Paper:

An Integrated Simulation of Tsunami Hazard and Human Evacuation in La Punta, Peru

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The 2011 Great East Japan earthquake and tsunami was a magnitude 9.0 Mw event that destroyed most structural tsunami countermeasures. However, approximately 90% of the estimated population at risk from the tsunami survived due to a rapid evacuation to higher ground or inland. Thus, tsunami evacuation is the most effective measure to reduce casualties. In this paper, we applied a new developed evacuation model integrated with the numerical simulation of tsunami for casualty estimation. This tool is to support decisions in disaster management and disaster prevention education. The model was developed in NetLogo, a multi-agent programming language and modeling environment for simulating complex phenomena. Geographic Information Systems (GIS) datasets are used as spatial input information for road and shelter locations. The TUNAMI model of Tohoku University is used for the integration of tsunami numerical simulation results. In this paper, the study is performed in a tsunami threatened urban area of Callao, Peru, called La Punta. Results show the various contributions of the model to disaster management and scenario analysis. Among the contributions are the casualty estimation in a tsunami risk area and the analysis of the spatial distribution of vertical evacuation shelters.

Keywords: tsunami simulation, evacuation simulation, tsunami hazard, human casualty

1. Introduction

It is expected that authorities in low-lying coastal areas at high risk of tsunami promote immediate evacuation after strong ground motion or when warnings are issued. In tsunami prone areas with only a short time available for evacuation, finding safety on high ground is an important issue and especially difficult in flat plains areas. The development of effective warning systems and evacuation strategies is of primary importance in mitigation measures for tsunami events [1, 2]. Also, simulation plays a decisive role in the analysis of risk, helping to prevent dangerous situations in huge crowds and improving the overall evacuation performance [3] in contribution to disaster management. It is the purpose of this research to explore the human behavior and the evacuation simulation and the integration with the well-known technique of tsunami simulation for a comprehensive assessment of tsunami risk.

1.1. Evacuation Simulation Models

There is a large number of evacuation models in previous studies. Models such as those related to building evacuation due to fire events [4–8], evacuation from ships [9] and aircraft [10] and also models to simulate traffic and regional evacuation in case of hurricanes, nuclear accidents and floods [11–13]. These and others [14, 15], were consulted to comprehend the state of the art in the field of pedestrian dynamics and traffic simulation. As a result, it was observed that there is increasing interest in microscopic and individual simulation of complex events. There is also a need for realistic and effective tools to simulate human behavior and the several phenomena and risks that threaten human safety.

A brief review of the most recent tsunami evacuation models is as follows:

- [16] The model uses multi agent systems moving on a road network map and following predefined rules. Some assumptions in this model are that (i) agents follow the shortest paths through a linked network. Short in terms of distance for pedestrians and time for vehicles. (ii) fast evacuees pass slower ones when space is available, and (iii) vehicle speed depends on road width. For this model, the model unit agent is the family (4 persons). Three kinds of agents are shown, i.e., the family walking, the family in a car, and 2 members of the family on a motorcycle. Tsunami casualties are counted when inundation depth exceeds 1.00 m at the actual location of an agent. In this case, there is a limitation on the representation of individual behavior and outcome for each evacuee.

- [17] In this model, Multi-Agent Transport Simulation (MATSim) is used as the toolbox for the implementation of large-scale agent based simulation. The purpose of this model is to find the best evacuation condition that benefits all agents. The set of repetitions and iterative learning framework lead to Nash equilibrium as the best approximation of the desired evacuation. Some of the findings in this study are that (i) the shortest path solution is not suitable for evacuation planning because it does not consider congestion effects and underestimates travel times; and (ii) Nash equilibrium considers these congestion effects but does not take into account the time-dependent aspect of the hazard.

- [18] The authors present a tsunami evacuation model based on a multi agent system approach. Each evacuee is an agent with the characteristics of age, speed, fatigue level and disaster mitigation awareness. Interaction of these data with the environment describes the evacuation behavior. The model considers only agents as pedestrians and there is no vehicle simulation for traffic conditions. Evacuation start time is also strictly based on questionnaire data. Departure times are based on situational conditions that trigger protective action.

- [1] other tsunami related models developed a static tsunami evacuation model using GIS tools in order to investigate and assess risk and evacuation planning in a multilingual society. Using multi agent simulation, [19] aims at understanding human behavior and its interaction effects in a tsunami disaster.

Among these models, there are several differences related to representation of the unit of simulation – the agent – and its characteristics such as evacuation start time decision, route choice, mobilization means, shelter selection and rules for avoiding obstacles. While some of them do not consider the vehicle agent in simulation, underestimating possible crowding and bottleneck conditions, others use a simplistic method of casualty estimation by stopping simulation at the estimated tsunami arrival time and categorizing all remaining agents as possible casualties. In this study, a casualty is understood as an individual trapped in a tsunami with very little chance for survive at the inundation depth and flow velocity. Therefore, integration of a more realistic condition of the probability of becoming a casualty related to tsunami characteristics will be applied here.

With evacuation simulation models, it is possible to analyze alternatives for safer routes, destinations, evacuee response and other possible decisions for disaster mitigation in an area [20, 21]. Emergency evacuation models may be classified at first on: (i) large-scale scenarios, e.g. hurricanes, nuclear power plants, tsunami, etc. and (ii) small-scale evacuation of buildings or vessels due to bomb threats, fire, etc. Traditionally, large-scale scenarios were modeled following a macroscopic approach with vehicular evacuation. In macroscopic models the flow or group of individuals on the move is the smallest unit simulated. In recent years, researchers are focusing on the microscopic simulation of individuals. Here, an agent or individual is the smallest unit simulated. Although it is the individual who is the main element during the develop stage, final attention lies on the overall emergent behavior of agents interaction. This is possible due to the fast development of computing capacity in memory processes, graphic rendering and data storage. Here, the model is developed for a large-scale scenario, however considering the microscopic level through an agent based simulation approach.

1.2. Agent Based Modeling

Models are used to gain understanding of and insight into aspects of the real world. In several cases, the cost of developing and experimenting with models is small compared to the cost of experimenting in the real world [22]. In the case of tsunami evacuation drills, for instance, the society or community involved is required to stop its daily activities and move along the streets to safe areas. Evacuation sometimes lasts for long distances and time, creating unpleasant feelings in residents and tourists. The level of participation is rarely near 100% of the population. It is therefore, difficult to repeat the exercise very often [21]. However, local stakeholders and authorities need to test the feasibility of their evacuation plans and the possible flaws related to it. For that reason, modeling techniques help on the understanding of systems which are difficult to observe in the real world.

Agent-based modeling and simulation (ABMS) is a relatively new technique to model systems comprised of autonomous and interacting agents [23]. Each agent individually assesses its situation and makes decisions on the basis of a set of rules. Various behaviors can be given to the agent for the individual decision-making process or the interaction with the environment and other agents. The main advantage of ABMS is that it captures the emergent phenomena from the bottom up by modeling agents interaction and behavior. Based on this, ABMS models are suitable for evacuation simulation that considers aspects of human behavior. Although pedestrians, and in general drivers, usually try to walk or drive minimizing detours or taking the optimal path to their targets, there are fluctuations in human behavior. Therefore, simulation results are to some extent uncertain. However, if the simulated crowd is large enough and the simulation run is repeated several times (Monte Carlo simulation), then uncertainty about individual behavior averages out at the macroscopic level of description [3].

1.3. Human Behavior in Tsunami Evacuation

Tsunami evacuation is a way of coping with an emergency and the key to successful evacuation is being able to move all people at risk to safer areas in the time available [24, 25]. Early Warning Systems (EWS) have been developed to contribute promoting fast evacuation when a tsunami happens. Even after great improvements in EWS tsunami technology, some people still decide not to evacuate from an area threatened by a dangerous situation such as a tsunami [26–30]. Therefore, it is important to look not only into available technology and ways to improve it, but to look at the people involved and their behavior and decisions. Warning is only one element and not necessarily the most important in evacuation behavior [25].

When we look into the individual, we may find that human behavior is the most complex and difficult aspect of the evacuation process to simulate [5]. Human behavior includes complex problem solving [31] and individual characteristics with both aspects difficult to capture in mathematical equations [32]. In several attempts with models, human behavior in evacuation is observed and the simplification of these individuals and their emergent behavior has been considered to explain a part of the whole phenomenon. For example, herding effects generally occur if the view is limited, e.g. by smoke, darkness of the night, etc., or if people do not have local knowledge, e.g. they do not know where emergency exits or shelters are. Under such circumstances people often rely on others, hoping that they know better [3]. Another example is the phenomenon of lane formation that is observed when a uniform walking direction emerges instead of walking equally distributed over sidewalks or corridors. This way, the number of encounters, braking and avoidance maneuvers among opposite direction pedestrians in counterflows are minimized. The resulting pattern is balanced in both directions and may be considered an optimal self-organization phenomenon [3].

Human behavior in tsunami evacuations has been studied through questionnaires on natural hazard risk perception [24, 33, 34] or post tsunami surveys addressing respondent behavior in a tsunami event [27, 29, 30, 35].

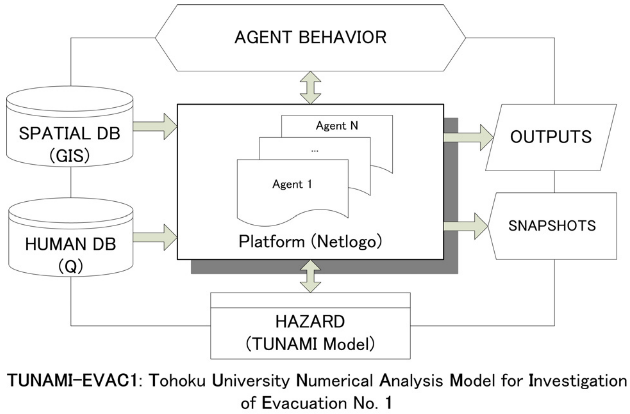


Fig. 1. Model scheme – Inputs, libraries and hazard characteristics are used in the NetLogo platform to obtain the screen and report outputs.

Fig. 2. Model interface – GUI of TUNAMI-EVAC1 with scenario variables and parameter inputs on the left, update screen on the center and real-time outputs on the right side.

2. Integrated Simulator

An outline of **Fig. 1** shows a scheme of the model. It consists of input data provided by spatial data in GIS format, human data related to evacuee preferences obtained from questionnaire results, the component of hazard is provided by TUNAMI inundation model output, and a set of agent behavior rules loaded into an agent-based simulation platform. The platform chosen in this study is the NetLogo modeling environment [36]. Outputs of casualty estimation, evacuation times, bottlenecks, shelter demand, etc. are obtained through report files, and snapshots or videos of the simulation process. The model is named *TUNAMI-EVAC1* an acronym for **T**ohoku **U**niversity **N**umerical **A**nalysis **M**odel for **I**nvestigation of **Evac**uation No.**1**. A screen snapshot of the model interface is shown in **Fig. 2**.

We provided agents with the minimum necessary capability to process information and execute evacuation through simple behavior divided into layers. A brief introduction to the agent architecture and each layer is as follows:

- Layer 0, evacuation decision: The timing for starting evacuation is assigned randomly to each agent based on tsunami departure curves that models start time behavior through the stochastic simulation of random selected time bound by two Rayleigh distributions. The first curve is obtained from the distribution of the start time of evacuation decision collected with a stated preference survey, and the second is based on Rayleigh distribution with a mean equal to the estimated tsunami arrival time obtained from numerical simulation.

- Layer 1, shelter decision: There are two possible options for scenario exploration: first, the nearest shelter is selected by an agent based on direct Euclidean distance measure and, second, any shelter can be selected randomly. Traditionally, the nearest shelter condition has been applied. In many cases, however, preferences are not for the nearest shelter.

- Layer 2, route decision and path finding: The method used for finding a route – not necessary the shortest – is the A* (A star) algorithm with heuristics in grid space. This is the most popular graph search algorithm used in the video game industry [37].

- Layer 3, speed adjustment: Speed variation is assumed to be a one-tail normal distribution of evacuee density in the agent field of view, with a maximum value of 1.33 m/s for pedestrians and 30 km/h (8.33 m/s) for cars [3, 38].

3. Tsunami Hazard and Human Evacuation at La Punta, Peru

Finding shelter during a tsunami emergency in flat plains areas with a fast wave arrival time is a challenging task. Vertical evacuation to high buildings rising above the expected inundation depth is one of the most suitable alternatives for this kind of urban district. However, if spatial distribution combined with the available capacity of these structures are not well displayed, over-demand and under-demand conditions will be observed among them. In this section, we conduct the numerical simulation of a possible great earthquake in Peru similar to the historical 1746 earthquake. The resulting tsunami propagation inland is integrated with a multi agent model of human evacuation. Using stochastic simulation of the initial spatial distribution of residents and evacuation behavior start time, we evaluated the capacity-demand relation at each official tsunami evacuation building in the La Punta district of Callao in Peru. The capacity-demand index (CDI) is introduced as a way of mapping and identifying areas for mitigation action supporting the evacuation process of a population at risk of a tsunami.

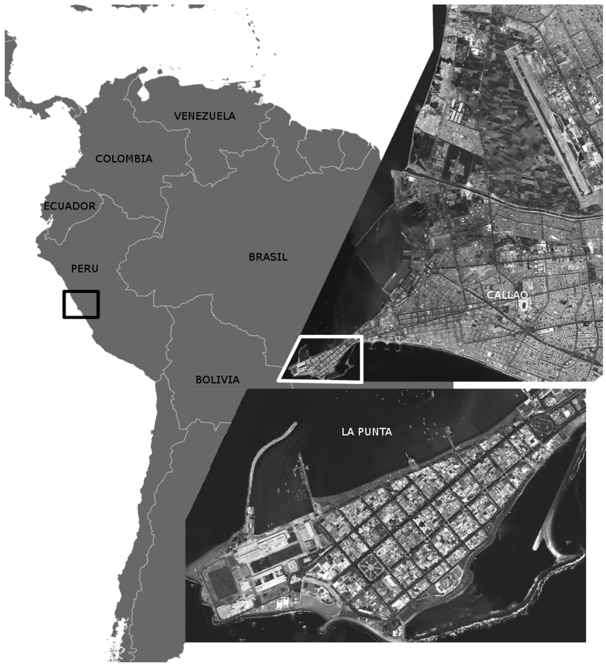


Fig. 3. La Punta district – Location of the study area of La Punta of the Callao province in Peru.

3.1. Study Area: La Punta, Peru

3.1.1. Historical Tsunami near La Punta

La Punta is part of the constitutional province of Callao, in central Peru (**Fig. 3**), and one of six districts in the first national port city of Callao. La Punta, a peninsula in the western part of the province, is almost entirely surrounded by the Pacific Ocean except on its northeastern side, where it is bordered by downtown Callao. It is one of the smallest districts in Peru, with 4,370 inhabitants [39] and a total land area of 0.75 km^2. Major earthquake and tsunami risks are present in this area, due to its low altitude topography, which is a maximum 3 m, and its geographic characteristics as a peninsula with a wide head on the sea and a narrow neck connected to the inland. Evacuation procedures and feasibility are of interest for the safety of La Punta residents and visitors. La Punta has been adversely affected by several historical earthquakes and tsunamis, such as the July 9 1586 earthquake with a magnitude of 8.6 and a local tsunami height of some 5 m [40]. Another two earthquakes on October 20 and 21 1687, with magnitudes 8.0 and 8.4, respectively, struck this area. The first one generated a local 5 m to 10 m tsunami. The second may have been located in southern areas [40]. One of the most memorable earthquakes in the Callao region is the great earthquake of October 28 1746, with a magnitude 8.0 to 8.6 that completely destroyed some central Peruvian coastal cities. A tsunami 15 m to 20 m in height resulting from this earthquake arrived half an hour after ground shaking and washed Callao city away in a 24 m run-up, killing 90% of the city's population [41]. Two centuries later, the Peruvian central coast experienced more activity on May 24 1940, with a local earthquake and tsunami of 3 m in height. An October 3 1974 event in Peru's capital Lima had a magnitude of 8.0 and a local tsunami height of 1.6 m [42, 43]. Since then, no large seismic activity has been reported in the Callao area. A possible seismic gap might be located in this area, threatening La Punta and other coastal cities with future large earthquakes and tsunamis.

3.1.2. Tsunami Evacuation Buildings

There are 19 official evacuation buildings in La Punta district and a 20th building located immediately outside of the district in Callao province (**Fig. 4**).

3.1.3. Population

The population by age according to the 2007 census [39] is shown in **Fig. 5**. We have considered 4 groups of agent types based on the age interval. **Fig. 5** shows the limit of each age interval in a vertical line. Children – kids in the figure – are considered to be from 1 to 11 years old; teenagers – teens in the figure – from 12 to 17, the main group of adults – adults in the figure – from 18 to 59, and the last group of pedestrians are persons over 60 years old – elders in the figure. **Table 1** shows the number of people in each group or agent type for the three scenarios simulated – horizontal, vertical, and horizontal and vertical. In all cases a 15% of pedestrians are considered to be handicapped, following the census data.

3.2. Tsunami Numerical Simulation

3.2.1. Tsunami Source

Instantaneous displacement of the sea surface identical to vertical sea floor displacement is assumed in the tsunami source model. The source consist of 280

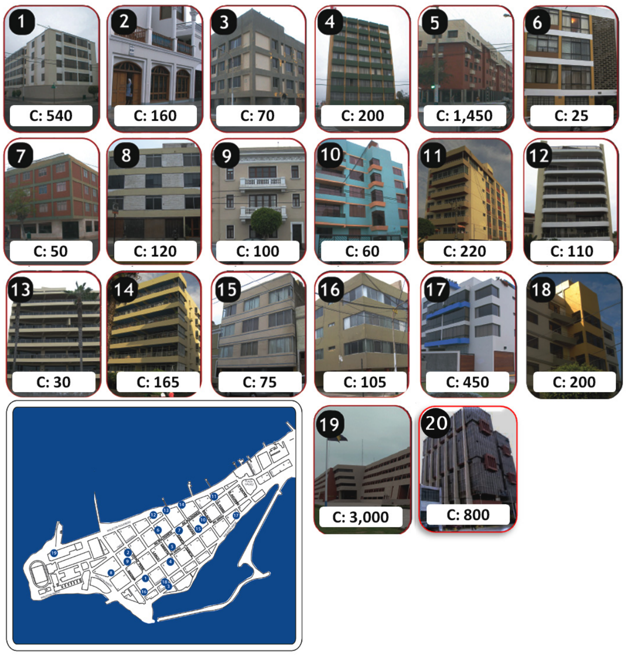


Fig. 4. Tsunami Evacuation Buildings (TEBs) in La Punta, Callao, Peru – The map shows the spatial distribution of TEBs.

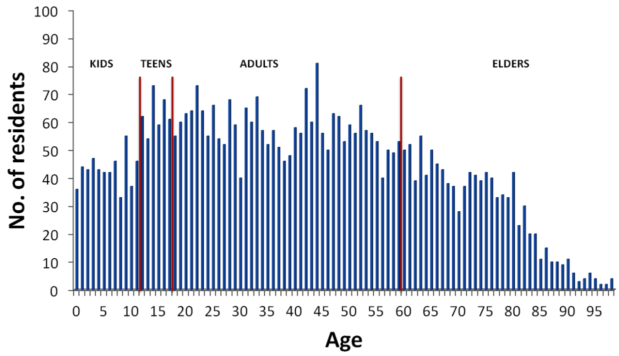


Fig. 5. Population by age – Age distribution in La Punta and four groups of agent type for simulation.

subfaults of 20×20 km each, proposed by [44] in the offshore zone of Lima. The tsunami simulation source is the result of a slip deficit rate with an interseismic period of 265 years since the 1746 historical earthquake in Peru (**Fig. 6**).

3.2.2. Numerical Modeling

Tohoku University's Numerical Analysis Model for Investigation of Near-field tsunamis (TUNAMI) was used as the tsunami modeling tool [45]. A set of nonlinear shallow water equations is discretized by the staggered leapfrog finite difference scheme. The bottom friction condition is in the form of Manning's formula constant in the whole domain.

Table 1. Number of agents by type in scenarios and maximum speed value allowed during simulation.

Type	Horizontal	Vertical	Horizontal and Vertical	Max. speed (m/s)
Kids	514	514	514	1.06
Teens	377	377	377	1.33
Adults	1678	2428	1678	1.33
Elders	901	1051	901	0.93
Cars	225	-	225	8.40

(*)Units: persons

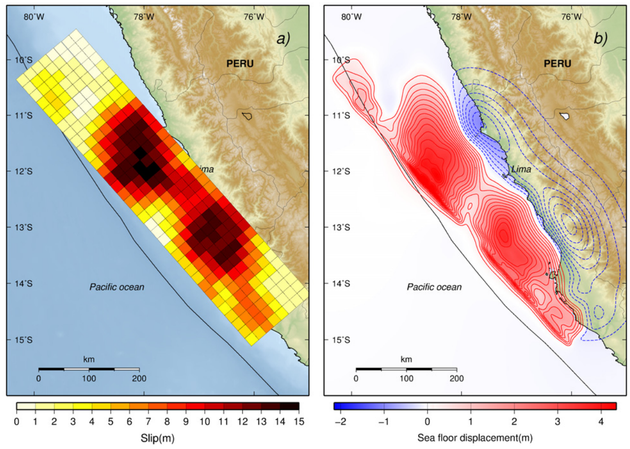


Fig. 6. Tsunami source – Slip distribution for a possible earthquake similar to the 1746 Peru Earthquake. There are 280 sub-faults of 20×20 km [44].

3.3. Evacuation Simulation

We used TUNAMI-EVAC1 [46] to observe tsunami inundation together with resident's evacuation behavior. The model was developed in NetLogo, a multi-agent programming language and modeling environment for simulating complex phenomena [47]. As mentioned above, the population modeled was categorized into four groups by age. The main difference in these groups or agent types is the maximum possible speed during evacuation. **Table 1** shows that Teens and Adults can reach 1.33 m/s [3].

Other types are assumed to have a speed reduction of 0.80 for Kids and 0.70 for Elders. Handicapped agents have an additional 0.50 speed reduction. In the case of cars, the maximum speed is 30 km/h (8.40 m/s) [38]. Speed varies as a half-tail normal distribution of density in the agent field of view of a 60-degree cone with a 5 m distance for pedestrians and 10 m for cars.

3.3.1. Cases for Simulation

For better comprehension of the necessity of tsunami evacuation buildings, we ran a case for horizontal evacuation alone with no use of tsunami evacuation buildings (TEBs). Next, as the main target of this section, the evaluation of the spatial distribution of TEBs is conducted for the vertical evacuation only case and a combined case of horizontal evacuation and vertical evacuation, possibly the most probable scenario in a real emergency.

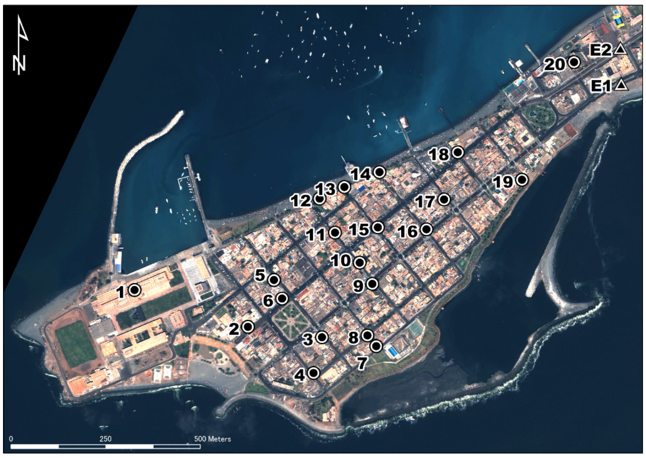


Fig. 7. Location of shelter and exits – TEBs (circles) and exits (triangles).

A detailed description of assumptions and constraints for each case is as follows:

1 Horizontal evacuation: In this case, pedestrians and cars are set to choose one of two possible exits out of the district – two streets leading northeast of the district (**Fig. 7** – triangles).

2 Vertical evacuation: Here, the total of 20 available TEBs is considered for shelter (**Fig. 7** – circles). Evacuees – pedestrians alone – choose the shelter nearest to their location regardless of the shelter capacity or condition. Thus, if the structure is full of evacuees related to its real capacity, evacuees are still allowed to enter the building. The reason for this decision is to observe over-demand for certain structures during the time of evacuation before the arrival of a tsunami. Further behavior can be considered in future evaluation, i.e. changing a shelter decision due to overcrowding of structures or selecting a shelter based not only on distance but capacity. Such behavior, however, despite any underlying rationality may not occur in a real emergency. We, therefore, leave these other conditions for future assessment and discussion.

3 Horizontal and vertical evacuation: The horizontal and vertical case is a combination of the two previously mentioned scenarios. In this case, pedestrians and cars are both considered. Possible shelter or escape points are the union of all points previously shown and detailed in **Fig. 7**.

3.3.2. Start Time of Evacuation

In all cases, the start time condition of pedestrians and cars follows the tsunami departure curve method proposed in [48]. A tsunami departure curve is a set of possible departure behavior among residents bound by two distributions of behavior obtained by questionnaire and numerical tsunami simulation (**Fig. 8**).

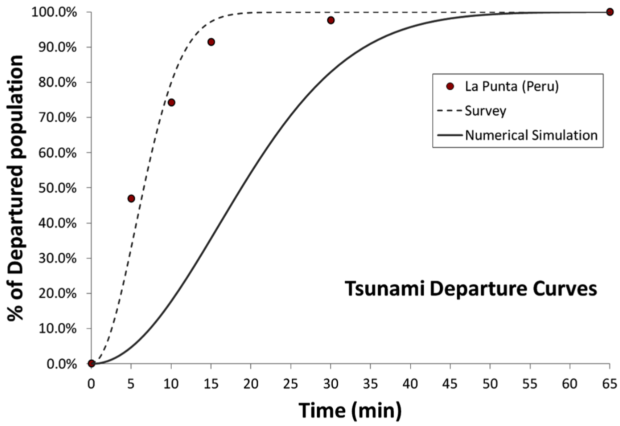


Fig. 8. Tsunami Departure Curves – Behavior of start time is obtained through the stochastic simulation of random selected times bound by these two distributions. The dashed curve is obtained from a pre-tsunami questionnaire survey with residents estimation of decision time for evacuation. The second curve is the Rayleigh distribution function with mean of the distribution equal to the estimated arrival time of tsunami obtained through numerical simulation.

In the case of La Punta, two pre tsunami or stated preference surveys were conducted in 2010 and 2011 in which we asked the following question to people who will evacuate in the case of an earthquake: "*In the case of a near-field tsunami, how many minutes would you take to decide and prepare yourself for evacuation? (From the end of the earthquake to the beginning of your evacuation to a safe place)*." Answers were given on multiple options in minutes intervals. Answers fit with the Rayleigh distribution obtaining a mean of distribution of 7 min – a fast evacuation compared to the expected tsunami arrival time of 20 min. Due to the lack of a post tsunami or revealed preference survey, a good approximation of the slow evacuation condition is related to a Rayleigh mean of distribution value equal to the expected arrival time of the tsunami (20 min) [48]. Finally, distributions characterized by a mean of 7 min and 20 min became the boundary of stochastic simulation of several departure curves for tsunami evacuation.

3.4. Results and Discussion

3.4.1. Casualty Estimation

The initial condition of residents is difficult to simulate in evacuation procedures due to the uncertainty of the time and date of a possible real event. In a nighttime scenario, it might be reasonable to initialize in the model a resident's location at a house; however in a daytime scenario, the dynamic status of people makes it difficult to assume an initial location for agents. We, therefore, accepted this uncertainty in the spatial initial location for agents and started the simulation at a random location inside a house or on the street or on a beach. We, then, ran 250 repetitions of scenarios with different initial location of agents in stochastic simulation, in order to build as

Table 2. Average values of casualties in three cases: a) horizontal evacuation; b) vertical evacuation and c) horizontal and vertical evacuation.

Type	Horizontal			Vertical			Horizontal and Vertical		
	Avrg.	S.D.	Max.	Avrg.	S.D.	Max.	Avrg.	S.D.	Max.
Kids	38	2	42	4	1	7	4	1	7
Teens	29	3	34	4	1	7	4	1	8
Adult	28	1	30	4	0	5	4	0	5
Elder	47	1	50	4	1	6	4	1	6
Cars	32	34	87	-	-	-	34	35	100
Total (pers.)	271	-	-	16	-	-	153	-	-

(*) Units: persons / S.D.: Standard Deviation

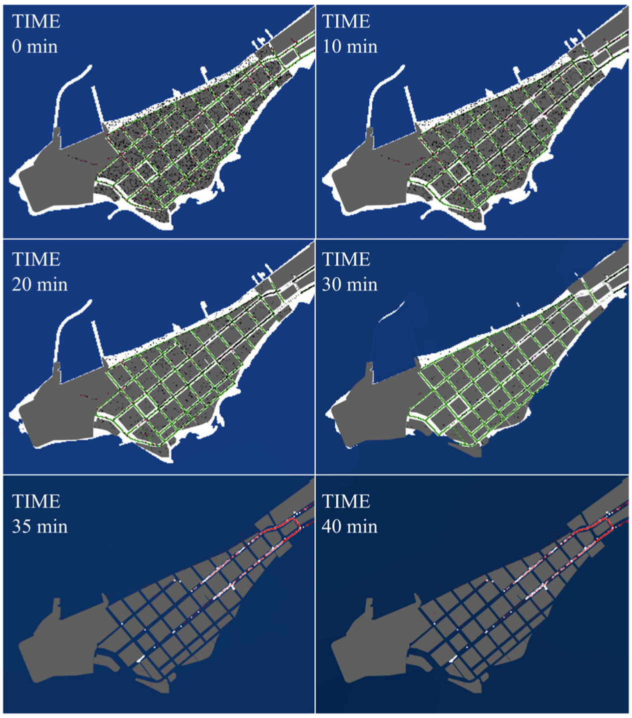


Fig. 9. Horizontal Evacuation scenario result – Casualties at traffic congestion are observed at the neck of the district.

many possible scenarios of spatial population distribution in the district. Averages of results are shown in **Table 2**.

The horizontal case shows the maximum average number of casualties, followed by the horizontal and vertical case, and then the vertical only case. Here, it is important to note that in the horizontal evacuation case 5,000 people among pedestrians and cars pretend to escape through only two narrow exits. As expected, traffic congestion is observed along exit roads and, in particular, near exits until the arrival of the tsunami. Snapshots each 10 min of simulation are shown in **Fig. 9**. Final white dots are points of traffic and dark dots are final casualties. The necessity of tsunami evacuation buildings is observed through the results of this case. Here, the standard deviation of cars is high compared to the pedestrian agent type, this is due to the influence of traffic and congestion conditions for vehicles, which clearly shows high uncertainty in possible outcomes. More repetitions are necessary to observe a better convergence of cars' casualty estimation. For purposes of this paper, e.g. the evaluation of building demand, if we use the vertical scenario as the reference scenario, then this variability can be neglected.

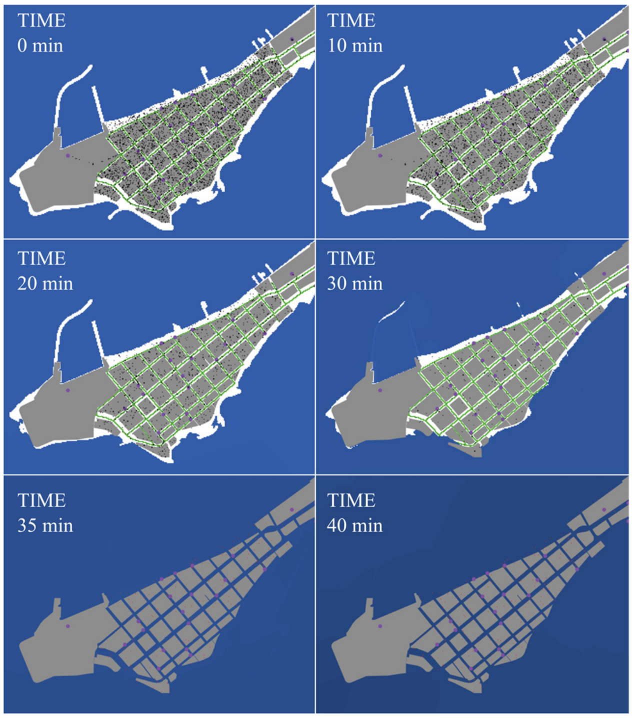


Fig. 10. Vertical Evacuation scenario result – Casualties are more related to the late evacuation than the congestion or crowding.

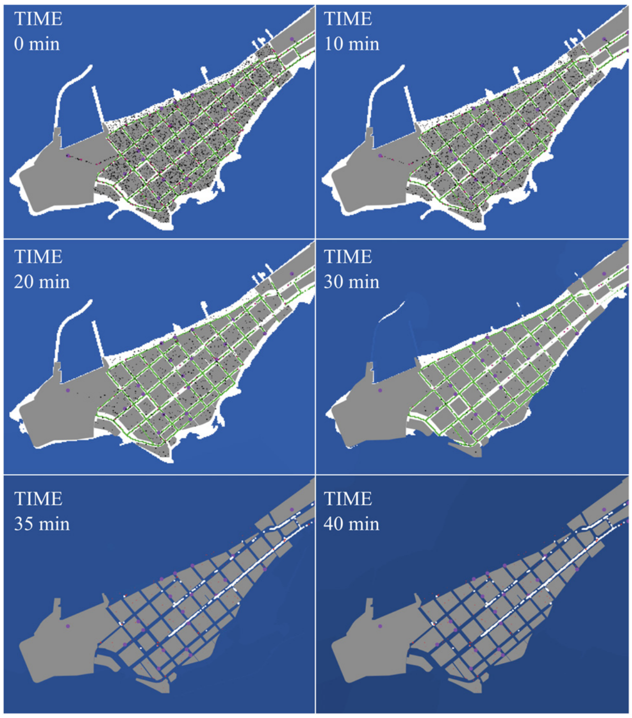


Fig. 11. Horizontal and Vertical Evacuation scenario result – Casualties are more related to the late evacuation than the congestion or crowding.

For the vertical evacuation case, no traffic congestion was observed due to the availability of enough space for pedestrians and the restriction on vehicles in the scenario

Table 3. Capacity and simulation results of 20 TEBs and 2 exits in two cases (Vertical Evac. and Horizontal and Vertical Evac.).

Code	Name	Vertical			Horizontal and Vertical			Capacity
		Avrg.	S.D.	Max.	Avrg.	S.D.	Max.	
S01	Escuela Naval	10	3	22	8	3	18	3000
S02	Av. Bolognesi No. 11	384	19	439	306	17	354	120
S03	Jr. Saenz Pena No. 275	183	13	220	145	12	182	540
S04	Jr. Tarapaca No. 155	311	18	361	247	15	287	105
S05	Jr. Saenz Pena cdra. 4	406	20	477	322	18	378	160
S06	Av. Bolognesi cdra. 1	157	12	184	124	11	164	100
S07	Jr. Larco No. 151	159	13	202	125	12	158	70
S08	Jr. Tarapaca No. 288	129	11	164	102	10	137	200
S09	Jr. Arrieta No. 295	258	16	304	204	14	246	200
S10	Jr. Arrieta No. 320	135	12	167	106	11	141	1450
S11	Jr. Arrieta No. 492	180	13	214	142	11	171	25
S12	Jr. Figueredo No. 470	154	12	185	122	11	161	110
S13	Jr. Figueredo No. 520	82	9	113	65	8	86	30
S14	Jr. Moore No. 496	157	11	196	124	11	159	165
S15	Av. Bolognesi No. 508	155	13	188	124	11	158	50
S16	Jr. Moore No. 380	322	17	373	255	16	295	75
S17	Jr. Tnte. Palacios No. 375	237	14	276	188	13	231	60
S18	Jr. Ferre No. 460	337	16	391	268	17	327	220
S19	Jr. Elias Aguirre No. 155	297	19	352	237	15	284	450
S20	Edificio SUNAT/SUNAD	141	11	174	113	10	146	800
E01	Exit 1	-	-	-	300	162	528	-
E02	Exit 2	-	-	-	293	166	500	-
	Total (pers.)	4194	-	-	3922	-	-	7930

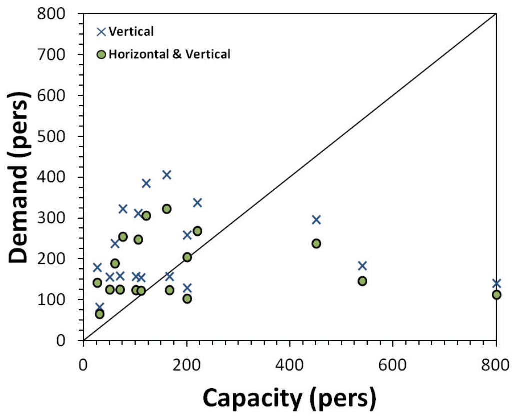
(*)Units: persons

(**Fig. 10**). The evacuation, apparently, runs smoothly with a minor number of casualties due to their late evacuation.

The third case simulated corresponds to the combination of horizontal and vertical evacuation cases. In this case, the number of casualties is lower compared to horizontal evacuation only due to the less use of some roads from pedestrians. It is observed that in several repetitions, although traffic congestion was observed at the narrow end of the district during evacuation, no casualties were observed at the end (**Fig. 11**). It is probable that casualties will occur, however, during traffic congestion as shown by some other repetitions that had results similar to the horizontal only case.

3.4.2. Shelter Demand

Table 3 shows detailed results for each tsunami evacuation building in regard to their capacity and the number of evacuees in vertical and horizontal and vertical cases. Furthermore, as observed also in **Fig. 12**, 13 of the 20 TEBs resulted with average over demand while 7 still had space available. In the upper inset in **Fig. 12** the difference in demand is clear from the vertical case to the horizontal and vertical case. While the horizontal and vertical case shows a lower demand of TEBs due to the possibility of shelter outside the area, the vertical case is shown to be more convenient to shelter more people and expect fewer casualties. It is necessary, nevertheless, to ensure the safety of evacuees even at over demanded shelters. As an example, building S11 with a capacity of 25 persons may expect around 180 residents in the area looking for shelter. This is seven times its capacity, meaning that a big group of people may not be able to access the roof area and will be compelled to remain on lower floors and thus at risk of inundation.



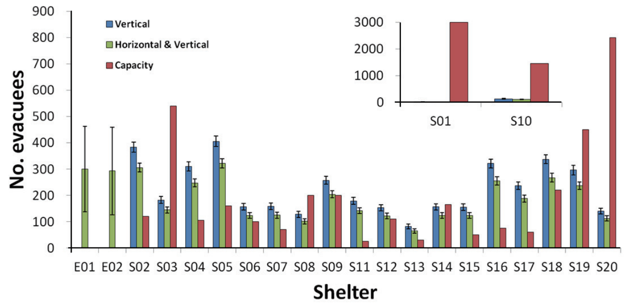


Fig. 12. Capacity and demand in La Punta – Out of 20 TEBs, 13 might present over-demand and 7 under-demands.

New areas for vertical evacuation around the district should, therefore be implemented because the actual spatial location of TEBs compromises the safety of residents.

3.4.3. Capacity Demand Mapping

In order to contribute to future mitigation plans and new alternatives for evacuation at La Punta, the resulting capacity-demand rate is mapped as shown in **Fig. 13**.

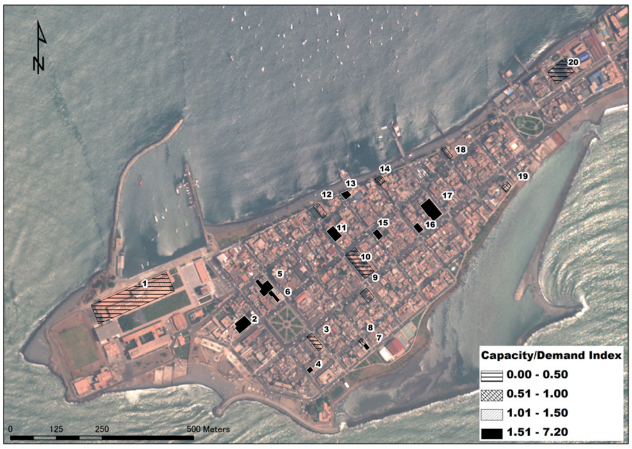


Fig. 13. CDI mapping – Capacity-demand mapping of TEBs. Fill black areas are over-demanded, horizontal lined areas are under-demanded (Vertical Evacuation case).

The relation capacity-average demand of the cases shown in **Table 3** represents the capacity demand index (CDI) following the simple relation in Eq. (1):

$$CDI = \frac{Demand}{Capacity} \quad . \ . \ . \ . \ . \ . \ . \ . \ . \ . \ . \ . \ . \quad (1)$$

In this sense, maps like the one shown in **Fig. 13** are easy for local stakeholders and laypersons to understand. A value of 0.0 to 0.5, therefore, indicates that less than half of the structure has been occupied, also values from 0.5 to 1.0 show that at most the total capacity of the structure is being used. Important information comes from CDI values over 1.0, where over demand conditions are encountered. As a result, it is possible to conclude from the CDI map that the nearest buildings are unfortunately of comparatively lower capacity than those located at both ends of the district. Due to the behavior of shelter selection (nearest), most of the structures closer to the beach area on the north coast present over demand, while the population on the south coast may apparently be accomodated within available structures.

4. Conclusions

The model of evacuation presented here for the integrated simulation of a tsunami hazard and human evacuation was developed in Netlogo considering aspects of human behavior. The study case in La Punta, Callao, Peru revealed the necessity of a vertical evacuation alternative in the area. New areas or improvements of already existing shelters must be conducted to ensure the safety of evacuees. As confirmed in many tsunami events around the world, the use of vehicles may bring difficulties to the evacuation procedure due to traffic congestion and bottleneck conditions. The simulator tool developed in this study may contribute to a better comprehension of evacuation system characteristics and possible measures for improving its performance.

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References:

[1] V. I. Clerveaux, T. Katada, and K. Hosoi, "Tsunami Scenario Simulator: A Tool for ensuring effective disaster management and coastal evacuation in a multilanguage society," Science of Tsunami Hazards, Vol.27, No.3, pp. 48-71, 2008.

[2] T. Hayakawa and F. Imamura, "Model of the determination of tsunami evacuation and its application," Journal of Japan Society for Natural Disaster Science, Vol.21, No.1, pp. 51-66, 2002.

[3] J. Meister, Simulation of crowd dynamics with special focus on building evacuations. Master thesis, University of Applied Sciences, 2007.

[4] R. Friedman, "An International Survey of Computer Models for Fire and Smoke," Journal of Fire Protection Engineering, Vol.4, No.3, pp. 81-92, 1992.

[5] S. Gwynne, E. Galea, M. Owen, P. Lawrence, and L. Filippidis, "A Review of the Methodologies Used in Evacuation Modelling," Fire and Materials, Vol.23, pp. 383-388, 1999.

[6] G. Santos and B. E. Aguirre, "A Critical Review of Emergency Evacuation Simulation Models," 2004.

[7] E. D. Kuligowski and R. D. Peacock, "A Review of Building Evacuation Models," tech. rep., 2005.

[8] X. Zheng, T. Zhong, and M. Liu, "Modeling crowd evacuation of a building based on seven methodological approaches," Building and Environment, Vol.44, pp. 437-445, Mar. 2009.

[9] J. Park, "Development of evacuation model for human safety in maritime casualty," Ocean Engineering, Vol.31, pp. 1537-1547, Aug. 2004.

[10] M. Amos and A. Wood, "Effect of door delay on aircraft evacuation time," 2004.

[11] M. K. Lindell and C. S. Prater, "Critical Behavioral Assumptions in Evacuation Time Estimate Analysis for Private Vehicles : Examples from Hurricane Research and Planning," Journal of Urban Planning and Development, Vol.133, No.1, pp. 18-29, 2007.

[12] T. J. Cova and R. L. Church, "Modelling community evacuation vulnerability using GIS," International Journal of Geographical Information Science, Vol.11, No.8, pp. 763-784, 1997.

[13] R. J. Dawson, R. Peppe, and M. Wang, "An agent-based model for risk-based flood incident management," Natural Hazards, Vol.59, pp. 167-189, Feb. 2011.

[14] M. Naser and S. C. Birst, "Mesoscopic Evacuation Modeling for Small- to Medium-Sized Metropolitan Areas," Tech. Rep. August, North Dakota University, 2010.

[15] J. Post, S. Wegscheider, M. Mück, K. Zosseder, R. Kiefl, T. Steinmetz, and G. Strunz, "Assessment of human immediate response capability related to tsunami threats in Indonesia at a sub-national scale," Natural Hazards and Earth System Science, Vol.9, pp. 1075-1086, July 2009.

[16] Y. Goto, M. Affan, Agussabti, Y. Nurdin, D. K. Yuliana, and Ardiansyah, "Tsunami Evacuation Simulation for Disaster Education and City Planning," Journal of Disaster Research, Vol.7, No.1, pp. 92-101, 2012.

[17] G. Lämmel, "Escaping the Tsunami : Evacuation Strategies for Large Urban Areas. Concepts and Implementation of a Multi-Agent Based Approach," Phd thesis, Technical University of Berlin, 2011.

[18] K. Watanabe and A. Kondo, "Development of Tsunami Evacuation Simulation Model to Support Community Planning for Tsunami Disaster Mitigation," Journal of Architecture Planning, Vol.74, No.637, pp. 627-634, 2009.

[19] M. Fujioka, K. Ishibashi, H. Kaji, and I. Tsukagoshi, "Multi agent Simulation Model for Evaluating Evacuation Management System Against Tsunami Disaster," Journal of Architecture, Planning and Environmental Engineering, Vol.562, pp. 231-236, 2002.

[20] F. Southworth, "Regional Evacuation Modeling: A State-of-the-Art Review," 1991.

[21] M. Kietpawpan, "Simulation Approach to Evaluating the Effectiveness of a Tsunami Evacuation Plan for Patong Municipality, Phuket, Thailand," Phd thesis, Prince of Songkla University, 2008.

[22] P. J. Sanchez, "As Simple as possible, but no simpler: A gentle introduction to simulation modeling," in Proceedings of the 2006 Winter Simulation Conference (L. F. Perrone, F. P. Wieland, J. Liu, B. G. Lawson, D. M. Nicol, and R. M. Fujimoto (Eds.)), pp. 2-10, 2006.

[23] C. M. Macal and M. J. North, "Agent-Based Modeling and simulation: Desktop ABMS," in Proceedings of the 2007 Winter Simulation Conference, pp. 95-106, 2007.

[24] T. Charknol and Y. Tanaboriboon, "Tsunami Evacuation Behavior Analysis," IATSS Research, Vol.30, No.2, pp. 83-96, 2006.

[25] E. L. Quarantelli, B. Baisden, and T. Bourdess, "Evacuation Behavior and Problems: Findings and Implications from the Research Literature," tech. rep., The Ohio State University, Disaster Research Center, Ohio, USA, 1980.

[26] F. Imamura, "Dissemination of Information and Evacuation Procedures in the 2004-2007 Tsunamis, Including the 2004 Indian Ocean," Journal of Earthquake and Tsunami, Vol.3, No.2, pp. 59-65, 2009.

[27] R. Lachman, M. Tatsuoka, and W. J. Bonk, "Human behavior during the tsunami of May 1960.," Science, Vol.133, pp. 1405-1409, May 1961.

[28] S. Tanaka, R. Tabuchi, R. Kimura, and G. Wu, "Tsunami Evacuation Behavior Reconsidered," Journal of Japan Society for Natural Disaster Science, Vol.25, No.2, pp. 183-195, 2006.

[29] T. Katada, M. Kodama, N. Kuwasawa, and S. Koshimura, "Issues of resident's consciousness and evacuation from the tsunami – From questionnaire survey in Kesennuma city, Miyagi Pref. After the Earthquake of Miyagiken-oki, 2003 –," Proceedings of the Japan Society of Civil Engineers, Vol.789, No.2, pp. 93-104, 2005.

[30] T. Saito, "Questionnaire Survey of Human Behaviors and Consciousness on the Tsunami of the 1989 Sanriku-Oki Earthquake," Journal of Japan Society for Natural Disaster Science, Vol.9, No.2, pp. 49-63, 1990.

[31] R. M. Gagne, "Principles of Instructional Design," Vol.44. Wadsworth Publishing Co Inc, Feb. 2005.

[32] X. Pan, C. S. Han, K. Dauber, and K. H. Law, "A multi-agent based framework for the simulation of human and social behaviors during emergency evacuations," Ai & Society, Vol.22, pp. 113-132, June 2007.

[33] D. K. Bird, "The use of questionnaires for acquiring information on public perception of natural hazards and risk mitigation a review of current knowledge and practice," Natural Hazards and Earth System Sciences, Vol.9, pp. 1307-1325, 2009.

[34] E. Gierlach, B. E. Belsher, and L. E. Beutler, "Cross-cultural differences in risk perceptions of disasters.," Risk analysis : an official publication of the Society for Risk Analysis, Vol.30, pp. 1539-1549, Oct. 2010.

[35] E. Mas, F. Imamura, and S. Koshimura, "Tsunami Risk Perception Framework for the Start Time Evacuation Modeling," in XXV IUGG General Assembly International Association of Seismology and Physics of Earths Interior, (Melbourne, Australia), 2011.

[36] U. Wilensky, "Netlogo," 1999.

[37] B. Anguelov, "Video Game Pathfinding and Improvements to Discrete Search on Grid-based Maps," Master thesis, University of Pretoria, 2011.

[38] T. Suzuki and F. Imamura, "Simulation model of the evacuation from a tsunami in consideration of the resident consciousness and behavior," Journal of Japan Society for Natural Disaster Science, Vol.23, No.4, pp. 521-538, 2005.

[39] Instituto Nacional de Estadistica e Informatica (INEI), "Censos Nacionales 2007," tech. rep., 2007.

[40] L. Dorbath, A. Cisternas, and C. Dorbath, "Assessment of the size of large and great historical earthquakes in peru," Bulletin of the Seismological Society of America, Vol.80, No.3, pp. 551-576, 1990.

[41] J. Kuroiwa Horiuchi, "Disaster Reduction. Living in harmony with nature," Editorial NSG, first edited, 2004.

[42] A. F. Espinosa, R. Husid, S. T. Algermissen, and J. De Las Casas, "The Lima earthquake of October 3, 1974: intensity distribution," Bulletin of the Seismological Society of America, Vol.67, No.5, pp. 1429-1439, 1977.

[43] C. Langer and S. William, "The 1974 Peru Earthquake Series," Bulletin of the Seismological Society of America, Vol.85, No.3, pp. 665-687, 1995.

[44] N. Pulido, Y. Yagi, H. Kumagai, and N. Nishimura, "Rupture process and coseismic deformations of the 27 February 2010 Maule earthquake, Chile," Earth, Planets and Space, Vol.63, pp. 955-959, Dec. 2011.

[45] F. Imamura, "Review of tsunami simulation with a finite difference method," in Long-Wave Runup Models, pp. 25-42, 1995.

[46] E. Mas, A. Suppasri, F. Imamura, and S. Koshimura, "Agent-based Simulation of the 2011 Great East Japan Earthquake / Tsunami Evacuation : An Integrated Model of Tsunami Inundation and Evacuation," Journal of Natural Disaster Science, Vol.34, No.1, pp. 41-57, 2012.

[47] U. Wilensky, "Modeling Nature's Emergent Patterns with Multi-agent Languages," in EuroLogo, (Linz, Austria), pp. 1-9, 2001.

[48] E. Mas, F. Imamura, and S. Koshimura, "Tsunami Departure Curves for Evacuation Simulation. A new approach to model the human behavior in tsunami evacuation.," pp. 1-23, 2012 (under review).

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- E. Mas, B. Adriano, S. Koshimura, F. Imamura, J. Kuroiwa, F. Yamazaki, C. Zavala, and M. Estrada, "Evaluation of Tsunami Evacuation Building Demand through the Multi-Agent System Simulation of Residents' Behavior," in Proceedings of International Sessions in Coastal Engineering, JSCE, Vol.3, 2012.
- B. Adriano, S. Koshimura, and Y. Fujii, "Tsunami Source and Inundation Modeling of the June 2001 Peru Earthquake," in Joint Conference Proceedings 9CUEE/4ACEE, Tokyo, pp. 2061-2065, 2012.

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- S. Koshimura, Y. Hayashi, K. Munemoto, and F. Imamura, "Effect of the Emperor seamounts on trans-oceanic propagation of the 2006 Kuril Island earthquake tsunami," Geophysical Research letters, Vol.35, L02611, doi:10.1029/2007GL032129, 24, 2008.
- S. Koshimura, T. Katada, H. O.Mofjeld, and Y. Kawata, "A method for estimating casualties due to the tsunami inundation flow," Natural Hazard Vol.39, pp. 265-274, 2006.

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