# EVALUATION OF TSUNAMI EVACUATION BUILDING DEMAND THROUGH THE MULTI-AGENT SYSTEM SIMULATION OF RESIDENTS' BEHAVIOR

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In plain areas prone to tsunami, finding a way to shelter and escape from the inundation becomes a difficult task for residents. The 2011 Great East Japan Tsunami has shown that the horizontal evacuation using cars can compromise the safety of people. Another alternative is the vertical evacuation. In many cases, not only the capacity of these shelters plays an important role, but the spatial distribution and the evacuee preference for the nearest shelter. Such preference and location creates a conflict between capacity offer and demand. In this paper, we used an agent based model to simulate the evacuation of pedestrians and cars in La Punta, Peru. Twenty designated buildings for vertical evacuation are available for sheltering and escape from tsunami. The stochastic simulation of population spatial distribution and their refuge preferences revealed the over demand of some shelters. Finally, a capacity-demand map was created to share results with local authorities as a first step for future countermeasures in the district.

***Key Words***: *tsunami evacuation, building demand, agent based simulation, human behavior*

## 1. INTRODUCTION

Finding shelter during an emergency of tsunami for plain areas with a fast arrival time of waves is a challenging task for local people. The vertical evacuation to high buildings rising over the expected inundation depth in the area is one of the most suitable alternatives for this kind of urban districts. However, if the spatial distribution combined with the available capacity of these structures is not well displayed, conditions of over-demand and under-demand will be observed among them. In this paper, we conducted the numerical simulation of a future tsunami scenario using a predicted slip distribution model provided by Pulido et.al. (2011) from the interseismic coupling model estimated by Chlieh et.al (2011). Tsunami inundation is integrated with the agent based model of human evacuation. Using the stochastic simulation of several possible scenarios, the relation capacity-demand at each official Tsunami Evacuation Building in La Punta district in Peru was evaluated. The Capacity-Demand Index (CDI) is introduced as a way for mapping and identifying areas for future mitigation actions by local stakeholders.

## 2. THE STUDY AREA

### (1) Historical Tsunamis near La Punta

La Punta is part of the Constitutional Province of Callao in central Peru and one of the six districts in the First National Port city of Callao. It is a peninsula area and one of the smallest districts in Peru, with 4,370 inhabitants (INEI, 2007) and a total land area of 0.75 km$^2$ (Fig. 1).

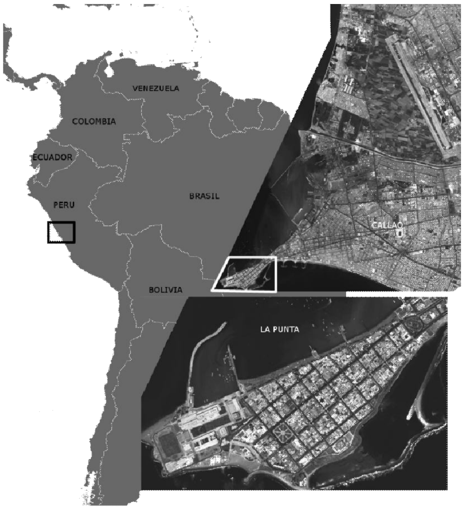


**Fig.1** Overview of the study area. Location.

Major risk of earthquakes and tsunamis are present in this area, due to its low topography. La Punta was affected by several historical earthquakes and tsunamis, such as the July 9th, 1586, earthquake of magnitude 8.6 and a local tsunami height of around 5 m (Dorbath, 1990), although some reports give a much larger value of 24 m (Berninghausen, 1962). Another two earthquakes on October 20th and 21st, 1687, of magnitudes 8.0 and 8.4, respectively, struck this area. The first one had generated a 5 m to 10 m local tsunami, while the second might have been located in southern areas (Dorbath, 1990). One of the most memorable earthquakes in the Callao region is the great earthquake of October 28th, 1746, with a magnitude 8.0 to 8.6 which completely destroyed some central Peruvian coastal cities. A tsunami of 15 m to 20 m in height resulted from this earthquake, it was reported half an hour after the ground shaking, and washed away Callao city with a 24 m run-up, killing 90% of its population (Kuroiwa, 2004). Two centuries later, the Peruvian central coast experienced more activity on May 24th, 1940, with a local earthquake and tsunami of 3 m in height. The October 3rd, 1974, event in front of Lima had a magnitude of 8.0 and a local tsunami height of 1.6 m (Langer and Spence, 1995). Since then, no large seismic activity has been reported in front of Callao area. A possible seismic gap might be located in this area, threatening La Punta and other coastal cities with a future large earthquake and tsunami.

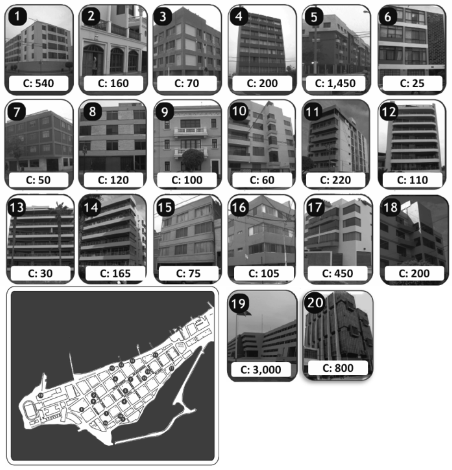


**Fig.2** Tsunami Evacuation Buildings (TEBs) in La Punta, Callao – Peru. The map shows the spatial distribution of TEBs and "C" is the capacity reported by the municipality.

### (2) Tsunami Evacuation Buildings

There are 19 official evacuation buildings in the district and a 20th building is located immediately outside of the district in the Callao province (Fig. 2). Previously it was considered in the evacuation plan, however after the 2007 Pisco Earthquake it suffered some structural damages and required retrofitting. Since then the district lost confidence on this building; however in 2009 it was successfully retrofitted.

## 3. TSUNAMI NUMERICAL SIMULATION

### (1) Tsunami source

An instantaneous displacement of the sea surface identical to the vertical sea floor displacement is assumed in the model of tsunami source. The source of tsunami simulation is a result of the slip deficit rate with the interseismic period of 265 years since the 1746 historical earthquake in Peru (Fig. 3).

### (2) Numerical Modeling

The Tohoku University's Numerical Analysis Model for Investigation of Near-field tsunamis (TUNAMI model) was used as the tool of tsunami modeling (Imamura, 1995). A set of non-linear shallow water equations are discretized by the Staggered Leap-frog finite difference scheme. Bottom friction condition is in the form of Manning's formula constant in the whole domain.

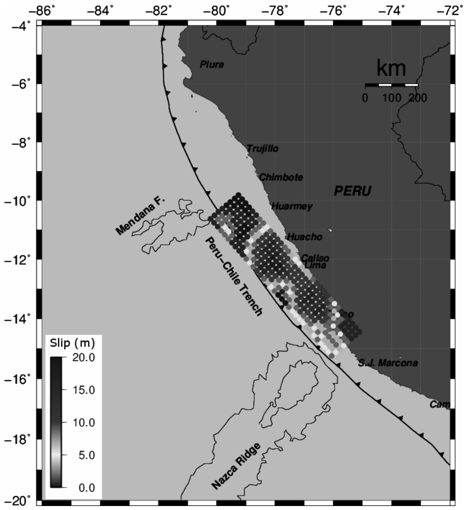


**Fig.3** Slip distribution from GPS data. There are 280 sub-faults of 20x20km. (Pulido et.al, 2011) (Figure in Yauri, S. (2011)).

## 4. EVACUATION SIMULATION

We used the TUNAMI-EVAC1 (Mas et al., 2012a) to observe the tsunami inundation together with the resident evacuation behavior. The model was developed in NetLogo, a multi-agent programming language and modeling environment for simulating complex phenomena (Wilensky, 2001). The model uses GIS data as spatial input and the tsunami numerical results to evaluate the probability of casualty at each step. Casualty estimation is a binary logistic model based on the experimental results of human instability reported in Takahashi et.al (1992). The population from the census data was categorized in four groups according to the age (Fig. 4).

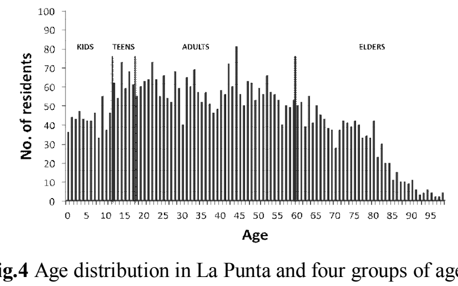


**Fig.4** Age distribution in La Punta and four groups of agent type for simulation.

The main difference in all these groups or agent type is the maximum possible speed during evacuation. The speed varies as a half tail normal distribution of density in the agent field of view of 60 degrees cone with 5m distance for pedestrians and 10m for cars. Table 1 shows agent types and their maximum allowed speed.

**Table 1** Agent type number at each scenario and their maximum speed value allowed during simulation

| Type | Vertical | Horizontal & Vertical | Max. Speed (m/s) |
|---|---|---|---|
| KIDS | 514 | 514 | 1.06 |
| TEENS | 377 | 377 | 1.33 |
| ADULTS | 2428 | 1678 | 1.33 |
| ELDERS | 1051 | 901 | 0.93 |
| CARS | – | 225 | 8.40 |

(*) Units: persons

### (1) Cases for Simulation

For a better comprehension of the necessity of Tsunami Evacuation Buildings, a case for the only horizontal evacuation with no use of TEBs was conducted. Next, a Vertical Evacuation case and a combined case of Horizontal Evacuation and Vertical Evacuation were evaluated. These are the conditions for each case:

**a) Horizontal Evacuation**

Pedestrians and cars choose one of the possible two exits out of the district – two streets leading to the northeast of the district (Fig. 6 - triangles).

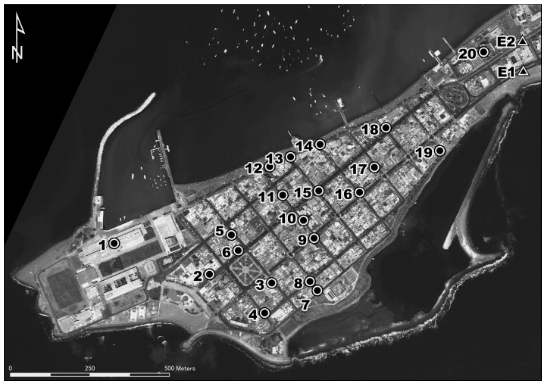


**Fig.6** Location of TEBs (circles) and Exits (triangles)

**b) Vertical Evacuation**

Twenty available TEBs are used for sheltering (Fig. 6 - circles). Evacuees – only pedestrians – choose the nearest shelter to their location regardless the capacity or condition at the shelter. To observe the over-demand of shelters, evacuees are allowed to enter the building without any restriction. Vehicles are not included in this case.

**c) Horizontal and Vertical Evacuation**

This is a combination of the two previous scenarios. Here, pedestrians and cars evacuate to any of all TEBs or Exits available in Fig. 6.

### (2) Start time of evacuation

In all cases the start time condition of pedestrians and cars follow the Tsunami Departure Curve method proposed in Mas et al. (2012b) (Fig.7).

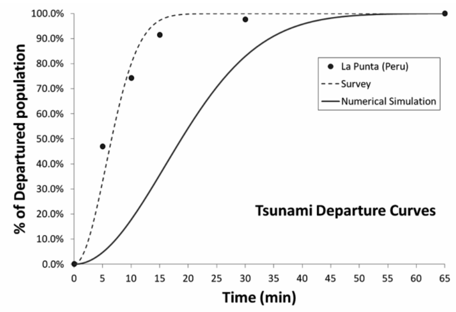


**Fig.7** Tsunami Departure Curves for the simulation cases. Behavior of start time is obtained through the stochastic simulation of random selected times bounded by two Rayleigh distributions. Left distribution obtained through stated preference surveys and the other distribution is based on the estimated arrival time of tsunami from numerical simulation.

## 5. RESULTS & DISCUSSION

### (1) Casualty Estimation

Due to the many possibilities of spatial initial condition of residents, in the model, outcomes are averaged from a set of repetitions (250 runs) of different scenarios with agents loaded at random locations in the district (indoors or outdoors). For the result of these scenarios, it was observed that the Vertical case yields to fewer casualties (16 pers.) due to the short distance for a rapid evacuation and the less use of vehicles that contributed to stagnation points in the other two cases. The Horizontal Case shows the maximum average number of casualties (271 pers.), followed by the Horizontal and Vertical Case (153 pers.). As expected traffic congestion is observed along the exit roads and in particular near to the exits until the arrival of tsunami. Snapshots at 0, 10, 20, 30, 35, 40min of the first case of simulation are shown in Fig. 8, while Fig. 9 shows the 40min snapshots of the other two cases.

### (2) Shelter Demand

The number of agents sheltered at each TEB was counted and averaged from all repetitions; a comparison of demand and capacity is shown in Fig. 10. Out of twenty (20) TEBs, 13 resulted with over-demands, while seven (7) were still with available space. It is necessary to ensure the safety of evacuees even at the over-demand shelters. As an example, building S11 with 25 persons of capacity may expect around 180 residents in the area looking for shelter. New areas for vertical evacuation should be implemented to support the rapid evacuation of residents in the area.

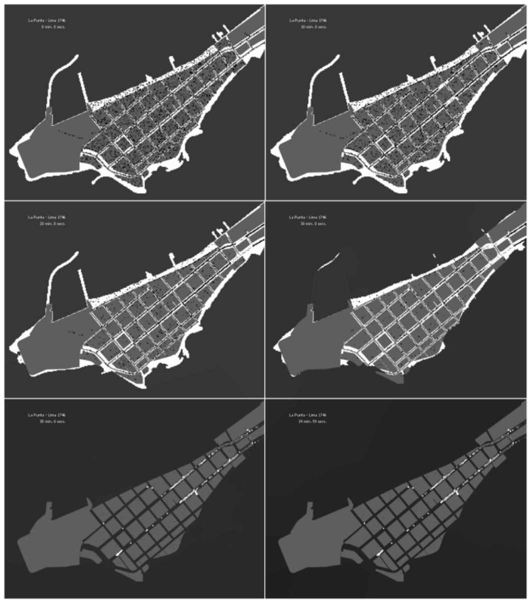

**Fig.8** Horizontal Evacuation Case. Casualties are observed at traffic congestion near the exit of the district. The necessity of a vertical evacuation is revealed here.

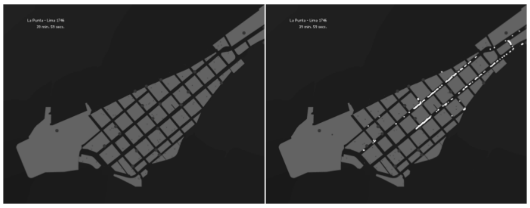

**Fig.9** Snapshot at 40min simulation for the Vertical Evacuation case (left) and the Horizontal and Vertical Evacuation case (right). White dots show areas of stagnation.

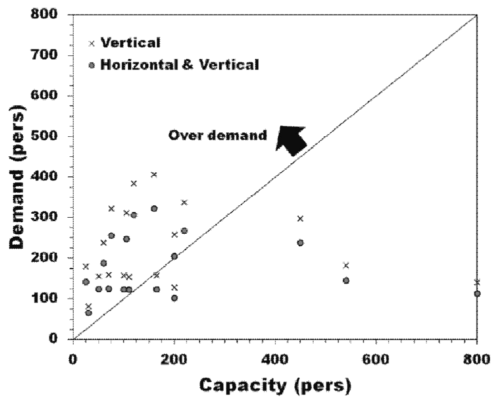


**Fig.10** Capacity and Demand of Shelters in La Punta. Out of 20 TEBs, 13 might present over-demand and 7 under-demands.

### (3) Mapping the Capacity-Demand

In order to facilitate the local authorities' decision of future countermeasures and alternatives for evacuation in La Punta, the resulting capacity-demand rate is mapped as observed in Fig. 11.


**Fig.11** Capacity-Demand mapping of TEBs. Black (over demand) - White (under demand) (H&V case).

The relation capacity vs. average demand of cases represents the Capacity-Demand Index (CDI) following the simple relation in Eq. (1)

$$CDI = \frac{\text{Demand}}{\text{Capacity}} \tag{1}$$

Therefore, a value of 0.0 to 0.5 indicates that less than a half of the structure has been occupied; from 0.5 to 1.0 at most the total capacity of the structure is being used. The important information comes for CDI values over 1.0, where over-demand conditions are probable. As a result, from the CDI Map it is possible to conclude that unfortunately the nearest buildings are comparatively of lower capacity with the ones located at the head and neck of the district. Due to the behavior of shelter selection (nearest), most of the structures closer to the beach area in the north coast present an over-demand while the south population apparently may fit in the available structures.

## 8. CONCLUSION

An evaluation of Tsunami Evacuation Building demand has been conducted through the simulation of agents in evacuation in La Punta. In this paper we have shown that the horizontal evacuation might lead to a high number of casualties due to the traffic congestion at the neck of the district. As estimated, the vertical evacuation would be a suitable solution for this area; however the spatial location of shelters complicates the evacuation process. Here, we identified the shelters with possible over-demand and their location according to the nearest shelter selecting behavior of evacuees. A CDI Map is proposed as a first step for future mitigation plans in the district. It is recommendable to allocate new areas for evacuation near to the north area of the district (close to the beach).

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