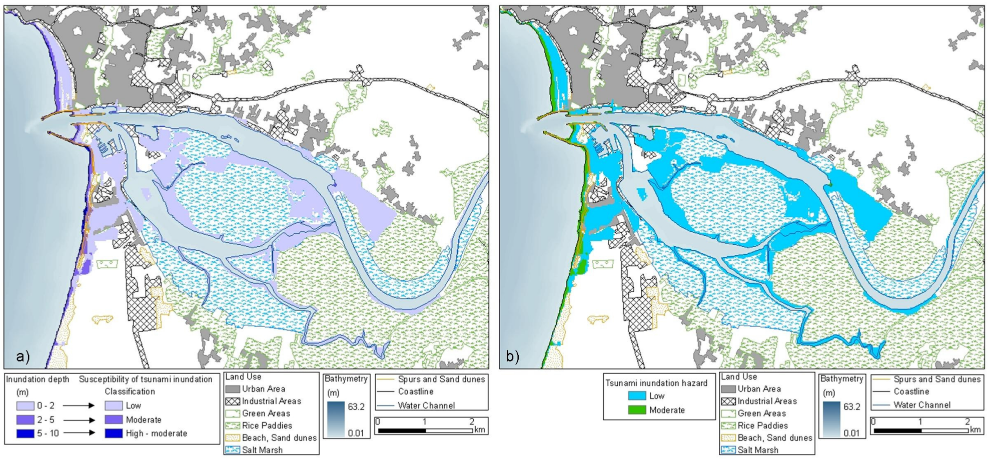

Figure 4.5. Results obtained by the application of the Criterion of Tsunami Hazard Assessment at Figueira da Foz, by removing the spurs and sandy dunes: a) inundation depth and susceptibility of tsunami inundation; b) tsunami inundation hazard.

5. EXPOSED POPULATION

The population data, retrieved from Census 2011 (INE, 2011) preliminary data, is mapped on an Information Reference Geographical Database (BGRI), comprising statistical sections disaggregated into smaller statistical subsections. The statistical subsections were combined with the tsunami inundation hazard obtained in Fig. 4.2b and Fig. 4.5b, as presented below in Fig. 5.1. In another approach, the population data was transferred to the urban areas retrieved from the Land Use Map of Portugal, COS' 2007 (IGP, 2010), as presented in Fig 5.2. No other elements were taken into account, like buildings, industries, port and shipyard, camping, vital structures (hospital, fire station, police station. city hall), etc.,.Furthermore, in the present study it was considered a stable referential, i.e. not assuming fluxes in the population.

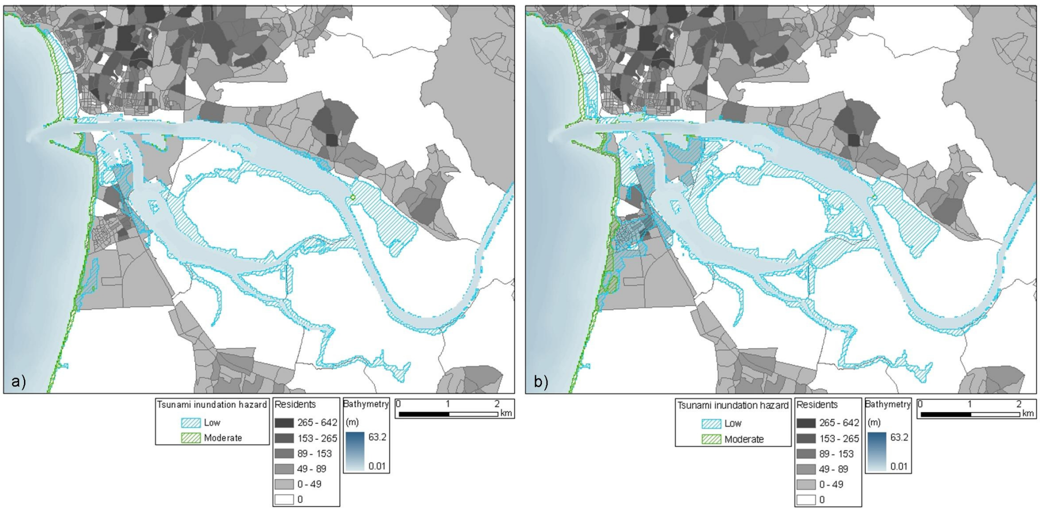

Figure 5.1. Residential population data (INE, 2011) at Figueira da Foz combined with the tsunami inundation hazard: a) for the normal topography with results from Fig 4.2b; b) for the worst case scenario with results from Fig 4.5b.

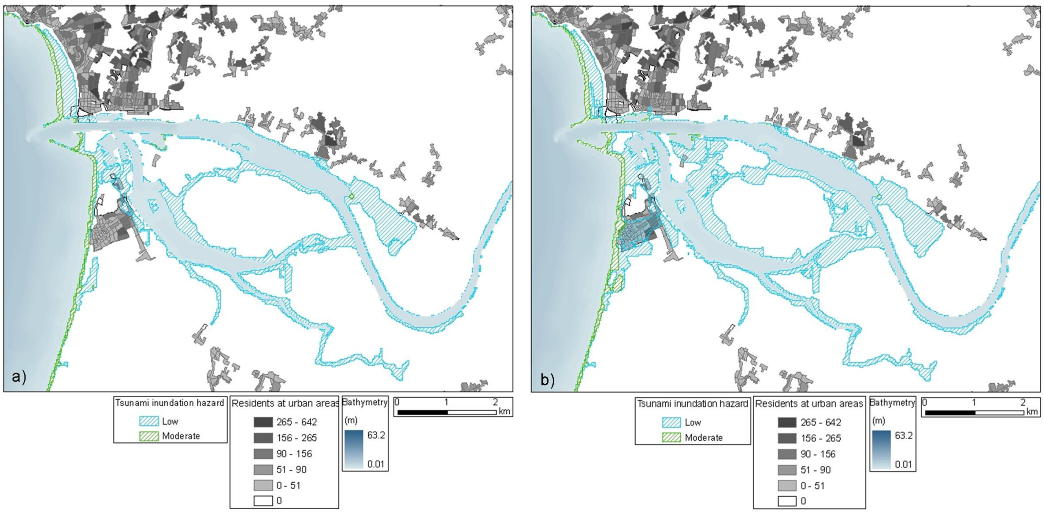

Figure 5.2. Residential population data (INE, 2011) at urban areas of Figueira da Foz combined with the tsunami inundation hazard: a) for the normal topography with results from Fig 4.2b; b) worst case scenario with results from Fig 4.5b.

6. TSUNAMI RISK ASSESSMENT

To assess the affected population more accurately two distinct methods were used: a polygon overlay areal interpolation method (Goodchild and Lam, 1980, Fonseca and Morais, 2011) and a dasymetric binary method (Eicher and Brewer, 2001). The first method comprises the data transfer from the source unit (statistical subsection) to the target unit (hazard zones), where they are spatially overlaid. A population ratio to surface area was estimated for the source unit and then applied to the target unit, which then allowed evaluating the number of affected persons for each target unit. The second method comprises a preliminary stage where ancillary data was used, by the form of a mask indicating inhabited and uninhabited land areas. Here, the inhabited areas equal the second level class "Urban fabric" of the Land Use Map of Portugal, COS' 2007 (IGP, 2010). Afterwards, the resident population number within each statistical subsection was transferred to each overlaid inhabited area. Finally, a population ratio to surface area was estimated which then allowed to evaluate the number of affected persons in each hazard zone.

Both methods have advantages and drawbacks. The first method relies on the assumption of a spatially homogeneous phenomenon, which is a fallacy when considering the population real distribution; the second method, neglects the fact that some population may be present in uninhabited areas, and it is highly dependent on proper land use data, its accuracy and availability. The first method is faster and simpler to implement while the second one gives us a closer approach to reality.

Table 6.1. shows the results obtained from the use of the above mentioned methods, where the highest percentage of exposed population is 4.58 % (the percentage relates to the 9 affected parishes: Alqueidão, Buarcos, Lavos, Maiorca, Paião, São Julião da Figueira da Foz, São Pedro, Tavarede and Vila Verde). This scenario corresponds to Fig. 5.2b, by considering the worst case scenario with dasymetric binary method. To improve its accuracy, other data should be considered. Since Figueira da Foz is a very popular area due to its beaches and tourism attractions, its population is season variable, reaching its maximum during summertime. Furthermore, daytime population is variable too, which is a relevant fact to be taken into account in this kind of assessment. As neither data is already available from 2011 Census, neither situations were considered, thus the affected population study will be continued in future work.

Table 6.1. Number and percentage of the affected population, on each studied case.

Tsunami inundation hazard	Polygon overlay areal interpolation method				Dasymetric binary method			
	Normal topography		Worst case scenario		Normal topography		Worst case scenario	
	Number	%	Number	%	Number	%	Number	%
Low	246	0,56	1949	4,40	303	0,68	2016	4,55
Moderate	27	0,06	52	0,12	0	0,00	15	0,03

6. CONCLUSIONS

Tsunami numerical modeling shows a local amplification at the beaches, which is in agreement with historical accounts. The numerical model results also show that spurs and sandy dunes are effective structures in the mitigation of tsunami hazard at Figueira da Foz. However, the lessons learned from the 2011 Japan Tsunami show that coastal protection measures are susceptible to collapse. In addition, the reported coastal erosion problems associated to storm surge during the last 50 years show evidences that the spurs and sandy dunes are already in a fragile state. Such fragility was confirmed in the present day by field survey conducted in the studied area. Therefore, the worst case scenario was tested, by eliminating the spurs and sandy dunes. Then, a criterion to asses the tsunami inundation hazard was applied showing the area has a classification of low and moderate. By removing the spurs and sand dunes, the tsunami inundation hazard areas increase by 46 % in the low hazard and 33% in the moderate hazard. Finally, population data was used in two different approaches: first consisted in a data transfer from the statistical subsection to the tsunami hazard zones, where they are spatially overlaid; second, comprised a preliminary stage where ancillary data was used, by the form of a mask indicating inhabited and uninhabited land areas. With these 2 methods, 4 different scenarios were obtained for the exposed residential population. This study shows that if a tsunami similar to the 1755 event hit Figueira da Foz and if the residential population did not evacuate in time, from 0.56% to 4.55% of the population could be injured and a maximum of 0.12% (corresponding to 52 people) could die. Since the studied area is season variable, reaching its maximum during summertime, further studies will continue to include these data in the risk analysis.

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