

A GIS-based analysis of constraints on pedestrian tsunami evacuation routes: Cascais case study (Portugal)

André Trindade¹  · Paula Teves-Costa^{1,2} · Cristina Catita²

Received: 31 March 2017 / Accepted: 15 December 2017 / Published online: 23 January 2018
© Springer Science+Business Media B.V., part of Springer Nature 2018

Abstract Tsunami hazard in coastal areas susceptible to flooding, although reduced (in terms of probability of occurrence), may pose a high risk. Therefore, in these areas, a detailed evacuation planning of the affected population is required as a risk mitigation measure. The knowledge and enforcement of evacuation routes may reduce the population vulnerability, making it more resilient and reducing risk. This paper presents a GIS approach for modelling evacuation routes based on the optimal path search problem, of the graph theory, which is implemented on ArcCasper tool. The methodology proposed considers the elements involved in the evacuation process, the worst credible tsunami inundation scenario (hazard extent and travel time), the number of people that needs to be evacuated in different time scenarios, the safe areas or destination points of the evacuation routes, the roads network characteristics and finally the time available to evacuate. The knowledge of those elements allows predicting some possible outcomes of the evacuation, such as the arrival time of the evacuees to a shelter and the identification of congestion hot spots resulting from the application of a flocking model which simulates the path to be used by evacuees avoiding obstacles. The municipality of Cascais was used to test the methodology proposed in this study. Cascais is one of the largest urban centres located about 25 km west of Lisbon, Portugal, with a high density of infrastructure along the coastline whereby most of the population and economic activities are exposed to a tsunami. The results, presented in the form of maps, allow identifying the optimal evacuation routes as well as the unfeasible routes. This crucial information could be used to the evacuation optimization regarding the location of meeting points and vertical shelters as well as to improve the accessibility of the areas to be evacuated.

Keywords Tsunami · Evacuation routes · Flocking maps · Network analysis · Cascais

✉ André Trindade
andretrindade@gmail.com

¹ CERU – European Centre on Urban Risks, Avenida Elias Garcia, n.º7, 2º, 1000-146 Lisbon, Portugal

² Instituto Dom Luiz, Faculdade de Ciências, Universidade de Lisboa, 1749-016 Lisbon, Portugal

1 Introduction

Information technology (IT) research on urban emergency problems essentially started in the nuclear threat era, and the earlier developments started in the late eighties with the first disaster evacuation simulations. However, this first attempt simply predicted traffic conditions during evacuations, given a certain density of population not yet containing an adequate network topology, which did not allow evaluation on topics like evacuation routing optimality, applicability and scalability (Shahabi 2015). By the end of the 1990s, some of the limitations on the application of GIS in the field of hazards (e.g. lack of data, weakness of existing data and deficiencies of available software) were overcome and there was a significant increase in risk assessment and mapping using geographic information systems (GIS) (Cova 1999).

This technical development and the synergy between GIS, intelligent transportation systems, remote sensing and telecommunications technologies allowed arising several different approaches. Probably the most disseminated approaches on evacuation routing methodologies (in terms of GIS usage) are those based on the cost-weighted distance determination of raster analysis (e.g. flow direction, flow accumulation and least-cost distance). Recent publications such as Mück (2008), Post et al. (2009), Kobayashi et al. (2011), Wood and Schmidlein (2011, 2013), Graehl (2011), Mas et al. (2012), Freire et al. (2013) and Wood et al. (2016) are good examples of this practice. These methodologies have the advantage of assessing the travel speed values considering the slope and land-cover surfaces, the spatial–temporal population distribution by creating weighted density surfaces from the statistical data and by generating evacuation time surfaces or evacuation routes (in the cases in which they incorporate the road network on the evacuation model). The approaches strongly depend on the spatial resolution of the input data or on the interpolated, reclassified or resampled cell size surfaces. These methods are best suited for large areas where spatial resolution is typically lower than 10 m but, for better resolutions where the level of detail is greater, the benefit of these methods is minimized.

On the other hand, GIS applications and location-based services (LBS) have become increasingly important in recent years and different use cases are constantly emerging with new graph-based approaches to the evacuation problem (Shahabi 2015). Most of the studies in this field (traffic flow, object/agent-oriented micro-simulation studies) use custom solutions that are not broadly accessible by non-expert users and require a rigorous computer programming knowledge. Even though there are different commercial or opensource software solutions with these functionalities (integrated in the GIS), used in recent tsunami evacuation studies, such as ArcGIS Network Analyst (Dewi 2012; González-Riancho et al. 2013), Mapinfo RoutFinder (Péroche et al. 2014) and PostGIS pgRouting (Schuster and Gomez 2013). This last one operates on the Dijkstra's algorithm (Dijkstra 1959) because it offers a better performance when using road network graphs (Shahabi and Wilson 2014). These approaches basically consist of calculating the shortest path search on a road network and measure the travelling cost between one source point and one destination point or the shelters service areas.

The present work relies on a map-oriented evacuation modelling as a graph pathfinding problem conducted on the ArcCASPER tool (Shahabi and Wilson 2014). It starts by the recognition of the elements involved in the evacuation process: (1) the number of people that needs to be evacuated in different time scenarios (assessed by a volumetric estimation method on the census data), (2) the safe areas or destination points of the evacuation routes, (3) the roads network characteristics (road type, capacity, slope and speed limit)

and (4) the time available to evacuate, considering the worst credible tsunami inundation scenario (hazard extent and travel time). The knowledge of these elements allows to predict some possible outcomes of the evacuation, namely the number of people affected, the time of arrival at a shelter and the congestion points on the simulated routes.

The Portuguese mainland territory presents a non-negligible probability of tsunamis occurrence (Omira et al. 2016; Wronna et al. 2015). According to historical records, large coastal areas have been flooded, natural and anthropogenic barriers have been overtopped, and different type of structures have been washed away and destroyed, causing many deaths as in the case of the devastating tsunami of 1 November 1755 (Baptista and Miranda 2009). In the last century, Cascais tide gauge station recorded three tsunami events generated by the earthquakes occurred on the 25 November 1941, 28 February 1969 and 26 May 1975. According to the implementation of the current regulations established by the international community (Intergovernmental Coordination Group of UNESCO's Oceanographic Commission), that strongly recommend the installation of a tsunami warning system, a warning message from the civil protection authorities should have been sent in the cases mentioned above.

To illustrate the implementation of the methodology for tsunami pedestrian evacuation routes estimation presented in this paper, the Cascais municipality (Portugal) was selected. This study, developed within the framework of INSPIRED project developed by the European Centre on Urban Risks (CERU, <http://www.ceru-europa.pt/en/projectos.php>), intends to contribute for an action plan to be implemented on the field by the local authorities in charge of the emergency management and planning, providing an effective decision support tool in one of the most touristic areas near Lisbon (Portugal).

2 Methodology

The objective of this work consisted in the search and development of a methodology that can be easily replicated, to analyse a road network solution for the tsunami pedestrian evacuation. To achieve this, multiple sets of geospatial data with analysis tools and techniques were combined and all were integrated into a spatial database in GIS environment. Taking into account that data sources may vary from area to area, a set of steps were provided to successfully lead to an optimal use of the ArcCasper evacuation simulation tool and also to take the proper conclusions from the obtained results. The requirements needed for the application of the proposed methodology are fundamentally the following: a robustly built road network properly classified with a set of required attributes, a good estimate of the population values to be modelled as evacuees and a carefully picked group of meeting points. Figure 1 presents an overview of the adopted workflow that will be discussed in the sequence of this section.

2.1 Input data and pre-processing

2.1.1 Population estimation and evacuation starting points

As regarding an efficient evacuation modelling, it is necessary to estimate the population exposed (P_e) to the inundation. The population of an urban area should not be considered as static but rather as dynamic in time and space (Kobayashi et al. 2011). To simulate approaches to the exposed population in different time periods, we evaluated four demographic scenarios

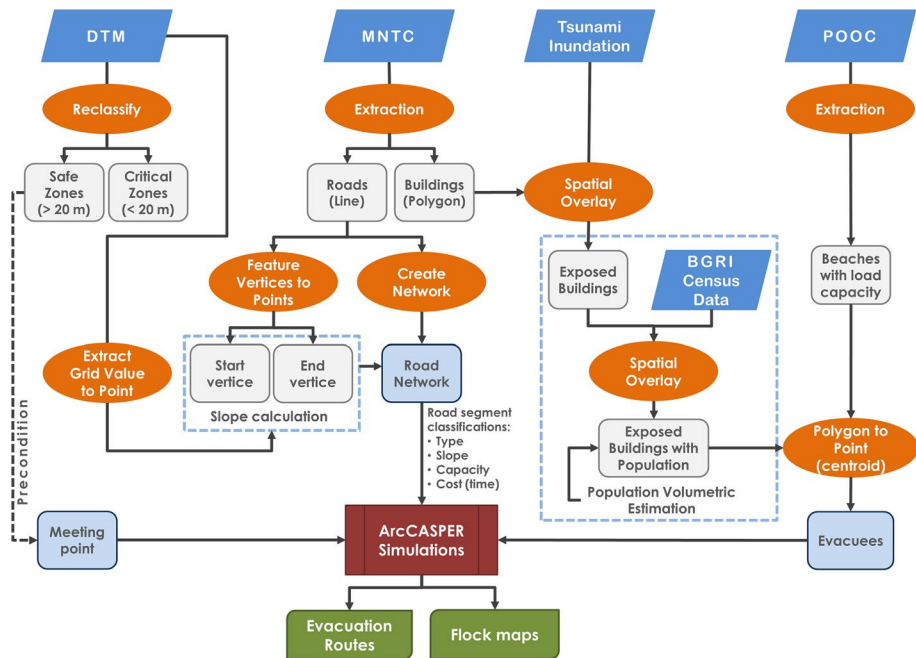


Fig. 1 Evacuation model workflow

which consider the resident population, the present population (workers) and the “floating” population (tourists and people on the beaches) at the following time periods: Day time—high season (DHS); Day time—off season (DOS); Night time—high season (NHS); and Night time—off season (NOS).

The maximum spatial disaggregation level of Census data, usually the statistical subsection (representing about a block in urban areas), is manifestly insufficient to provide the exact points of origin of an evacuation route because it sometimes generalizes extensive areas of the territory (mainly in less urbanized areas). However, information on building population is required for this kind of micro-spatial analysis. To a fine scale, population estimation is always associated with a significant percentage of error but, according to Qiu et al. (2010), a volumetric method can be a more effective approach than a purely statistical one (e.g. ordinary least squares regression) due to the incorporation of spatial patterns in modelling. Lwin and Murayama (2009) propose a method that consists on distributing the population value by the volume that each building occupies (considering the building footprint and the number of floors), in the total building volume of the statistical subsection to which it belongs. The target buildings can be selected from those which intersect the inundation grid pixels with a positive wave height value. The computation is performed using the following equation:

$$BP_i = \left(\frac{P_c}{\sum_{k=1}^n BA_k \cdot BF_k} \right) BA_i \cdot BF_i \tag{1}$$

where BP_i , population of building i ; P_e , exposed population; BA_i , footprint area of building i ; BF_i , number of floors of building i ; i, k , summation indices; and n number of buildings that fall inside the same statistical subsection.

2.1.2 Evacuation destination

The meeting points in safe concentration zones, in the context of horizontal evacuation, are the places where the exposed population should go after a tsunami warning. These sites should be in high places, for example 20 m above sea level, and they must be public locations with adequate capacity to safely accommodate a large number of evacuees during the flood period (Péroche et al. 2014). In addition, they should be located at a reasonable distance from the starting point, be easily accessible by the population and, considering the response phase, they should not remain isolated with blocked or flooded adjacent roads (Scheer et al. 2011). In an ideal situation, safe areas should be defined in the municipal emergency plan. However, the tsunami risk is not always addressed because often the evacuation time is not known. A simple solution to locate these areas can be archived by using a DEM to extract the areas with elevation higher than 20 m and intersecting them with areas of appropriate size and classification from a land cover/use layer (like the CLC—Corine Land Cover).

2.1.3 Road network classifications

The evacuation was modelled as a problem based on graph theory maximizing the flow of evacuees moving in a road network and minimizing movement costs. To perform this kind of network analyses, it is essential to define a “Cost” attribute (or impedance). In this study, due to all the constraints involved, assigning the time (in minutes) as the “Cost” attribute proves to be more interesting for the afterword analysis than the distance (which is usually used). All road network elements have also essential attributes such as the number of lanes of each road segment (arc or line that connects two nodes), the type of road and the slope that may condition the traversal speed of the evacuees.

The Network Analyst extension of ArcGIS was used for the simulation of pedestrian circulation. The use of cars or other vehicles is not recommended for evacuation purposes, not only for obstructing the ways but mainly because they represent a threat to the physical safety of pedestrians. Here, the travel speed refers to the walking speed of a human. Several authors addressed this issue and proposed speeds that widely varies from 2.80 m/s (Post et al. 2009) to 1.0 m/s (Yagi and Hasemi 2010; González-Riancho et al. 2013). In the present study, a fixed average value of 1.4 m/s is considered for the normal speed of an adult. In the case of mobility impairment on road segments (stairs or slopes over 15%), this speed is reduced to 0.7 m/s.

The first step to classify a road segment according to its slope is to assign an elevation value to the start and end vertices of the segment. This can be achieved by extracting the elevation values of some points from a DEM (digital elevation model) and interpolating the values of the nearest points to the vertices. Finally, this attribute is joined to the segment feature. The slope is calculated as a percentage applying the following equation:

$$\text{Slope}(\%) = \left(\frac{\text{END}_{\text{elev}} - \text{Start}_{\text{elev}}}{\text{segment length}} \right) \cdot 100 \quad (2)$$

To simulate the flow of evacuees and to optimize the routes considering potential jamming problems, the capacity attributed to each road was introduced. This capacity refers to the number of evacuees which could move simultaneously, side by side, in a unit of a

road segment, constraining the network (graph) to its road and intersection capacities. This value was determined by the number of lanes (3 m each, including sidewalks) multiplied by five (number of evacuees per lane) or, on unconfined roads between buildings (open space), by the number of lanes times ten.

2.2 Routes simulation using the ArcCASPER tool

The simulations and the analysis of evacuation routes were performed using ArcCASPER evacuation routing extension which runs on the top of the Network Analyst tool of the ArcGIS software. It is a free proprietary software available for commercial and non-commercial use. CASPER (Capacity-Aware Shortest Path Routing Evacuation), developed by Shahabi and Wilson (2014), is a pathfinding algorithm that efficiently considers the capacity constraints of the transport network and the flow of a number of evacuees to minimize congestion and travel times throughout the routing performance. The algorithm combines the road capacity with its length to predict speeds under different traffic conditions and also differentiates between population size and density, or flow, to generate evacuation routes. It enforces a time delay between each evacuee starting point minimizing global evacuation time and eliminating the need to schedule evacuation times. As input to generate the evacuation routes, this process uses a graph (roads network), a traffic model and the source and destination points. The traffic model is a mathematical model of real-world traffic and is the feature that ensures an optimal flow with a minimum number of traffic jams. In the simulations performed in this work, among several available options, a Power traffic model was used as it presents the best performance in predicting congestions and estimating evacuation time (Shahabi 2015).

The ArcCASPER extension also uses the CARMA (Capacity-Aware Reverse Map Analyser) module to traverse the graph backwards and generate data to enhance CASPER runtime by sorting the source points according to their predicted evacuation time. This feature is inspired by CCRP (Capacity Constrained Route Planner) and A*(A-star) algorithm (Hart et al. 1972) that is a faster version of Dijkstra's algorithm. The diagram in Fig. 2 demonstrates the major steps of the CASPER routing process.

On top of ArcCASPER extension, there is also the possibility to run an agent-based simulation (microscopic descriptive method) based on the flocking model (Reynolds 1987) originally designed to simulate a group of birds flying. Groups of people exhibit a very similar flock-like behaviour pattern in distress situations. In this case, the flocking simulation was intended to represent agents (evacuees) following a path and avoiding obstacles. It takes as an input the road network, the initial locations of all the evacuees, the evacuation routes and assumes one agent for every start point (regardless of the exposed population value), then moves them, one by one, in small time intervals along the path to the meeting point. This model enforces several rules such as: (1) the agents cannot be closer than a predefined threshold to each other; (2) agent's speeds are based on the free space in front of them and on a pre-assigned speed; and (3) in case of collision, both agents will have a speed penalty. The application of this flocking model generates a point cloud in which each point represents a set of evacuees at any given evacuation time stamp (snapshot). It allows the identification of hot spots where the movement of evacuee's flow suffers slowdowns or stagnates (congestion prediction). A lower points concentration over the road segment means a more fluid movement (related to evacuee's flocks with low population values) while clusters (higher density of points) are related to speed reductions and more crowded locations.

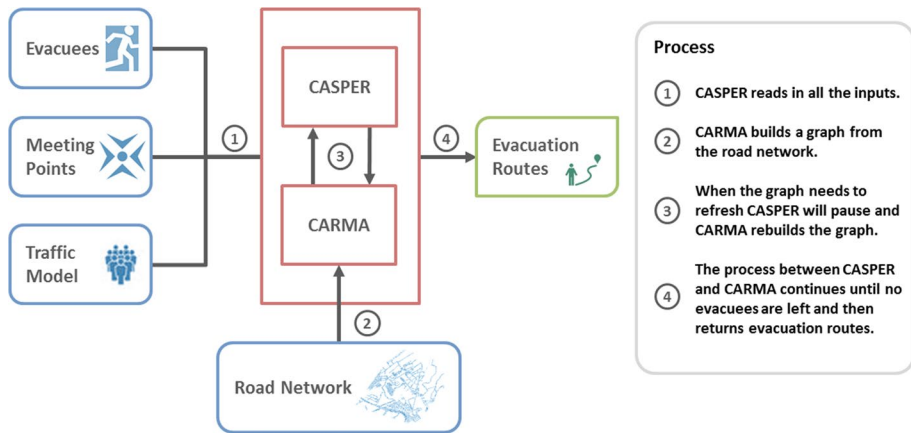


Fig. 2 CASPER architecture and routing process Adapted from Shahabi (2015)

Before running the application, it requires some setting and parameterization. The CARMA direction, that indicates how evacuees should be sorted before getting processed, was set as “BW Continuous”—this configuration processes first the farthest evacuees from the meeting point, being the order revised if necessary. In addition, the application was also configured to allow the *U*-turns and the one-way streets feature was disabled because the simulations refer to pedestrian evacuation. The initial space between evacuees that are sharing their start location (i.e. evacuee density on each road segment) was set to have a delay of 10 s. The Critical Density per Unit Capacity was set to 10, meaning that more than 10 evacuees would affect the traversal speed, and the Saturation Density per Unit Capacity was set to 100 meaning the threshold of evacuees that will reduce to half of the original traversal speed on a road segment. The flocking profile that indicates the type of evacuee affecting the physics of the simulation (e.g. top speed, dimension, acceleration, safe distance between each other) was set as “person”, and the temporal resolution of simulation, as well as the snapshot interval, was both set to 30 s.

3 Application to Cascais (Portugal)

3.1 Study area

The Cascais Municipality, located 25 km west of Lisbon the Portuguese capital (see Fig. 3), has a coastline with 24 km of length, 4.2 km corresponding to seventeen beaches. It is next to the coastline, especially in the southern part, that the urban density is larger and where the main infrastructures and major economic activity of the municipality are concentrated. Due to the extension of the study area and the scale of analysis required for evacuation modelling (an extensive number of nodes and edges on the road network may present major problems on processing the route simulations), the Cascais county coastal area was divided into several sectors. To illustrate the methodology application, two sectors were selected (Fig. 3):

Sector I—*Cascais (Boca do Inferno–Praia da Rainha)*. This sector comprises three beaches and it is one of the most vulnerable because of its high population density. The

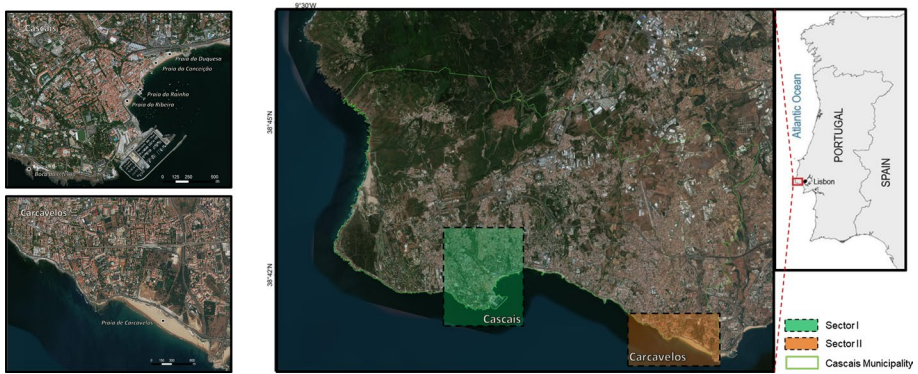


Fig. 3 Study area—Cascais municipality and the selected 2 sectors

area includes downtown and the historical centre of Cascais village, where support infrastructures with great population attraction capacity, harbours, marinas, sea-defence structures, restaurants, commercial areas as well as institutional infrastructures like the Town Hall are located. At *Praia da Ribeira*, there is an old river mouth, currently channelled, which potentially can be turned into a waveguide allowing water to enter through the old creek bed. *Praia da Conceição* and *Praia Duquesa* may present problems at the evacuation moment because they are separated from the upper grounds above 20 m by the railway line.

Sector II—Carcavelos. This sector contains the coastline between the beaches of Parede and Carcavelos up to the railway. It appears to be a particularly vulnerable area due to its orography, which is flat and with low altitude, and the beach of Carcavelos is one of the largest in the county. In this area, in addition to residential buildings, there are other important infrastructures such as schools and hotels. If not affected by the flood, some of these structures could be used as a shelter.

3.2 Tsunami inundation scenario

In this study, the most adverse or worst possible tsunami inundation scenario was considered despite its low likelihood. This decision concerns the fact that the worst scenario provides a clear indication of the maximum distance from the coastline that will be affected by the flooding (run-in) as well as the maximum wave height (run-up). Adopting the worst credible situation, the less severe scenarios are inherently safeguarded.

The tsunami risk assessment in Cascais county, performed by Baptista and Omira (2014), provided as the worst-case scenario the occurrence of a tsunami generated by an earthquake with epicentre at the Horseshoe Fault (HSF)—Marquês de Pombal Fault (MPF) zone (earthquake of magnitude 8.8 similar to the one that occurred on 1 November 1755) at high tide condition. According to Ribeiro et al. (2006), the composite source of the HSF and MPF is favoured as a solution for the 1755 event due to the sub-parallel orientation as well as to the almost geometric continuity of the two faults, which facilitate the strain/displacement transfer between them (Omira et al. 2012).

The hydrodynamic simulation to calculate the maximum wave height grid (2-m cell size) was developed by Baptista and Omira (2014). This simulation estimates 15 m for the maximum vertical height above sea level, reached by the wave inland (run-up) in Cascais,

where the ancient creek acts as a waveguide increasing the penetration of water onshore (Fig. 4). The most heavily affected area is Carcavelos (sector II), where the flow depth in the beach area can reach 12 m. In this case, the flow velocity in the potential flooded zone can exceed 5 m/s (approximately 18 km/h).

Baptista and Omira (2014) also estimated the first wave travel time between the source and the coastline, presenting values of about 42 min until Cascais village and 45–48 min until Carcavelos (cf. Fig. 3 for locations).

3.3 Exposed population scenarios

Population data were provided by 2011 Census (INE 2011). These data were surveyed by building blocks (BGRI—Portuguese statistical subsection) in January 2011, considering the resident and the present population during the day. Four scenarios of exposed population (P_e) to be evacuated were considered (cf. *item* 2.1.1): (1) the DOS scenario was assumed to be the present population (P_p); (2) the NOS scenario was assumed to be the total resident population (P_r); in addition, two high season scenarios were used considering the tourist population (P_t) and the population present on the beaches (P_{pb}). According to Cascais Municipality, hotel's capacity of the whole municipality is about 7400 beds, spread over 49 hotel units in 2011. Considering a 100% hotel's occupancy rate, the tourist population will be 7400 (P_t) that will be spatially distributed differently considering the night or the day scenario. In the NHS scenario, the tourist population will be distributed according to the hotels location (P_{t2}) and added to the correspondent statistical subsections, whereas for the DHS the tourist population was considered spread over all the exposed statistical subsections (P_{t1}).

The DHS scenario corresponds to the most populated because it considers also the population present on the beaches (P_{pb}). This number was calculated by using the load capacity of each beach proposed in the Spatial Planning for Coastal Zones (POOC 1998, 2003), which corresponds to the number of users admitted simultaneously on the beach according

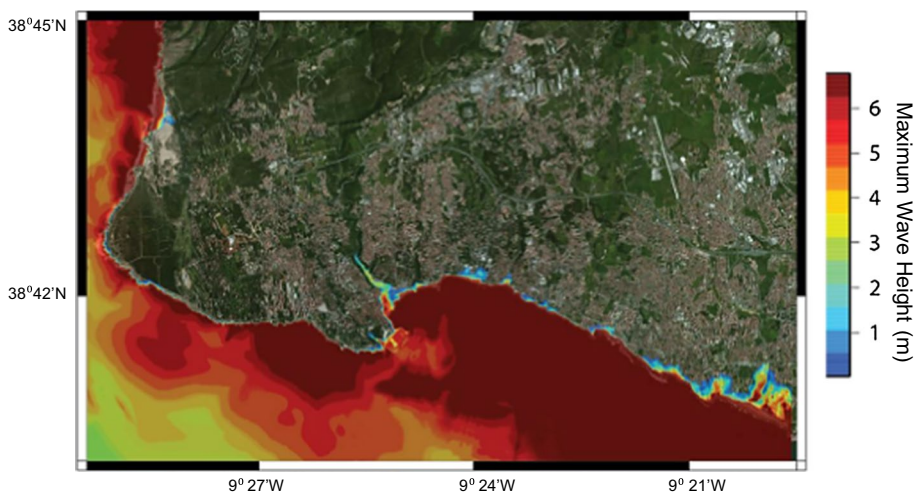


Fig. 4 Tsunami inundation in Cascais generated in MPF-HSF by a magnitude 8.8 earthquake, considering high tide conditions. From Baptista and Omira (2014)

to the sand area and the beach type. Table 1 presents the formulae used to compute the exposed population to tsunami inundation for each scenario as well as the results for the two study area sectors.

3.4 Evacuation routes start and end points

The network data set representing routes was generated using ArcGIS 10.2 (ESRI 2013) based on the linear data of pathways and road network contained in the Numerical Topographical Model (MNTC) of 1: 2000 scale, provided by Cascais Municipal Council (CMC), and complemented, by minor updates, with recent vector data from the OpenStreetMap database. The cartographic reference system of the data set is the “Datum 73 Hayford Gauss IPCC”, GCS-D73, and the vertical reference system is MSL (Mean Sea Level) in Cascais. Both buildings and beaches polygons were extracted from the MNTC and converted to points (e.g. their centroids) containing as attributes the population values, calculated for each scenario. These points were then considered as the origin points of the routes in our methodology (Fig. 5).

Taking into account the criteria to determine the safe areas (cf. *item 2.1.2*), 5 sites in Cascais and 4 in Carcavelos were chosen as candidates for meeting points. All these sites present altitudes above mean sea level greater than 20 m, and they are located in schoolyards, public gardens, parking lots and vacant lots (or open fields). This identification task was carried out through visual analysis and field survey. To conclude the road network construction, the start and end points of the routes to be defined (buildings/beaches polygon centroid points and meeting points) were snapped to the nearest road edge or segment thus integrating the network.

3.5 Evacuation time

Evacuation routes created after running the simulation are lines connecting each evacuated point to a designated meeting point. Their attributes are the total travel time, the number of evacuees and the identification of the origin and the destination points (ID codes). Knowing the travel time of each route, we can classify it according to the required evacuation time (T_e) which is the time available between the tsunami warning and the arrival of the first wave. The evacuation time (T_e) is defined considering these three components: the response time (T_{response})—time between the official event detection and the transmission of the alert; the time of reaction or preparation of the population (T_{reaction})—time elapsed between the notification of warning and the beginning of the evacuation; and the tsunami travel time (TTT)—time between the tsunami generation and the arrival of the first wave.

Table 1 Exposed population (P_e) for each demographic scenario (P_p , present population; P_r , resident population; P_{t1} , tourist population spread over all the exposed statistical subsections; P_{t2} , tourist population distributed by statistical subsections with hotel units; P_{pb} present population on the beaches—load capacity)

Scenario	Computing formulae	SECTOR I	SECTOR II
DHS	$P_e = P_p + P_{t1} + P_{pb}$	4521	5664
DOS	$P_e = P_p$	3323	714
NHS	$P_e = P_r + P_{t2}$	1632	480
NOS	$P_e = P_r$	1555	446



Fig. 5 Evacuation starting points, buildings and beaches within the tsunami inundation zone

The response time considered was 13 min according to Omira et al. (2012) for the analysed worst-case tsunami scenario. The reaction time varies from person to person and depends on several factors such as age, health condition, the knowledge of tsunami warning signs and the behaviour to adopt in case of tsunami evacuation (Yun and Hamada 2014). The reaction time may be estimated by analysing the surveyed data after a tsunami occurrence (Mas et al. 2012; Post et al. 2009) or by numerical simulation (Fraser et al. 2014). Some approaches define a static time value after the warning to the evacuation onset as 10 min (Dewi 2012; Park et al. 2012); others consider that the population does not initiate evacuation simultaneously, establishing time intervals that vary from 5 to 45 min (Charnkol and Tanaboriboon 2006), 5 to 15 min (González-Riancho et al. 2013) and 7 to 38 min (Mas et al. 2012). In this work, it was assumed a reaction time of 15 min for the whole population. The evacuation time was calculated by subtracting the sum of these two components (T_{response} and T_{reaction}) to TTT (Eq. 2), for each study area sector (Table 2):

$$T_e = \text{TTT} - (T_{\text{response}} + T_{\text{reaction}}) \tag{2}$$

where $T_{\text{response}} = 13 \text{ min}$; $T_{\text{reaction}} = 15 \text{ min}$.

Table 2 Evacuation time (T_e in minutes) for each sector

Sector	Evacuation time (T_e) (min)
I Cascais	14
II Carcavelos	20

4 Results and discussion

4.1 Evacuation routes simulation and flock maps

The evacuation routes when “solved” generate as many polylines as the number of evacuees start locations. Maps displayed in Fig. 6 show routes for sector I for the four exposed population scenarios. For instance, the NOS scenario (night off season Fig. 6d) has fewer evacuees starting points due to the unoccupied buildings and no people on beaches. Each output route polyline has the following attributes: EvcCost (total traversal time on the route considering the congestions); OrgCost (traversal time without congestion considerations); EvacCount (number of evacuees routed); EvcName (evacuee origin point ID); and ToPos (meeting point ID). The routes were classified by comparing the EvcCost to the evacuation time (T_e) and if EvcCost is larger than T_e than that route is classified infeasible.

The maximum EvcCost for the worst simulated scenario ranged from 28 min in Cascais and 30 min in Carcavelos. Taking into consideration all the simulated routes, it appears that almost 80% of the total population in the DHS scenario would evacuate within the T_e , in both studied sectors. However, our simulations show that a large number of evacuees cannot get to the closest meeting points before the first wave arrival. The flock simulation maps corroborate this statement (Fig. 7). These flock maps allow, through a more detailed analysis of evacuation routes, to identify hot spots where the evacuee’s flow suffer any sort of slowdown and, in some cases, even stagnate. A lower concentration of points means either more fluid movement as evacuee flocks with low population values, while clusters of points means speed reduction and more crowded locations. Examining the flock maps, it can be verified that along the beaches the first routes congestion occurs despite the departure delay. This can also be observed for origin points from buildings with higher exposed population. The concentration of points on these routes occurs again in route confluences even if in some situations can cause the diversion of evacuee sets leading them to alternative routes to avoid new congestion. This is particularly noticeable for sector I (Fig. 7a), where smaller sets of evacuees avoid congestion by opting for longer paths.

The identification of congestion areas, conditioning the evacuation in due time, shows the needs to look for alternatives like, for instance, vertical evacuation procedures (Scheer et al. 2011).

4.2 Evacuation plan map and vertical evacuation solution

The final goal of these studies is to draw up an evacuation plan maps for the target areas. Figure 8 presents a sketch of an evacuation plan for the central part of sector I. The represented evacuation routes are those that presented a better performance among the four modelled scenarios. Each section of these optimal routes was selected considering the

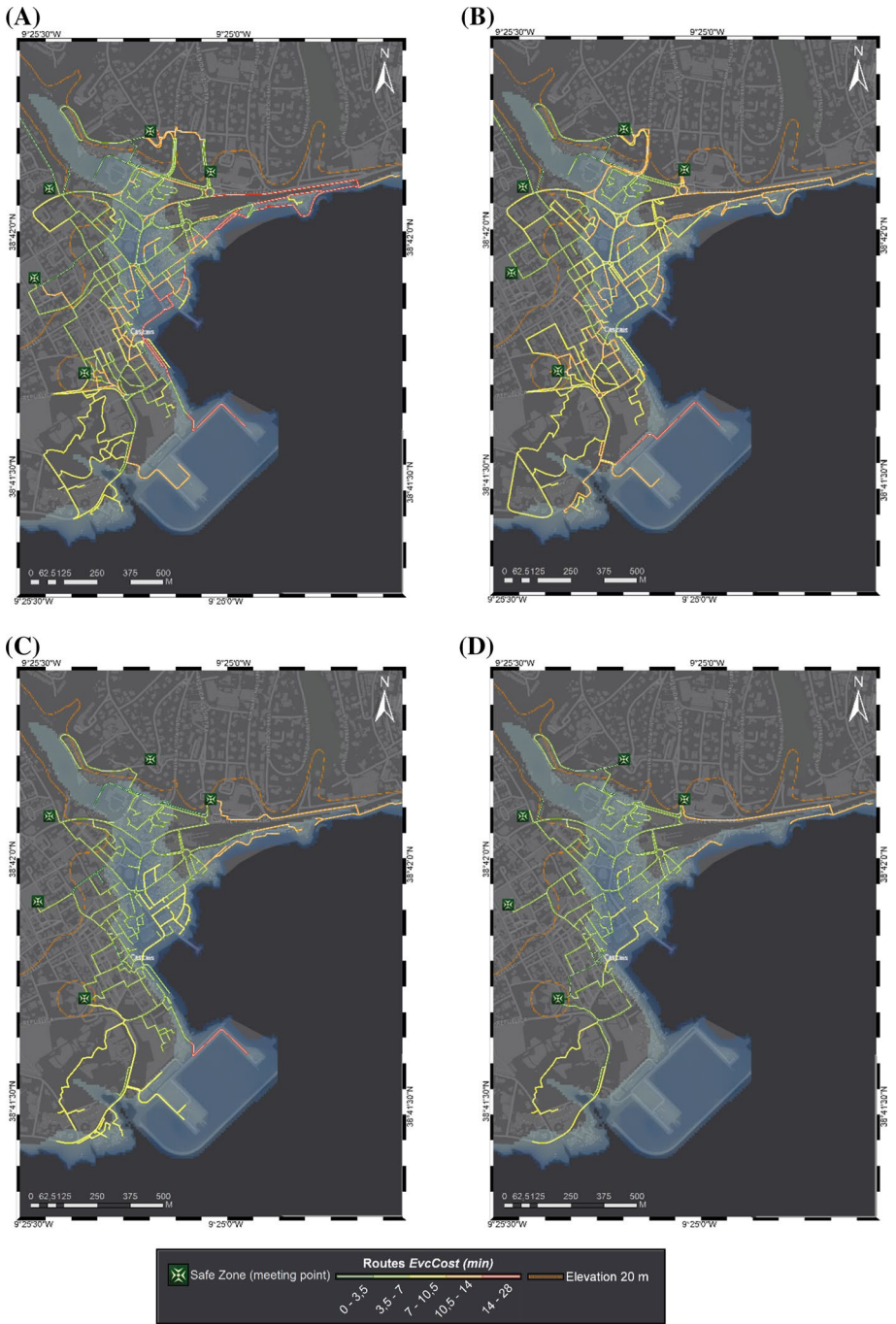


Fig. 6 Evacuation routes simulation for the sector I considering: **a** DHS scenario; **b** DOS scenario; **c** NHS scenario; **d** NOS scenario

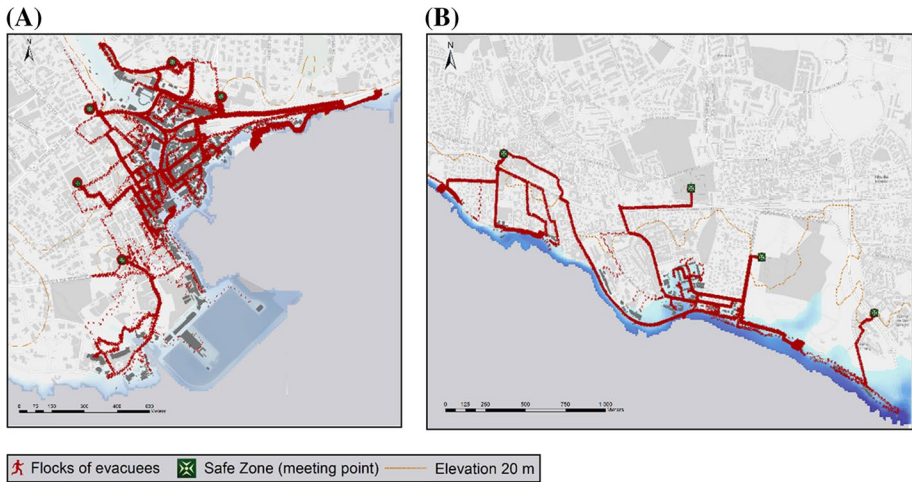


Fig. 7 Flock simulation maps for DHS scenario, **a** sector I, **b** sector II

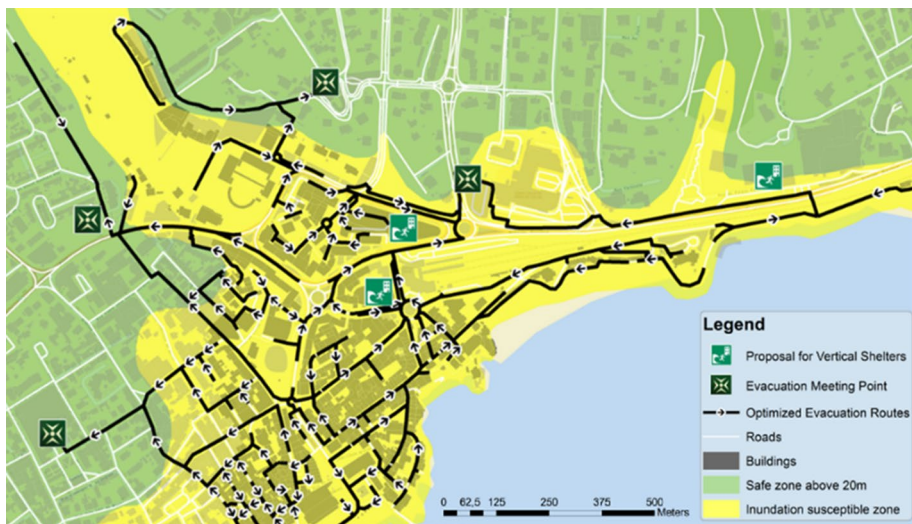


Fig. 8 Evacuation plan map proposal for Cascais sector I, including vertical shelter locations

shorter traversal time from each source point and was generated by joining segments that overlap prevailing the lowest cost segment.

One solution to overcome congestion in the evacuation routes and/or to decrease the evacuation time is to resort to vertical evacuation. Along the congestion areas on the infeasible routes of sector I, three buildings were identified as candidates to be used as vertical shelters. However, it is necessary to check if they meet all the requirements for this: non-residential concrete structures of collective use, with more than three floors, located along the simulated evacuation routes and having space to accommodate several additional

evacuees who cannot escape to the meeting points. It is also necessary to assure, by competent engineers, that the proposed buildings will be able to withstand the impacts caused by floating debris and large objects carried by the waves or brought back during the receding waters. These buildings should be well signposted and they may remain surrounded by water for some time, which is why they must also have access to livelihoods, like some food, drinking water, emergency kits and communications.

5 Conclusions

The methodology presented on this study proposes, beyond the hazard aspects and the identification of the potentially exposed areas, a simple process to determine pedestrian displacement on a road network, considering some constraints, in order to make more efficient simulations of evacuation routes. The method to estimate the exposed population, for four different times and periods of the day, and the method to calculate the evacuation time, do not absolve the model of a certain degree of uncertainty. Also, the basic travel speeds considered (1.4 and 0.7 m/s), which arises from a generalization of velocities for the entire population, do not consider different demographic groups (elderly, children or people with reduced mobility) neither, for example, account the fatigue. The evacuation speed then becomes controlled by the roads capacity influencing the simulated traversal time and congestions.

From the analysis of the simulations maps, it was concluded that the best solution to minimize traversal times, that exceed the T_c , should be the adoption of a vertical evacuation strategy, as suggested in the map of Fig. 8 where some buildings could play the vertical shelters role. However, the selection of these or other buildings as vertical shelters, as well as the construction of specific vertical shelters, is an issue that must be discussed by local decision-makers.

Other solutions that can address this issue in future work are related to the adoption of different departure times (e.g. some people may begin the evacuation soon after the natural signs) or consider whole refuge zones (i.e. the intersection between the 20-m contour line and the road network). Some improvements to the evacuation modelling, that were not considered in this study but should be taken into account, are the specific effects that a triggering earthquake might cause, like the blocking of the roads by collapsed buildings, or the accessibility of potential vertical shelters.

Cascais has an effective management challenge on the tsunami risk mitigation, due to its exposure to tsunami hazard. By adopting the worst possible scenario, it is provided a clear indication on the limits and maximum length of a probable flood and the maximum wave heights, which consider the shortest evacuation time, safeguarding the risk situations caused by other less restrictive scenarios. This hazard is affected by the dynamics of many components that may influence its magnitude and impact on the territory.

The acceptance and selection of the feasible evacuation routes are a decision of the local authorities. They have also to decide on the selection or construction of vertical shelters, as well as the definition of the meeting points. Improving the accessibility of the evacuation starting points or the enlargement of some roads, to decrease the travel time, is also decision to be taken into account. Further actions consist of signalling the evacuation routes, the vertical shelters and the safe areas/meeting points, leading to local tsunami risk mitigation.

Acknowledgements This work was developed within the framework of INSPIRED and Baywatch projects, developed by the European Centre on Urban Risks (CERU) and financed by the European and Mediterranean Major Hazards Agreement (EUR-OPA) (Grant No. UID/GEO/50019/2013), Council of Europe.

References

- Baptista MA, Miranda JM (2009) Revision of the Portuguese catalog of tsunamis. *Nat Hazards Earth Syst Sci* 9:25–42
- Baptista MA, Omira R (2014) Tsunami risk assessment for Cascais County. Final report. Instituto Dom Luiz, Universidade de Lisboa (**in Portuguese**)
- Charnkol T, Tanaboriboon Y (2006) Evacuee behaviors and factors affecting the tsunami trip generation model: a case study in Phang-nga, Thailand. *J Adv Transp* 40(3):313–330
- Cova TJ (1999) GIS in emergency management. In: Longley PA, Goodchild MF, Maguire DJ, Rhind DW (eds) *Geographical information systems: principles, techniques, applications, and management*. Wiley, New York, pp 845–858
- Dewi RS (2012) A GIS-based approach to the selection of evacuation shelter building and routes for tsunami risk reduction, a case study of Cilacap coastal area Indonesia. Double degree international programme of geo-information for spatial planning and risk management, University of Twente (Netherlands) and Gadjah Mada University (Indonesia)
- Dijkstra EW (1959) A note on two problems in connexion with graphs. *Numer Math* 1(1):269–271
- Fraser S, Wood N, Johnston D, Leonard G, Greening T (2014) Variable population exposure and distributed travel speeds in least-cost tsunami evacuation modelling. *Nat Hazards and Earth Syst Sci* 14:2975–2991
- Freire S, Aubrech C, Wegscheider S (2013) Advancing tsunami risk assessment by improving spatio-temporal population exposure and evacuation modeling. *Nat Hazards Earth Syst Sci* 68:1311–1324
- González-Riancho P, Aguirre-Ayerbe I, Aniel-Quiroga I, Abad M, González S, Larreynaga J, Gavidia F, Gutiérrez OQ, Alvarez-Gómez JA, Medina R (2013) Tsunami evacuation modelling as a tool for risk management: application to the coastal area of El Salvador. *Nat Hazards Earth Syst Sci Discuss* 1:2163–2205
- Graehl NA (2011) Pedestrian evacuation time analysis for Crescent City, CA. Crescent City, Del Norte Local Transportation Commission
- Hart PE, Nilsson JN, Bertram R (1972) Correction to a formal basis for the heuristic determination of minimum cost paths. *ACM SIGART Bull* 37:28–29
- INE (2011) Censos 2011, Instituto Nacional de Estatística (**in Portuguese**) http://censos.ine.pt/xportal/xmain?xpid=CENSOS&xpgid=censos2011_apresentacao. Accessed 15 Jan 2016
- Kobayashi T, Medina RM, Cova TJ (2011) Visualizing diurnal population change in urban areas for emergency management. *Prof Geogr* 66(1):113–130
- Lwin K, Murayama Y (2009) A GIS approach to estimation of building population for micro-spatial analysis. *Trans GIS* 13(4):401–414
- Mas E, Suppasri A, Imamura F, Koshimura S (2012) Agent-based simulation of the 2011 great east Japan earthquake/tsunami evacuation: an integrated model of tsunami inundation and evacuation. *J Nat Disaster Sci* 34:41–57
- Mück M (2008) Tsunami evacuation modelling. development and application of a spatial information system supporting tsunami evacuation planning in South-West Bali. Dissertation, German Remote Sensing Data Center (DFD), Oberpfaffenhofen, p 131
- Omira R, Baptista MA, Mellas S, Leone F, Richemond NM, Zourarah B, Cheral JP (2012) The November, 1st, 1755 Tsunami in Morocco: Can Numerical Modeling Clarify the Uncertainties of Historical Reports? In: *Tsunami - Analysis of a Hazard - From Physical Interpretation to Human Impact*. <https://doi.org/10.5772/51864>
- Omira R, Matias L, Baptista MA (2016) Developing an event-tree probabilistic tsunami inundation model for NE Atlantic Coasts: application to a case study. *Pure appl Geophys* 173:3775–3794
- Park S, van de Lindt JW, Gupta R, Cox DT (2012) Method to determine the locations of tsunami vertical evacuation shelters. *Nat Hazards* 63:891–908
- Péroche M, Leone F, Gutton R (2014) An accessibility graph-based model to optimize tsunami evacuation sites and routes in Martinique, France. *Adv Geosci* 38:1–8
- POOC (1998) Resolução do Conselho de Ministros no 123/98: Plano de Ordenamento da Orla Costeira (POOC) Cidadela - S. Julião da Barra, Diário da República no 241 (**in Portuguese**)
- POOC (2003) Resolução do Conselho de Ministros no 86/2003: Plano de Ordenamento da Orla Costeira (POOC) Sintra – Sado, Diário da República no 144 (**in Portuguese**)

- Post J, Wegscheider S, Mück M, Zosseder K, Kiefl R, Steinmetz T, Strunz G (2009) Assessment of human immediate response capability related to tsunami threats in Indonesia at a sub-national scale. *Nat Hazards Earth Syst Sci* 9:1075–1086
- Qiu F, Sridharan H, Chun Y (2010) Spatial autoregressive model for population estimation at the census block level using LIDAR-derived building volume information. *Cartogr Geogr Inf Sci* 37(3):239–257
- Reynolds CW (1987) Flocks, herds and schools: a distributed behavioral model. *ACM SIGGRAPH Comput Graph*. 21(4):25–34
- Ribeiro A, Mendes-Victor L, Cabral J, Matias L, Terrinha P (2006) The 1755 Lisbon earthquake and the beginning of closure of the Atlantic. *Eur Rev* 14(2):193–205
- Scheer S, Gardi A, Guillaude R, Eftichidis G, Varela V, Vanssay B, Colbeau-Justin L (2011) Handbook of tsunami evacuation planning. EUR 24691 EN—2011 Luxembourg: Publications Office of the European Union 54
- Schuster M, Gomez C (2013) Evacuation routing out of tsunami hazard zones. In *GI Forum 2013: creating the GISociety*, Berlin, pp 206–215
- Shahabi K (2015) Scalable evacuation routing in dynamic environments. Dissertation, University of Southern California
- Shahabi K, Wilson JP (2014) CASPER: intelligent capacity-aware evacuation routing. *Comput Environ Urban Syst* 46:12–24
- Wood NJ, Schmidtlein M (2011) Anisotropic path modeling to assess pedestrian-evacuation potential from Cascadia-related tsunamis in the US Pacific Northwest. *Nat Hazards* 62:275–300
- Wood N, Schmidtlein M (2013) Community variations in population exposure to near-field tsunami hazards as a function of pedestrian travel time to safety. *Nat Hazards* 65(3):1603–1628
- Wood N, Jones J, Schmidtlein M, Schelling J, Fraizer T (2016) Pedestrian flow-path modeling to support tsunami evacuation and disaster relief planning in the U.S. Pacific Northwest. *Int J Dis Risk Reduct* 18:41–55
- Wronna M, Omira R, Baptista MA (2015) Deterministic approach for multiple-source tsunami hazard assessment for Sines, Portugal. *Nat Hazards Earth Syst Sci* 15:557–2568
- Yagi S, Hasemi Y (2010) Requirements and verification methodology for the design performance of tsunami-hinan buildings (temporary tsunami refuge building). *J Disaster Res* 5:591–600
- Yun NY, Hamada M (2015) Evacuation behavior and fatality rate during the 2011 Tohoku-oki earthquake and tsunami. *Earthq Spectra* 31(3):1237–1265