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ADVANCES OF TSUNAMI RISK REDUCTION FOR FACILITIES AND INFRASTRUCTURE WORKS IN PERU

A. Delgado(1), M. Estrada(2), C. Jimenez(3), J. Kuroiwa (RIP)(4)

(1) *Director General Manager, Disaster Risk Reduction Peru International SAC-Lima-Peru, adelgado@drperu-international.com*
(2) *Professor, National University of Engineering – Lima -Peru, estrada@uni.edu.pe*
(3) *Associate Professor, National University of San Marcos – Lima - Peru, cjimenezt@unmsm.edu.pe*
(4) *Emeritus Professor, National University of Engineering-Lima-Peru, jkuroiwa@drperu-international.com*

Abstract

The 2004 Indian Ocean Tsunami that killed around 230,000 people and the existence of a seismic gap in the Central Region of Peru, including Lima city (Peru's Capital) and Callao (the main seaport), with 10 million inhabitants, gave added impulse to tsunami research and tsunami damage reduction measures in buildings, facilities and infrastructure projects.

From 1982 to the present, some 25 civil engineering professional and Master's theses have been developed at National University of Engineering (Universidad Nacional de Ingeniería, UNI), with bathymetry information provided by the Directorate of Hydrography and Navigation (Dirección de Hidrografía y Navegación, DHN) of the Peruvian Navy. Key data such as the arrival time of the first tsunami wave, tsunami height**,** and inland inundation limits were found for the most important cities and ports along the Peruvian coast. One of the main applications was in the multi-hazard map of the Peru Sustainable Cities Programme (PSCP), involving 175 cities, which sought to protect around 8 million Peruvians from natural and technological disasters. The PSCP was selected as the best of 81 projects on disaster risk reduction in the Americas in 2012. Members of the selection committee were representatives of Organization of American States (OAS), United Nations Development Program (UNDP), United Nations Human Settlements Programme (UNHABITAT), International Federation of Red Cross (IFRC) and United Nations Office for Disaster Risk Reduction (UNDRR**,** formerly known as UNISDR).

Tsunamis are analyzed for damage caused in ports in Peru, Japan**,** and Chile. The case of the tsunami protection study in the North Terminal of Callao Port is explained, where a study was conducted to determine the height and the arrival time of the tsunami wave, and it is recommended that a more in-depth study be led by Japanese and Peruvian experts.

The summary of the tsunami hazard study for the highway tunnel under the extension of the second runway of Lima International Airport is presented, as well as recommendations and protection works.

A proposal for a tsunami-resistant standard in Peru prepared at the request of National Training Service for the Construction Industry (SENCICO), is also presented in summary.

Recently, an investigation was carried out at the doctoral thesis level consisting of the numerical simulation of the seismic source of tsunamigenic earthquakes applied to the Peruvian case within the seismotectonic setting of the subduction zone between the Nazca and South American plates. A summary of the main results of this research is presented.

Keywords: Tsunami risk reduction; tsunami simulation; port; infrastructure works.

1. Introduction

The Indian Ocean tsunami of 2004 caused more than 230,000 victims; and the Japan 2011 tsunami, more than 18,000 victims. In Peru, there has been seismic silence along the coast of its capital city, Lima, and principal port of Callao. This is why importance must be given to earthquake and tsunami risk reduction. All along its coast, Peru has large cities that also need to take appropriate measures.

In this article, we present the Sustainable Cities Programme as a successful example of the application of risk reduction techniques for 175 Peruvian cities. The programme was introduced and directed by one of the authors, Julio Kuroiwa Horiuchi, engineer, who passed away in July 2019.

Mention is made of its application for two major infrastructure projects in the city of Lima: for the Port of Callao, and the tunnel under the second runway of Lima's International Airport.

We present the summary of proposed regulations for designing buildings to resist tsunami- generated forces. This proposal was put forward in a publication of the National Training Service for the Construction Industry (SENCICO) entitled "PRACTICAL GUIDE FOR REDUCTION OF CATASTROPHIC RISK BY TSUNAMI IN PERU".

Finally, we present the Ph.D. thesis written by Cesar Jimenez. This research consists of the numerical simulation of the seismic source of tsunamigenic earthquakes applied to the Peruvian case within the seismotectonic setting of the subduction zone between the Nazca and South American plates.

2. Resilient Cities 2017 – 2030

In Peru, 1998 saw the start of the Sustainable Cities Programme (SCP) [Spanish acronym: PCS], which lasted until 2016. Funding for the Programme was obtained from the Office of the President of the Council of Ministers, the Civil Defence Institute (INDECI), and the United Nations Development Programme (UNDP). For the cities in Ecuador, the Organization of American States (OAS) provided the funding.

The SCP consisted in drawing multiple hazard maps – including the tsunami hazard – for the coastal cities. The Bureau of Hydrography and Navigation of the Peruvian Navy contributed in the case of the coastal cities. They prepared the tsunami inundation maps, using numerical models, and to date inundation maps are available for all the cities along the Peruvian coast (85 cities) [1].

In the period 1998 to 2016, the SCP carried out the studies in 175 cities, including four Ecuadorean cities [2, 3]. Based on the multiple hazard map, land-use plans were drawn up to reduce the risk of disasters. Then, profiles were developed for low-cost, easy-to-execute risk reduction projects, which were to be implemented by the municipalities responsible for the SCP.

The SCP proved to be a successful model, and it obtained many national and international awards. In an international competition sponsored by the United Nations, the World Bank, and the OAS, the SCP came first out of 81 projects on risk disaster risk reduction (DRR). INDECI received the award during a ceremony held by the DRR Continental Platform in Chile in October 2012.

In November 2016, Eng. Julio Kuroiwa was invited by the Municipality of Metropolitan Lima to present his proposal for the Lima Resilient City Project. This project on resilient cities is being implemented in major cities worldwide [4, 5]. The proposal was extended to the whole country, and it has the title: Programa de Ciudades Resilientes 2017 -2030 (PCR 2017-2030) [Resilient Cities Programme 2017-2030 (PCR 2017-2030)].

For this PCR 2017-2030, two new attributes were added to the Sustainable Cities Programme 1998-2016 [6], as follows:

- **Effective participation of communities in Disaster Risk Management:** It has been observed that whenever an intense earthquake or tsunami occurs, roads become impassable. This makes it difficult for emergency aid to reach the disaster site. During the first 24 hours, rescue work has to be done mainly by the organised community. Training activities must be carried out in the communities so that they will be able to respond appropriately in the first few hours following the disaster.
- **Committed participation of civil society:** The proposal states that the participation of civil society is important. It is stressed that private enterprise should take an active part in the Resilient Cities Programme, otherwise its investments and businesses are exposed to very high losses in the event of intense earthquakes and tsunamis. This wake-up call was given by the United Nations, warning entrepreneurs that losses caused by disasters are out of control.

3. Port of Callao – Lima: Multi-Purpose North Terminal

The main objective was to determine the wave height on the coast at the Port of Callao, Lima, Peru for a return period of 100, 475, and 1,000 years. To this end, an evaluation was made of a series of studies collected from recent international research regarding paleotsunamis for the region of Sanriku, Japan, which had been motivated by investigations of the Indian Ocean tsunami of 2004.

It was assumed, in principle, that the subduction zones of Japan and South America (where Chile and Peru are located) have similar characteristics of energy accumulation in the interseismic period: that is, that the Pacific and North American Plates, where the north-eastern part of the Island of Honshu, Japan is (this being the main island of the Japanese archipelago in the centre of which its capital, Tokyo, is located), as well as the Nazca and South American Plates, are approaching each other at a rate of 7 to 9 cm/year.

On a high cliff at Oya beach, in the locality of Kesennuma, prefecture of Miyagui, sediments were found that had been deposited on average every 1,000 years. The earthquake and tsunami of 869 occurred 1,140 years ago; this indicates that said tsunami and that of 2011 are events with a return period of 1,000 years. Their wave height is on average 33% higher than the run-ups calculated for the tsunamis of Sanriku in 896 and 1933. The practical aspect of Tsunami Engineering developed in Japan is based on these studies, and it is applied internationally in Latin America, mainly in Chile, Mexico and Peru. For example, the thesis “Plan de Evacuación de Ciudades Afectadas por Tsunamis, Zona La Punta – Pucusana” [“Plan for Evacuation of Cities Affected by Tsunamis, Zone La Punta – Pucusana”] developed by Alberto Delgado and Celia García, follows that school, and its indicators are now being corrected in light of the lessons of the Tohoku tsunami of 2011 [7].

Moreover, coseismic deformation took place: that is, deformation of the earth’s crust, rising of the ocean bed, and subsidence that occurred simultaneously with the earthquake, as well as the displacement of the north-eastern part of Honshu, which moved some 4 m eastward on the Pacific coast and approximately 1 m the other side of Honshu Island, on the coast of the Sea of Japan [8].

This advance, reported by Science magazine as one of the most considerable in 2011 [8], has enabled a group of Peruvian and Japanese researchers to reconstruct the coseismic deformations generated by the earthquake and tsunami of 1746 that destroyed Callao [9], based on historic data from the macroseismic area.

According to them, the following results can be assumed:

- Wave Height in Multipurpose North Terminal in the Port of Callao for return period of 1000 years = 10.0 m.
- Wave height in Multipurpose North Terminal in the Port of Callao for return period of 475 years = 7.0 m.
- For this study, the wave height for a return period of 100 years is assumed to be 3.0 m.

According to the Japanese Government, the GFDRR (Global Facilities for Disaster Reduction and Recovery) and the World Bank, in their report *“Aprendiendo de Grandes Desastres”* [“Learning from megadisaster”] [10] recommend:

- That structures be designed for tsunamis that recent history indicates to have a return period of 100 years.
- The Report of the Japanese Government, the GFDRR, and the World Bank recommends that although facilities could, indeed, be designed for a return period of some 1,000 years, in engineering terms this would not be rational, and the cost would be prohibitive; however, if tsunamis with higher wave heights are generated, for example with a

return period of 475 and 1,000 years, (and it is not known when this might occur), the recommendation is that the structural measures be accompanied by non-structural measures.

- The most important non-structural measure is achieved with the participation of the community, training the people to protect their lives and physical safety in such a way that they will react in an educated way to the different scenarios they may have to face.
- Based on the Emergency Plan 2014 drawn up by the Port of Callao, there needs to be a comprehensive diagnosis of the tsunami risk, detailing the expected impact and magnitude of these natural events, as well as an analysis of the vulnerability of each of the port facilities.

We consider it vital to prepare the probable scenarios resulting from this phenomenon, which would include the determination of maximum inundation lines, evacuation routes, and safety zones, with the aim of protecting, first and foremost, the life and safety of personnel, and safeguarding the valuable investment in infrastructure.

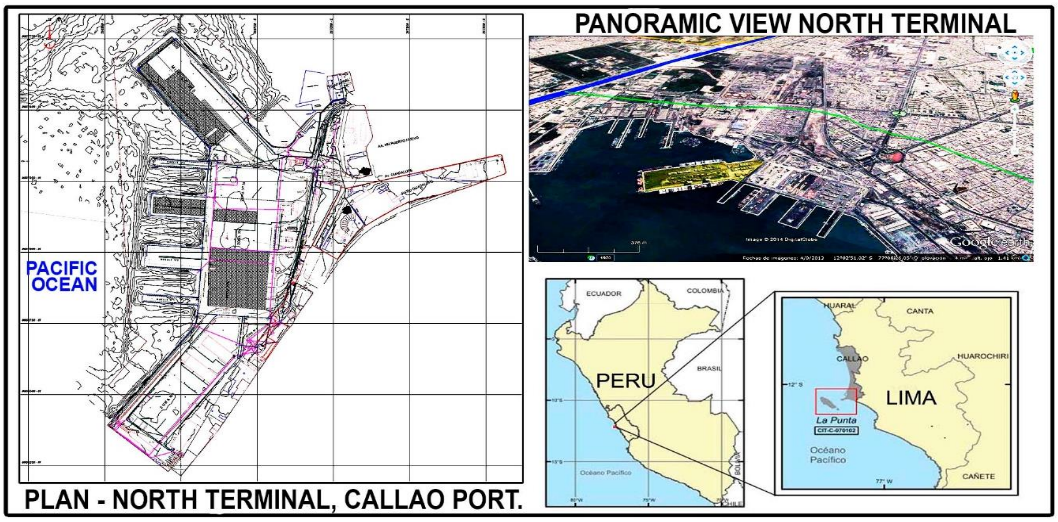
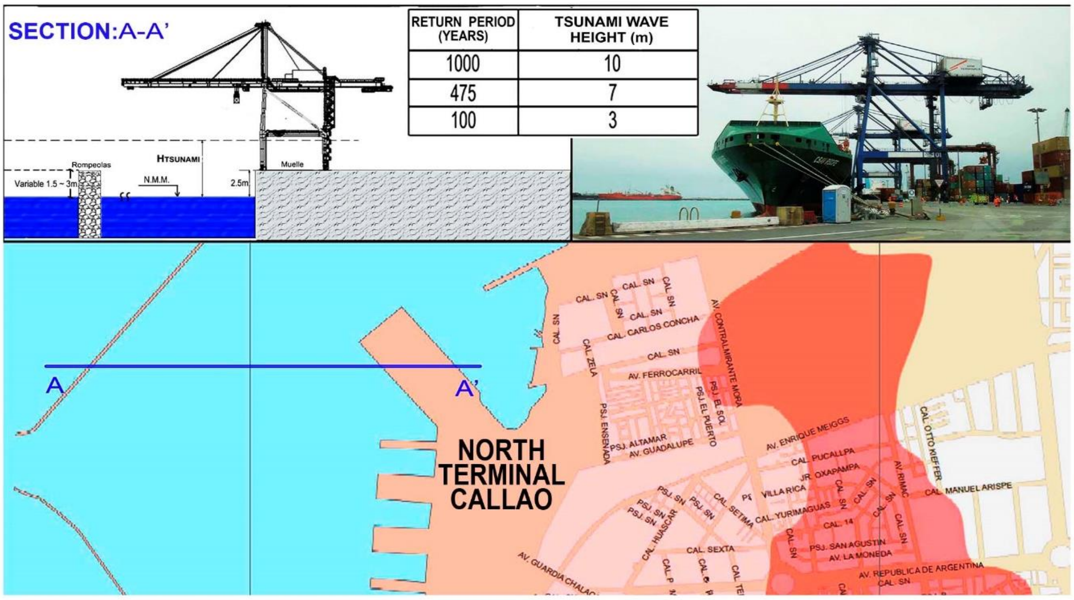


Fig. 1. Location of Callao Port and Plan View of North Terminal (Source DRPINT SAC)



RETURN PERIOD (YEARS)	TSUNAMI WAVE HEIGHT (m)
1000	10
475	7
100	3

Fig. 2. Tsunami wave height and cross section of North Terminal (Source DRPINT SAC)

4. Tunnel under Runway Two of Lima's International Airport

A study was made of the seismic and tsunami hazard that could affect the tunnel under the new runway (second runway) of the Jorge Chávez International airport of Lima, Peru (section III-B of Av. Néstor Gambetta, Callao).

As mentioned in Section 3, for this project the scientific advances in the most notable tsunami studies of recent years were also taken into account, including horizontal and vertical coseismic displacements, and the results of paleotsunami research [8, 11].

In addition, in Peru we have studied in some detail the tsunamis of 1966 and 1974: their mareograms were recorded in La Punta, and the respective refraction diagrams were developed as a Civil Engineering thesis in the FIC/UNI [7]. We have also studied the effects of the Camaná tsunami of 23 June, 2001; and the tsunami that affected Pisco on 15 August, 2007.

In Peru, Chile, and Mexico, the Yamaguchi formula has often been applied to determine wave height; this was based mainly on the Sanriku 1933 tsunami. Comparing the wave height that occurred in Sanriku with the wave heights of the Tohoku-Oki 2011 tsunami, on average the wave heights of 2011 tsunami are 1.33 times. Assuming that the Callao 1746 tsunami was generated by an earthquake of Mw 8.6 to 8.8, to adjust it to a return period of 1,000 years, the adjustment factor was rounded off to 1.4. Multiplying the 1746 wave height of 7.0 m by 1.4, we obtain a height of 9.8 m.

From a practical point of view, using a correction coefficient of 1.4 with the Yamaguchi formula, the values obtained are very close to those obtained in the earthquake and tsunami in several critical places, such as south of Lagunillas (Yamana, Pisco) in 2007.

Bearing in mind that on the coast facing the tunnel project area the bathymetric conditions are more favourable than in the area of La Punta and the location of DHN, the appropriate wave height, in principle, is considered to be 10.0 m.

According to all earlier studies, the wave height on the coast facing the project "of the tunnel under Runway 2 of Jorge Chávez Airport" is 10 m for a tsunami return period of 1,000 years, which is confirmed in this Final Report.

Taking into consideration that the distance between the sea front and the axis of Avenue Gambetta that passes below Runway 2 of "Jorge Chávez" International Airport is 1.2 km., and assuming a 1% reduction in height, the tsunami wave will advance 1.0 km, largely depending on the degree of friction on land and the obstacles encountered by the tsunami waves as they progress on land.

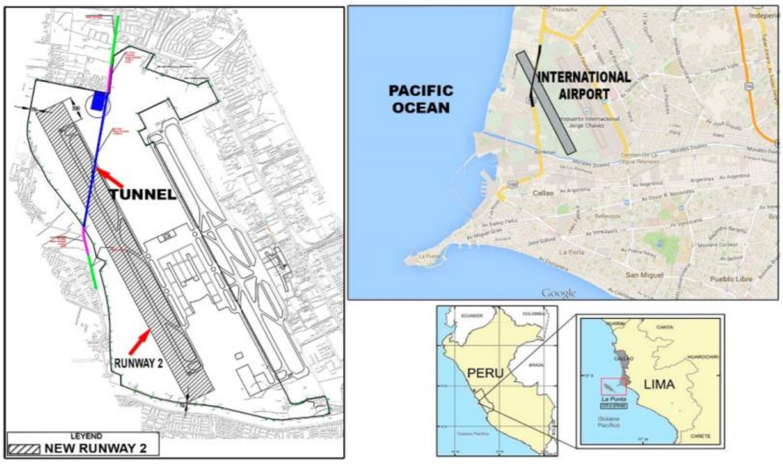


Fig. 3. Location of Lima's International Airport and the tunnel under the second runway. (Source DRPINT SAC)

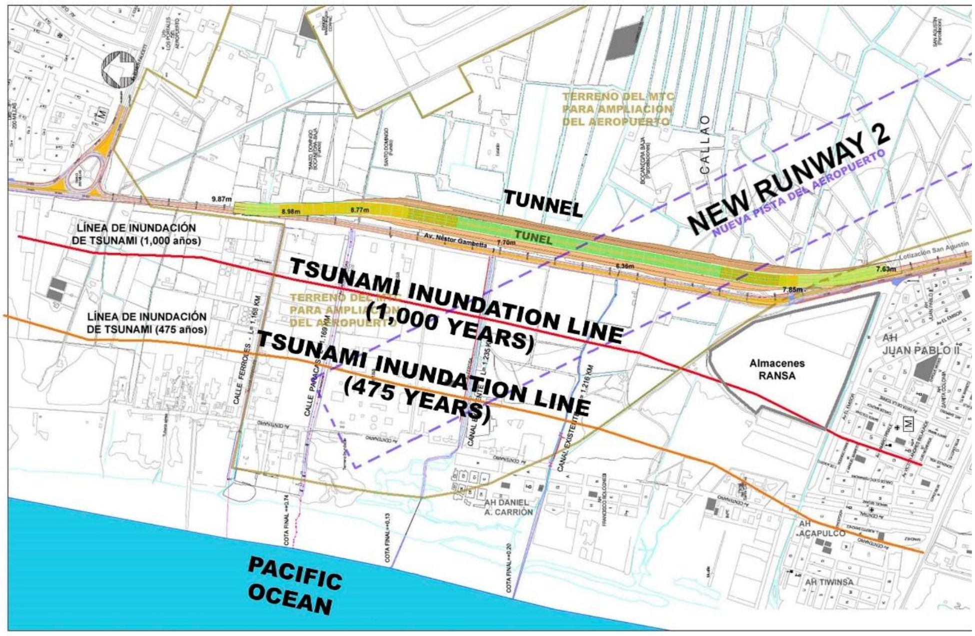


Fig. 4. Inundation limits of the tsunami and the tunnel under the second runway. (Source DRPINT SAC)

5. Advances on tsunami numerical simulation

Peru is located within the Pacific Seismic Belt, making it one of the most active seismic zones in the world. According to the theory of "seismic gaps", the occurrence of a tsunamigenic earthquake in the central region of Peru is very likely. In the PhD Thesis of Jimenez (2019) [12], it is proposed to develop a methodology to obtain the seismic source distribution for tsunamigenic earthquakes from the inversion of tsunami waveforms and geodetic data.

It considers the applications to seismic events and tsunamis that have affected the Peruvian coasts (Fig.5.). For example, the 1940 Lima earthquake and tsunami (Mw 8.0), the 1966 Huacho earthquake and tsunami (Mw 8.1), from the inversion of 3 tsunami waveforms. The earthquake and tsunami of Camana of 2001 (Mw 8.4) from the joint inversion of tsunami and geodetic data. The Pisco earthquake and tsunami of 2007 (Mw 8.0), from the inversion of tsunami data. The earthquake and tsunami of Chile 2014 (Mw 8.1) from the joint inversión of tide and geodetic data. The application of the reliability test is emphasized to evaluate the resolution and the range of application of the seismic, tsunami and geodetic methods.

A numerical procedure to forecast the tsunami parameters (maximum tsunami height and arrival time) has been implemented from a database of pre-simulated seismic unitary sources.

The results of this investigation will allow to obtain the distribution of the asperities (zones of greater seismic energy release), which will allow to develop plans of prevention, forecast and mitigation of disasters by natural phenomena.

The applications to seismic events and tsunamis that have affected the Peruvian coast are presented. For example, the earthquake and tsunami of Lima of 1940 (Mw 8.0) is studied. An important result is that the first period of tsunami waveforms from linear and non linear models fits with a very good correlation. This fact allows the use of linear equations in tsunami waveform inversion, where only the first period is used.

The 1966 Huacho earthquake and tsunami (Mw 8.1) is studied. The slip distribution is obtained from the inversion of 3 tsunami waveforms of the Peruvian tidal network. The tsunami moment agrees very well with the seismic moment for a corresponding magnitude of Mw 8.1. *Fig. 6* shows the slip distribution.

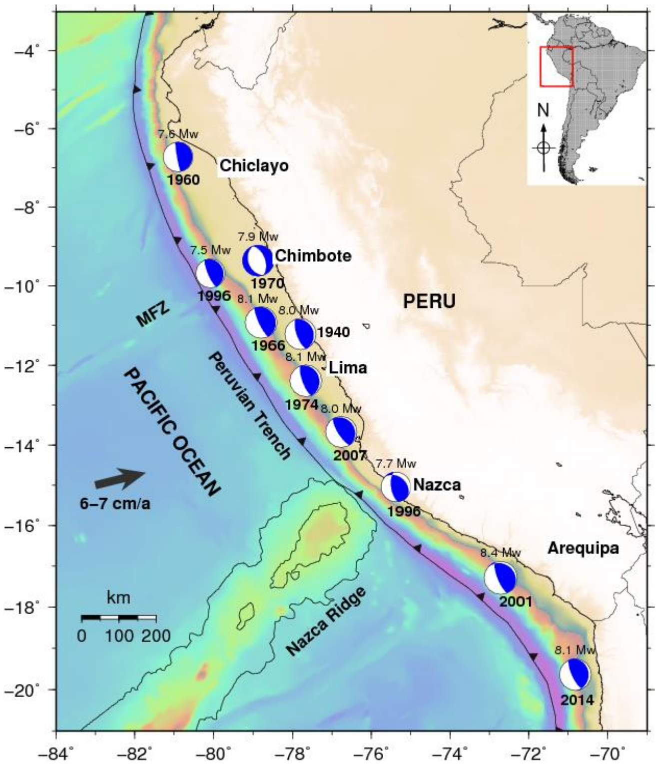


Fig. 5. Seismic events that have generated tsunamis (in the near field) that have affected Peru from 1940 to 2014. The main tectonic units are also shown, such as: the marine trench, the Mendaña Fracture Zone (MFZ) and the Nazca ridge. The Nazca plate converges at a speed of 6 to 7 cm/year.

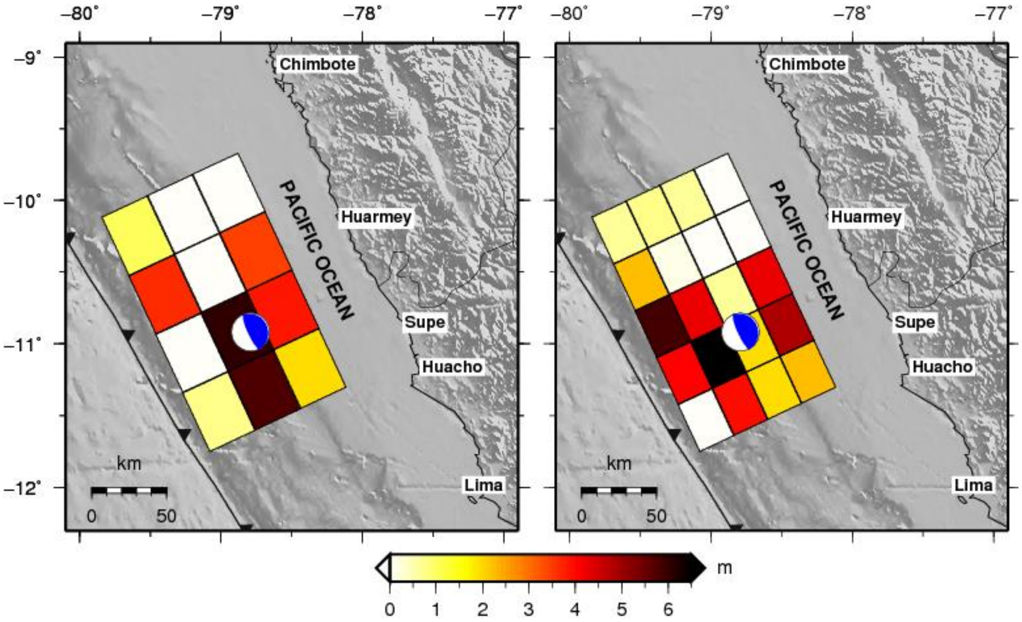


Fig. 6. The distribution of the 1966 tsunami source is shown. The focal sphere is located at the position of the epicenter. Note the great asperity, in dark color, in front of the cities of Supe and Huacho. a) Seismic source with 12 subfaults and b) Seismic source with 20 subfaults, our preferred model.

The 2001 Camaná earthquake and tsunami (Mw 8.3) is studied based on the joint inversion of tsunami and geodetic data. The results in Fig. 7. shows that the main asperity is located in front of Camana city, this explain the great damage in this city. Another coseismic effect was the subsidence of Camana (84 cm of subsidence) and great part of the southern región of Peru. The tsunami was destructive with heigth waves of 7 to 8 m.

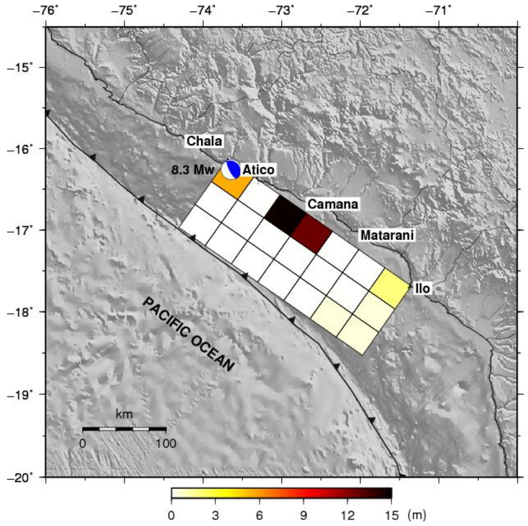


Fig. 7. Distribution of the asperities of the 2001 Camana earthquake. The main asperity (in black and brown) is located in front of Camana. Notice the subfaults near the marine trench (white color) that have not been fractured and the subfaults with a small dislocation (in cream color).

The earthquake and tsunami of Chile 2014 (Mw 8.1) was evaluated based on the joint inversion of tsunami and geodetic data. A reliability test was applied to evaluate the resolution and range of application of the tsunami and geodetic method. Emphasis is given to methods of obtaining geodetic deformation.

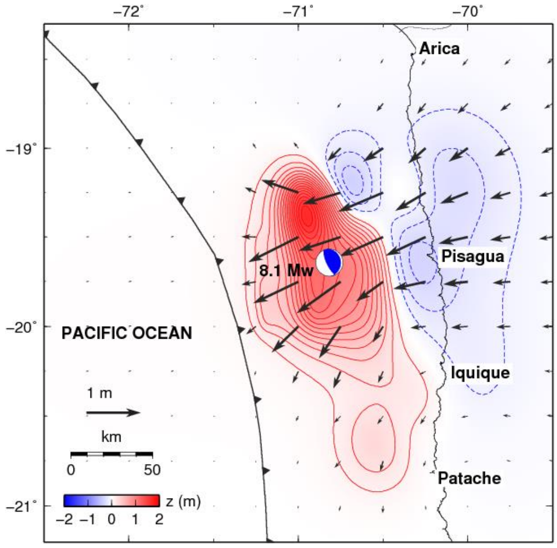
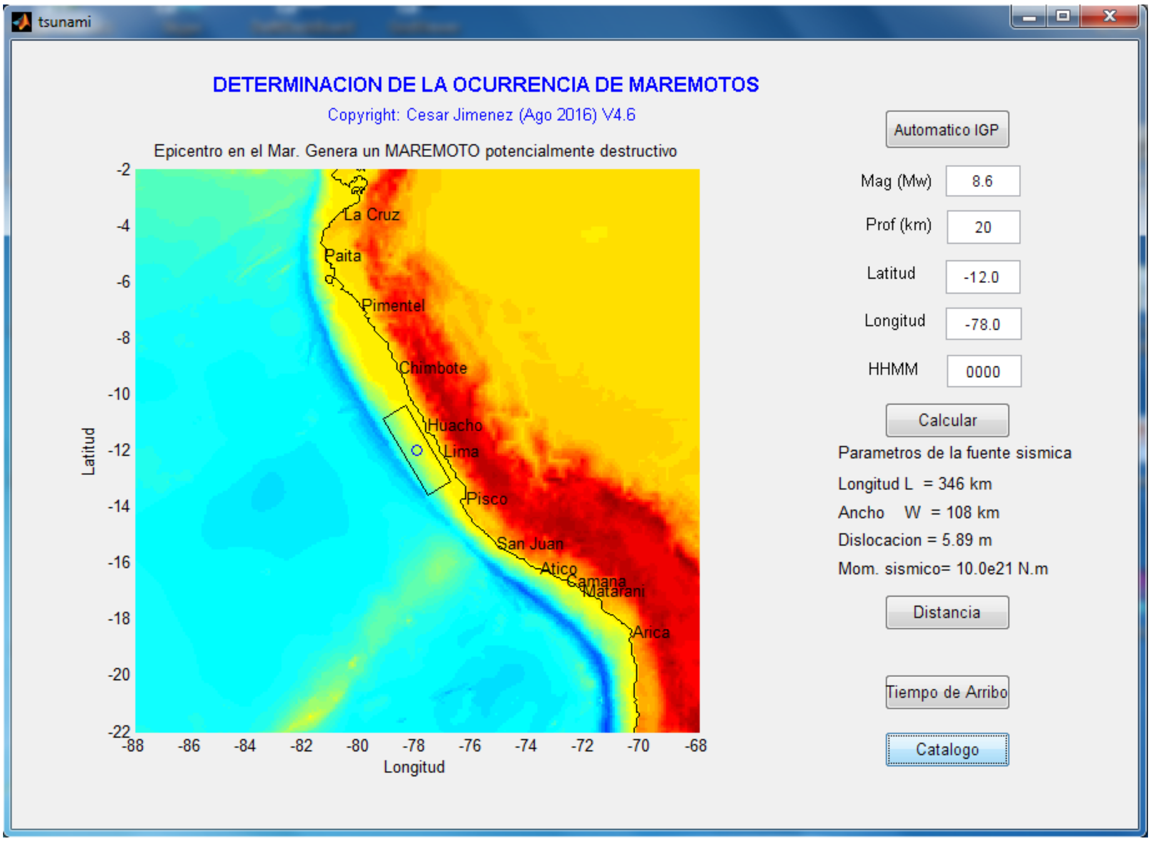


Fig. 8. Vertical coseismic deformation field of the 2014 Chile earthquake, the red colour indicates the uplift and the blue colour indicates the subsidence. The arrows represent the horizontal displacement. The interval of the deformation level curves correspond to 0.1 m. The focal diagram represents the mainshock.

We describe a numerical procedure to forecast the parameters of a tsunami from a database of pre-calculated seismic unit sources. This procedure is used in the Pre-Tsunami application, coded in Matlab, which is useful in the National Tsunami Warning Center (CNAT) of Peru (Jiménez et al., 2018).



DETERMINACION DE LA OCURRENCIA DE MAREMOTOS

Copyright: Cesar Jimenez (Ago 2016) V4.6

Epicentro en el Mar. Genera un MAREMOTO potencialmente destructivo

Mag (Mw) 8.6

Prof (km) 20

Latitud -12.0

Longitud -78.0

HHMM 0000

Parametros de la fuente sismica

Longitud L = 346 km

Ancho W = 108 km

Dislocacion = 5.89 m

Mom. sismico= 10.0e21 N.m

Fig. 9. The "Pre-Tsunami" Graphical User Interface (Version 4.6). The input are the hypocentral parameters and the output are the tsunami parameters: arrival time and máximum tsunami height.

We have implemented a numerical procedure to forecast the parameters of a tsunami, such as the arrival time of the front of the first wave and the maximum wave height in real and virtual tidal stations along the Peruvian coast, with this purpose a database of pre-computed synthetic tsunami waveforms (or Green functions) was obtained from numerical simulation of seismic unit sources (dimension: 50×50 km2) for subduction zones from southern Chile to northern Mexico. A bathymetry resolution of 30 arc-second (approximately 927 m) was used. The resulting tsunami waveform is obtained from the superposition of synthetic waveforms corresponding to several seismic unit sources contained within the tsunami source geometry. The numerical procedure was applied to the Chilean tsunami of April 1, 2014; in the case of the Arica tide station an error (from the maximum height of the observed and simulated waveform) of 3.5% was obtained, for Callao station the error was 12% and the largest error was in Chimbote with 53.5%. The aim of the this research is tsunami early warning, where speed is required rather than accuracy. Based on our results, we state an accuracy within 15% of error.

With the information of hypocentral parameters, conditions of tsunami generation and algorithm of precomputed seismic unit sources, we have implemented an application with a graphical user interface developed in Matlab programming language. The input data are the hypocentral parameters: magnitude Mw, hypocentral depth (this is used for discriminating the sources greater than 60 km depth), geographical latitude and longitude of the epicenter and origin time. The outputs are the parameters of seismic source geometry and a diagram of the likely rupture geometry on a map (Fig. 9).

The graphical user interface of Pre-Tsunami application is quite friendly and easy to use by the operator of the tsunami warning and constitutes an important computational tool to forecast and decision making for issuing bulletins, alert or alarm in case of occurrence of tsunamis. The output of the model will be useful to forecast tsunamis in the near, regional and far field. The output parameters are: the arrival time of the front of the first wave and the maximum height of the tsunami wave. These results will be useful for issuing the alert or alarm of the tsunami.

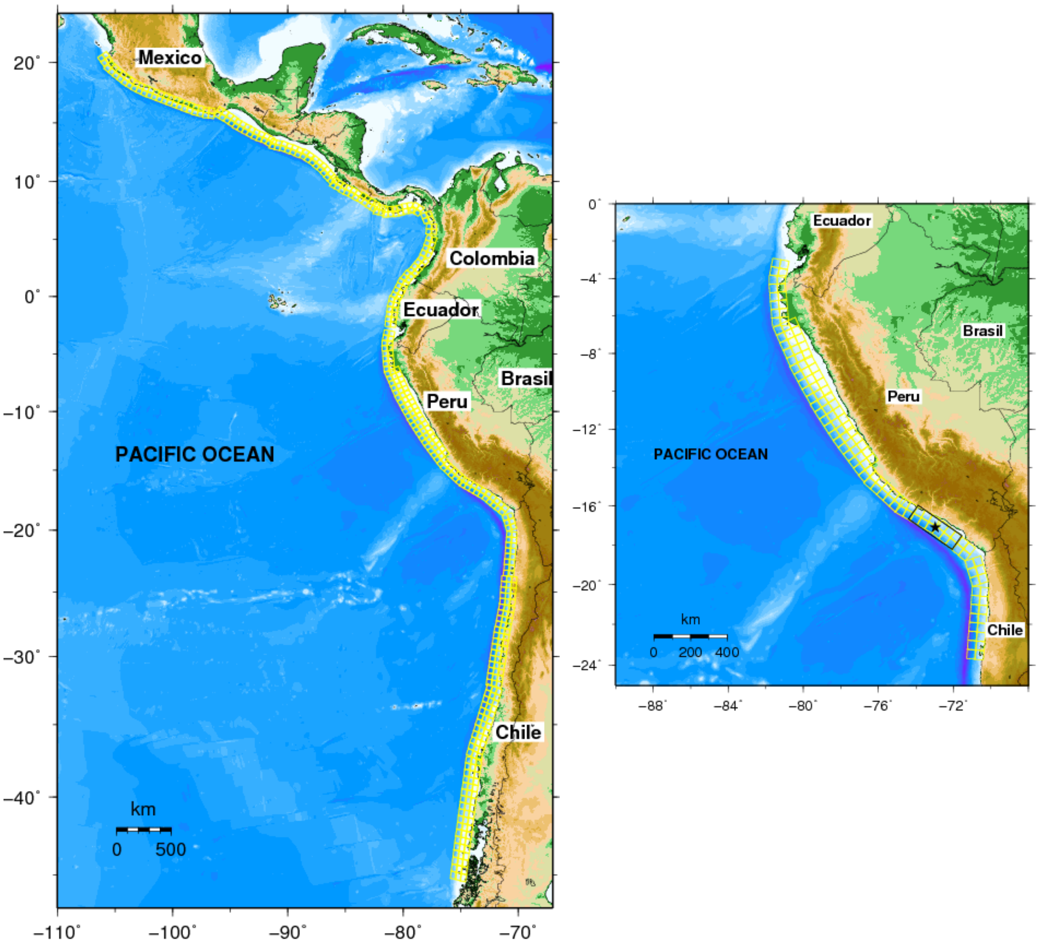


Fig. 10. a) The unitary pre-calculated seismic sources are represented by the small yellow squares. It covers the subduction zone from northern Mexico to southern Chile, with 465 seismic unit sources. b) Zoom from southern Ecuador to northern Chile.

The current addition in the database of the simulation is shown in Fig. 10, geographically, from southern Chile to northern Mexico with 465 seismic unit sources simulated. We hope to conduct the simulation of seismic unit sources for the entire Pacific Ocean corresponding to subduction zones of Pacific Seismic Ring. This implies a large computational effort with the simulation of more than 1000 seismic unit sources, for a computational grid around the Pacific Ocean with 30 arc-sec resolution or 1 min resolution for the far field.

6. Proposal for a Technical Standard on Tsunamis and Buildings

In 2016, Kuroiwa and Jimenez published the “PRACTICAL GUIDE FOR REDUCTION OF CATASTROPHIC RISK BY TSUNAMI IN PERU” [13], commissioned by SENCICO-Peru. In this practical guide, the authors evaluated several scenarios of tsunami destruction all over the world, for example the 2001 Camana-Peru tsunami, 2004 Sumatra tsunami, the 2007 Pisco-Peru tsunami, the 2010 Chile tsunami and the 2011 Tohoku-Japan tsunami, between others. They presented the learned lessons of these seismic events.

In accordance with the objectives of the Practical Guide, of the tsunamis that have occurred globally and those that have affected Peru, those that have left the most valuable teachings have been selected, not only because of the way they occurred, but also because they have been investigated carefully, according to the following subtopics:

- Damage caused by earthquakes and tsunamis due to soil liquefaction, one of the main causes of the huge losses economic events in the earthquakes in Maule-Chile in 2010 and Tohoku-Japan in 2011.
- Undermining and erosion of the foundations of buildings and urban infrastructure caused by tsunamis. Undermining study in countries relatively close to the origin of the 2004 Indian Ocean tsunami. Great amounts of mass removals during the earthquakes in the Kuril Islands in Russia, 1997 and 1998.
- Damage caused to buildings and urban infrastructure caused by the Indian Ocean tsunamis of 2004 and Tohoku, Japan, of 2011, for example.

In the urban planning of the coastal areas flooding by tsunamis, the vision of the process of this type of hazard must be integral, taking into account the impact generated by the invasive phase of the waves and the return of the waters, in the urban structures. For this, i) the selection and conditioning of the site must be considered; ii) the design and construction of urban locations and buildings; and iii) the protection of housing and key elements, consisting of vital public services: water, sewage, energy, transport and communications; and essential services: hospitals, educational centers, emergency operations centers, fire stations and police stations, among others. Equally important are public spaces in coastal cities, due to their potential to become suitable spaces for the preparation of temporary shelters.

7. Concluding remarks

In Peru, the application of advanced tsunami risk reduction tools has made it possible for many infrastructure works, both public and private, to be designed and built to resist the effects of tsunamis.

The Resilient Cities Programme will make it possible to reduce the damage caused by earthquakes and tsunamis to property and lives. It is important that the Peruvian Government continue applying this programme.

The advances on tsunami numerical modeling are very important to obtain the seismic source or slip distribution and the tsunami parameters, which will be used for planning and design of building construction and facilities. Also, this numerical tool allows to obtain a database of pre-simulated seismic unit sources, which will be used in the implementation of a tsunami early warning system.

8. Acknowledgements

The authors express their profound gratitude to Prof. Julio Kuroiwa (RIP), deceased in July 2019, who left part of this article prepared. His teachings on earthquake engineering and tsunamis will last for generations to come, since they are recorded in numerous articles, books, and other publications. Prof. Kuroiwa was the founder of the company Disaster Risk Reduction Peru International SAC (DRPINT SAC) source of some material for this paper.

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Thanks are also due to the President of the Republic of Peru, Martín Vizcarra, who has been promoting Disaster Risk Management in Peru and the Resilient Cities Project; and also to the Ministry of Housing, Construction and Sanitation for support given to the programme.

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