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IMPACT OF EARTHQUAKE MAGNITUDE ON THE ESTIMATION OF TSUNAMI EVACUATION CASUALTIES

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ABSTRACT

The importance of evacuation plans has been widely proven in recent tsunami events. Several evacuation models have been proposed to develop these plans and estimate city evacuation times. Typically, single extreme earthquake scenarios are used in these estimations; however, the impact of earthquake damage on the evacuation routes is usually neglected in these models. This article deals with the evaluation of the effect of three different earthquake magnitudes and the following tsunamis. Several spectral accelerations were sampled for each magnitude to estimate city damage, and from there the reduced capacity of evacuation routes due to earthquake debris. An agent-based evacuation model was used to assess the evacuation times for the city of Iquique, located in north Chile. Results show significant variability for different magnitude scenarios, thus leading to an observed increment on evacuation times up to 40% and an increase in the number of casualties due to the evacuation delay caused by earthquake debris spread on the evacuation routes.

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Impact of earthquake magnitude on the estimation of tsunami evacuation casualties

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ABSTRACT

The importance of evacuation plans has been widely proven in recent tsunami events. Several evacuation models have been proposed to develop these plans and estimate city evacuation times. Typically, single extreme earthquake scenarios are used in these estimations; however, the impact of earthquake damage on the evacuation routes is usually neglected in these models. This article deals with the evaluation of the effect of three different earthquake magnitudes and the following tsunamis. Several spectral accelerations were sampled for each magnitude to estimate city damage, and from there the reduced capacity of evacuation routes due to earthquake debris. An agent-based evacuation model was used to assess the evacuation times for the city of Iquique, located in north Chile. Results show significant variability for different magnitude scenarios, thus leading to an observed increment on evacuation times up to 40% and an increase in the number of casualties due to the evacuation delay caused by earthquake debris spread on the evacuation routes.

Introduction

In recent years several tsunamis have struck densely populated areas around the world [1]. Hence, fast evacuation of the population from the inundation zones is crucial to minimize casualties. Different cities have tried to achieve this by developing emergency evacuation plans in order to reduce possible congestions of pedestrians and vehicles. Several approaches and varied methodologies and assumptions have been used to develop these plans, such as the least-cost-distance (LCD) models, network models, and agent-based models (ABM). Even though their effectiveness over city evacuation plans will depend on the objective selected to optimize [2], evacuation modeling has shown to be an important tool to compare different scenarios and manage the response of people.

Previous literature on simulated city evacuations due to an incoming tsunami is available elsewhere [3,4,5,6]. Evacuation modeling can be categorized according to scale, i.e. macroscopic or microscopic. One example of a macroscopic approach is the LCD models, which use speed reduction factors in a grid depending on the material characteristics of the ground (e.g., grass,

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asphalt, gravel). Other models consider the movement of the pedestrians and vehicles as a flow, using ideas from fluid dynamics. However, these models neglect important characteristics of the evacuation processes, such as congestion and the problem of where and when people evacuate.

In microscopic models, the behavior of each individual is modeled mathematically, and considers a heterogeneous distribution of properties. One of the most used methodologies in this family is Agent Based Modeling (ABM), in which each person is simulated as an entity with its own rules, allowing for the emergence of a global phenomenon from the combination of several individual agents following a set of decision rules.

However, most of the time, the effect that induced earthquake damage has on the evacuation process has been neglected. For building evacuations, the effect of falling contents has been studied previously [7,8,9,10]. In the case of city-scale evacuations, the damage caused by fires following earthquakes [11,12], and more recently, debris caused by earthquakes [13] are some exceptions of the usual lack of building damage in evacuation models. Moreover, the evacuation models are normally tested for specific tsunami scenarios. Although these results are valuable, the lack of variability in the hazard description impedes for a more robust evaluation of evacuation plans.

In this article, an ABM is used to represent the evacuation process of a city due to an incoming tsunami generated after an earthquake strikes the city. In order to consider the variability of the hazard, three values of earthquake magnitude were used to evaluate the possible tsunamis that could reach the coast of the city for a given epicenter. Additionally, for each magnitude, one hundred simulations for peak ground acceleration were run to estimate the damage underwent by the city, thus reducing the street cross-section space for people to evacuate. The model uses a collision avoidance algorithm [14] to represent the interaction between pedestrians, vehicles and debris generated by the damage induced by the earthquake. Potential casualties for the geographical setting of the city of Iquique in north Chile are presented herein.

Methodology

Let us define first an earthquake magnitude and epicenter. Both parameters are used to estimate damage in the city define characteristics of the tsunami that will affect the geographical area of study. Damage evaluation is obtained using the platform Hazus [15], which also requires spectral accelerations at the building locations. Since a given earthquake magnitude can generate infinite plausible earthquake scenarios, several spectral accelerations are sampled using a ground motion prediction equation (e.g., [16]), thus leading to the damage distribution in the city. Furthermore, a single tsunami inundation scenario is used for each earthquake magnitude. Although this methodology neglects the tsunami variability, it serves as a first attempt to solve the problem.

Evacuation simulation starts once the damaged and debris configuration of the city have been defined. The evacuation and tsunami simulations are run simultaneously, and start when the ground motion finishes. The evacuation simulation finishes when all pedestrians reach to the different safety zones.

Damage evaluation

The Hazus model used to estimate the damage of the buildings is based on an empirical approach that uses the spectral accelerations at 0, 0.3 and 1 s, as well as the magnitude of the event. Each spectral acceleration is obtained using a ground motion prediction equation (GMPE), where the intra and inter residuals are sampled using a normal distribution. Hazus calculates the expected value of debris in each building of the city in tons, which are then transformed to volume using the conversion factor proposed by the U.S. Army Corps of Engineers (USACE), i.e. 1 ton of debris = 2 cubic yards (0.76 m^3) [17].

The debris is considered to block partially the evacuation routes of the city, thus increasing the probability of congestion and evacuation times. The blockage is modeled using the methodology proposed in [18], where the length of debris in a section of a building can be estimated as a normal random variable. The mean and standard deviation are determined by the geometry of the building (width and height) and by the characteristics of the collapse.

Tsunami inundation

The assessment of the number of potential evacuees being drowned by the tsunami requires high resolution tsunami simulations to provide adequate spatio-temporal details on the tsunami inundation phase. Initial conditions for tsunami simulations are set from the seismic scenarios assuming a uniform slip model. The tsunami is then propagated on the bathymetry of the Pacific Ocean, and the grid resolution increases as the water depth is shallower to capture essential wave processes such as refraction, reflection, shoaling, breaking, and runup.

The Okada [19] model is used to obtain the vertical displacement at the seafloor from the rupture models. This deformation is transferred instantly to the free surface, obtaining the initial condition for the tsunami propagation. The propagation and inundation of the tsunami is modeled with the open source software GeoClaw developed by Berger et al. [20] and LeVeque et al. [21], which solves the nonlinear shallow water equations using shock capturing finite volume methods.

Evacuation model

The evacuation process is simulated using an ABM considering a collision avoidance algorithm to capture the congestion problem. The model was first presented in [22] for building evacuations, and then expanded for pedestrians interacting with vehicles on a city scale [13]. Each agent of the model has the objective of reaching a safety zone, and follows the shortest path to this objective. The movement of the agents is simulated using the Optimal Reciprocal Collision Avoidance (ORCA) algorithm [14]. For each time step, agents compute their movement independently and simultaneously considering the velocities of the other agents and the obstacles present in their evacuation route. When the agent density is high, agents will tend to reduce their speed since they cannot use the same physical space, which results in the natural emergence of congestion in the simulation.

The ORCA algorithm assumes that agents have a circular geometry. Even though the algorithm allows for agents to have different sizes, herein agents are divided in two size categories: pedestrians and cars, with radii of 0.225 m and 1.015 m, respectively. Additionally, each agent has a maximum speed of movement, which is sampled using a Weibull distribution [22]. The shape and scale parameters of the distribution for pedestrian speed are $k = 10.14$ and $\lambda = 1.41$ m/s, respectively, and $k = 40$ and $\lambda = 15.5$ m/s in the case of vehicles. With these parameters, the mean values of maximum speed are 1.34 m/s and 55 km/h for pedestrians and cars respectively. Moreover, slopes in the city reduce the maximum speed of agents, which is accounted by a reduction factor ϕ, estimated using the formula included in [23],

$$\phi = e^{-3.5(|\tan(\theta)+0.05|-0.05)} \tag{1}$$

where θ is the elevation angle of the street relative to the horizontal.

Together with the speed, the starting time of the evacuation is one of the most studied parameters in evacuation modeling. As an earthquake strikes a city, people do not start the evacuation immediately. Several studies have estimated the probability distributions for these pre-evacuation times, which have then been used in several evacuation simulations of cities (e.g., [4]). However, before people can evacuate using the city streets, they must first evacuate the buildings where they are inside. Several investigations do not consider this time people spent during the building evacuations, and place agents on streets at the start of simulations. To obtain a more realistic response of the evacuation, herein the evacuation curves proposed in [13] are used. Initial and ending building evacuation times are sampled depending on the number of building floors, based on several model evacuation runs using typical Chilean buildings layouts. The evacuation curve between the starting and ending times is assumed to have the shape of a beta cumulative distribution function (CDF). Fig. 1 shows evacuation curves generated using the mean values of the initial and ending time distributions for different number of floors. Each curve is then scaled to the number of people inside the buildings.

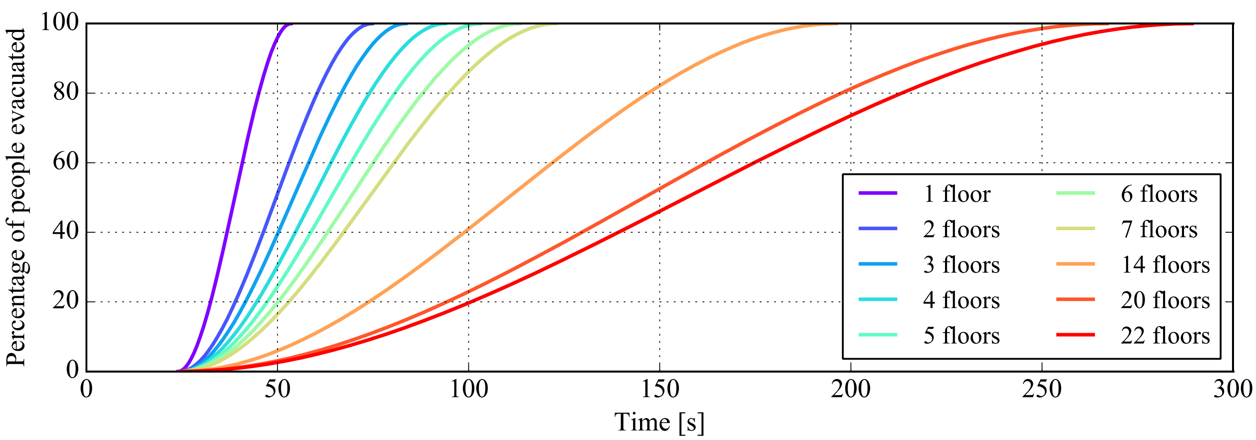

Figure 1. Evacuation curves for typical Chilean buildings using the mean values of initial and ending time distributions presented in [12].

Case study

The methodology presented herein is applied to the coastal city of Iquique in the north of Chile (20º13’S, 70º09’W). Iquique has a population of about 180,000 people and has suffered several tsunamis along its history. The most recent event the M_W 8.2 earthquake in 2014, which produced a tsunami that reached the coastline 19 minutes after the ground motion ended [24].

The National Office of Emergency of the Ministry of Interior and Security (ONEMI) has established that in case of a tsunami emergency, people have to evacuate to areas with an elevation of 30 m.a.s.l. [25]. The evacuation zone defined for the city of Iquique is shown in Fig. 2 and has a mean length of about 2 km from the shoreline to the 30 m contour line. Instead of studying the entire city, this research is restricted to the downtown and historic zone of the city. This is because our main objective is to evaluate the general response of the city considering the variability of the scenarios and the damage caused, instead of reproducing a complete evacuation in the city. Moreover, the selected area concentrates an important fraction of the population of the city and is a good representation of the type of buildings of the entire city.

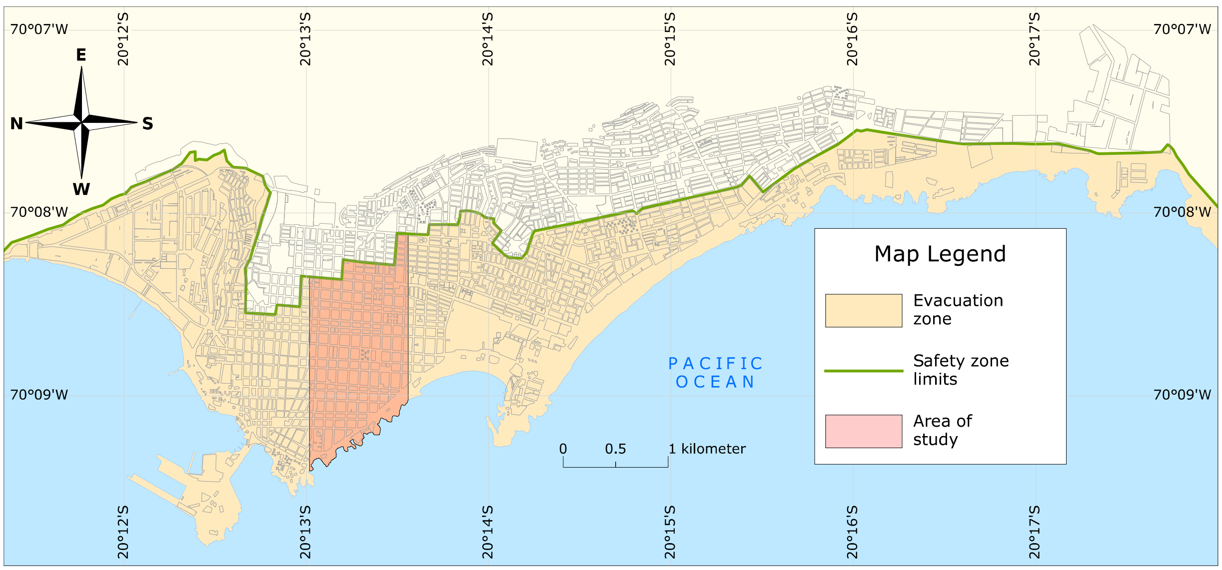

Figure 2. Map of Iquique showing the evacuation zone defined by authorities and the area of study.

The distribution of people in the city was estimated using the 2012 census data [26] together with an Origin-Destination survey [27]. The number of cars was determined using the motorization rate of the city [28]. For the area of study, an estimated 34,000 people and 4,500 vehicles were considered in the case of a morning scenario [29]. Additionally, cars were divided into two categories: moving and parked. Parked cars were placed in order to reflect the reduction of the cross-section capacity of streets, while moving cars are moving agents, as explained in the previous section. Considering an average density of 40 veh/km-lane, and that the network of interest has 50 km-lane, the total number moving vehicles at the moment the earthquake strikes was estimated as 2,000, and are placed randomly on the area considered. The distribution of the population is shown in Fig. 3, together with the evacuation routes established by the authorities.

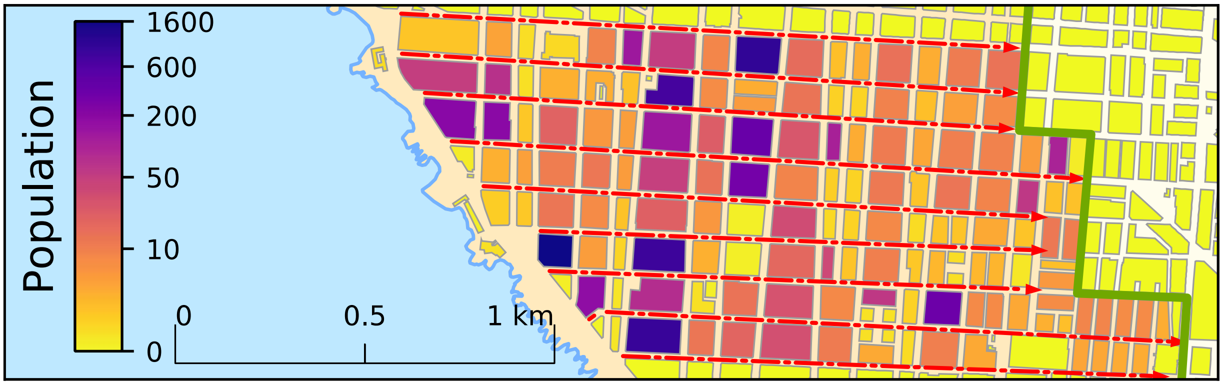

Figure 3. Study area of the city with evacuation routes (red lines) and population distribution.

The distribution of building debris is calculated using the demand of the event. Three moment magnitude values were used, M_W 8.0, 8.5 and 9.0, each with their epicenter located at fixed latitude and longitude (20º13'22''S, 70º29'34''). For each magnitude, several spectral values are sampled using the ground motion prediction equation proposed by Abrahamson et al. for subduction earthquakes [16], and considering a shear wave velocity of the upper 30 m of soil of 872 m/s for the study area [30]. For each scenario, a tsunami simulation was performed during 40 minutes. The tsunami is propagated over a bathymetry obtained from the General Bathymetric Chart of the Oceans (Gebco) 30 arc-second grid for deep water, and from nautical charts near the coast. Furthermore, the inundation is computed over a detailed topography obtained from a Lidar campaign, using a 2 m resolution grid. Tsunami simulations results are presented in Fig. 4, where the first arrival time for tsunami waves is defined using a threshold of 10 cm for the inundation depth.

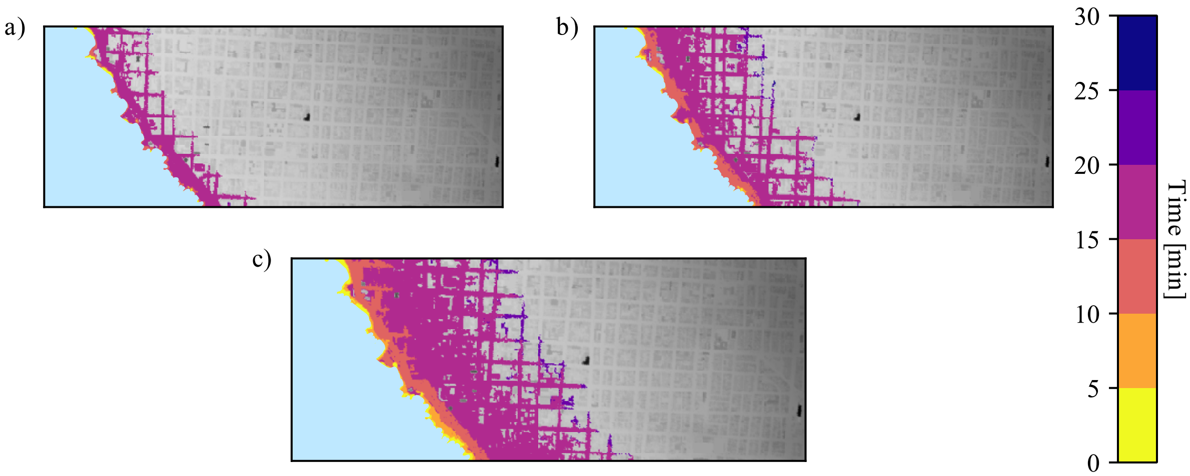

Figure 4. Tsunami inundation arrival times for magnitudes: a) M_W 8, b) M_W 8.5, and c) M_W 9. The colors represent the arrival times when water height reaches 10 cm.

Results

A total of 100 simulations were performed to evaluate spectral accelerations for each earthquake magnitude in order to consider the randomness of the wave propagation process. These intensities were used to estimate the damage of the city. Fig. 5 shows the distribution of PGA and spectral accelerations at 0.3 and 1 second for the three moment magnitudes studied, which are the values required by Hazus to estimate the amount of debris. As it should, higher values of spectral accelerations are sampled as the earthquake magnitude increases.

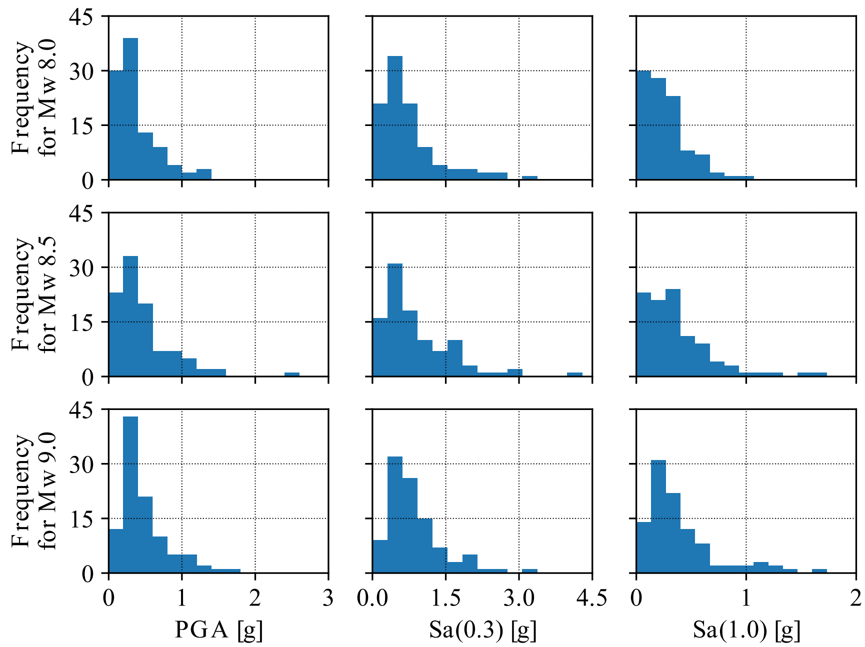

Figure 5. Histograms of the spectral accelerations at periods 0 (PGA), 0.3 and 1 second for earthquake magnitudes M_W 8.0, 8.5 and 9.0.

Two outputs are used to analyze the evacuation process: the evacuation time for which 95% of the population has reached the safety zones ($T_{95\%}$), and the number of casualties caused by the tsunami. Although the total evacuation time, defined as the time that the last evacuee takes to evacuate, is a more natural output choice, it is not necessary affected by the congestion of the entire evacuation. Therefore, in order to have more representative model of the real behavior of the complete simulation, the 95% evacuation time is used.

The median evacuation times are 23.6, 23.8 and 23.8 minutes for the three different magnitudes studied herein, which are related to the low accelerations sampled and therefore, to low quantities of debris. These values are consistent with the times obtained in an evacuation drill performed in Iquique in 2013 [31]. However, as seen in Fig. 6a, for bigger magnitudes the $T_{95\%}$ values have a greater variability, reaching times of almost 40 minutes in the worst scenario. In fact, the maximum evacuation times show an increment of 23%, 48% and 63% relative to the median for the magnitudes evaluated.

Together with the evacuation times, another relevant result is the number of casualties that the tsunami generates. In this work, casualties correspond to people that are reached by tsunami flows with inundation depths of at least 10 cm. This also applies for people that have not yet evacuated the building at the moment of the flood arrival. In this context, casualties represent injured, dead, or people trapped within buildings. Fig. 6b shows the number of casualties for the three simulated magnitudes. In the case of the M_W 8.0 tsunami, only one simulation had casualties (4 casualties). However, for the M_W 8.5 and 9.0 scenarios, the number of simulations with at least one casualty increases to 19 and 78, respectively. In the worst case, the tsunami will produce almost 600 and 1,000 casualties, respectively.

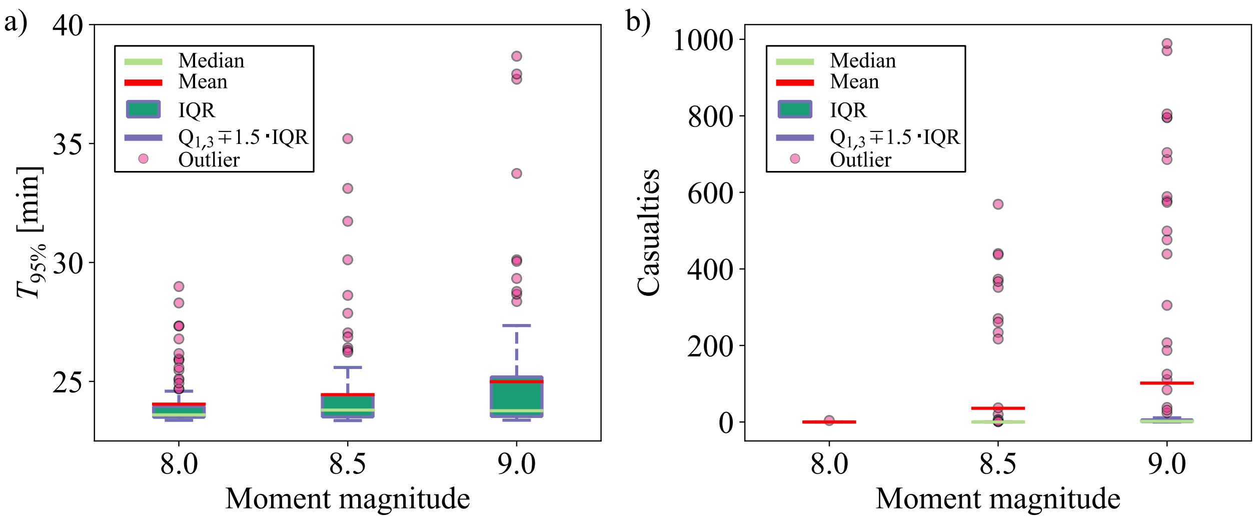

Figure 6. Box plots for different moment magnitudes: a) Evacuation times for 95% of the population, and b) Tsunami casualties.

Conclusions

This work combines two concepts that are usually not considered when simulating city evacuations. First, the impact of different earthquake magnitudes, their respective tsunami inundations, and building damage on the evacuation process. Second, the effect of building debris in the evacuation, represented by physical obstacles on the evacuation routes, generates a reduction of the capacity and congestion.

Considering building debris in the simulations increases evacuation times. Previous works that have simulated tsunami evacuations for extreme scenarios have normally omitted the generation of debris, and hence their evacuation times are underestimated. Similarly, casualties estimated herein show the imperative of an evaluation of the state of the evacuation routes, and their capacities after an earthquake.

However, there are several limitations of the model that must be considered when analyzing and interpreting the results. First, that the debris partially blocks the evacuation routes, and agents are not allowed to walk over the debris. This assumption could be unrealistic in a real scenario depending on the height of debris. Second, the use of a single tsunami simulation for each magnitude reduces the uncertainty of results. A complete analysis should also consider the variability of tsunami inundations for a given magnitude. One way of achieving this variability would be to use different slip distributions that are not uniform. Finally, the location of the epicenter for the simulations was arbitrarily selected. A more robust assessment could use different epicentral locations and earthquake magnitudes in a probabilistic seismic risk analysis.

Even though the work has limitations, as explained previously, the types of analyses presented could be very useful in the development of public policies for tsunami hazard zones, such as emergency plans for vertical evacuation. Evacuation plans should be tested for several scenarios instead of a single extreme scenario that could not consider several factors that, in other case, could generate a more harmful response.

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