TSUNAMI HAZARD EVALUATION FOR INFORMAL SETTLEMENTS LOCATED AT THE NORTH OF CALLAO – PERU

M. Estrada(1), J. Morales(2), A. Delgado(3), R. Cuadros(4), J. Kuroiwa (RIP)(5)

(1) *Professor, National University of Engineering – Lima - Peru, estrada@uni.edu.pe*
(2) *Assistant Researcher, Japan-Peru Center for Earthquake Engineering Research and Disaster Mitigation – Lima - Peru, jmoralest@uni.pe*
(3) *Director General Manager, Disaster Risk Reduction Peru International SAC - Lima - Peru, adelgado@drperu-internatioinal.com*
(4) *Planning Architect, Disaster Risk Reduction Peru International SAC - Lima - Peru, cuadrosrocio@yahoo.es*
(5) *Emeritus Professor, National University of Engineering UNI - Lima - Peru, jkuroiwa@drperu-international.com*

Abstract

Urban growth in many of the peripheral spaces of the city of Lima has developed in an informal, disorderly way, ignoring the implementation of technical guidelines to regulate land use and occupation and without control by local authorities. This scenario typifies human settlements in areas highly exposed to tsunamis, housing large, densely concentrated populations, and which lack properly designed buildings for housing; violating intangible areas and public spaces designated for services and other urban activities. Such are the human settlements in the area between the coastline of the bay of Callao and the west side of Lima's Jorge Chavez International Airport, facing the Pacific Ocean.

The seismic activity produced by the subduction of the Nazca and South American Plates off the Peruvian coast has generated harmful tsunamis, such as the 1746 Lima earthquake, which, according to historic data and evidence, razed the port of Callao and flooded the low-lying zone of Callao addressed in this article.

This study was carried out considering the high probability of a tsunamigenic earthquake, the natural and constructed alterations of the relief of the terrain, presence of medium-height buildings and facilities, the urban layout characteristics, existing road network, and expansion of Jorge Chávez International Airport; making it possible to identify wave generation and propagation times, evaluate the scale of the flood areas, estimate physical and economic damage to housing and facilities, and provide recommendations for damage prevention and mitigation; therefore becoming a tool of great importance for local sustainable town management.

A tsunami-flooding sensitivity study was made for earthquake magnitudes from Mw 8.5 to 8.8, with a step of Mw 0.1, based on studies conducted by the Japan-Peru Center for Earthquake Engineering Research and Disaster Mitigation –CISMID, Civil Engineering Faculty of the National University of Engineering. For the propagation analysis, the shallow waters theory was applied using TUNAMI-N2 software developed by Tohoku University, Japan; and for the flooding stage, the topography had to be updated by processing images acquired with UAVs. For this last stage of the simulation, the variation of a very important parameter was considered: surface roughness of the flood zone, using different values according to soil occupation conditions. Finally, probable flood zones were identified, and evacuation routes and refuge areas are proposed to safeguard the population.

It should be noted that this study had the support of Lima Airport Partners, concessionaire of Jorge Chavez International Airport, to whom the authors express their gratitude.

Keywords: Tsunami hazard analysis; Manning´s roughness coefficient; human settlements.

1. Introduction

The City of Lima is in a highly seismic area and scientific studies show a seismic silence of 274 years that is accumulating energy which must be released at any moment, since the last great earthquake of October 28, 1746 that not only caused great destruction in the City of Lima, but also caused a large tsunami that affected an important area of Callao and Lima, according to the evidence that has been compiled over the time. Seismic history also shows that these events are recurrent over time and although they cannot yet be predicted when they will happen it is necessary to evaluate the most probable area that could be affected by this phenomenon, especially in areas highly vulnerable. This is the case of the current study where the analyzed area is mainly occupied by informal settlements, social infrastructures and the expansion of the new landing track of the Jorge Chavez International Airport.

During the urbanization process of the study area there has been an important change of the topography in the last 20 years that has to be considered for the correct analysis of the inundated area due to the tsunami and for the proposal of the evacuation plan.

Tsunami numerical simulations is conducted using different seismic scenarios from 8.5 Mw to 8.8 Mw that will produce the inundation areas and their respective inundation depths. It ss important to mention that numerical simulations have considered different values of roughness coefficient that will represent in the best way the conditions of the land use. Having these results, it will be proposed the best alternative for evacuation routes that will take the shortest time for people to reach the safe areas. Also, for this matter it is necessary to understand the urban characteristics to determine the concentration of people and infrastructure. In addition, buildings damage level will be estimated from inundation depths for all the scenarios.

Disaster Risk Reduction (DRR) activities have been aimed at promoting the improvement of risk knowledge and the development of an effective response. These actions have been mostly led by the Citizen Security and Civil Defense Management of the Callao Regional Government and in some cases have been implemented with the contribution of international cooperation.

It is intended to provide a technical tool that facilitates the safeguarding of the population against a tsunami, through the identification of evacuation routes and safe areas that allow the temporary shelter of the affected population.

The development of the proposal is based on three criteria that are synthesized in the integration of disaster risk management with existing technical regulatory instruments, strengthening local resources and capacities; and improving the culture of population prevention.

2. Urbanistic Description of the Study Area

The area of study is located south of the Bay of Callao, in the area of direct influence generated by the most important air and port infrastructure of the country: the Jorge Chavez International Airport and the Port of Callao. Fig. 1 shows the study area with the perimeter of the International Airport expansion.

The study area, consists of human settlements located on a very low slope esplanade, crossed by ancient agricultural drainage axes facing the sea. These human settlements occupy an area of 85.3 Hectares, there are no areas of urban expansion and currently they are adjoining with large port logistics support plants, the expansion of Jorge Chavez International Airport, urban prison facilities and the Pacific Ocean.

As of 2018, a total population of 31,468 is estimated and an average density of 369 inhabitants per hectare. Housing based on self-construction and progressive execution or in stages, is characterized by technical and legal informality due to: (i) the occupation of land intended for protection; (ii) inadequate use of building materials, and (iii) non-compliance with technical building standards. The various urban facilities of educational, commercial, health, recreational, safety, etc.; are oriented to cover only the basic needs of the local population.

Local urban context of the area under study can be characterized by: High urban pressure towards the coastal edge due to the absence of feasible land for urban expansion, growing informal occupation towards this area occupying reclaimed land from the sea filled with construction residual material, limited internal road accessibility in the whole study area, insufficient emergency services, extreme conditions of precariousness of the houses, especially in areas of recent occupation, high vulnerability of public spaces, lack of knowledge on

DRR of both, people and decision makers from the study area and restricted fluidity of vehicle and pedestrian traffic in normal and emergency situations.

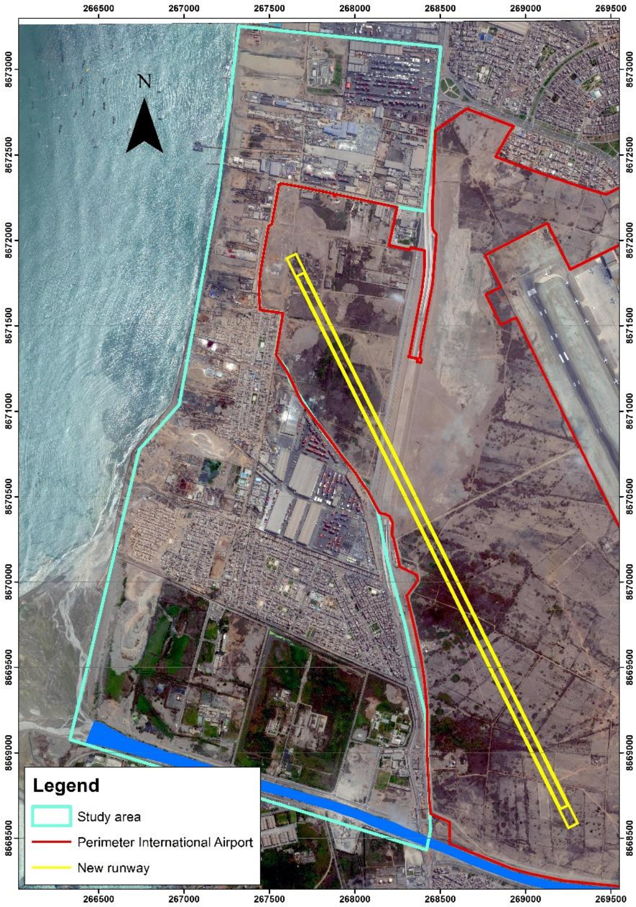

Fig. 1 – Map of the study area at west of International Airport Jorge Chavez and north of Callao Port. The yellow polygon shows the location of the future runway

Given the geographical physical conditions of the study area location in which the first-class port facilities are located in the country (Callao port and Jorge Chavez International Airport) and where in addition, the use of industrial urban land predominates; the location of the study area plays a strategic role in the territorial and urban development of its jurisdiction. For these reasons it is necessary to know what could be the inundated areas covered by the tsunami under different seismic scenarios and in this way give the proposals for the evacuation routes and refuge places to authorities and population that are living in this location.

3. Historical Tsunamis in Peru

Because of its location, Peru has experienced some of the largest tsunamis that have occurred in the world, according to the tsunami database taken from the National Geographic Data Center (NGDC) four large tsunamis have affected Peruvian coasts in the last three decades. Fig. 2 shows the location of the latest earthquakes that generated the mentioned tsunamis and their aftershocks and Table 1 describes them.

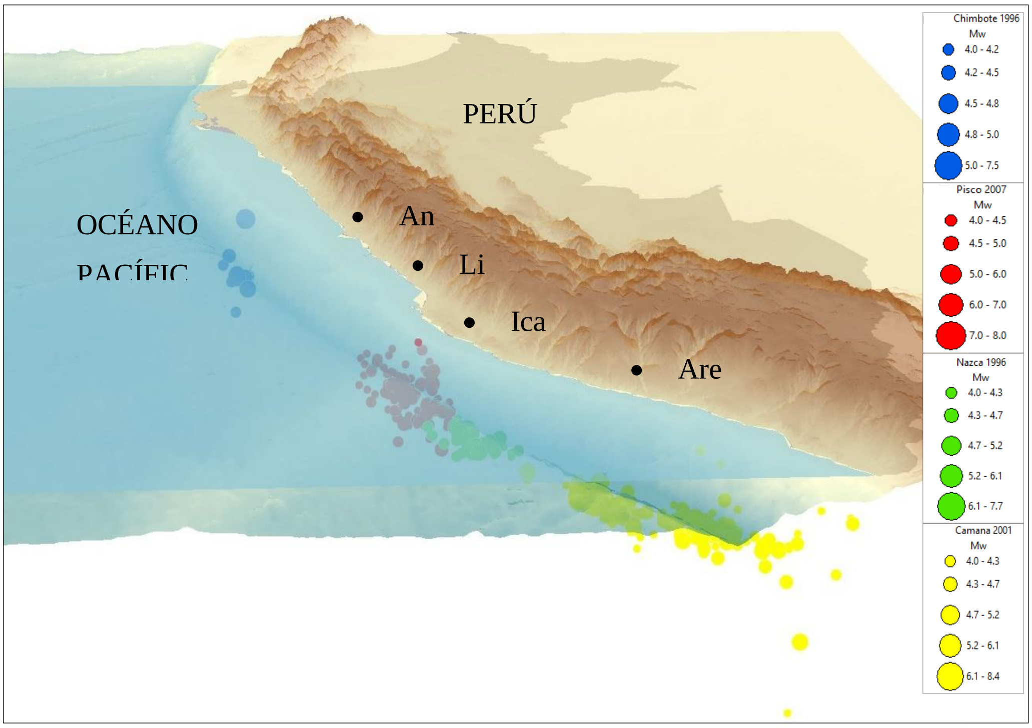

Fig. 2 – Location of the last four earthquakes and their aftershocks that produced tsunamis in Peru

Table 1 – Last tsunamis recorded in Peruvian coasts

Date	Magnitude (M_w)	Affected Cities
21/02/1996	7.5	Chimbote, Callao
12/11/1996	7.7	Chincha alta, Arica, Nazca, Marcona
23/06/2001	8.4	Camana, Moquegua, Tacna,
15/08/2007	7.9	Nazca, Pisco, Lima

For example, the tsunami that occurred on June 23, 2001 in southern Peru was generated by an earthquake of magnitude Mw 8.4. According to the USGS, at least 75 people died, where 26 people were killed due to the tsunami, 2687 people were injured, 17510 homes were destroyed and 35549 homes were affected in the Arequipa, Camana and Tacna areas [1]. Another more recent example is the tsunami that occurred on August 15, 2007, where the coastal areas of Chincha and Paracas in Ica Region were the most affected. According to the Peruvian Geophysical Institute (IGP) report, waves reached maximum run-up heights of up to 2.91 m and distances of 102.7m inland [2].

One of the largest tsunamis in Peru occurred on 1746 after an earthquake with an estimated magnitude of 8.9 Mw. The results of this event, according to historical chronicles, were of approximately 5,000 people death and almost 3,000 buildings destroyed or much damaged [3]. According to these chronicles this tsunami produced waves of more than 21 m of height and the arrival time was approximately of 30 minutes after the earthquake [4]. Fig. 3 shows a comparison of Callao City before and after the 1746 earthquake and tsunami, where is evident the destruction of the majority of houses [3].

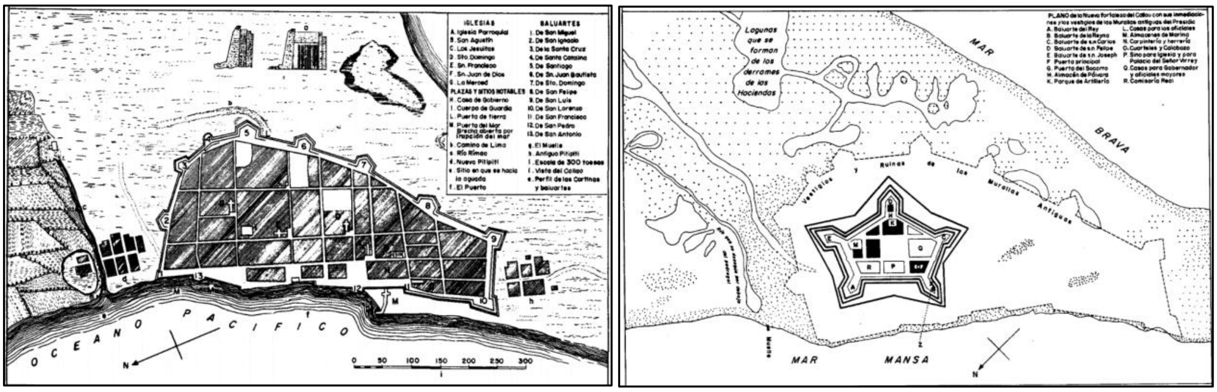

Fig. 3 – Left, Callao city before the 1746 earthquake and tsunami. Right, Callao after the 1746 event [3]

4. Topography Update for the Tsunami Simulation

A multitemporal analysis of the study area images was performed, images that were obtained from the satellite imagery catalog of the Google Earth service. With this acquired information, a comparison of images that cover exactly the same area but that were captured on different dates can be made, which makes possible to detect changes in land use.

Fig. 4 shows the changes made in the study area where the number of informally constructed houses have increased. This difference of the coastline morphology has been carried out through informal transformation from sea areas into land areas that have been filled without any technical supervision. This situation makes this area of informal settlements, not only to be exposed to the tsunami attack, but also, for the soil conditions, in the case of a severe earthquake this land may suffer of liquefaction phenomenon producing even more damage to buildings that are on this ground. For these reasons it is necessary an update of the topography and will be carried out using Remote Piloted Aircrafts (RPA).

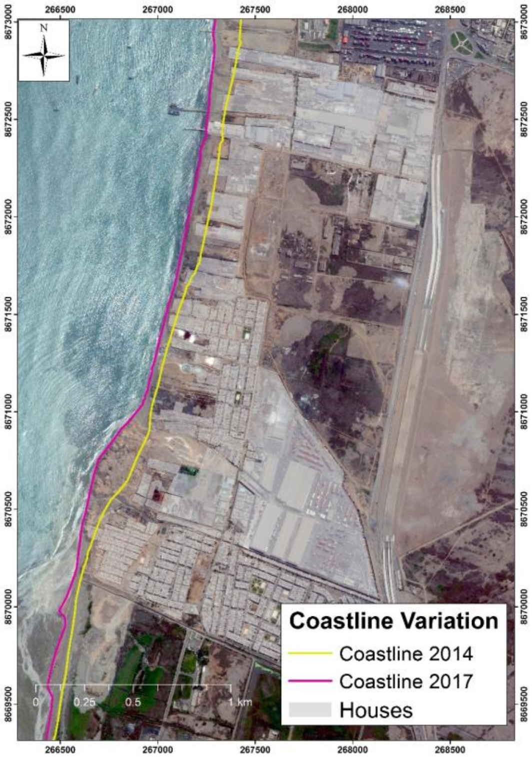

Fig. 4 – Coastline variation obtained from the multitemporal analysis carried out

By processing the aerial data, it can be generated a digital elevation model (DEM) as well as an updated orthophoto of the area under study. These new geographic products have to be well georeferenced, for this purpose Ground Control Points (GCP) were deployed throughout the study area by using high precision differential GPS equipment.

Data acquisition in the form of images was performed using RPAs with a 16 MP (megapixels) camera. Flight plan was carried out with both the Pix4D Capture and Map Pilot applications for DJI in their versions for Android and iOS operating systems respectively. Fig. 5 shows the RPA trace and some preliminary results of the flight carried out and Table 2 shows main properties of the flight.

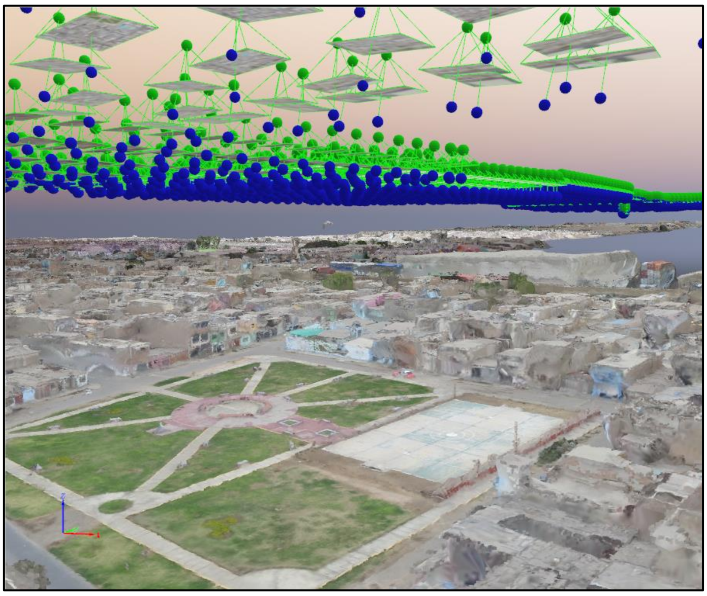

Fig. 5 – RPA trace and preliminary results of the study area

Table 2 - Flight plan properties and detail of the most important parameters that characterize it

n	Parameter	Value
1	Flight area	114 Ha
2	Average flight velocity	9 m/s
3	Number of images	1731
4	Flight height	100 m
5	Spatial resolution	4.5 cm/pixel

As a tsunami spreads in shallower and deeper waters, and especially during the flood stage, the bottom resistance becomes increasingly relevant as an element of energy dissipation. This is included in the numerical modeling schemes through a specific term, which is usually based on the Manning model for the calculation of friction energy loss.

In the case of the Manning model, an empirical coefficient that represents the level of friction must be determined. The implementation of the friction terms varies among the numerical models, there being some in which only global friction coefficients can be prescribed in a whole study area, while some allow spatial variations of the roughness coefficient.

The results obtained by using RPA are useful not only to know the ground elevation, but also to estimate land use and roughness coefficient, the relation between these two parameters is shown in Table 3 [5].

It is common to use a Manning coefficient value (n = 0.025) in aquatic areas, while in terrestrial areas this coefficient may change depending on land use. Land use can be determined from the Urban Development Plan of the Constitutional Province of Callao (see Figure 13) and verified with field work.

Table 3 - Roughness coefficients according to land use (Kotani et al. 1998) [5]

Land Use	**Roughness coefficient**
Residential area (high density)	0.080
Residential area (medium density)	0.060
Residential area (low density)	0.040
Industrial area	0.040
Cropland	0.020
Forest	0.030
Water bodies	0.025
Others	0.025

5. Tsunamigenic Earthquake Scenarios

In order to evaluate the tsunami hazard of the study area, a review of the historical seismicity is performed to determine the seismic scenarios most likely to occur. With this information, the parameters of the seismic source are established to calculate the initial deformation of the ocean surface. Next, the numerical simulation of the tsunami is performed. As a result of this analysis, the variation of the water level in the probable areas of inundation, the time of arrival of the first wave and the maximum heights of the waves on the study area coasts are obtained.

In the present study, the source models are based on four different seismic scenarios. The first is a model based on the distribution of interseismic coupling in the subduction zones for a period of 265 years since the earthquake of 1746, here also the measurements of the seafloor deformation obtained from GPS sensors and acoustic transponders are included, as well as information on historical earthquakes to finally propose the distribution of landslides resulting in a magnitude of 8.8 Mw (Pulido et al., 2011) [6].

The other three scenarios were calculated by scaling the energies generated from the aforementioned model, so that they result in earthquakes of the following magnitudes 8.5, 8.6, 8.7 and 8.8 Mw. When performing this scaling, the dislocations in each of the sub-faults will be modified, generating different deformations on the seabed and as a consequence different height of the waves on the free surface of the water.

The source of the first seismic scenario is divided into 280 sub faults, each of 20 km x 20 km, in an area of rupture 700 km long by 160 km wide. The calculated momentum magnitude is 8.8 Mw (see Fig. 6 right down). The distribution of landslides shows two main asperities, the largest located 70 km west of Lima with a landslide of 15.4 m, and the second one south of Lima with a value of up to 13.0 m, Fig. 6 shows the distribution of displacements.

The other 3 scenarios have the same characteristics with the exception of the slip values. For the scaling of seismic scenarios less than 8.8 Mw generated by Pulido et. al., 2011, the author was asked for the geometric and seismic characteristics of the 280 sub-faults that generated this seismic scenario. The scaling for earthquakes of lower magnitude was carried out through a coefficient that multiplies the displacement or dislocation of each of the sub-faults and then calculate the energy, as seismic moment (M0), generated by this displacement, then all these energies are summed up obtaining the energy of the entire fault and the equivalent moment magnitude (Mw) is calculated. The Eq. (1) shows the relation between the moment magnitude and the seismic moment.

$$Mw = \log(M_0 + 1)/1.5 - 10.73 \qquad (1)$$

By applying this scaling, the geometric characteristics of the source were maintained (the length and width remained constant), generating equivalent seismic sources with lower displacements or dislocations at the time of rupture. The results of this escalation are shown in Figure 10.

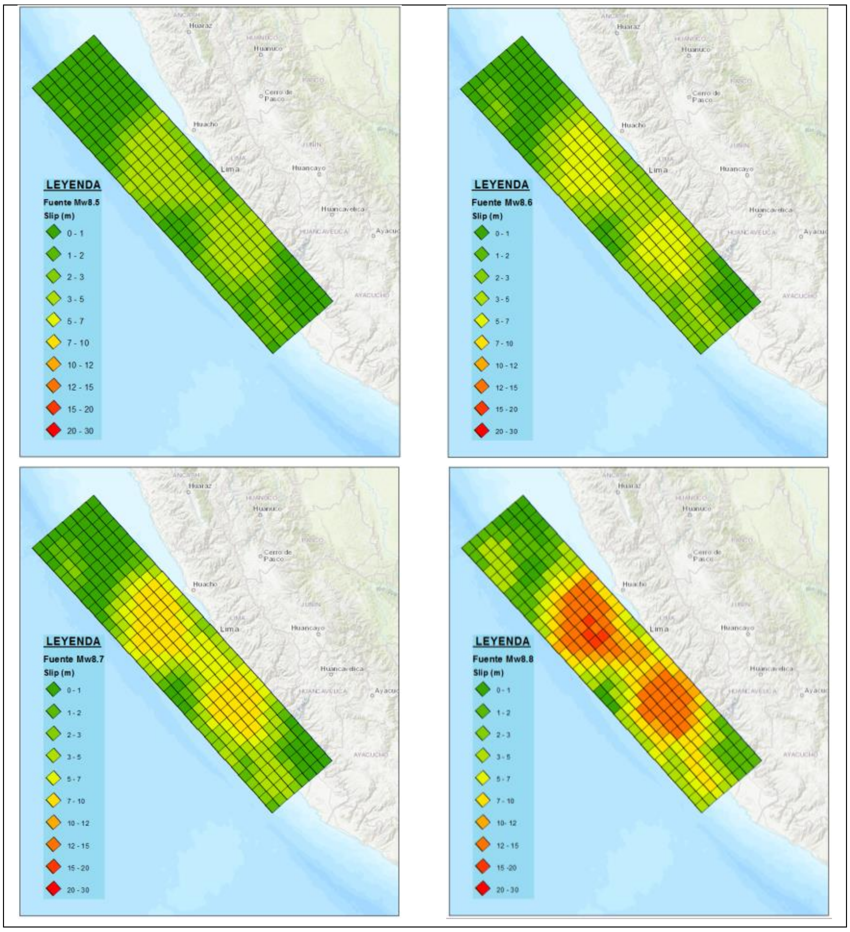

Fig. 6 - Distribution of displacements of the four seismic scenarios, from 8.5 to 8.8 Mw

6. Evaluation of the Affected Areas

In order de assess the potential affected areas, a tsunami numerical simulation is carried out by using the TUNAMI-N2 program (Tohoku University Numerical Analysis Model for Investigation of Near Field Tsunami No. 2), the source code is based on the shallow water theory and was developed by the Disaster Control Research Center (DCRC - Tohoku University, Japan).

Propagation and inundation analysis were performed using UTM coordinate system in the WGS84 datum, Zone 18S. The calculation area is divided into five domains or regions, where the domains are connected to others using the nested mesh system. The Fig. 7 and the Table 4 shows the extension of mentioned domains.

For this simulation, the bathymetry and topography were taken from the website of the General Bathymetric Chart of the Ocean (GEBCO) with a spatial resolution of 30 arc seconds, which for the geographical location of study is approximately 900 m, and subsequently is interpolated to 45 meters used up to domain 3. For domains 4 and 5 the bathymetry that was collected during the SATREPS project was used with a spatial resolution of up to 5 meters, the topography was obtained from aerial images taken with RPAs that were processed using photogrammetric techniques. The resolution topography of up to 30 cm was interpolated to obtain a resolution of 5 and 15 meters in domains 5 and 4 respectively, these resolution values are show in Table 4.

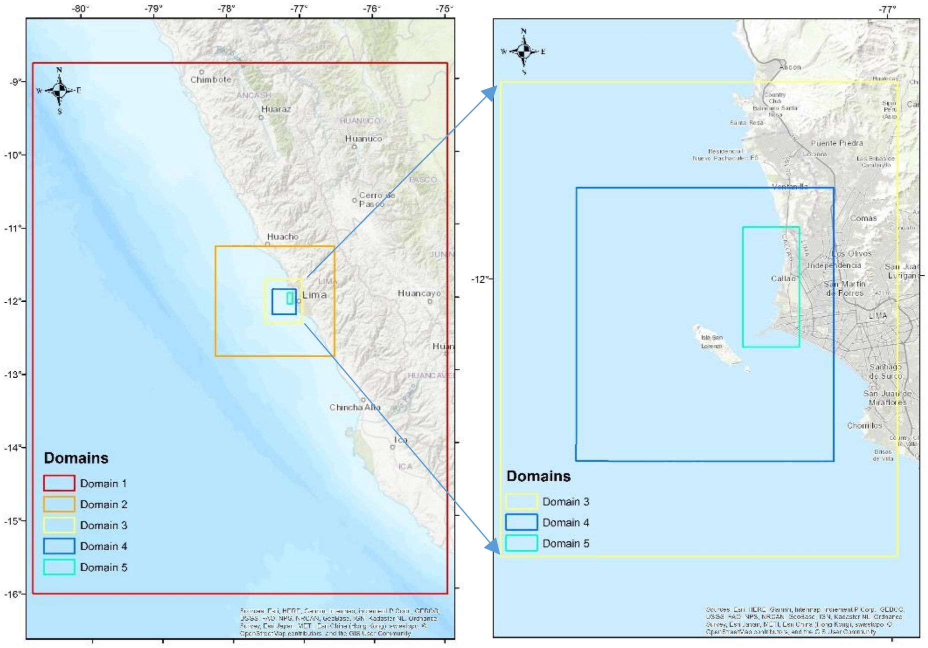

Fig. 7 – Extension of the domains used in the numerical simulation (Basemap from GEBCO and NOAA)

Table 4 – Domains extension, data source and resolution of the topography and bathymetry

Domain	East (m)		North (m)		Res. (m)	Data source	
	Min	Max	Min	Max		Bathymetry	Topography
1	-123900	504255	8222000	9028355	405	GEBCO 27 s	GEBCO 27 s
2	152600	333095	8582900	8750435	135	GEBCO 9 s	GEBCO 9 s
3	228200	283370	8633500	8699695	45	DHN 45 m	SRTM+Google
4	238675	274540	8646775	8684890	15	DHN 15 m	SRTM+RPAS
5	261885	269720	8662700	8679430	5	DHN 5 m	SRTM+RPAS

The total simulation time is five hours and the time interval for the simulation, in order to satisfy the numerical stability, is 0.2 seconds. In order to know the behavior of the tsunami, synthetic tide gauges were placed along the coast of the Study Zone, synthetic points were also placed in the Tentative Refuge areas in case of a tsunamigenic earthquake. The position of the synthetic tide gauges is show in Fig. 9 and the results for Point 5, located almost in the middle of the study area, are presented in Fig. 8.

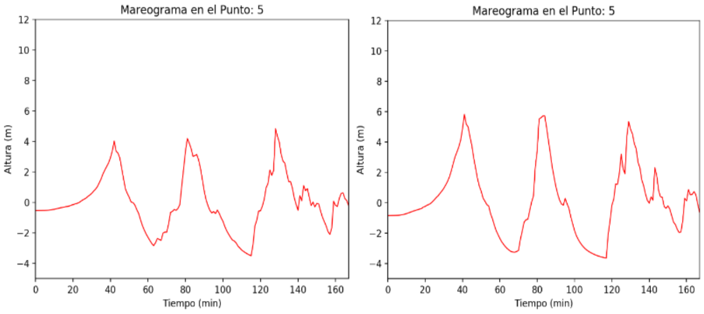

Fig. 8 – Synthetic signals from the tsunamis of 8.7 Mw (left) and 8.8 Mw (Right)

The results of the inundation depth and the inundation area are presented through thematic maps that represent inundation levels using colors from green to red (like traffic lights), The Fig. 9 shows these results obtained from all the scenarios computed.

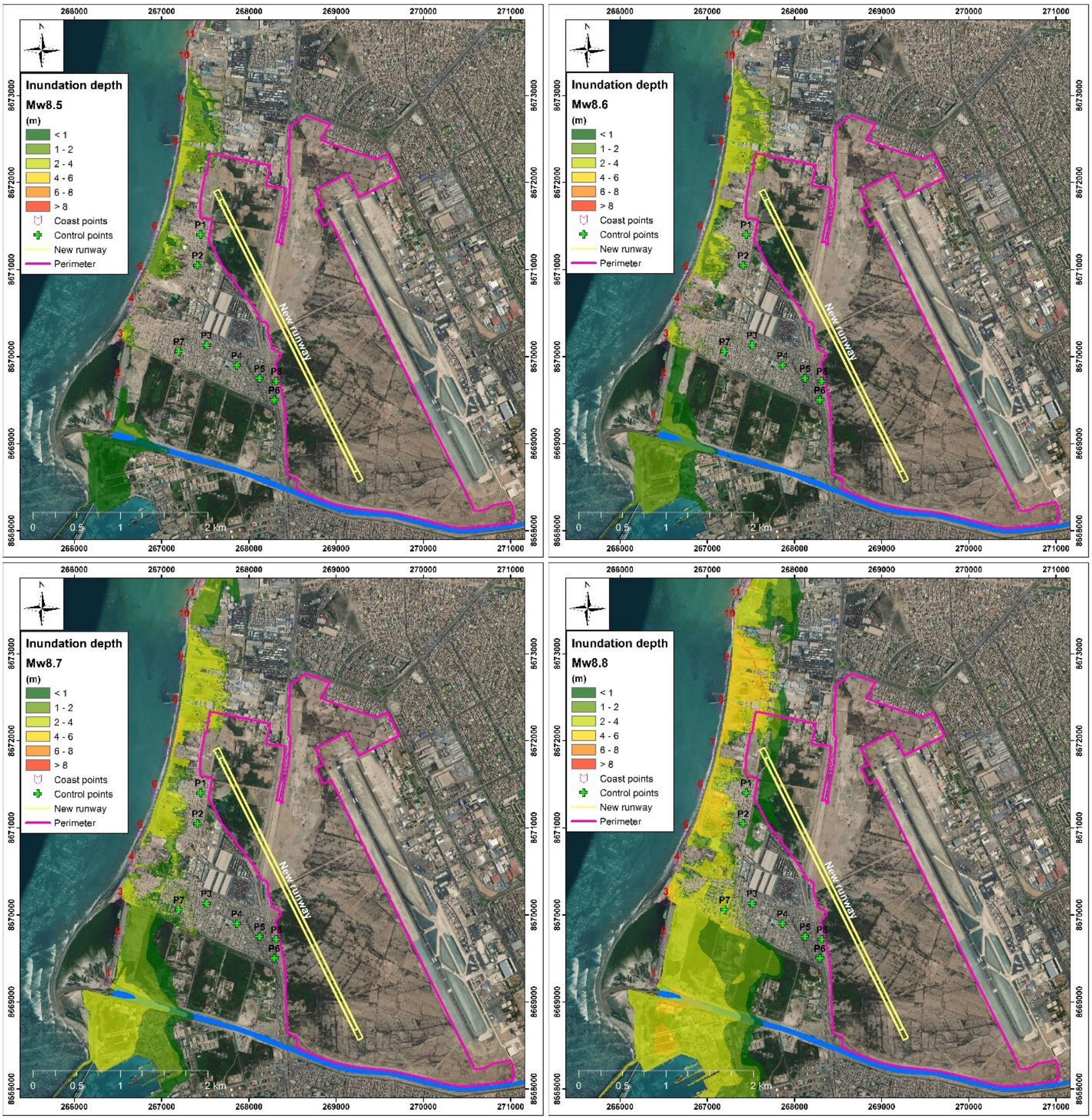

Fig. 9 – Inundation depth maps under four scenarios (8.5 to 8.8 Mw)

The inundation analysis was complemented with field surveys to obtain physical information of the buildings within the study area. This information allows to estimate the damage in buildings and to recognize where the more vulnerable areas in case of a tsunamigenic earthquake are.

Periodic field trips were made with the teams of evaluators for a period of two weeks. This information is encrypted and taken to a database in a geographic information system (GIS) platform for georeferencing.

After the field surveys, four parameters of buildings were obtained, predominant material, the number of stories, shown in Fig. 10, the land use and their condition.

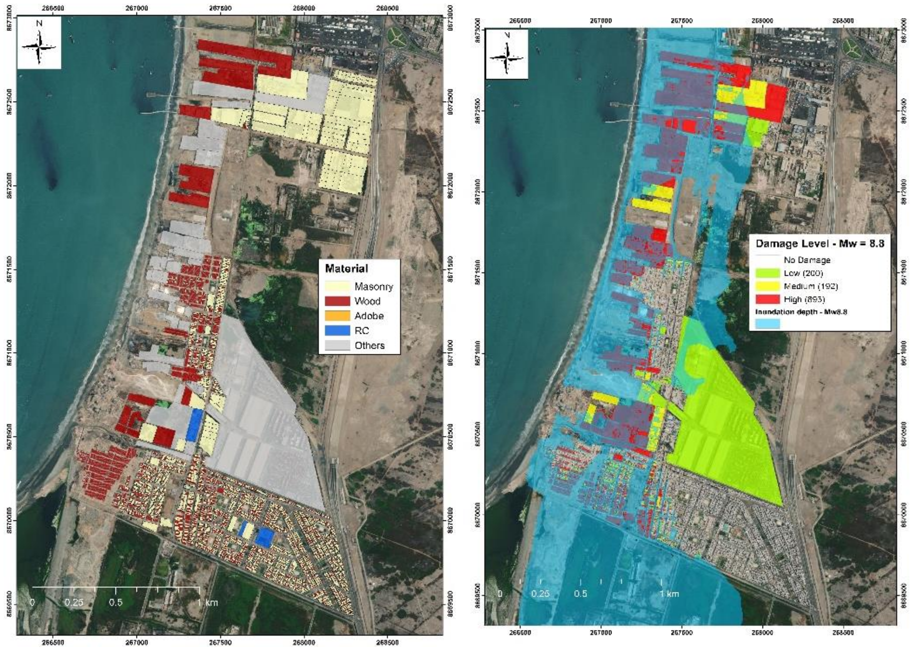

Fig. 10 – Physical characteristics of the buildings in the study area, left: predominant material, right: Damage level for 8.8 Mw scenario.

By combining the inundation results with the exposure model shown in Fig. 10, it is possible to estimate the damage levels in this buildings produced for the earthquake and the tsunami. This estimation of the damage levels was achieved using fragility curves for different materials developed from the earthquakes and tsunamis that occurred in Chile in 2010 and in Indonesia in 2004 [7]. **¡Error! No se encuentra el origen de la referencia.** shows the results obtained by applying this methodology in the study area.

7. Evacuation Plan Proposal

Due to the need to expand the Jorge Chavez International Airport, it is planned to develop the runway No. 2, which makes it necessary to build a fence on its west side, which will produce a partial enclosure of approximately 30,000 inhabitants living in the affected area.

In this case it is proposed to open a new 10 meters road between the north of the urban settlements and the west of the airport expansion, in the Fig. 11 this new road is shown heading to IV- 1 highway. It is important to point out that the necessary area for this road will be transferred by the airport. The other evacuation routes have been designed so that they are as perpendicular as possible to the coastline, with the aim of the population that is evacuating reaches high levels as quickly as possible and can escape the effects of the tsunami, as it is shown in Fig. 11. Possible places of refuge have also been identified, Fig. 11 right, especially open areas such as parks that are outside the flood area.

Finally, all this study and especially the knowledge about evacuation routes must be known by the local authorities so that they are transmitted to the local population and that this knowledge is strengthened through citizen participation in evacuation drills.

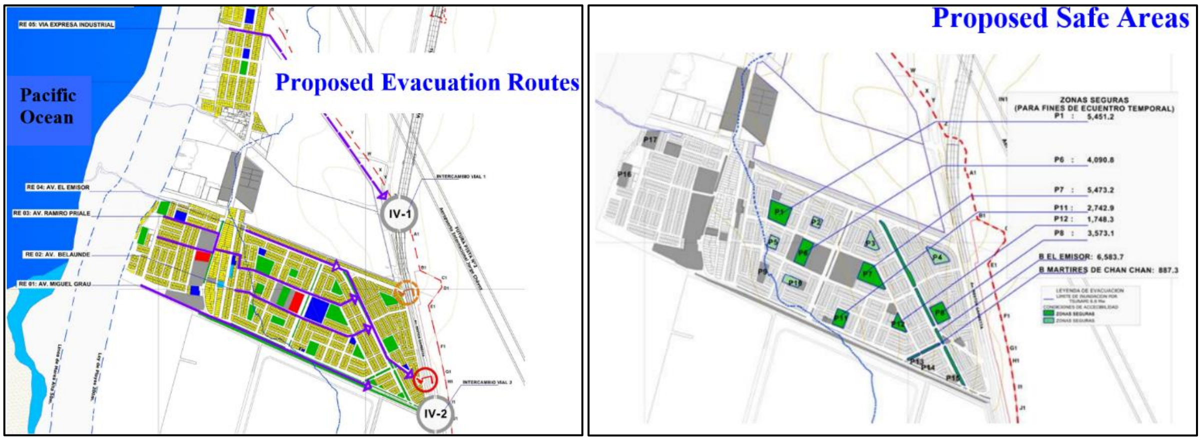

Fig. 11 – Left: Evacuation routes proposed, shown in purple color, right: Possible places of refuge, blue line represents the tsunami extent inland.

8. Concluding remarks

It has been identified that the development of urban settlements without control and planning expose the population to suffer the effects of natural phenomena like earthquakes and subsequence tsunami. This leads to the development of studies that mitigate the possible effects in these cases. Likewise, to be able to measure the magnitude of the effect in case of a tsunami it is very important to know the parameters that influence its calculation, that is why in this study the type of land occupation and the physical characteristics of the buildings have been considered and through new technologies, with the use of UAV the updating of the topography has made it possible to evaluate the flood zone more accurately. Finally, the proposal of evacuation routes and refuge areas must be socialized between the authorities and the population so that it has a positive effect in mitigating the risk of earthquake and tsunami disasters not only in this area but also in ll urban settlements that are located near to Peruvian coast.

9. Acknowledgements

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