When the Tsunami Comes to Town – Improving Evacuation Modeling by Integrating High-resolution Population Exposure

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ABSTRACT

Tsunamis are a major risk for Lisbon (Portugal) coastal areas whose impacts can be extremely high, as confirmed by the past occurrence of major events. For correct risk assessment and awareness and for implementing mitigation measures, detailed simulation of exposure and evacuation is essential. This work uses a spatial modeling approach for estimating residential population distribution and exposure to tsunami flooding by individual building, and for simulating their evacuation travel time considering horizontal and vertical displacement. Results include finer evaluation of exposure to, and evacuation from, a potential tsunami, considering the specific inundation depth and building's height. This more detailed and accurate modeling of exposure to and evacuation from a potential tsunami can benefit risk assessment and contribute to more efficient Crisis Response and Management.

Keywords

Tsunami, evacuation modeling, population exposure, 3D analysis, Lisbon.

INTRODUCTION

Exposure mapping as part of risk assessment basically affects all stages of the disaster management cycle. Proper modeling and simulation of evacuation considering high resolution exposure and infrastructure patterns is of utmost importance for mitigation of potential impacts. Tsunamis are a major risk for Lisbon (Portugal) coastal areas whose impacts can be extremely high, as confirmed by the occurrence of several events in the past (Baptista and Miranda, 2009). Tsunami hazard is usually represented by inundation maps that identify areas and depths of tsunami flooding or run-up. The recent Regional Plan for Territorial Management for the Lisbon Metropolitan Area (PROT) includes a tsunami hazard map, showing that significant urbanized areas may be at risk of inundation. However, no estimation of exposure or evacuation planning is conducted, despite quantitative assessment of tsunami risk being necessary to support spatial planning and for local authorities to provide population protection. Since all human beings are equally vulnerable in case of tsunami (Villagrán de León, 2008), first stage of tsunami preparedness includes assessing and mapping concentrations of population present (IOC, 2008). This is especially required at local scale where data is most needed for Emergency Management (Freire, 2010). A previous study (Freire, Aubrecht, and Wegscheider, 2011) has shown that full horizontal evacuation can be problematic in the city of Lisbon, even if initiated immediately after a tsunami-triggering earthquake. This suggests that vertical evacuation into the upper levels of existing built-up structures be considered as a potential solution (FEMA, 2008), especially in areas where exposed people need to traverse significant distances in short time periods (Wood and Schmidtlein, 2011). So far there is an absence of studies modeling detailed population exposure and pedestrian evacuation from tsunami in 3D considering tsunami flood depth, building size and function, and other characteristics of urban terrain.

The present work aims at improving the assessment of tsunami risk and contributing to more efficient and effective Emergency Management (EM) by modeling and quantifying residential population exposure at the building scale, and simulating and analyzing the duration of horizontal and vertical pedestrian evacuation.

STUDY AREA AND DATA

The study area for estimating population distribution and exposure corresponds to the Tsunami Inundation Susceptibility zone in three coastal *freguesias* (communes) of the municipality of Lisbon, Portugal, located on the western part of the city: Santa Maria de Belém, Ajuda, and Alcântara. This hazard zone reaches as far as 1770 m inland, occupies 275 ha (680 acres) and has close to 9,000 residents (INE, 2001), and is characterized by a mixed use of residential areas, public and private facilities, leisure and industrial areas. For simulating and analyzing evacuation time it was necessary to subset this study area in order to eliminate edge effects caused by imposing artificial limits on data sets and analysis (Figure 1).

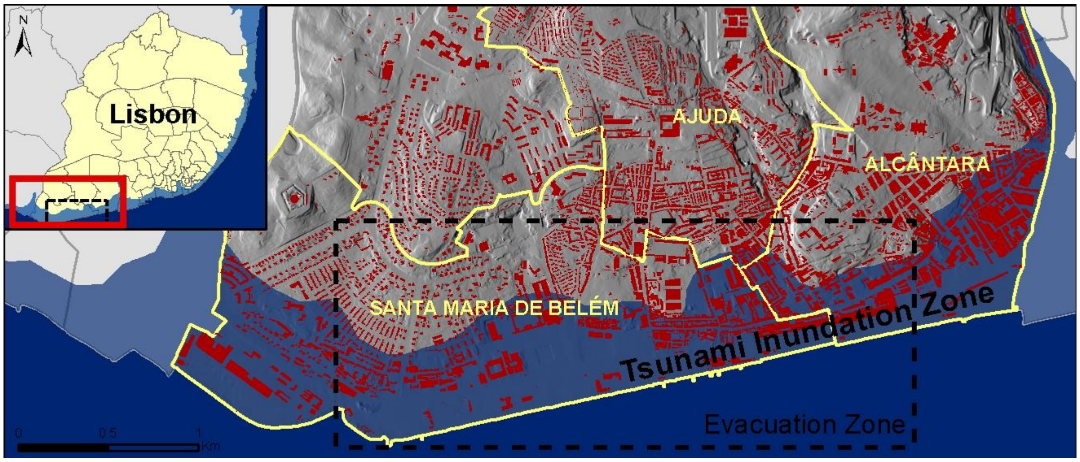

Figure 1. Study area and tsunami evacuation zone with building structures overlaid on DTM

For the study area, the most detailed digital spatial data sets available were combined in order to estimate population distribution and modeling evacuation at the highest resolution possible. These data were obtained from various sources and in different formats, and are listed in Table 1.

Data set	Date	Data type	Resolution (m / Scale)
Tsunami Inundation map	2010	Vector	--
DTM	1998	Raster	1
LiDAR (nDSM)	2006	Raster	1
Land Use/Land Cover map	2007	Vector	1:25,000
Census resident population (block)	2001	Vector	--
Buildings map	1998	Vector	1:1000
Street centerlines	2004	Vector	--

Table 1. Input data sets used

As a pre-modeling step, all spatial data sets were projected to the same national projected coordinate system (ETRS89-PT-TM06). The map depicting the Tsunami Inundation Susceptibility zones was produced for the PROTAML report (CCDR-LVT, 2010) and was obtained in digital vector format. This map shows areas susceptible to flooding by tsunami using two classes or levels, *High* and *Moderate*, without indication of water depth.

MODELING AND ANALYSIS

The methodology was implemented in a Geographic Information System (GIS) and includes two main stages: a) estimating residential population distribution and exposure to tsunami flooding by building, and b) modeling pedestrian evacuation considering horizontal and vertical displacement.

Estimating Population Distribution and Exposure to Tsunami Flooding

The modeling of population distribution and potential exposure to tsunami flood waters is based on re-allocating census 2001 population counts from enumeration block zones to suitable individual buildings considering their volume and function, using areal interpolation, and combining this information with flood depth.

Since the official map of buildings from the municipality stores the footprints of all the built-up structures without any attributes, it was necessary to identify suitable residential buildings. 2D geometric attributes were computed for all the building structures (4,464) within census blocks affected by the tsunami hazard zone within the study area, and their mean height above ground was calculated using the normalized Digital Surface Model (nDSM). Only those buildings with at least a footprint area of 25 m^2, 4-m width, and one floor (2.9 m) above ground were considered suitable for residence and regular human activities. This allowed to discard structures such as garages, shacks, and annexes. The resulting selection (3,122) was further combined with a detailed national Land Use/Land Cover map to derive main building function and to identify residential units (2,191). Total resident population in each census block zone is then interpolated to respective residential buildings according to their volume, following the approach presented in Freire, Santos, and Tenedório (2011). This modeled population distribution represents maximum expected residential densities on a typical night, assuming that everyone is in their home.

The result from this stage is a simple 3D model of buildings (LOD 1) having: (i) functional information, (ii) an estimation of number of floors and (iii) resident population by floor for 2001, within the tsunami hazard zone. Based on this information, 1,662 residential buildings with 8,727 residents are estimated to be in the hazard zone.

For assessing the population exposure to tsunami flood waters, it was necessary to estimate the inundation depth for each building. Given that the Tsunami Inundation map only shows areas susceptible to flooding by tsunami without indication of water depth, it was necessary to estimate the actual flood depth throughout the study area. This was accomplished by first deriving the mean elevation above mean sea level (run-up height) from the Digital Terrain Model (DTM) along the farthest reach of the tsunami inundation zone inland. The obtained elevation of 14 m was subtracted from the DTM to create a 1-m grid of water depth for the tsunami inundation zone. By combining this surface of flood depth with the previous 3D buildings model it was possible to quantify, for each building, the number of floors and resident population above and below maximum tsunami flood level. Due to the apparent higher resolution of the DTM used for estimating flood depth compared to the one used for producing the Tsunami Inundation map, some small areas within the hazard zone are above the estimated flood level. These results are summarized in Table 2.

		Bldgs. below water			***Bldgs. above water***			
		Completely below water	Partially below water	***Subtotal***	Partially above water	Completely above water	***Subtotal***	***TOTAL***
Bldgs.	No.	853	*744*	1,597	*744*	65	65	1,662
	%	51.3	*44.8*	96.1	*44.8*	3.9	3.9	100
Residents	No.	2,349	3,167	5,516	3,009	202	3,211	8,727
	%	26.9	36.3	63.2	34.5	2.3	36.8	100

Table 2. Summary of results of exposure analysis

Table 2 shows that 65 residential buildings having 202 residents are completely above water, while 1,597 residential buildings having 8,525 residents are affected by flood waters; of these, 853 buildings having 2,349 residents are completely below water. In the 774 buildings that are partially flooded, 3,167 residents are in floors below flood level, while 3,009 occupy floors above this level. Overall, it is estimated that 5,516 residents are below flood level in the study area.

Modeling Horizontal and Vertical Evacuation

The evacuation analysis assesses the time needed, after an evacuation is initiated, for the population to reach safe areas, assuming they are travelling on foot. First it was necessary to quantify and locate the population needing evacuation (i.e., living below flood level), and identify safe locations, either to outside the flooded area (horizontal exits) or within the hazard zone (vertical shelters). All the buildings within the hazard zone were analyzed for shelter potential, regardless of their function. To be deemed shelters, buildings need to have at least one 'safe floor' more than two floors above flood level, to provide a safety margin. For calculating each shelter's capacity (number of people fitting into safe floors) it was assumed that 50% of floor area was available for 1 person/m^2.

The evacuation modeling is based on a least-cost distance (LCD) approach, where the best (i.e. the fastest) evacuation route from any given source to a safe location is computed, and the time needed to reach it is calculated. This allows the definition of a 'catchment' area for each safe location, in which all contained buildings are closer to that shelter. The basic approach for horizontal evacuation was developed in the framework of the German-Indonesian Tsunami Early Warning System (GITEWS) project (Post et al., 2009; Strunz et al., 2011; Wegscheider et al., 2011) and was adapted and expanded in this work to include vertical evacuation. The output of the model, the time needed for evacuation towards a safe area, is based on several parameters: (i) extent of the hazard impact area (i.e. potential inundation area), (ii) characteristics of the outdoor evacuation paths (slope, land cover, street network.), and (iii) population density. For this simulation it was additionally assumed that it would take 1 minute to climb or descend each floor. The derived evacuation time surfaces are used in combination with the detailed population distributions and safe locations to calculate the number of successful evacuees after certain time intervals. Results from the modeling are illustrated in Figure 2.

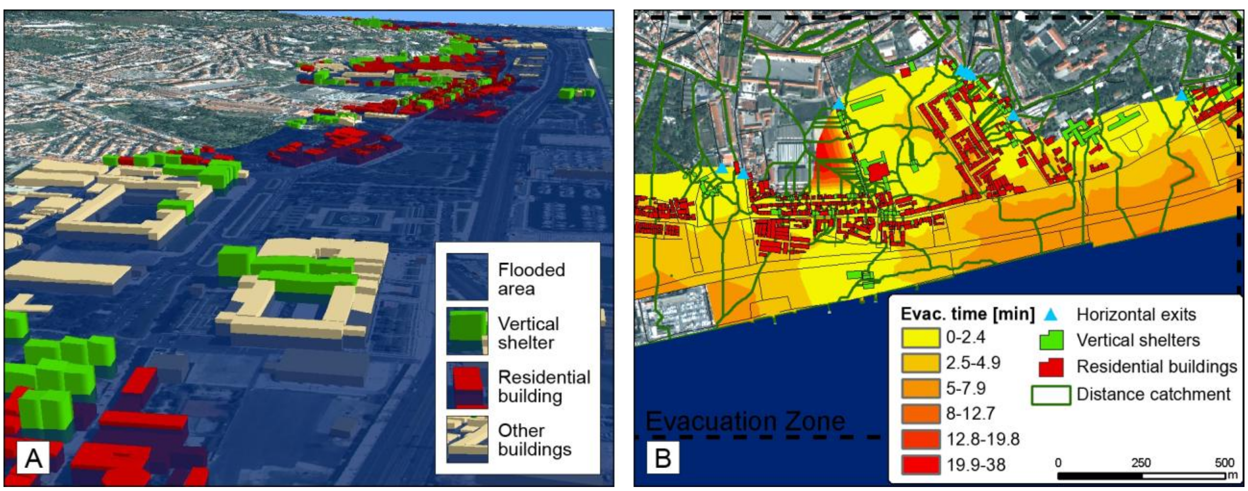

Figure 2. 3D building exposure to tsunami flood waters (A) and evacuation modeling (B)

Within the smaller evacuation analysis area, 165 of the total 1,541 buildings were identified as potential shelters for vertical evacuation; 134 of these are residential, out of 1,134 with the same function. The 4,755 residents served by all the safe locations (horizontal exits and vertical shelters) are able to evacuate to safety after 10 minutes, with 4,570 being able to evacuate in 5 minutes.

CONCLUSIONS AND OUTLOOK

This work is an effort towards improving evacuation modeling in an urban setting by integrating high-resolution population exposure to tsunami. A spatial modeling approach based on 3D analysis was presented for estimating residential population distribution and exposure to tsunami flooding by individual building, and for simulating their evacuation travel time considering horizontal and vertical displacement. Results include finer evaluation of exposure to, and evacuation from, a potential tsunami, considering the specific flood depth and building's height.

This more detailed and accurate modeling of population exposure to and evacuation from a potential tsunami can benefit risk assessment and contribute to more efficient Crisis Response and Management. The analysis would profit from having actual data on specific building use and by considering the building's structural stability and suitability for evacuation. Planned future developments include modeling population exposure in daytime period and using a refined Tsunami inundation map (when it becomes available), as well as updating the building's map for using with census 2011 data.

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