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A Criterion for Tsunami Hazard Assessment at the Local Scale

Angela Santos[1] and Shunichi Koshimura[2]

1. Centre for Geographical Studies, Institute of Geography and Spatial Planning, Universidade de Lisboa, Edifício da Faculdade de Letras, Alameda da Universidade, Lisboa 1600-214, Portugal

2. Laboratory of Remote Sensing and Geoinformatics for Disaster Management, International Research Institute of Disaster Science, Tohoku University, Aoba 6-6-03, Aramaki, Aoba-ku, Sendai 980-8579, Japan

Abstract: A criterion for tsunami hazard assessment at the local scale is proposed. It is based on travel times and water level height, calculated by the tsunami numerical model, combined with the existence or not of an easy evacuation path from the shoreline to safely high ground and evaluated by field survey. Furthermore, the 1755 Lisbon Tsunami is considered as the worst case scenario, allowing evaluating the impact of a similar scenario at Figueira da Foz municipality, Portugal. The results show that all the beaches are inundated and should be evacuated within an hour after the earthquake. Since there is safely high ground nearby most areas leading to a local tsunami hazard of "low". However, the presence of unstable sand dunes that has been showing signs of collapsing at the south of Cova and Leirosa allowing the tsunami to penetrate inland, inundating the residential areas. For that reason, the local tsunami hazard is "moderate". The other area which has "moderate" classification is Cabedelo, because it does not have any coastal protection from tsunami waves, and does not have easy access to the high ground. The marina and fishing port have "very low" classification, nevertheless it is recommended that vessels evacuate to an offshore area.

Key words: Tsunami hazard, tsunami numerical model, field survey, evacuation path, 1755 Lisbon Tsunami.

1. Introduction

The 1755 Lisbon Earthquake and Tsunami caused many fatalities and damages in Portugal, Spain and Morocco [1]. In Portugal alone this historical event is considered the worst disaster ever recorded in the country being responsible for more than 12,000 fatalities. In Lisbon the combined effects of the earthquake, fire and tsunami damaged approximately 82% of the residential buildings [2]. The historical accounts of the 1755 Lisbon Tsunami reported an unexpected run-up of 36 m [3] in Figueira da Foz (Fig. 1a) without any fatalities. The municipality has developed significantly since the 18th century, with the increasing urbanization of the coastline, the construction of a marina and a fishing port. In addition, the beaches are very popular during the summer, increasing the exposed population at the coastline. Although the frequency of earthquakes and tsunamis in Portugal is quite low [4], it would be important to understand what would be the impact of a similar tsunami scenario at the modern Figueira da Foz municipality.

The analysis of the witnesses' accounts of the 2011 Tohoku Tsunami showed that knowledge about the past events combined with the regular practice of evacuation exercises is the key for a safe evacuation, even during an extreme event [5]. However, in Portugal, evacuation exercises and drills are not organized on a regular basis on university campuses. For that reason, a pilot evacuation-exercise was conducted in 2012 at the Lisbon University campus [6]. The average walking velocity of the participants

Corresponding author: Angela Santos, postdoctoral, research fields: tsunami engineering, tsunami hazards and risks. E-mail: angela.santos@campus.ul.pt. This research was supported by the TsuRiMa Project—TSUnami Risk Management for spatial planning and civil protection (PTDC/CSGEO/118992/2010), funded by the FCT (Foundation of Science and Technology), Portugal.

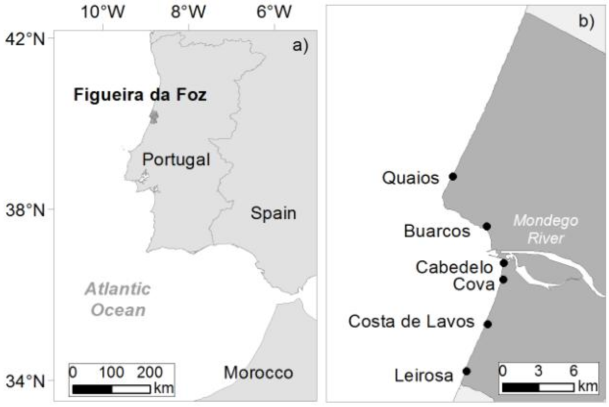

Fig. 1 Framework of the study area: a) Location of the Figueira da Foz municipality; b) Urban areas where the field survey conducted.

was measured as 0.94 m/s. A more recent survey also conducted at the university campus showed the regular users are not aware of the safety procedures for an emergency evacuation [7].

Moreover, on January 5 to 7, 2014, the Hercules storm, which was identified as a meteotsunami [8], caused more than 16 million euro in damages on the Portuguese coastline [9]. In spite of the warnings issued by the authorities, many people put themselves into a danger situation by going to the shoreline to watch the waves. Nobody died, however approximately 20 people needed assistance [8], and about eight people were injured due to the tsunami waves [10]. A field survey [10] showed the wave's velocity was approximately 11 m/s (39.3 km/h), compatible to a tsunami. Thus, people that do not evacuate to high ground cannot escape from the waves in time. This fact was validated by the witnesses' videos showing some locals being caught by the tsunami waves on the same surveyed spot [11, 12]. Reports at the urban areas of Figueira da Foz municipality (Fig. 1b) compiled by [8] showed the waves were 7 m height. The parking lot at Cabedelo was overtopped, damaging walls and the fishing port. At Leirosa, the market gardens were flooded and at least one person was injured [13]. All the wooden sidewalks at the beaches of Cabedelo, Costa de Lavos and Leirosa were destroyed. A field survey conducted on these areas before and after the 2014 Tsunami [8] showed the sand dunes are collapsing at the south of Cova. In fact, the tsunami waves penetrated inland, inundating the pine trees.

Therefore, the objective of this study is to propose a criterion for TH (Tsunami Hazard) assessment at the local scale. It combines travel times and water level height (calculated by the tsunami numerical modeling) and the existence or not of easy evacuation path from the shoreline to safely high ground (evaluated through the field survey). The criterion is then applied to Figueira da Foz urban areas (Fig. 1b), by considering the 1755 Lisbon Tsunami.

2. Tsunami Numerical Model

2.1 Numerical Model Setting

The numerical model of the 1755 Lisbon Tsunami was validated at a regional scale [14], with a re-evaluation of the historical accounts of reporting tsunami travel times, combined with geological records found onshore UK [15-17] and the presence of turbidites in the deep ocean [18, 19]. The tsunami numerical model animation carried out is available online (https://sites.google.com/a/campus.ul.pt/tsurima/publications). In addition, seismic intensity modeling [20] also supported the tsunami source area model, with the source dimensions of 200 km by 80 km [21]. Thus, the tsunami numerical modeling was conducted at Setubal urban area, Portugal [22] by considering the initial sea surface proposed by [14]. The tsunami numerical model results showed there were three major waves, as reported by the witnesses' accounts [3]. Furthermore, the vulnerability assessment was also conducted at Setubal urban area [23]. These authors concluded that the most vulnerable buildings are located on the west and east part of the city, which was validated by the witnesses' accounts. Therefore, in this study, the initial sea surface displacement was calculated based on the fault parameters proposed by [14] and used the formulas [24]. The results are presented in Fig. 2a, with a maximum uplift of + 6.0 m.

In order to calculate the tsunami inundated areas, the non-linear shallow water equations were used, discretized with staggered leap-frog scheme [25]. In addition, the numerical model was applied to a nesting of five domains. The domains have progressively smaller areas and finer cell size grids, and are included in the previous domain, as shown in Fig. 2. The first domain is the widest and has a cell size of 810 m (Fig. 2a). Then, domains two and three have cell sizes of 270 m (Fig. 2b) and 90 m (Fig. 2c), respectively. Finally, domains four and five have cell sizes of 30 m (Fig. 2d) and 10 m (Fig. 2e), and show the details of the coastal zones and topography. This method has been applied in several tsunami numerical modeling studies [26]. In the construction of each domain, several bathymetry charts were used [27-30], as well as topography maps [31-33]. Previous numerical model results at Figueira da Foz [34] showed the sand dunes were natural barriers. However, the 2014 Tsunami proved these structures are collapsing [8]. Thus, although the Cova urban area is protected by a sand dune which reaches 14 m high [8], a small portion of the south sand dune (approximately 60 m) was removed from the topography model in domain 5 (Fig. 2e), in order to provide the worst case scenario for the inundation results. A similar situation occurs in Leirosa (Fig. 1b) and for that reason a small portion of the south sand dune of approximately 60 m was also removed.

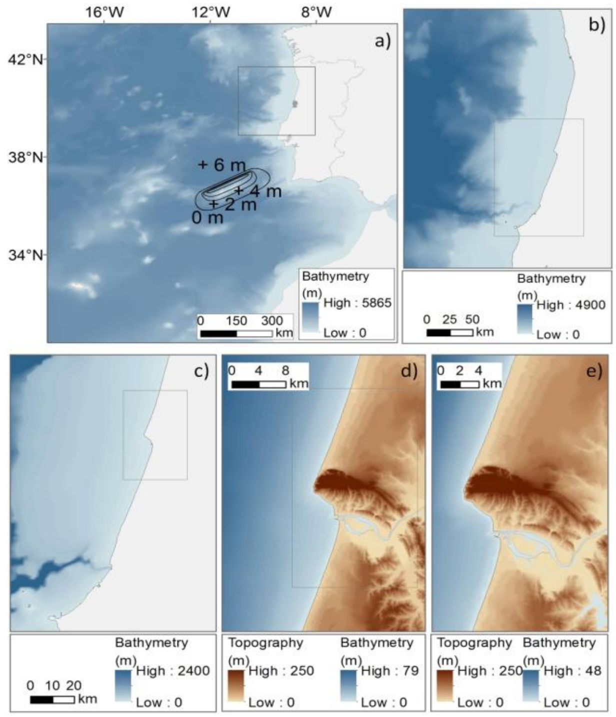

Fig. 2 Nesting conditions for the numerical model: a) Initial sea surface displacement with 810 m cell size; b) 270 m; c) 90m; d) 30 m; e) 10 m.

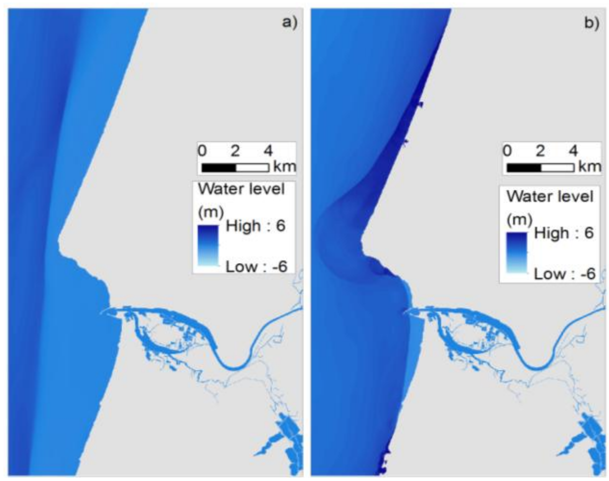

Fig. 3 Tsunami water level snapshots (minutes): a) 65; b) 70.

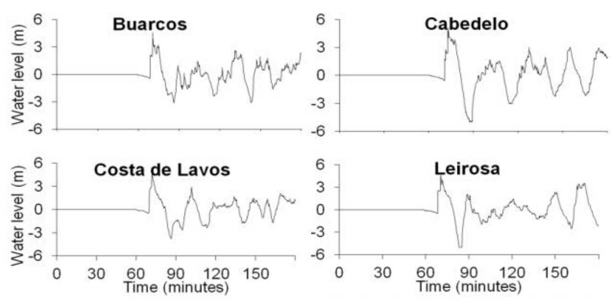

Fig. 4 Water level waveforms at Figueira da Foz.

2.1 Numerical Model Results

The first tsunami wave takes more than one hour to reach Figueira da Foz, approaching Figueira da Foz from the west, with the wave-front with a north-south direction, as shown in Fig. 3a. At about 70 minutes after the earthquake (Fig. 3b) the tsunami reaches the entire north coastline of the municipality, inundating the beaches. Simultaneously, the tsunami reaches the southern coast of the municipality. The tsunami water level waveforms show the tsunami reaches Buarcos and Costa de Lavos from 71 minutes, and Cabedelo is hit from 74 minutes (Fig. 4).

The tsunami water level waveforms also show there are several waves, hitting the coastline (Fig. 4), being the first one and the highest. Still, even after three hours, the waves reach about 3 m high in Cabedelo and Leirosa.

The maximum water level (Fig. 5a) shows there are local amplifications, especially at the north of the municipality (8-10.7 m high), in Buarcos at the Figueira da Foz beach, reaching 8.4 m high and in Leirosa with 8.5 m.

All the beaches are inundated. In addition, Cabedelo, Cova and Leirosa urban areas are also inundated, and for that reason more details are presented in these areas (Fig. 5 (b); (c)). The tsunami penetrates more than 15 km upstream the Mondego River.

The entire Figueira da Foz beach is inundated till 350 m, with inundation depth up to 6.6 m high, as presented in Fig. 5b. The Cabedelo area is completely inundated, reaching the Mondego river and the fishing port, corresponding to an extension of 750 m. At the Cabedelo beach the maximum inundation depth reaches 6.64 m high.

The Cova urban area is protected by a sand dune, and the inundation depth reaches a maximum of 5.51 m at the beach. However, since the sand dune was removed from the numerical model, the tsunami could reach about 910 m inland (Fig. 5b), inundating several streets of the south Cova neighborhood, as well as the pine trees. The inundation depth on the streets gradually decreases from about 0.80 m to about 0.05 m.

In Leirosa, the tsunami inundated the north and south of the urban area. At the north, the inundation reaches about 450 m inland, affecting mostly the lower parts of the beach and the market gardens. At the south, the tsunami reaches about 300 m inland of the neighborhood.

3. Tsunami Hazards

A criterion for TH assessment was proposed [35],

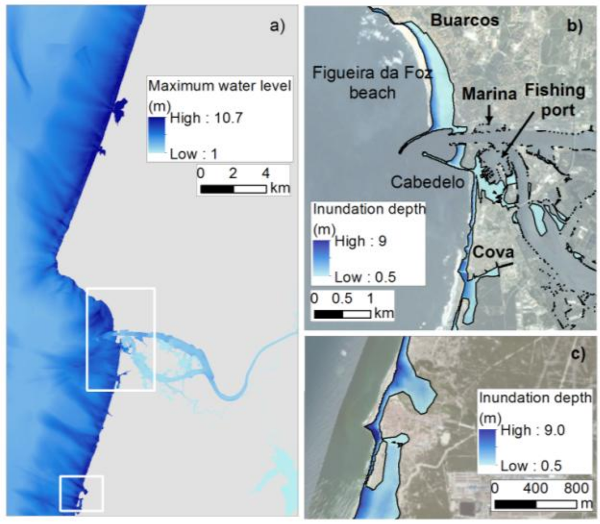

Fig. 5 a) Maximum water level height; b) Inundation depth details at Mondego River mouth; c) Inundation depth details in Leirosa.

Criterion for Tsunami Hazard Assessment at regional scale

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

Tsunami Hazard Matrix

T. Time \ W. L. height	Very low	Low	Moderate	High	Critical
Critical	Moderate	High	High	Critical	Critical
High	Moderate	Moderate	High	High	Critical
Moderate	Low	Moderate	Moderate	High	High
Low	Low	Low	Moderate	Moderate	High
Very low	Very low	Low	Low	Moderate	Moderate

Fig. 6 Tsunami hazard assessment criterion, based on travel times and maximum water level, updated from [39].

based on the combination between the suscetibility of water level height and travel times. However, in this study an upgrade of that proposal is presented, which contains minor revisons at the classification. The new classification varies between "very low" and "critical" (Fig. 6), and the color scale has also been upgraded by considering the "very low" classification in blue, while the others vary between light yellow ("low") and dark red ("critical").

Thus, according to the criterion, and since the tsunami arrives at Figueira da Foz municipality from

65 minutes after the earthquake, the susceptibility of travel time is “very low”. The susceptibility of water level varies between “very low” and “high” (Fig. 7a), obtained from the classification of the maximum water level (Fig. 5a). These lead to a TH that varies between “very low” and “moderate” (Fig. 7b). The “very low” clssification is obtained offshore Figueira da Foz beach and in the Mondefo river. The “low” classification is obtained eslewhere on the study area, expect in two areas of the north Quiaios, with a “moderate” TH, which is desert areas without any beach access.

4. Field Survey

In this study a new TH criterion is proposed based on the crossing between regional TH (Fig. 6) and the existence or not of easy evacuation path from the shoreline to safely high ground (evaluated through the field survey), as presented in Fig. 8.

The field survey was conducted on several occasions on 2012, 2013 and 2014 in the urban areas of the municipality of Figueira da Foz. The survey was conducted based on post-tsunami field survey techniques [36-38]. The objectives of the survey were to obtain detailed topography by using GPS and assess the evacuation conditions on each beach.

The photos presented in Fig. 9 were taken on February 1, 2013 in Quiaios. The survey showed the area is located on high ground: The urban area is at 7.7 m high, having higher ground nearby; the sand dunes reach about 10 m high, which provides a natural barrier to the ocean waves (Fig. 9c). Furthermore, the survey showed there are several easy beach accesses to high ground (Fig. 9b). Still, if a tsunami occurs, people should evacuate the beach because that area is completely inundated with “low” TH. Therefore the local TH is classified as “low”.

Fig. 10 shows details about the Mondego river mouth area. The photo presented on Fig. 10b showing details about Buarcos and Figueira da Foz beach was taken on April 15, 2012. The field survey showed the area is located on high ground, between 8-11 m, with quick and easy access from the beach to even higher ground nearby, to the old town. The Figueira da Foz beach is up to 6 m high, and is approximately 400 m wide. The tsunami numerical model results show the beach is inundated, therefore people should evacuate the area to the road. The beach has several wooden paths

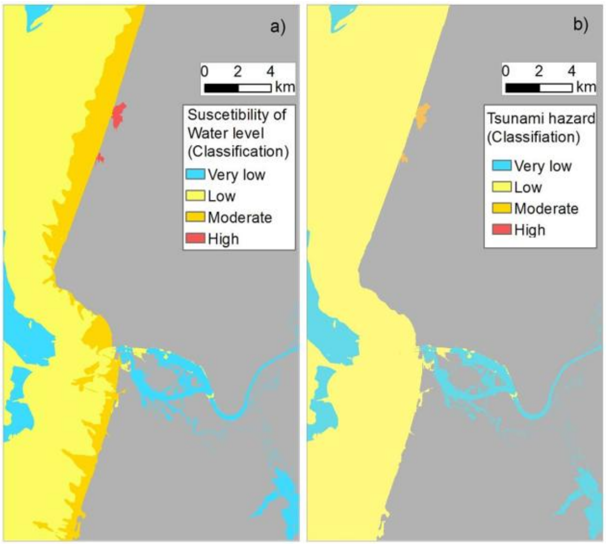

Fig. 7 Criterion for tsunami hazard: a) Susceptibility of water level; b) Tsunami hazard.

Tsunami Hazard Assessment at the local scale

T. Hazard / Easy E. Path	Very low	Low	Moderate	High	Critical
No	Low	Moderate	High	Critical	Critical
Yes	Very low	Low	Moderate	High	Critical

Fig. 8 Tsunami hazard assessment at the local scale, by the combination between tsunami hazards and the existence of an easy evacuation path.

Fig. 9 Survey at Quiaios: a) Framework; b) Details at one of the beach accesses; c) Urban area overview.

so the access from the shoreline to high ground is easy and a person will take less than 10 minutes to evacuate safely (an adult will take approximately seven minutes to evacuate the beach, considering the average walking velocity of 0.94 m/s measured by [6]), as a consequence the local TH at Buarcos area is "low".

The photo presented in Fig. 10c was taken at the Cabedelo parking lot on April 15, 2012. The field survey showed the area is flat, at about 5 m high. The sand dunes reach approximately 9 m high, and offer some protection. The numerical model shows the tsunami penetrates inland through the parking lot, inundation everything till the fishing port. The TH was classified at "low" (Figs. 7b and 10a), however the field survey shows the area is quite dangerous because boulders located at the parking lot may move inland. This fact was observed during the 2014 Tsunami [8]. On the other hand, because the area is flat, it will be difficult for a person to walk to a safe distance from the calculated inundated area, and most likely use the car.

In addition, the tsunami numerical model results show the Cabedelo area may be isolated. These results were also validated by the 2014 Tsunami, in which the only road access was full of sand and debris (Fig. 10d). For these reasons, the local TH is "moderate".

The local TH at the fishing port and marinas are "very low" but it will be recommended that the boats and vessels evacuate to the "very low" TH area offshore the Figueira da Foz beach (Fig. 7b) since the boats might collide with each other, causing damages or even sinking.

The photos presented on Fig. 10 (e); (f) show details at Cova, from the north and south view, and were taken on June 2, 2013. Field survey shows there has been efforts to reinforce the sand dune at Cova (north view) by the construction of several breakwaters with 5 m high, adding layers of large boulders, the construction of a brick sidewalk, at 8.8 m high, and the parking lot is at 10 m high (Fig. 10e). However, the south view of Cova (Fig. 10f) shows there is indeed a significant erosion of the sand dune.

Fig. 10 Survey at the Modengo River mouth: a) Framework of the area; b) Photo taken at Buarcos; c) Photo taken at Cabedelo parking lot; d) Photo taken by Pedro A. Cruz [13] at the base of the sand dune, in Cabedelo; e) Photo taken at Cova (north view); f) Photo taken at Cova (south view).

Although the sand dune reaches 14 m high, if no further intervention is carried out, the sand dune will collapse. This validates the tsunami numerical model's hypothesis of removing this portion of the sand dune. Thus the tsunami would inundate the south Cova neighborhood. Field survey also showed there was easy access from the beach to high ground, with several stairs available. However, the collapsed sand dune would not allow this evacuation at the south of Cova and the tsunami would penetrate inland at the residential area. Therefore, the local TH is "moderate".

Details about Costa de Lavos and Leirosa are presented in Fig. 11. The field survey conducted at Costa de Lavos showed the urban area was located on high ground, at 10-11 m high, being protected by a reinforced sand dune. The photo presented in Fig. 11b was taken on June 14, 2013, and it shows the south area of Costa de Lavos where a natural sand dune stands stable. The lower part of the sand dune is at about 7 m high, and the top of it is at about 11 m high. Thus, validating the numerical model results which show the inundation area is restricted to the beach. The survey also showed there are several wooden paths allowing an easy access to safely high ground. Therefore the local TH is "low".

The field survey at Leirosa shows the urban area is located at 6-11 m high, protected by a reinforced sand dune, with easy access to high ground, like in Costa de Lavos. However, the north and south areas are quite vulnerable. A photo of the north area taken on June 1, 2013 (Fig. 11c) shows the fishermen keep their fishing boats and equipment on high ground, at about 11 m high. However, the market gardens are located at about 6 m high, do not have any coastal protection, and are flooded by the 2014 Tsunami [39], as presented in Fig. 11d, destroying the vegetables' plantations [13]. These results validate the tsunami numerical model which show the market gardens are inundated, and therefore, vulnerable to tsunamis. On

Fig. 11 Survey at Costa de Lavos and Leirosa: a) Framework; b) Costa de Lavos; c) Survey at the north of Leirosa; d) Photo taken by Pedro A. Cruz [13] at the garden markets, north of Leirosa; e) Survey at the south of Leirosa; f) Photo taken by Pedro A. Cruz [13], south of Leirosa.

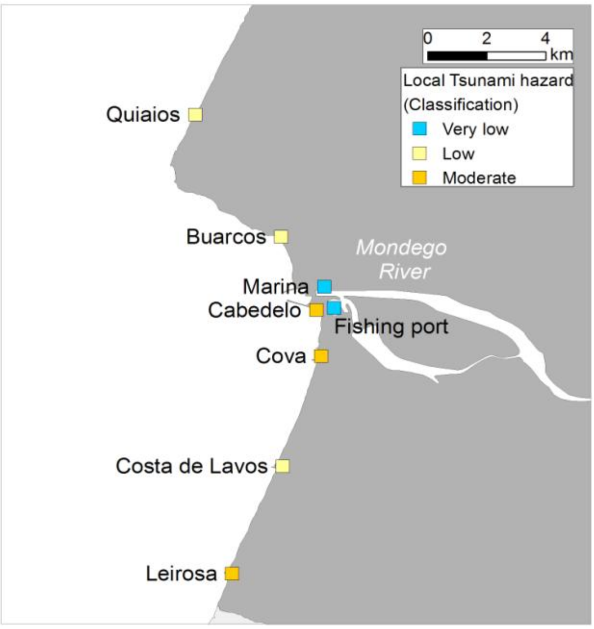

Fig. 12 Local Tsunami hazard at Figueira da Foz.

the other hand, the south of Leirosa is protected by a 10 m high sand dune, as shown by the photo taken on June 14, 2013 (Fig. 11e). However, the area was also affected by the 2014 Tsunami where several boulders were dragged and the lower parts of the wooden side walk were destroyed (Fig. 11f). Although the urban area was not flooded, the presence of several water marks showed the sand dune could easily collapse if hit by a tsunami. Thus, like in the south of Cova, if no further intervention is conducted on the area, the sand dune will not stand, allowing the urban area to be inundated by the tsunami till 280 m inland, as calculated by the tsunami numerical model. As a consequence, the local TH in Leirosa is “moderate”.

The summary of the results is presented in Fig. 12, where the local TH varies between “very low” and “moderate”. The lowest classification was obtained in the marina and fishing port, while the “moderate” classification was obtained in Cabedelo, Cova and Leirosa, which are areas potentially inundated by a tsunami. Quiaios, Buarcos and Costa de Lavos should be safe from a tsunami, and the inundated areas are restricted to the beaches.

5. Conclusions

In this study the 1755 Lisbon Tsunami was analyzed in order to understand the impact of this historical event (as the worst case scenario) would have at Figueira da Foz municipality. The numerical model results show the tsunami would reach the municipality from 65-70 minutes after the earthquake, and within 75 minutes the entire coastal area and the Mondego river would be hit. The sea surface perturbation would last for several hours, where several waves could be observed. Nevertheless, the first wave would be the highest. The calculated maximum water level shows there are local amplifications at the north of Quiaios, Buarcos and Leirosa. The historical accounts report an unexpected water level high amplification at Buarcos [3], validating the numerical model. The inundation depth reaches up the 6 m high at the beaches, showing that it is important that people evacuate the beaches to higher ground.

A criterion for regional TH assessment is upgraded from a previous study, based on the combination of susceptibility of tsunami travel times and water level height. The proposed regional TH criterion shows the susceptibility of travel time is “very low”, while the susceptibility of water level varies between “very low” and “high”. These lead to a TH classification of “low” at the study area. The exceptions are “very low” classification offshore Buarcos and Figueira da Foz beach, and in the Mondego river. In addition, a small area at the north of Quiaios has a TH classification of “moderate”, but there is no access to it and therefore it is a non-populated area.

Then, a local TH assessment is proposed by combining the regional TH with the existence of easy evacuation path to safely high ground, evaluated through the field survey at the Figueira da Foz urban areas.

The numerical model results at Quiaios, Buarcos and Costa de Lavos show the inundation areas are restricted to the beaches and the urban areas are safe. In addition, survey results show these areas are located on high ground, above 8 m high. Furthermore, Quiaios and Costa de Lavos are protected by both natural and reinforce sand dunes, while Buarcos is protected by roads and boulders, with easy evacuation path to safely high ground. Thus these areas have "low" local TH.

The numerical model results at Cabedelo urban area show the tsunami penetrates inland through the parking lot, inundation everything till the fishing port. Survey results show the area is located only at 5 m high. Although there is a sand dune that reaches 9 m high, with easy access from the beach, the parking lot is not protected. Furthermore the difficult evacuation access leads to a "moderate" local TH. On the other hand, the marina and fishing port have "very low" local TH but it would be recommended that vessels evacuate to the "very low" TH area offshore Buarcos and Figueira da Foz beach since the boats might collide with each other, causing damages or even sinking.

Previous studies at Cova showed the urban areas are protected by sand dunes [38], however the erosion show signs they are collapsing. Therefore, parts of the sand dunes were removed from the numerical model, showing the residential areas could be inundated. The survey shows the areas are protected by both natural and reinforced sand dunes, like Quiaios and Costa de Lavos. However, the natural sand dunes are indeed collapsing. Furthermore, the 2014 Tsunami showed the weaknesses of these structures. Thus, if no further intervention was conducted on the natural sand dunes, they would collapse, exposing the residential areas to the tsunami waves. Thus, local TH was classified as "moderate".

The north of Leirosa is approximately 6 m high, and does not have any protection, being inundated by the 2014 Tsunami. Like in the south of Cova, the south of Leirosa also presents fragile sand dunes, and if no further intervention is conducted, the tsunami could inundate the residential areas. For these reasons the local TH was classified as "moderate".

The proposed TH criterion can be applied to any coastal area in the world. Most emphases should be given to near field tsunami, in which coastal communities have less than one hour the escape safely to higher ground.

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