Natural Hazards (2025) 121:6719–6751
https://doi.org/10.1007/s11069-024-07061-7

ORIGINAL PAPER

Tsunami risk mitigation: the role of evacuation routes, preparedness and urban planning

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Received: 16 August 2024 / Accepted: 29 November 2024 / Published online: 11 December 2024

Abstract

The southwestern Portuguese coast, particularly the Algarve region, is at significant risk of an earthquake exceeding magnitude 8, which could generate a destructive tsunami. Coastal areas such as Quarteira and Vilamoura in the Loulé municipality are especially vulnerable due to their dense population of permanent residents and seasonal tourists, compounded by the long distances required to reach safety zones. Despite the known seismic and tsunami hazards, there have been limited studies that develop tailored mitigation strategies specific to tsunami evacuation. This study contributes to the tsunami science by evaluating potential building damages due to shaking and tsunami impact and providing decision support for evacuation strategies. Using Geographic Information Systems (GIS), tsunami scenarios are modeled based on historical seismic events, such as the 1755 Lisbon earthquake, to identify high-risk coastal zones and optimize evacuation routes, considering local topography and population density. Additionally, wave propagation and arrival times are analyzed to ensure timely access to population escape and to mitigate damage to critical infrastructures. Our findings contribute to the developing a comprehensive tsunami risk mitigation strategy for the Loulé municipality, focusing on prevention, public safety, and emergency preparedness. This research supports land use planning, disaster risk reduction, and emergency planning decisions while also advancing the understanding of urban risk by addressing hazards, exposure, and vulnerability in coastal areas. Key objectives of this study include acquiring and implementing historical tsunami data, assessing recommending evaluating the region´s vulnerability, and recommendations for good practices and mitigation measures. The study emphasizes the importance of raising public awareness, enhancing governance, and strengthening capacity to effectively reduce disaster risks.

Keywords Earthquake, tsunami · Building vulnerability · Evacuation routes · Multi-hazard · Urban risk management · Loulé · Portugal

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1 Introduction

Historically, tsunamis received limited attention until the 21st century. In the mid-20th century, even devastating earthquakes of the 1950s did not draw widespread focus to tsunami risks. At that time, tsunamis were rarely included in academic curricula, even in prestigious institutions. It was not until 1970 that Wiegel (1970) introduced the first university course at UC Berkeley, which included a chapter on tsunamis. Later, Wiegel (2009) summarized sources of ancient tsunami information. In subsequent years, Ambraseys (1985) contributed to tsunami science by examining the effects of P-waves from the vertical rupture of oceanic faults, particularly in relation to the 1969 Portugal earthquake. However, this analysis only marginally addressed what is now understood as the typical mechanism of tsunami generation.

Tsunami hazard and assessment studies have gained increased global attention, particularly in the aftermath of the 2004 Indian Ocean tsunami (e.g. Borrero et al. 2006; Løvholt et al. 2006, 2014) and of the 2011 Tohoku Great East Japan tsunami. These disasters, which resulted in the loss of 230,000 and 18,500 lives, respectively, and caused an estimated US$ 10 billion and US$ 220 billion in damages (Basquin et al. 2023), highlighted the urgent need for improved tsunami preparedness and mitigation strategies. In response, countries at high risk, such as Indonesia and Japan, implemented significant mitigation measures, including the establishment of the Indian Ocean Tsunami Early Warning System (Taubenböck et al. 2009; Løvholt et al. 2014), emphasizing the importance of proactive disaster management. Furthermore, losses in ecosystems services may influence all dimensions of disaster risk (Walz et al. 2021).

The 2004 Sumatra earthquake marked a pivotal moment, initiating a new era in tsunami science with more rigorous investigations into tsunami generation, propagation, and impacts. This global shift spurred advancements in tsunami research in Portugal, where Portuguese researchers played a key role in developing modeling techniques that use horizontal discretization of a few hundred meters in deep waters and a few meters near the coast and inland (Baptista et al. 1998 a, b, and Conde et al. 2014).

After 2004, tsunami simulations became increasingly sophisticated, with a focus on validating models using empirical data on wave arrival times, first wave characteristics (run-up or run-down), and inundation extension. This renewed interest in tsunami science also enhanced understanding of historical seismic events, particularly the 1755 Lisbon earthquake, offering valuable insights into source, propagation, and localized impacts. Researchers worldwide made significant progress, and international organizations launched early warning initiatives, which were notably absent during the Sumatra disaster.

The 2011 Tohoku earthquake in Japan significantly enriched tsunami science by providing a wealth of data from seismological records, GPS measurements, and aerial footage, deepening the understanding of tsunami dynamics. A bibliometric analysis conducted by Jain et al. (2021) revealed that between 2004 and 2019, 149 papers were published on tsunami science, with a primary focus on the physical aspects of wave simulation. Okal (2015) compared 17 recent tsunamis, attempting to classify them based on the responses of authorities and the population. However, much less attention has been given to population evacuation strategies, despite the authors emphasizing a “dire need for interdisciplinary research to combine sources and results from various subject areas”. To highlight recent papers on this subject, we cite Celibkas et al. (2023), Cheff et al. (2019) and Liu et al. (2023).

As a brief note, we can say that a comprehensive tsunami risk assessment comprises several key tasks, as referred in Table 1).

In the present work, points 1 to 6 are based on prior studies conducted by other authors, which involved making a series of selections among various methodological approaches. While a hazard model (such as Lopes et al. 2025) can be applied, our approach focuses on the worst credible tsunami scenario: a high-tide impact, which requires a larger-scale evacuation. All these approaches (steps 1 to 10) are essential to reaching the "Last Mile" (Shah 2005) in tsunami preparedness, with the goal of minimizing casualties and achieving the most effective management solutions.

Another major advancement in tsunami research was the incorporation of paleo-tsunami studies, which identified ancient tsunami events along the Portuguese coast dating back to the 6th century BC (Baptista et al., 2009). This research established long recurrence intervals for mega-tsunamis, with multiple sites on the Iberian Peninsula supporting these findings (Hindson and Andrade 1999). Special attention should also be given to the identification of tsunami-induced deposits in the Algarve from the 1755 Lisbon tsunami (Font et al. 2010). Gupta et al., (2013) provided the first comprehensive comparison of the 1755 Lisbon, 2004 Sumatra, and 2011 Tohoku tsunamis, offering valuable insights into the similarities and differences among these significant events.

As mentioned earlier, Portugal has made significant progress in simulating tsunami wave behavior from the seismic source to the coast (see Sect. 2). However, there have been relatively few studies aimed at reducing the impact on local populations. Notable exceptions include research in Portimão (Oliveira et al. 2016), Setúbal (Santos et al. 2017), Lagos (Trindade et al. 2014; Matias et al. 2018), Cascais (Trindade et al., 2018), Sines (Lopes et al., 2025), and more recently Loulé. Studies in Lisbon's harbor (Conde et al. 2014) have

Table 1 Organigram of the entire problem of management tsunami impact

1) Tsunami occurrence: initiated by a fault rupture, which generates seismic activity and triggers a tsunami;
2) Simulation of tsunami physics: modelling the phenomenon from the fault scarp on the ocean floor through to the coastline, following the ocean floor bathymetry;
3) Coastal approximation: as the tsunami nears the shore, it exhibits site-specific behavior influenced by the low water bathymetry;
4) Material dragging: dragging of material from the erosion provoked by the water passage;
5) Impact on built environment: effects caused by the impact of the water, the flow velocity and the inundation extension on the built stock, following the impact of shaking;
6) Water recession: part of the water returns to the ocean, affecting post-event recovery and debris distribution.
7) Wave arrival timing: timing of multiple waves, as observed in historical events (e.g. three waves reported in 1755, by eyewitnesses, Pereira de Sousa 1919);
8) Population in affected zones: identifying people present in the affected areas at the time of the alert;
9) Evacuation strategy: developing strategies to efficiently evacuate populations affected by both the earthquake shaking and subsequent tsunami waves;
10) Public communication strategy: best way to inform the population of what they need to do **before** the wave arrival, **during** the water flow and **after** the water stopped and part of it started to return to the ocean.

also contributed to evacuation modeling and disaster preparedness strategies. Omira et al. (2012), building on a previous study by Baptista et al. (2008), developed a pilot study for the Algarve where the entire problem of mitigation of tsunami risk was contemplated. Although these studies used similar tsunami scenarios, they introduced different evacuation models that offered valuable insights for regional disaster response.

The present research was conducted in the coastal areas of Quarteira and Vilamoura, within the municipality of Loulé (Algarve), at the request of local authorities to assess and plan pedestrian evacuation routes from high-risk coastal zones to designated safe areas. Studies indicate that a tsunami originating from the Horseshoe Fault (HSF) could reach Loulé in approximately 25 min. While this work shares similarities with studies conducted in Portimão, it adopts a more comprehensive approach by developing new evacuation tools. We have gained valuable insights and made recommendations for future efforts in tsunami preparedness. Although this study could be replicated in other locations, it is important to recognize that each area has unique characteristics that may need the development of additional tools. By integrating advanced modeling techniques with a focus on the safety of local populations, this study enhances the understanding of tsunami preparedness and response strategies.

2 Portugal's tsunami history and advancements in tsunami risk management

Portugal, being prone to tsunamis, has experienced several events affecting its mainland coastlines. The works of Baptista and Miranda (2009) provide a detailed outline of the country's tsunami history, focusing on the most significant events, briefly summarized below (see also Baptista 2020 for the enumeration of the six more important tsunamis since the 18th century):

- In 60 BC, after the earthquake (M8.5), a tsunami affected Portugal and Galicia.
- The Tagus estuary tsunami of January 26, 1531 (M6.5), which flooded Lisbon and the estuary.
- On December 27, 1722, an earthquake (M6.5) occurred in the submarine area near Algarve shore, especially affecting Tavira. It was felt all over Algarve from Saint Vicent Cape to the Spanish border, with strong agitation observed in the river waters.
- The devastating Lisbon tsunami of November 1, 1755 (estimated M8.7-9.0) wreaked havoc along the Iberian and north Moroccan coasts, and other parts of the Atlantic. Reports documented waves reaching heights of 10–15 m at Saint Vicent Cape and inland inundations throughout the Gulf of Cadiz. The earthquake, fire and tsunami killed more than 50,000 people altogether.
- The Lisbon tsunami on March 29, 1756, caused significant water agitation in the Tagus River.
- Following an earthquake on March 31, 1761, a North Atlantic tsunami was observed in Lisbon. Funchal (Madeira) and Terceira (Azores) also noticeably observed the tsunami.
- On December 18, 1926, an earthquake in Lisbon resulted in pronounced agitation in the Tagus River, affecting numerous boats docked along the shoreline.
- On May 8, 1939, a minor tsunami occurred in the Azores, specifically affecting São

Miguel and Terceira islands, following an earthquake (M7.1). The highest peak-to-peak amplitude recorded was 30 centimeters at Ponta Delgada (São Miguel Island).

- The earthquake on February 28, 1969 (M7.9) generated a low-amplitude tsunami that was clearly detected at all tidal stations in Continental Portugal, Azores, Spain, the Canary Islands, and the Casablanca station in Morocco. The maximum observed amplitude reached 120 centimeters in Casablanca.
- Lastly, on May 26, 1975, an earthquake (M7.9) occurred in the North Atlantic near the Azores archipelago. A tsunami with a maximum amplitude of 34.5 centimeters was observed in Ponta Delgada (São Miguel Island) and Horta (Faial Island).

Figure 1 illustrates the tectonic environment associated with the geological faults situated at the southwestern edge of the Iberian Peninsula, highlighting the locations of major earthquakes and tsunamis, as well as the case study area of Loulé. Several geological structures are potential candidates for the cause of the 1755 Lisbon earthquake, but a conjugation of faults, including the Horseshoe Fault (HSF), is likely the most plausible explanation. However, other experts, such as Zitellini et al. (2004) and Fonseca (2020), propose alternative explanations. Zitellini et al. (2004) consider the possibility of an active structure from the eastern border of the Horseshoe Abyssal Plain prolonged to the Guadalquibir Bank (GBF) in Gulf of Cadiz, as more recently Ramos et al. (2017) support.

Prior to 60 BC, from paleo-tsunami studies reported in Baptista et al. (2009), there are few evidences to events occurring back to 6.5 kyr BC with interval times ranging from 300 to 1200 yrs.

The 1755 tsunami in the Algarve region of southern Portugal caused a significant loss of life and widespread devastation (Pereira de Sousa 1919; Chester 2008). While its impact was felt along the entire Algarve coastline, it was notably more destructive in the western

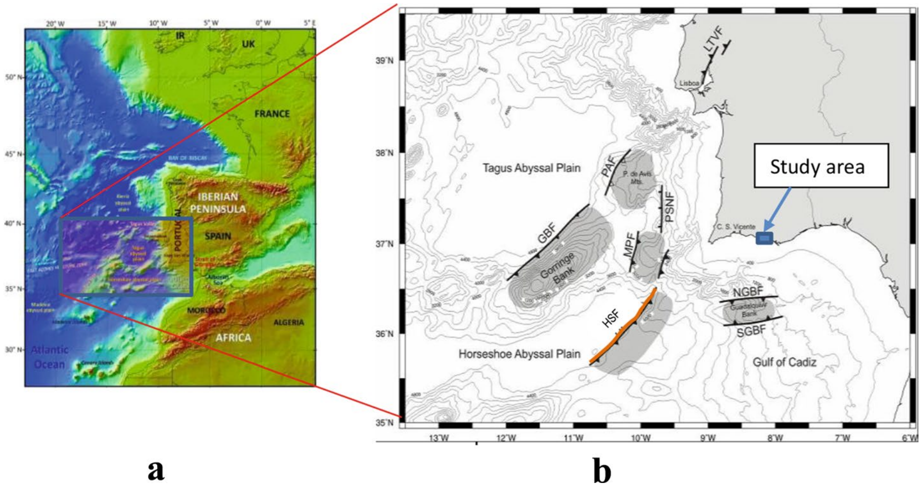


Fig. 1 **a**) Location and bathymetric map with continental margins and abyssal plains around Iberia.(Adapted from Hernández-Molina et al. 2011); b) Tectonic environment in Southwest Portugal with main geological structures (Ribeiro et al. 2009). *MPF* Marquês de Pombal Fault System; *PSNF* Pereira de Sousa Normal Fault System; *GBF* Gorringe Bank Fault; *PAF* Príncipes de Avis Fault; *HSF* Horseshoe Fault (highlighted in orange); *NGBF* Northern Guadalquivir Bank Fault; *SGBF* Southern Guadalquivir Bank Fault; *LTVF* Lower Tagus Valley Fault. Blue rectangle: study area, in Loulé Municipality

region, spanning from Lagos to Loulé. Cadis (Spain) was also severely impacted by the tsunami. (Martínez-Solares, 2001).

In light of this context and the devastating impact of tsunamis on both the population and the local economy, there is an urgent need for intensified scientific and political efforts to prioritize disaster preparedness in Portugal's densely populated coastal regions. Although substantial advancements in tsunami knowledge have been achieved through projects such as ASTARTE (2007–2013), TRANSFER (2006–2009), TSUMAPS-NEAM (2015), EPOS platform (2024), and the UNESCO-ICG/NEAMTWS (2018), a significant gap remains in the "last mile": the practical implementation of these findings at the local level to effectively prepare and protect communities. This includes: (i) mitigating tsunami impacts by identifying and optimizing evacuation routes; (ii) estimating the time people need to reach safe zones and (iii) incorporating urban planning recommendations to foster the development of tsunami-resilient communities.

Bridging this gap is essential to transform theoretical knowledge into actionable solutions, thereby enhancing coastal safety and preparedness in Portugal. Currently, the Portuguese Institute for Sea and Atmosphere (IPMA) is responsible for detecting and disseminating tsunami alerts to ANEPC (National Civil Protection Authority), the Directorate General of the Maritime Authority (DGAM) and the Navy Search and Rescue Service (MRCC). IPMA also collaborates with emergency management entities in several Northeast Atlantic countries, including Morocco, Spain, England, Denmark and Ireland.

While some progress has been made—such as the deployment of audible warning systems (sirens) and the establishment of evacuation routes in Lisbon, Cascais, Setúbal and Portimão (Algarve), with preparations underway in Loulé—there remains a critical need to enhance these systems along Portugal's extensive coastline, particularly in areas more susceptible to tsunami impacts, especially low-elevation coastal zones (below 10 m in height (UNESCO/IOC 2022). The implementation of robust tsunami warning and evacuation systems, including time arrival of tsunami waves, clear signage for evacuation routes and the designation of safe meeting points, is essential for safeguarding coastal communities.

This paper aims to contribute to the broader goal of the Tsunami Early Warning and Mitigation System (NEAMTWS) by enhancing both public and local authority awareness of tsunami risks and response measures. Specifically, it focuses on the development and implementation of a tailored tsunami evacuation plan for the coastal areas of Quarteira and Vilamoura, located within the Loulé municipality in the Algarve region (see Fig. 1b).

Disasters lead to widespread community disruption, resulting in shared experiences of loss, damage to structures and infrastructure, economic impacts, and interruptions to essential services (Ferreira et al. 2016b). An effective tsunami evacuation plan must consider the physical condition of evacuation routes—such as road width, building safety, and serviceability—along with the potential impacts of ground shaking and subsequent tsunami waves.

Researching the condition of evacuation routes and the speed at which the population can move from danger zones to refuge sites are critical factors in ensuring a successful evacuation (Leone et al. 2018). In the case of a tsunami triggered by an earthquake, as in this study, it is likely that buildings will sustain damage even before the tsunami waves arrive. Therefore, integrating building vulnerabilities into tsunami risk assessment models is essential. This study considers worst-case scenarios for both the rupturing fault (tsunami wave height) and the evacuation of the population to safer areas for fault ruptures in the south and southern Algarve. We do not examine the probabilistic aspects of various scenarios, each with its own probability of occurrence.

This scenario, involving an Mw 8.5 earthquake near the Horseshoe Fault (HSF) (Fig. 1b), serves as a proxy for the 1755 Lisbon earthquake (Reis et al. 2022) and may have a return period exceeding 1,000 years. As detailed in Sect. 2.2, the arrival time of the tsunami is expected to be approximately 25–30 min, with potential run-up heights reaching 10–15 m. The shaking intensity in the study area (Loulé) corresponding to a rupture in this fault aligns with the standards defined in the Portuguese Norm (EN-1998-1, 2004) for a longer return period. However, when considering the more appropriate GMPE (Ground Motion Prediction Equations) for the tectonic environment of Southwestern Iberia (Douglas 2021), we observe values comparable to those proposed by the Portuguese Norm for the HSF scenario. Additionally, we briefly examined another seismic scenario known as the Guadalquivir source (GQF) for comparative purposes with the HSF.

Under worst-case scenarios, the hypothetical discrepancy between the generation of shaking and the tsunami is reduced by the significant uncertainties involved in the entire process. Furthermore, faults located south of Algarve or near the Algarve coast do not typically generate large seismic events. The example of the 1722 earthquake is one of the largest recorded events but had minimal impact in terms of tsunami effects (Baptista et al. 2007a). However, the arrival times for this event were around 10 min, which is much shorter than the 25 to 30 min considered in our study (see Sect. 2.2). While one might argue that a 10-minute arrival time poses a greater immediate threat than a 25-minute arrival time, the inundation area would be much smaller. In contrast, for a hypothetical earthquake with a larger return period originated in the GQF fault (Hidromod 2016), the expected arrival time would be approximately 20–25 min, with a run up of about 8 m in the study area. This scenario presents a more severe situation than the HSF scenario in terms of arrival time, but it is less severe regarding run-up height.

In summary, the present research mainly focuses on the following objectives:

- Acquiring and implementing historical tsunami impact data and tsunami inundation modelling results from existing literature;
- Assessing building damage caused by an earthquake followed by a tsunami;
- Evaluating the level of endangerment in the study area;
- Providing decision support for evacuation for the case of a tsunami following a strong shaking (time available for evacuating and extension of inundation);
- Collaborating closely with local administration and decision-makers for final evacuation routes.

By achieving these objectives, this research can aid vulnerable regions in developing and implementing standards that help prevent and reduce disaster risks, ensuring better preparedness and crisis management. This work contributes not only to Sustainable Development Goals (SDGs) 11 (Sustainable Cities and Communities) and 13 (Climate Action) but also to other SDGs, as outlined by the United Nations (2015).

3 Methodologies

3.1 The study area – Quarteira and Vilamoura

The vulnerability of the Algarve region in Portugal (Fig. 2a) to tsunamis, particularly from strong earthquakes near Saint Vicent Cape, underscores the need for comprehensive risk management. In response, significant steps should be taken, especially in areas like Loulé, one of Portugal's wealthiest municipalities, known for its beautiful beaches and luxury resorts.

The municipality of Loulé is located in the south of mainland Portugal, in the Algarve region as shown in Fig. 2a. Covering an area of approximately 764.39 km² and home to 70,622 inhabitants (INE 2021), it is the largest municipality in the region by both area and population. Loulé encompasses three distinct areas from south to north: coastline, crags, and hills. This diversity endows the municipality with unique territorial, heritage, landscape, ecological, and environmental features, which offer significant advantages. Given its privileged central location in the region, Loulé is well served in terms of accessibility, both by road and rail networks, as well as by its proximity to Faro International Airport, which makes it an attractive municipality in which to invest, live, work and visit. Loulé is one of the Algarve's main business areas. Administratively, the municipality is divided into nine parishes: Almancil, Alte, Ameixial, Boliqueime, Quarteira, Salir, São Clemente, São Sebas-

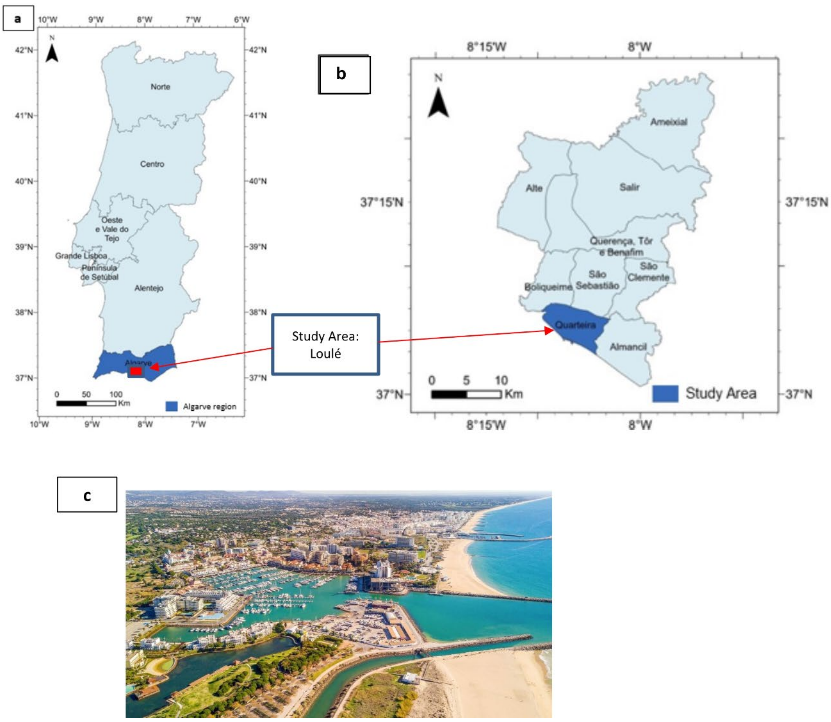


Fig. 2 **a**) Portugal and Algarve region; **b**) Loulé's Municipality and study area (Quarteira parish); **c**) aerial view of Vilamoura with the marina (fore-front), and Quarteira beach (further up) with a 2 km seafront and its residential buildings. (Image: /www.terraevents.com)

tião, and the combined parish of Querença, Tôr, and Benafim. The study area is located in Quarteira (Fig. 2b). According to the 2021 Portuguese General Population and Housing Census (INE 2021), Quarteira parish has a population of 24,421 inhabitants and experiences a considerable influx of visitors during the summer season.

Portugal is one of the best tourist destinations in the world. Tourism is also a fundamental economic activity for generating wealth and employment in Portugal. According to data from Tourism Portugal, in 2022, 26.5 million visitors were registered, of which 15.3 million were foreigners, mostly from the United Kingdom (around 70%, INE 2023), Germany, Spain, France and the United States of America. As for tourism revenue, according to data from the Bank of Portugal, the total for 2022 reached 21.1 billion euros (7% of GDP).

Tourism and services are the backbone activities of the Algarve region's economy (around 80%). The narrow range of economic activities and the dependency on the external market, particularly foreign tourists, make the productive structure in the Algarve extremely vulnerable. Out of the more than five million visitors to the Portuguese region of Algarve in 2023, 1.4 million were domestic travelers (INE 2023). The United Kingdom accounted for the highest number of international visitors, totaling over 1.1 million. In 2021, Loulé recorded 1.603.841 overnight stays in hotel establishments (hotels, guesthouses, hotel-apartments, tourist villages and tourist apartments), representing 10% of the Algarve region's total. Most of these accommodations are located in Quarteira parish, the study area of research, which includes the beaches of Quarteira and Vilamoura with its specificities, well outlined in (Fig. 2c). Other areas of Algarve may have a different morphology with different problems of tsunami inundation and evacuation strategy.

Since the 1970s, the rise of the tourism sector has caused significant transformations in Algarve urban development, particularly in coastal regions. The economic and social demands of tourism have led to the construction of coastal agglomerations increasingly closer to the waterline. Quarteira's seashore street, located between the land and the sea, connects residential areas, touristic apartments, and commercial spaces. These areas have become increasingly vulnerable, not only due to the rise in mean sea level caused by climate change (Proença et al. 2023) but also due to exposure to earthquakes and tsunamis. The increasing exposure of large numbers of people and assets along the coast has significantly amplified the levels of risk and vulnerability.

Aggravating this issue is the local population's lack of familiarity with tsunami and earthquake events, along with widespread illiteracy regarding evacuation procedures. This includes recognizing the signs of an earthquake, identifying abnormal sea conditions, responding to early warnings, hearing tsunami sirens, and observing evacuation behavior in others. This interplay of physical exposure and social vulnerability highlights the urgent need for comprehensive risk management and disaster preparedness strategies in these coastal areas.

Furthermore, the presence of Faro Airport, located within a tsunami inundation zone, exacerbates these risks. A tsunami event could not only endanger passengers and staff at the airport but also trigger cascading problems that would ripple through the broader economy. The airport's vulnerability underscores the critical importance of implementing robust evacuation and disaster response plans, not just for residential and commercial areas but also for key infrastructure sites that are vital to the region's economic stability.

3.2 Wave propagation and tsunami inundation

In this study, areas potentially susceptible to tsunami inundation were identified following methodologies established for the Portuguese coast by Baptista (2007b, 2009) and applied in the Algarve Seismic and Tsunami Risk Study (ERSTA 2010). The study utilized the COMCOT multiple grid model developed at Cornell University (Liu 2005) to simulate wave propagation from the seismic source (HSF) to near the coastline, estimating the both run-up and inundation extent. These simulations were based on digital models of the region's bathymetry and altimetry, with data provided by the Portuguese Hydrographic Institute (IH) and Army Geospatial Information Center (CIGeoE), respectively. For wave propagation at sea, the model used grid resolutions on the order of hundreds of meters, while inland areas employed finer grid resolutions, down to a few meters, to accurately assess inundation.

Regarding tsunami travel times to the study area, Martínez-Loriente et al. (2021) compares results from three key studies (Barkan et al. 2009; Gutscher et al. 2006; Baptista et al. 1998a, b) alongside historical records for various points along the Portuguese coastline, focusing on the Horseshoe Fault (HSF) source. According to Martínez-Loriente et al. (2021), tsunami travel times from this source to Quarteira are estimated at 25 to 30 min, with historical accounts from the 1755 tsunami reporting run-up heights exceeding 10 m (Tedim-Pedrosa et al., 2008) (Fig. 3a). These values closely align with those proposed by Omira et al. (2009) (Fig. 3b). For this study, we adopted the values from Martínez-Loriente et al. (2021), as they allowed for easier interpolation within Fig. 3. Based on these data, and taking into account existing uncertainties, a maximum run-up height of 15 m was selected for the study. Among the uncertainties we can name the hydraulic rugosity of bottom (Man-

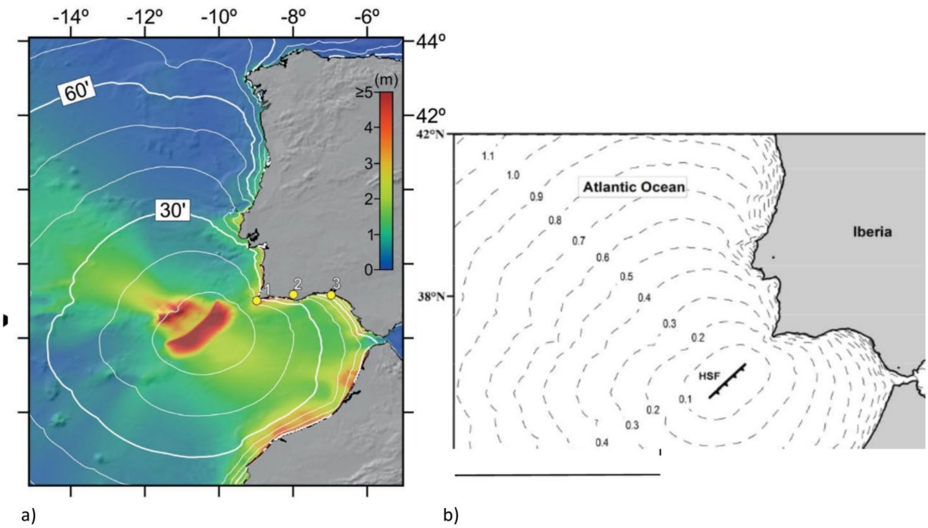


Fig. 3 **a**) Horseshoe Abyssal plain Thrust (HSF) tsunami simulation, as selected scenario for this study, showing maximum wave heights at large and tsunami travel times (10 min intervals) highlighting the most affected areas. Yellow circle: 1- Saint Vicent Cape; 2 – Loulé; 3 - Huelva.(Adapted from Martínez-Loriente et al. 2021; which computed values for point 1 and 3. **b**) Similar studies made by Omira et al. (2009): times in hours

ning Coefficient) assigned to the model, which causes great variations on the inundation extension (Omira et al. 2011; Reis et al. 2023 and Lopes et al. 2025).

As noted previously, we used an event scenario near the Horseshoe Fault as a proxy for the 1755 Lisbon earthquake. In the worst-case scenario for Loulé, inundation extends beyond the beach and riverbed, driven by the region's altimetry (Fig. 4a), and reaches up to 2.3 km inland. This results in a flooded area of approximately 11 km^2, covering around 30% of Quarteira's total area (Fig. 4b). In Fig. 4b, color-coded tsunami inundation zones identify areas requiring evacuation based on the potential tsunami impact. With tsunami waves potentially arriving in nearby coastal areas within 25 to 30 min after a major seismic event (Martínez-Loriente et al. 2021), the window for official evacuation alerts will be narrow, underscoring the need for immediate self-evacuation upon experiencing strong, prolonged shaking. During the 2011 Tohoku tsunami, for example, the water front in flat, agricultural areas advanced at speeds around 15 km/h, accelerating to as much as 20 km/h as flow depth increased, particularly when carrying floating debris (Oliveira et al., 2021). However, this velocity gain provides minimal advantage for evacuation, highlighting the critical need for immediate action at the first sign of strong tremors. It is essential to pre-plan evacuation routes, safe zones and to implement these plans thoroughly, involving both residents and visitors in preparedness efforts to enable faster and more organized responses (Bonilauri et al. 2021).

3.3 Assessment of building damage due to earthquakes and tsunamis

As mentioned earlier, the primary goal of this study is to establish reliable tsunami evacuation routes and safe areas. Estimating seismic damage is one of the criteria used to understand how route selection is affected. To achieve this, it is essential to identify areas that are more likely to experience road disruptions after a seismic event. Thus, we assumed that buildings could sustain damage from seismic waves before the tsunami wave strikes.

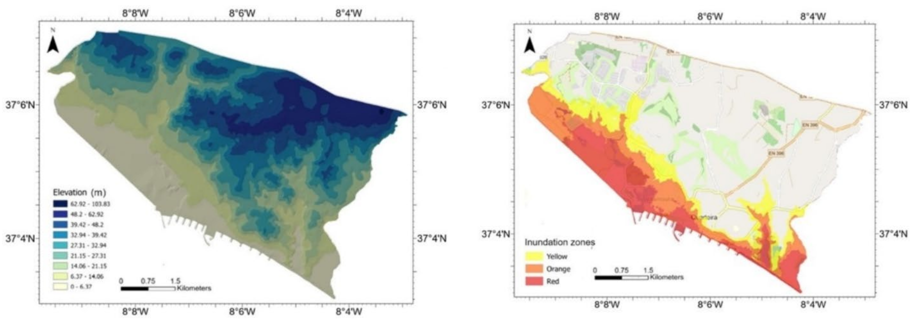


Fig. 4 **a**) Altimetry in meters (courtesy Câmara Municipal de Loulé). **b**) Inundation zones (hazard zones) for the study area. Red zone: This area could be affected even by a small tsunami (inundation up to 5 m). It typically covers beach and marine areas that people should evacuate from in tsunami warnings. Orange zone: This area could be affected by a large tsunami (inundation up to 10 m). Yellow zone: This area could be affected by a very large tsunami (inundation up to 15 m). It covers the maximum credible tsunami scenario, causing the highest impact events. Produced with ArcGis Pro®

Most of the Portuguese building stock is vulnerable to seismic action, particularly those structures that do not comply with modern seismic codes and are in high-hazard zones. In Portugal, the first modern Portuguese seismic code dates from 1958 (RSCCS 1958) and was successively updated and replaced in 1961 (RSEP 1961), 1983 (RSA) and, as of 2019, by the Eurocodes (NP EN 1998). According to the latest national housing census (INE 2021), 18% of the building stock in Loulé predates 1958 and lacks adequate seismic design, while 22% was constructed between 1961 and 1980, and 60% after 1981. It is worth noting that many of these buildings require maintenance or more extensive interventions due to the degradation or alteration of their original structures, resulting in compromised structural integrity. Oliveira (2008) describes at length the several uncertainties existing from fault source to vulnerability of the stock of buildings.

Utilizing data from the Portuguese Housing Census (INE 2011), and its Buildings Geographic Database (BGE), which contains point-based data for all residential building units, it was feasible to categorize the housing inventory of the Quarteira parish. The main variables collected to characterize the vulnerability of Quarteira resident buildings (16,700 buildings) were: (i) epoch of construction; (ii) number of storeys and (iii) state of preservation.

There are several methods to develop seismic vulnerability or fragility functions for the various typologies present in a territory. We reference three publications from the last 20 years (Giovinazzi and Lagomarsino 2004; Mota-de Sá, 2016; and Di Chico et al., 2024), where the methods can be classified as follows: (1) analytical, which uses engineering structural modelling; (2) empirical, which relies on data collected from various earthquakes; and (3) hybrid methods. In this study, we employed the empirical method initially developed by Giovinazzi and Lagomarsino, based on the EMS-98 Scale (Grünthal 1998).

In this method, buildings are classified into typological classes, and the vulnerability, V_{final}, of each building is computed considering (Eq. 1):

$$V_{final} = V_i^* + V_m \tag{1}$$

where V_i^* is the most probable value of the vulnerability index, Vi, of the corresponding building class (Table 2), and ΔV_m is the sum of behavior modifier scores. These modifiers alter the vulnerability index for each building taking into account specific characteristics, such as plan regularity, presence of soft stories and setbacks (vertical irregularities) (Table 3). The eight typological classes adopted, based on the data available from the 2011 Census (INE 2011), along with their corresponding Vulnerability Index (Vi), are presented in Table 2.

The behavior modifiers (ΔV_m) values were taken from Mota de Sá (2016) and are presented in Table 3.

Table 2 Building typologies from Census data and corresponding mean vulnerability index, V_i^*

Class	Epoch of construction	Vi^*
1	Masonry (< 1919)	0.81
2	Masonry (1919–1945)	0.75
3	Reinforced concrete (RC) (1946–1960)	0.70
4	RC (1961–1985)	0.60
5	RC (> 1985 and < 5 storeys)	0.52
6	RC (> 1985 and 5–10 storeys)	0.54
7	RC (> 1985 and > 10 storeys)	0.56
8	RC > 2000	0.40

Table 3 Vulnerability modifier factors and scores, ΔV_m (Ferreira et al. 2010)

		Epoch of construction (class)							
		1	2	3	4	5	6	7	8
Number of storeys	1–3	-0,04	-0,04	-0,02	-0,02	0	0	0	0
	4–5	0,04	0,04	0	0	0	0	0	0
	>= 6	0,04	0,04	0,08	0,04	0	0	0	0
State of conservation	Good	-0,04	-0,04	0	0	0	0	0	0
	Reasonable	0	0	0	0	0	0	0	0
	Bad	0,04	0,04	0,04	0	0,02	0,02	0,02	0
Plan regularity	Yes	0	0	0	0	0	0	0	0
	No	0,02	0,02	0,02	0,02	0,02	0,02	0,02	0,02
Soft storeys	Yes	0,08	0,08	0,08	0,08	0,08	0,08	0,08	0,08
	No	0	0	0	0	0	0	0	0
Setbacks	Yes	0,04	0,04	0,02	0,02	0,02	0,02	0,02	0,02
	No	0	0	0	0	0	0	0	0

The Housing Census (INE 2011) assigns 16,700 buildings in the study area. For the remaining 220 constructions, which are not represented in the Census, such as hotels, building housing offices and essential or critical buildings (health, education, security, cultural, etc.), the characterization followed the same variables; however, Google Street View® have been used as an important tool for remotely conduct systematic observation of the building stock. All the data underwent extensive treatment for standardization and was then incorporated into ArcGis Pro®.

After calculating V_{final} (Eq. 1), the mean damage grade (μ_D) can be determined using the semi-empirical formulation presented in Eq. (2). This equation correlates the mean damage with vulnerability for a specified intensity I, following the six damage levels, Dk.

$$\boldsymbol{\mu}_{\boldsymbol{D}} = 2{,}5 \times\ +2{,}5 \times \boldsymbol{tanh}\frac{\boldsymbol{I} + 6{,}25 \times \boldsymbol{V}_{\boldsymbol{final}} - 13{,}1}{2{,}3}(2) \tag{2}$$

These damage levels (Dk = 0, 1, 2, …, 5) were established according to the EMS-98 damage scale (Grünthal 1998) and offer an understanding of the anticipated impacts: D0 (no damage), D1 (negligible damage), D2 (moderate damage), D3 (substantial damage), D4 (near collapse), and D5 (collapse).

To determine the intensity of shaking (I) we used the EC-8 formulation established in NP-EN-1998, which considers the PGA (Peak Ground Acceleration) corresponding to the offshore seismic action (Type I), adjusted based on the soil type at each building's location. This approach follows the soil classification outlined in EC-8 standards (EN-1998, 2004), where the upper soil layers were grouped into several categories based on studies made within the ERSTA project (2010), Chap. 4 (Carvalho et al. 2010). Finally, PGA values were converted into intensity (I) using the Gutenberg and Richter (1942) proposal and applying Eq. (2).

As previously noted, we assume that buildings could sustain additional damage from tsunami wave impacts. To address this, several types of information are essential. First and foremost, the hydraulic impact of tsunami waves on structures primarily depends on flow velocity and water height. Reis et al. (2022) studied this phenomenon numerically; however, vulnerability and fragility curves were largely derived from empirical observations collected during past events. After the 2004 Indonesia and 2011 Japan tsunamis, fragility curves for inundation impacts became available due to the unprecedented scale of the surveys conducted (over 200,000 buildings). They provided important information for our study and for defining the building damage states, Di (D0 - no damage to D5 - total collapse) (De Risi et al. 2017; Charvet et al. 2017; AIJ 2011). Thus, according to the building's location relative to the tsunami inundation area, an additional aggravated damage value is determined and added to the initial damage as indicated in Table 4. These values are derived from empirical data gathered during the Sumatra tsunami of 2004 (Valencia et al. 2011) in the framework of SCHEMA (2009) EU project to develop a few fragility curves applied to Euro-Mediterranean coastal cities. Each inundation zone in Table 4 corresponds to an incremental "damage state, Di." Note that the values expressed in Table 4 with larger values in the case of smaller buildings are in agreement with the findings of Suppasri et al. (2012), when analyzing that large dataset provided by the Ministry of Japan on damaged buildings in the Tohoku earthquake and tsunami. Some experimental work made in laboratory (McGovern et al. 2023) may also corroborate these numbers. It also shows that velocity impact may increase by 20% the static hydraulic forces.

The analysis did not include debris, but considering it in future assessments is important for a complete evaluation of tsunami impacts. Debris, such as umbrellas, backpacks, beach chairs, recreational boats, small cafes, and walkways, significantly affects the speed of water rise and the level of destruction caused by obstacles in its path.

Figure 5a, shows the distribution of damaged buildings for a distant earthquake scenario (Type I), as outlined in the national annex of the country's seismic design regulation (NP EN 1998). It can be noted that the majority exhibit "conditional use" (resulting from minor (D1) and moderate (D2) damages that will impact the buildings' overall functionality, particularly concerning their utilization due to the collapse of non-structural elements), with some buildings experiencing severe damage (D3), which we can categorized as "unusable".

When we combine the damages resulting from the earthquake with those resulting from the impact of the tsunami waves on the structure (as outlined in Table 4), the map depicted in Fig. 5b reveals a significant number of buildings facing severe damages (D4) and partial or total collapses (D5).

Additionally, Fig. 6 highlights buildings with three or more storeys that are at significant risk of partial or complete damage from tsunami impacts and debris, including vehicles and boats. Due to their design and location directly along the shoreline, these buildings are poorly suited for vertical evacuation and lack protective barriers beyond the beach sand. The area is densely populated with hotels, services, and commercial establishments, with ground floors housing cafes and shops that attract many people. This concentration of activity increase the area's vulnerability, due to its high population density and the extreme

Table 4 Additional degree of damage associated with each zone

Zone	Description	Damage state aggravated
1	Buildings w/water elevation between 0 m and 5 m (inclusive)	+2.00
2	Buildings w/water elevation between 5 m and 10 m (inclusive)	+1.25
3	Buildings w/water elevation between 10 m and 15 m (inclusive)	+0.50
4	Buildings w/water elevation higher than 15 m	+0.00

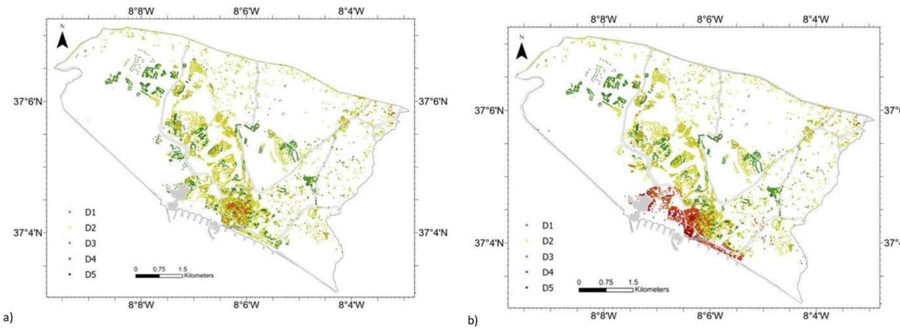
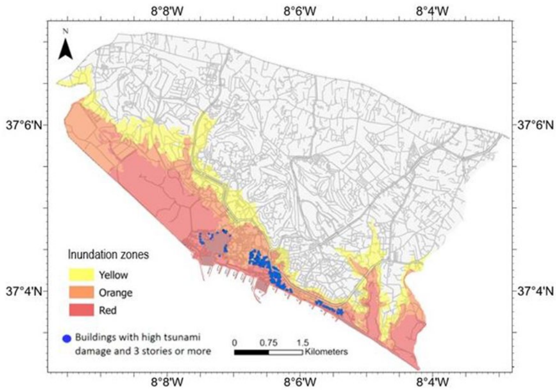


Fig. 5 **a**) Shaking damage map. **b**) Combined shaking-tsunami damage map. Produced with ArcGis Pro®

Fig. 6 Inundation zones (hazard zones) for the study area and mid-rise buildings with high tsunami severe damage. Produced with ArcGis Pro®



forces associated with tsunamis. While some locations may naturally provide high ground for evacuation, other areas would benefit from designated vertical evacuation structures, which should be clearly identified and constructed to withstand such events. However, even a well-implemented early warning system will be ineffective if people and organizations are not prepared to respond swiftly and appropriately to the alerts.

Table 5 illustrates the percentage of construction that would be inundated following a tsunami incidence in Quarteira. Notably, half of the hotels in this parish are located within the red zone (Fig. 6), the area most prone to tsunami impact. This highlights the critical need to raise awareness among both the permanent and transient population, including tourists. Evacuation time is one of the most critical factors in a tsunami event due to the relatively short window between the detection of an imminent tsunami and the arrival of the wave at the shoreline. It is imperative that individuals promptly evacuate the designated zones (red, orange, and yellow) and follow predetermined evacuation routes, without waiting for confirmation from official sources. Immediate action upon sensing an earthquake or upon receiving a tsunami alert is essential to minimize casualties.

Table 5 Identification of buildings at risk of tsunami inundation

Physical elements	Tsunami red zone	Tsunami orange zone	Tsunami yellow zone
Housing stock	6%	12%	9%
Hotels	52%	18%	4%
Health facilities	-	-	-
Schools	23%	3%	-
Security facilities	50%	50%	-
Social facilities	-	-	-
Cultural facilities (casino)	100%	-	-
Local administration	100%	-	-

4 Tsunami evacuation planning in the context of disaster risk management

There is a notable scarcity of comprehensive, scientifically grounded studies on best practices for large-scale evacuations during tsunami events. Although some theoretical studies have been conducted, both in Portugal and internationally, these research efforts lack some calibration from real situations. As referred in the Introduction, some studies have been conducted in Portugal, dealing with the evacuation of populations. According to the worse case situation, the selected tsunami scenario is originated in the (HSF) with a magnitude M = 8.5. This is a rare event with a corresponding return period above 1000 years.

As already referred, according to the findings of a varied researchers (Sect. 3.2), it becomes evident that the tsunami's arrival time in Loulé might be approximately 25 min for a tsunami originated in the Horse Shoe Fault (HSF) (Fig. 3). Nevertheless, if the alert is triggered post-detection at the tide gauge in Sagres, just 15 min will be available for evacuating the vicinity of the study area.

4.1 Criteria for selecting evacuation routes and safe locations

Effective emergency procedures for evacuations and rescue operations are established for various scenarios, including confined spaces, exhibitions, fairs, festivals, shopping centers, and apartment buildings (Kretz 2007). While these protocols are primarily designed to address incidents such as urban fires, they may also be relevant in cases of explosions, terrorist attacks, and other emergencies. However, there is a notable lack of focus on creating specific evacuation plans for earthquakes and tsunamis.

In this study, we employ simple graph models in GIS framework to evaluate evacuation routes. The critical points for modelling are still very crude, particularly in estimating walking velocity, which is influenced by several parameters. These include not only the physical characteristics of the routes—such as incline and the presence of obstacles—but also demographic factors like the age of the population being evacuated. Historical data suggest that younger individuals tend to evacuate more quickly, while older adults may require additional time, often leaving others behind. Moreover, individuals with disabilities and young children need special attention, as they may have limited mobility.

The integration of modern communication technologies (Acar et al., 2011) can facilitate the swift dissemination of evacuation information, enhancing overall response times. However, human behavior introduces further complexities that can impede evacuation efforts, including trauma, panic, fear, and phobias, all of which can significantly affect how individuals respond during emergencies (Cocking et al. 2009; Kinateder and Warren 2021).

To effectively anticipate and respond to the movements of individuals during evacuations, various theoretical models can provide crucial insights into this complex phenomenon, encompassing factors such as evacuation duration and population dynamics. Notably, agent-based models (ABM) and empirical models are particularly valuable for this purpose, as highlighted by Johansson and Kretz (2012) and Kitamura et al. (2020).

To select suitable evacuation routes and safe meeting points, it is essential to identify the most effective paths and shelters for evacuees in advance of an earthquake. Safe locations are designated open areas situated above the potential inundation zone of a tsunami. This project focused on determining the fastest possible evacuation routes, considering various urban characteristics, including elevation, land cover, and both natural and man-made obstacles or barriers. The chosen evacuation routes specifically avoid areas that may be compromised by strong earthquakes, such as collapsed bridges and buildings that could obstruct pathways and create hazardous conditions.

By employing this methodology, we were able to calculate the most efficient paths from any point within a hazard zone to a safe meeting point outside that zone. Consequently, this approach allowed us to: (i) identify evacuation corridors, (ii) estimate evacuation times and capacities, and (iii) create a comprehensive map detailing the routes to safety.

A crucial aspect of ensuring a safe evacuation is leaving the expected inundation area quickly and following a safe route to reach designated meeting points. The selection of escape routes and safe locations were selected in close collaboration with local technicians from the Municipal Civil Protection Service of Loulé, who have extensive knowledge of the area. They identified open spaces such as gardens and school playgrounds, which our risk assessment indicated would perform favorably post-earthquake in terms of building safety (both structural and non-structural).

All paths identified in Fig. 7 were thoroughly inspected to assess their suitability as evacuation routes. Inspections ensured that paths do not traverse private properties and are unobstructed by physical barriers such as walls or other impediments. Additionally, the assessment took into account factors that may not be visible on ortho-photo maps or similar imagery, including recent public works or developments not yet reflected in current maps or cadastral redords.

The project followed the Reference Guide for Evacuation Planning in case of Tsunami, issued by the Portuguese National Authority for Emergency and Civil Protection (ANEPC 2022). This compliance included the installation of evacuation signage (strategically placed signs along designated routes to aid navigation during an emergency) and the implementation of sirens to facilitate immediate communication of evacuation alerts.

4.1.1 Paths categorization and parameters

The paths identified in Fig. 7 were classified according to several key attributes, as detailed below:

1. Road types

- Paths were categorized based on road types, specifically by the number of lanes (1, 2, 3,

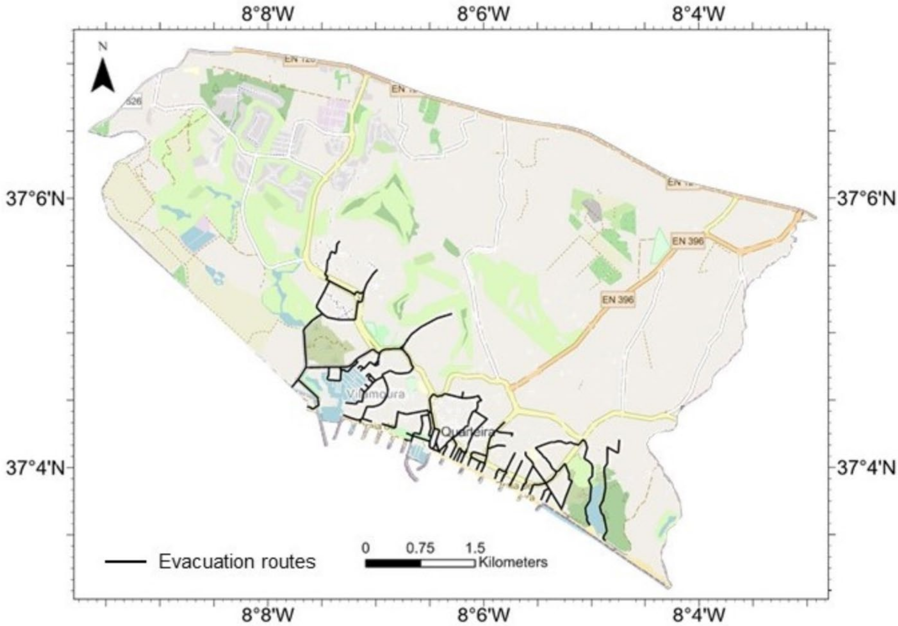


Fig. 7 Segments used for evacuation routes. Produced with ArcGis Pro®

or 4 lanes). Each lane was assumed to be 3 m wide.
- Lanes designated exclusively for vehicle parking were excluded from this analysis to focus on clear pedestrian routes.

2. Walking speed

- Walking speeds varied by road class, taking into account factors like slopes and lane count. For sandy surfaces, a walking speed of 1.8 km/h (0.5 m/s) was assumed. Further details on walking speeds are provided in Table 6.

3. Flow of people at nodes

- At convergence points (nodes) where two sections meet, the number of people from each section was combined and carried forward to the next section.
- In cases where a section bifurcates, it was assumed that half of the people would continue along each of the newly formed sections.

4. Evacuation time isolines

- Evacuation time isolines were plotted based on travel times from critical points, such as the beach or marina. These isolines illustrate areas reachable within 10, 15, and 20 min after an alert.
- An additional 10-minute buffer was included to account for reaction time and the time

Table 6 Evacuation walking speeds and respective weights (Bonilauri et al. 2021; Leone et al. 2018)

			Speed after application of reduction coefficient (km/h)		
Class	Slope (%)	Associated speed (km/h)	Two-lane road	Single lane road	Passageways, stairs, walkways
Reduction coefficient			**1.0**	**0.8**	**0.5**
1	<3	4.85	4.85	3.88	2.43
2	[3–6[	4.55	4.55	3.64	2.28
3	[6–9[	4.26	4.26	3.41	2.13
sand	-	1.80	-	-	-

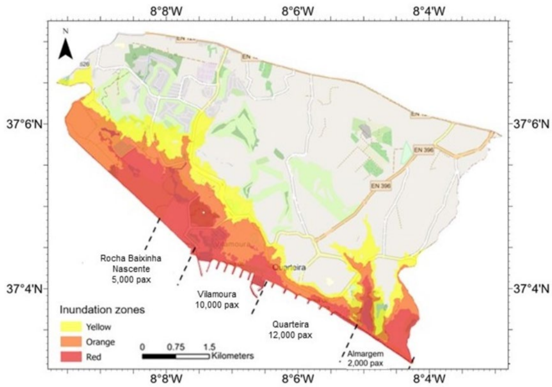


Fig. 8 Maximum beach capacity, referring to the bathing season from June 1st to September 30th, 2021.Source: (Fonte: https://apambiente.pt/apa/arh-do-algarve) (infopraia.apambiente). Produced with ArcGis Pro®

taken to transition from the sandy beach to the designated evacuation routes.

In addition to calculating evacuation times, it is essential to estimate the number of people that can be evacuated from each zone within these established timeframes (see Fig. 8). This capacity assessment ensures that each zone can accommodate safe and timely evacuation for its population in case of an emergency.

The present study is grounded in the following hypotheses, which consider seasonal, temporal, and situational factors influencing the effectiveness of evacuation planning:

- The number of people requiring evacuation during a tsunami varies significantly with the season (summer, winter, and holidays) and time of day (daytime, nighttime). Recognizing these variations enables more accurate planning and resource allocation, ensuring evacuation strategies are scaled to the expected number of evacuees under different conditions.
- The highest risk scenario occurs during mid-day in summer when beaches are heavily populated. Since recent studies on population dynamics in beach areas are unavailable, we estimated maximum occupancy using guidelines from COVID-19 legislation. According to Portuguese COVID-19 restrictions, sun umbrellas were required to be spaced at least three meters apart (eportugal.gov.pt 2021). Using this spacing metric, and assuming an additional umbrella can fit between each of these placements, the density of umbrellas and thus beachgoers is effectively tripled (as illustrated in Fig. 8).

Assumptions Beach visitors and those in nearby bars and shops are counted among evacuees, while residents in nearby apartments are presumed to remain safe if they access higher floors above the inundation limit. However, if structural damage occurs due to initial tremors, the evacuation demand may increase.

- During quieter times, a key concern is the population frequenting shops and restaurants, particularly those situated along the promenade and the streets immediately parallel to the coastline. In the event of an emergency, swiftly evacuating these individuals is essential. Evacuation procedures should guide them either to upper floors in nearby buildings or along designated evacuation routes to ensure their safety.
- In winter, the concentration of people in these areas is generally low, reducing the overall risk.

Figure 9 presents isolines showing the time needed for an individual with good mobility to reach specific areas from the beach, following designated routes and factoring in reaction times. For successful evacuation within these timeframes, it is essential that the public is well-informed about procedures and evacuation routes, and that they cooperate fully. To support this, the Municipal Civil Protection Service conducted on-site evaluations to identify optimal locations for all signage. These placements were then validated by the Quarteira parish council, road network division, traffic safety authorities, and maritime authority. As an example of preparation, authorities should be ready to direct car traffic to pre-established locations.

The evacuation time isolines and the capacity of each section were used to calculate the number of people that can be evacuated. The capacity (C) of each section is calculated as follows:

$$\mathbf{C} = 0.8 \times \ \mathbf{width} \times \ \mathbf{length} \ (units: \ Number \ of \ people; \ m) \tag{3}$$

For example, a section measuring 5000 m in length and 3 m in width can accommodate the evacuation of approximately 12,000 people. This capacity value, referenced in Eq. 3 was derived from consulting multiple sources, including (Kretz 2007), as well as analyses of crowd densities observed at the rear ("tail") of marathon events.

Figure 10 illustrates the inundation and evacuation zones as follows:

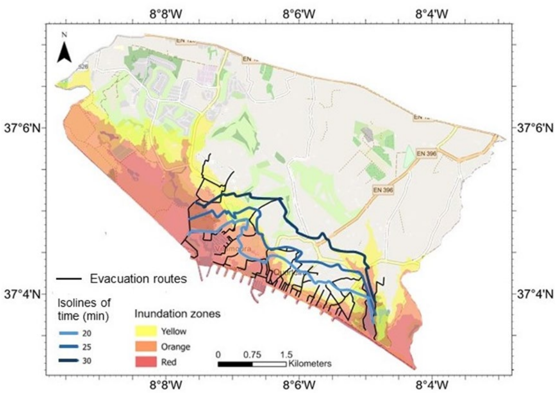


Fig. 9 Evacuation route map and time isolines (in minutes)

- Red, orange, and yellow zones: These indicate areas at risk of inundation by the tsunami.
- Green zone: This represents the parts of the study area outside the tsunami's reach.

In the Vilamoura and Quarteira areas, residents and visitors, upon receiving an alert, generally have viable routes to reach safe locations within the green zone. However, people in Rocha Baixinha Nascente, face considerable distances to reach safety, presenting additional challenges in an emergency. The Almargem area presents a mixed scenario, emphasizing the importance of prompt alerts and ensuring that the public is well informed about immediate evacuation actions.

After establishing the evacuation routes, the next step was to set up clear and effective signage. This task received particular attention from the Municipal Civil Protection team, who addressed several technical considerations, such as defining the distances between signs, determining exact locations for clear visibility without obstructions, and deciding what information to display.

The timing of evacuation initiation is crucial and requires clear coordination with the authorities, which is in charge for triggering the sirens. The following protocol is recommended:

- For maximum safety, evacuation should begin immediately if strong, prolonged shaking is felt, rather than waiting for official tsunami confirmation, which may come 15–20 min later.
- Once the tsunami waves are detected at tidal gauges, sirens are triggered, and mobile alerts are released. In the event of a false alarm, a different siren pitch should inform the public.

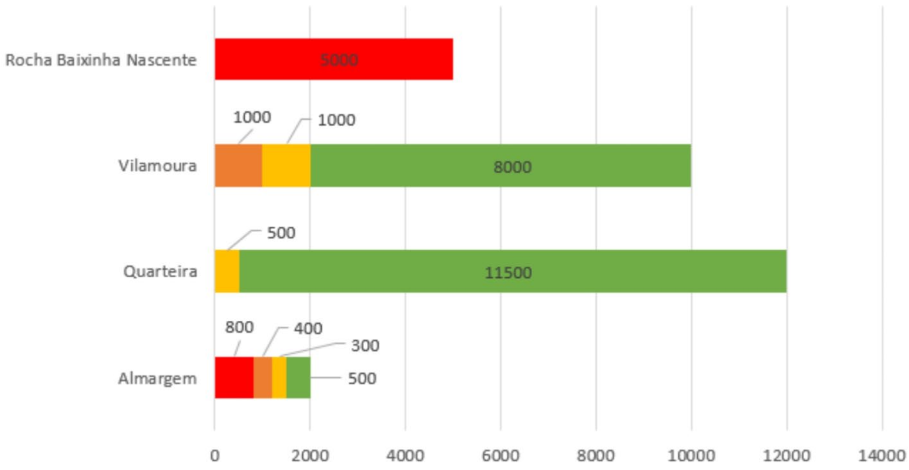


Fig. 10 Number of people evacuated at each of the beaches in each hazard area. Green represents safe places, in accordance with Fig. 9, with origin in the four beach sectors represented in Fig. 8

4.2 Identified gaps and proposed solutions

Detailed fieldwork across various areas within the study region identified key gaps and proposed solutions to address the following challenges (Table 7):

A key contribution of this study is to highlight the essential role of city council authorities in the decision-making process. Scientific recommendations alone cannot effectively complete the "last mile" (Shah, 2005) of an emergency preparedness project without collaboration from local officials who possess detailed knowledge of the terrain and constraints. Their involvement from the outset is critical to project success.

On January 12, 2024, the Loulé City Council officially unveiled (Fig. 11) the tsunami evacuation signage project for the Quarteira parish (Fig. 12), along with a community awareness campaign (Figs. 12 and 13). This project was also presented at the "Tsunami Ready" Meeting in Paris in February 2024, following an invitation from UNESCO.

5 Recommendations for developing tsunami-resilient communities

Building tsunami-resilient communities has immense potential to reduce disaster risk, especially in earthquake- and tsunami-prone areas. In Portugal, however, limited research has specifically focused on urban planning for high-risk regions. Furthermore, the studies that do exist often fail to account for the complexity of multi-hazard threats and cascading effects, which are crucial for comprehensive disaster preparedness. Even when research is conducted, the implementation of building codes and urban planning regulations remains inconsistent.

Table 7 Solutions to evacuation barriers

	Problem	Solution
Obstacles to pedestrian circulation	Fencing networks in vacant or undeveloped land impede pedestrian movement.	Ensure that tsunami evacuation signage is highly visible and easily understandable to guide the population effectively.
Beach congestion	A high density of beach umbrellas and sun loungers can obstruct a swift evacuation.	Implement procedures for the rapid removal of these obstacles to facilitate quick and easy evacuation.
Pedestrian bridge limitations	To the west of Vilamoura, evacuation is constrained by two pedestrian bridges: i) Concrete Bridge: While structurally sound for pedestrian traffic, it allows for a smaller flow of evacuees. ii) Wooden Bridge: Narrower and potentially resonant under heavy foot traffic, posing risks during mass	i) Reinforce the wooden bridge. ii) The construction of a new pedestrian passage with higher capacity can significantly enhance the network's performance during evacuation conditions.
Hotel rooftop limitations	Most hotels in Quarteira have mechanical equipment (HVAC) or solar panels on their rooftops, hindering their use as vertical evacuation safe zones. The Marina Hotel, despite its large terrace area (about 2500 m^2) that could safely accommodate many people, both from the beach and from the boats in the marina, is unsuitable due to the risk of glass façades shattering from vibrations provoked by water flow.	Explore alternative safe zones or designate areas on hotel rooftops that are free from existing infrastructure and mechanical equipment to safely accommodate evacuees.

Fig. 11 Project presentation conducted by the Coordinator of the Loulé Civil Protection. Examples of orientation signage and meeting points

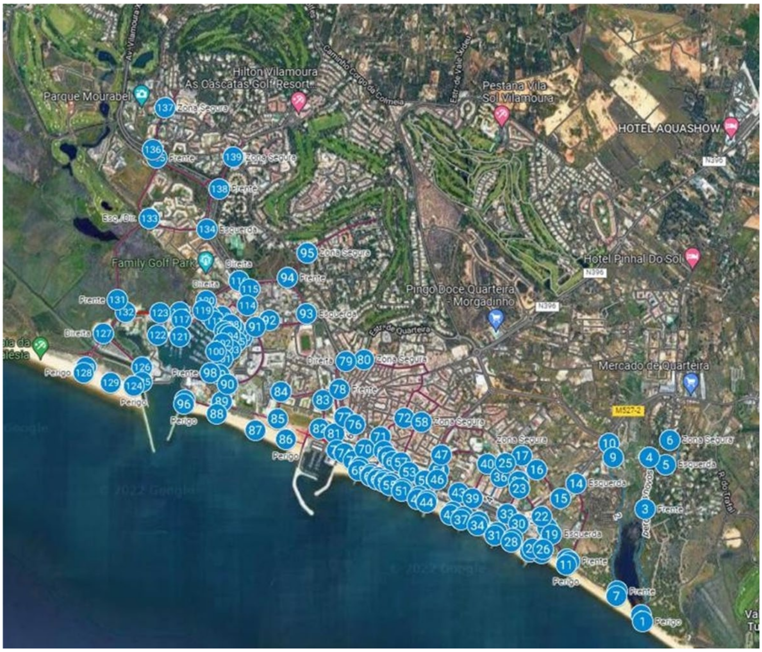


Fig. 12 Location of 139 signs for evacuation routes (blue circles)

Urban planning is a critical tool in reducing the harmful impacts of natural disasters and enhancing community resilience. International frameworks like the Hyogo Framework for Action (UNISDR 2005), the Sendai Framework for Disaster Risk Reduction (UNISDR 2015), and the 2030 Agenda for Sustainable Development emphasize the importance of integrating disaster risk reduction and resilience-building into urban planning. Despite these global commitments, effective integration into planning processes remains a significant challenge.

Fig. 13 Flyer created by the Loulé Civil Protection outline the main evacuation routes and provide essential safety guidance (available at https://www.cm-loule.pt/pt/40362/alerta-tsunami.aspx)

5.1 Key strategies for tsunami risk reduction

To safeguard lives, property, and economic activities in tsunami vulnerable areas, it is essential to adopt a combination of structural and non-structural strategies:

1. Strengthen building standards and land-use policies

- Design and construct buildings to withstand earthquake and flood risks, ensuring they incorporate materials and structures that mitigate damage from seismic activity and tsunami inundation;
- Enforce zoning regulations that limit construction in high-risk coastal areas and direct development to safer regions.

2. Incorporate hazard assessments into urban planning

- Conduct comprehensive hazard assessments to identify areas most vulnerable to tsunami impacts and integrate these assessments into planning. Restrict development in these zones and prioritize elevated, safe areas for critical infrastructure.

3. Develop Early Warning System

- Establish robust early warning systems to alert residents and visitors of imminent tsunami threats, allowing for timely evacuations.

4. Public education and awareness campaigns

- Launch targeted education campaigns to increase awareness of tsunami risks, evacuation routes, and safety protocols. Prioritize high-risk facilities such as schools, nursing homes, and tourist areas to ensure widespread knowledge of emergency procedures.

5. Promote safe zones and vertical evacuation shelters

- Avoid constructing buildings in low-lying coastal areas, particularly on smooth, shallow beaches and canal sides that amplify wave impacts. Instead, consider developing tsunami evacuation parks or elevated green spaces designed to withstand inundation levels (Cedillos 2010);
- For populations unable to reach high ground, designate tall, secure buildings (e.g., hotels over five stories) within evacuation zones as vertical evacuation shelters.

6. Engage local authorities and tourism management

- Engage local government and tourism agencies in risk reduction planning. Accurate evacuation simulations, collaborative planning, and tourist education will ensure preparedness and improve their safety.

7. Enhance training and drill programs for vulnerable populations

- Conduct regular evacuation drills for schools, nursing homes, and other vulnerable facilities. This includes protocols for relocating populations with specific needs, such as children, the elderly, and individuals with disabilities. Integrate tsunami drills into national emergency drills for fires and earthquakes, to ensure that students and staff are familiar with these procedures.

8. Strengthen building standards and land-use policies

- Effective communication of tsunami risks and evacuation procedures is crucial for equitable disaster response. Inclusive measures are essential to reach vulnerable populations, minimizing disparities in access to information (Dion et al. 2014). For instance, individuals with hearing impairments, who may not hear sirens, could be notified through visual alerts such as colorful flags, a practice used in countries like Japan. See Table 8 for additional examples of inclusive communication practices.

9. Financial incentives and insurance for resilience

- Incentivizing resilient building practices through financial measures can play a crucial role in building community resilience against tsunamis: (i) Tax Incentives and Subsidies: Provide tax breaks or subsidies for new resilient construction and retrofitting of existing structures; (ii) Insurance Coverage: Encourage earthquake and tsunami insurance, particularly in areas with low coverage rates, such as Portugal, where only 20% of the building stock is covered by earthquake insurance (Januário 2023). Expanding coverage can support faster recovery and minimize economic loss after a disaster.

10. Cost-effective investment for enhanced resilience

Table 8 Type of information to disseminate to a varied population

People with disabilities	- Red-and-white flags to alert hearing impaired of tsunami threat; - Evacuation routes must be accessible for people with reduced mobility; - First responders should get familiar with basic sign language.
Child and Youth	- Early warning messages must reach schools and daycare centers; - Tsunami drills for teachers, students and parents.
Elderly	- Caregivers, neighbors, and others should be ready to provide assistance and help the elderly.
Tourists and travelers	- Warning messages should be issued in all relevant languages. These should be available at hotels front desks, touristic offices and airport arrivals.

- By combining these recommendations with cost-effectiveness models, communities can prioritize investments to maximize resilience in tsunami-prone regions (Cutter et al. 2018). Aligning strategic planning with economic efficiency will enable communities to mitigate risks effectively and improve their capacity to adapt to future disasters.

6 To sum up and directions for future research

A tsunami on the scale of the 1755 earthquake would have far more severe consequences today, given the significant population growth and urban development along the Portuguese coast. The increased density of people and infrastructure in these vulnerable coastal areas underscores the critical need for ongoing efforts to develop tsunami-resilient communities. Such efforts must involve a combination of structural and non-structural measures to effectively mitigate the risks and enhance community preparedness. This study focuses on the coastal city of Quarteira in the Algarve region of southern Portugal, a location particularly vulnerable to tsunami impacts. It can be replicated to other coastal areas considering their specificities in several aspects.

The tools used to assess tsunami hazards, exposure, and vulnerability are well-established from a scientific perspective, and in this study, they were applied to support national and regional disaster risk reduction efforts. The findings highlighted that the southern part of Quarteira is a high-risk flood zone (Fig. 9). Consequently, residents and beachgoers in this area would need to walk or run a considerable distance to reach safe zones, located in the northern part of the city.

The study's outcomes underscore the urgent need for comprehensive disaster risk reduction strategies, especially in densely populated coastal regions where the potential consequences of a tsunami could be catastrophic. To effectively mitigate exposure to tsunami hazards, it is imperative that land use regulations within the Loulé municipality incorporate tsunami risk considerations. Mainstreaming disaster risk reduction and natural hazard adaptation into urban planning represents a crucial step in building resilient cities, particularly in the context of Portugal's densely populated coastal regions. Guidelines should recommend a "minimum urban structure" that includes strategic public buildings, public spaces, and infrastructure networks to facilitate the evacuation of the population to designated safe areas. Areas with high and very high tsunami hazard levels should be prohibited for critical and essential facilities. Additionally, specific protection and strengthening standards should be established for facilities housing vulnerable populations, such as hospitals, schools, and residential areas. "Building back better" is the most effective approach to mitigate the effects of both seismic shaking and water impacts on the built environment.

Future studies should prioritize identifying individuals at risk and evaluating the effectiveness of evacuation route education and tsunami awareness campaigns for both residents and tourists. Tourism is critical to the region and must be fully integrated into disaster management strategies. Collaborative efforts between the municipality and the tourism industry are essential to increase risk awareness and implement initiatives such as earthquake-resistant construction and clear safety protocols. Communication with guests should be improved to ensure cooperation during evacuations, supported by guidelines for both guests and hotel staff. By investing in protective measures and awareness within the tourism sector, the region enhances guest safety, ensures business continuity, and strengthens overall resilience, benefiting the national economy and supporting rapid recovery post-disaster.

Education and community awareness are essential to any tsunami resilience program, as they are the most cost-effective ways to address local tsunami risks. Future research should also explore panic psychology and evacuee behavior, since even minor tsunami events can lead to tragedy if people are not well-informed and prepared.

In terms of physics of wave propagation, several improvements could be made, particularly regarding inland propagation. This includes examining the influence of building debris on evacuation routes, urban layout, and the presence of large floating objects (such as cars and parts of damaged houses). Lessons learned from Tohoku, as captured by video cameras (Oliveira et al., 2021)—including the velocity of the front wave in different urban and rural morphologies and the balance of incoming flows from various roads—provide valuable data. Probability scenario assessments considering other fault sources and other population´s geography could be performed if we would look at cost –benefit aspects.

One of the significant improvements in mitigating the impact of earthquakes and tsunamis will be the deployment of submarine cables, planned to replace the CAM (Continent-Azores-Madeira) ring, equipped with advanced "obs-instrumentation". By 2027, it is expected to notably enhance the alert time for earthquake and tsunami arrivals along the Portuguese territory, including the coastal regions (Howe et al. 2022). This development represents a major advancement in mitigating the impacts of earthquakes and tsunamis, and will have crucial implications for improving risk management, namely in the way to inform the population.

The main goal of this paper was to reach the so-called "last mile," as pointed out by Shah (2005), by disseminating knowledge to populations and decision-maker stakeholders. We found that, after gathering all scientific and technical knowledge, it is crucial to collaborate closely with local authorities and involve them in the entire study. Their insights regarding things such as poorly maintained trails, restricted access to fenced properties, narrow pathways,—issues only observed in the field by people familiar with the territory—are essential for designing safe evacuation routes. Additionally, the signs indicating the best trails should always be developed in consultation with local residents; otherwise, the intended messages may not be understood, leading to confusion rather than clarity.

Acknowledgements Much of the experience summarized in this paper is related to the projects that the authors have been directly involved in over the past 8 years. The present work has been supported by the Serviço Municipal de Proteção Civil de Loulé. Authors would like to acknowledge the Engineers Telma Guerreiro, Tatiana Neves, Fernando Leandro, Filipe Saleiro, Paulo Guerreiro and Comandante João Matos Lima for their support and assistance with data collection. Mónica Amaral Ferreira is grateful for the Foundation for Science and Technology's funding (Doi: https://doi.org/10.54499/CEECINST/00122/2018/CP1528/

CT0025). The authors are grateful for the Foundation for Science and Technology's support through funding UIDB/04625/2020 from the research unit CERIS (Doi: https://doi.org/10.54499/UIDB/04625/2020). Further more, we thank Dr. Cláudia Reis and Dr. Rosa Félix from the Instituto Superior Técnico for their suggestions to the research and Hugo O'Neill for image editing.

Author contributions Conceptualization, MAF. (Mónica Amaral Ferreira); CSO. (Carlos Sousa Oliveira); RF. (Rafael Francisco). Methodology, MAF, CSO, RF; formal analysis, CSO, MAF, RF and writing—original draft preparation, MAF. Writing—review and editing: MAF, CSO, RF; visualization: CSO, MAF, RF; supervision: MAF. Computation: RF.

Funding Open access funding provided by FCT|FCCN (b-on).
The authors are grateful for the Portuguese Foundation for Science and Technology's support through partial funding UIDB/04625/2020 from the research unit CERIS. Mónica Amaral Ferreira is supported by the Portuguese Foundation for Science and Technology (doi: https://doi.org/10.54499/CEECINST/00122/2018/CP1528/CT0025).

Data availability No new data was created.

Declarations

Informed consent Informed consent was obtained from all subjects involved in the study.

Competing interests The authors have no relevant financial interests to disclose.

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