Paper:

Seismic Source of 1746 Callao Earthquake from Tsunami Numerical Modeling

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[Received November 2, 2012; accepted February 8, 2013]

In this paper a model of slip distribution is proposed for the 1746 Callao earthquake and tsunami based on macroseismic observations written in historical documents. This is done using computational tools such as tsunami numerical simulation through a forward process by trial and error. The idea is to match historical observations with numerical simulation results to obtain a plausible seismic source model. Results show a high asperity from Cañete to Huacho, which would explain the great destruction in this area. The rupture directivity of the seismic source, from north to south, would explain the value of the arrival time of the first tsunami wave at Callao. A kinematic seismic source model was used as a first approximation of the event. The estimated magnitude was Mw9.0.

Keywords: seismic source, tsunami, simulation

1. Introduction

Many researchers have tried to infer seismic sources of historical events such as the 1755 Lisbon earthquake [1, 2], the 1693 Catania earthquake [3], and the 1700 Cascadia earthquake [4], etc., from macroseismic observations recorded in historical documents and from observations of marine geology and paleo-tsunami studies [5, 6], using tsunami numerical modeling techniques. Other authors such as Dorbath [7], using only macroseismic information, have qualitatively estimated the magnitude and rupture area size.

At the present time, we have suitable numerical tools and geophysical instrumentation such as broadband seismic stations, digital tide gauge stations, geodetic GPS and radar interferometry INSAR for studying seismic sources and crustal deformation. This is not the case for historical events such as the 1746 earthquake, however. In this sense, we can only infer or estimate a seismic source model from macroseismic and tsunami descriptions of historical documents found in the literature.

2. Historical Aspects

Silgado [8], among other authors, performed a compilation of the historical aspects of this event. Below is a summary of the historical account provided by Soloviev [9]:

> The tragedy began on October 28, 1746, at 22:30 pm. To the north, the quake was felt as far as Guayaquil, 1100 km from Lima, and a Jesuit mission located near the confluence of the Marañón and Huallaga rivers, 750 km from Lima. In Huancavelica, south-south-east of Lima, there was severe thunder accompanying movement. Buildings south of Lima collapsed all the way to Cañete, and north to Huacho about 120 km north of Lima, where a new bridge over the river collapsed at Huaura. Roads leading to the interior were blocked by landslides. The valleys of Supe, Barranca and Pativilca were seriously damaged by the earthquake and tsunami. Movement was also felt in Cusco, Tacna and border towns. Aftershocks were felt in Lima overnight and within 24 hours, no fewer than 200 events were counted.
>
> The port of Callao suffered the most damage from this catastrophe. The city was enclosed by a wall whose base was sometimes beaten by the tide and waves. The population reached 5,000 people. Half an hour after the quake, the sea rose 10 m and, in

its advance, broke the walls and inundated the city. When the sea receded, most of the houses and buildings were taken from their foundations and washed away. Most of the walls of the city, including the gates, were washed away. Almost all of the inhabitants of the city perished in this disaster. The water rose about 4 km inland, reaching even those who tried to escape to Lima. Only 200 people were saved, and these by clinging to wooden objects, but were thrown between the coast and San Lorenzo island, a distance of up to 8 km. Of the 23 ships anchored in the harbor, 19 were sunk and 4 were carried inland. At around 04:00 of the next day, Callao was inundated again by another tsunami wave. The maximum inundation height was estimated at 24 m.

In the port of Santa (see **Fig. 1**), waves hit the ship Concepcion with such force that it sprang a leak and sank. The crew of the Soledad, which was near Nazca, noted that the sea had retreated, and took precautions, so the ship was saved. The tsunami destroyed the ports of Caballas (Ica), Pisco, Chancay and Guañape (La Libertad). Near Huacho, the road was completely flooded and vehicles that stayed on the road, together mules, were swept away when the sea receded. In Huaura (Salinas), the sea flooded areas around 4 km inland, drowning mules and drivers. Near Callao, after the earthquake, part of the coastline suffered subsidence, to where a new bay was formed. In the space of six hours after the inundation at Callao, the tsunami reached Concepción, Chile; and at Acapulco, Mexico, a ship was washed ashore.

From historical records of authors cited in the literature [10], we found the following important facts, which will be useful in defining seismic source through a forward process based on trial and error. Note that in doing so, parameters of the simulated tsunami will need to fit these historical observations.

a) The arrival time in Callao of the first tsunami wave was at around 30 minutes.

b) The maximum height of the first tsunami wave was about 10 m at Callao.

c) The maximum inundation height (runup) was 24 m (at the cliffs of the Costa Verde zone), see paragraph 5.3 and **Fig. 6**.

d) After the earthquake, a permanent subsidence at Callao was reported.

e) Total destruction stretched from Cañete in the south to Barranca and Pativilca in the north. This implies large asperity or slip between these locations.

f) Maximum horizontal inundation was 4 km probably at the old Rimac River bed.

g) Tsunami waves arrived at Callao from the northwest. See **Fig. 2**, from a picture of the period [11].

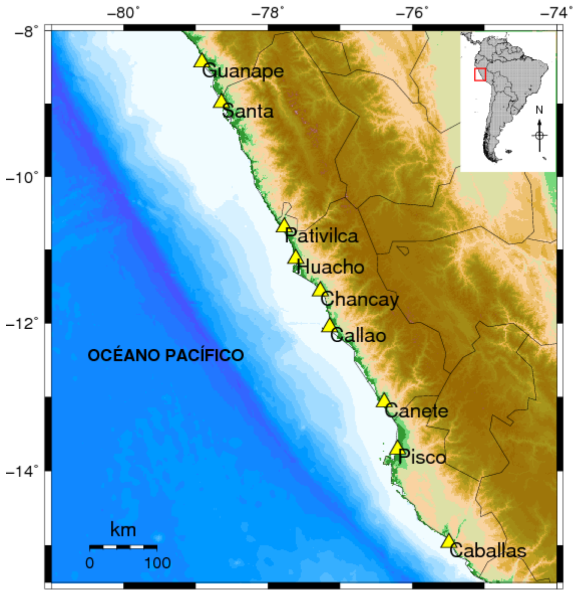

Fig. 1. Location of ports and resorts affected by the tsunami.

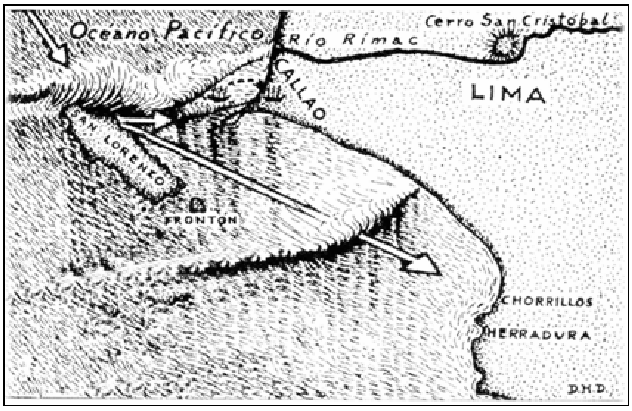

Fig. 2. 1746 Tsunami, from a picture of the period [11].

h) According to Silgado [8], the intensity was X-XI MM in Lima and Callao. It is possible that the occurrence of some cracks in the main square in Lima would imply very great acceleration.

Due to the lack of more historical data to thoroughly confirm the testimonies in the record, we will, at this stage, use available information as the main constraint to be satisfied by the seismic source model proposed here.

3. Data Acquisition

3.1. Topographic and Bathymetric Data

To prepare digital elevation model data, satellite and survey data topographic and bathymetric was acquired. These data were digitally processed to obtain a digital elevation model with a grid resolution of 30 m (inundation grid) and 900 m (generation and propagation grid), as well as intermediate grids. **Table 1** specifies the resolution of

Table 1. Characteristics of digital elevation models.

Model	Type	Resolution
SRTM 90	Topography	90 m
DHN survey	Bathymetry	100 m
Gebco 30	Topo-bathymetry	900 m

each topographic and bathymetric model.

The DHN (Dirección de Hidrografía y Navegación) bathymetry and SRTM topography have been processed (through two-dimensional interpolation) to obtain a fine resolution digital elevation model of 30 m in raster or matrix format to be used in the inundation phase for the numerical simulation. To develop codes and routines, we used Fortran and Matlab programming language, libraries and Mapping Toolbox utilities as well as Surfer 7.0 software. For application of the linear model of tsunami propagation, we used Gebco30 bathymetry.

4. Methodology

4.1. Forward Method by Trial and Error

If we know the parameters that characterize a system and its initial and boundary conditions, then we can predict the behavior of the system at any instant in time. This problem of predicting future behavior, is called the "forward problem." The "inverse problem" is to use the results of certain observations: tidal, field data, and paleotsunami deposits, etc. to infer values of parameters characterizing a system [12].

In this paper we use information from historical documents to estimate parameters of a seismic source (slip distribution). The solution of the forward problem is not unique, but chooses that set of values providing the best correlation between observed and simulated data. The trial and error method involves varying parameters in this case, slip and depth and performing the numerical model and comparing the output with historical data, then repeating the process as often as necessary to achieve a rough correlation.

4.2. Constraints on the Size of the Source and Magnitude of the Earthquake

According to the seismotectonic pattern, the size of seismic source in the central region of Peru is restricted by the Nazca ridge (15°S) to the south and the Mendaña's fracture (10°S) to the north. This region covers a distance around 600 km. According to the empirical relation of Papazachos [13]:

$$\log(L) = 0.55M - 2.19 \quad \dots\dots\dots \quad (1)$$

where L is in km. Magnitude would have a maximum limit of Mw9.0. Furthermore, the fact that it caused cracks in the main square in Lima indicates that there was strong acceleration due to an event of great magnitude, i.e., of at least Mw9.0. Dorbath [7] estimated a magnitude of Mw 8.6 and 9.0 Mt, Beck [14] estimated Mw8.8, and Ocola [15] calculated Mw 9.2 based on macroseismic intensity.

This paper proposes a magnitude of Mw9.0 as an initial assumption. Later, it will be shown that this magnitude fits results from tsunami numerical simulation.

Table 2. Focal mechanism parameters.

Focal mechanism	Angle
Strike angle	329°
Dip angle	20°
Slip angle	90°

Table 3. Geometry parameters of the fault.

Parameter	
Longitude	550 km
Width	140 km
Mean slip	11.5 m
Depth	8.0 km

4.3. Focal Mechanism and Fault Parameters

Focal mechanism parameters (see **Table 2**) are estimated according to following assumptions: the azimuthal angle should be parallel to the marine trench in central Peru (about 329°). The dip angle for the central region of Peru is 20° (average dip for CMT solutions) and the displacement angle (rake or slip angle) is estimated in 90° for maximum vertical deformation. These are the fixed parameters in the proposed method.

According to empirical equations relating fault dimensions to magnitude, fault dimensions would be for a magnitude Mw9.0: $L = 575$ km and $W = 144$ km. However, in this paper we set these dimensions to: $L = 550$ km and $W = 140$ km. According to the relation between scalar seismic moment and moment magnitude:

$$\log(M_0) = 1.5M_w + 9.1 \quad \dots\dots\dots \quad (2)$$

We have: $M_0 = 3.98 \times 10^{22}$ Nm, using the following definition of scalar seismic moment:

$$M_0 = \mu LWD \quad \dots\dots\dots\dots \quad (3)$$

where: $\mu = 4.5 \times 10^{10}$ N/m^2, is the average rigidity of the elastic medium. After calculating the dislocation value or mean slip D, we have: $D = 11.5$ m. The geometry of the rupture area must be heterogeneous composed of several fragments to represent the maximum asperity in the area from Cañete to Barranca. The depth of the top of the fault is taken initially as: $H = 5$ km, and after the trial and error method used, is set finally to $H = 8$ km (see **Table 3**).

5. Tsunami Numerical Modeling

5.1. Seismic Source Model

According to Perfettini [16], the Nazca ridge appears to be a barrier aseismic to earthquake rupture. Because no

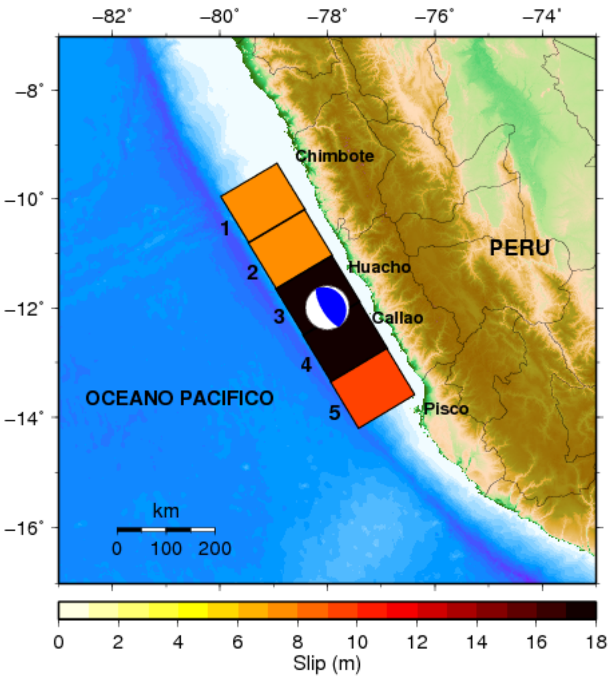

Fig. 3. Fragments of the seismic source (slip distribution).

Table 4. Slip distribution for each of 5 fragments. Coordinates correspond to the lower left corner and depth to the upper side along the vertical axis faults.

N°	Lat (°)	Lon (°)	H_j (km)	Slip (m)
1	-14.2000	-77.4200	8.00	09.00
2	-13.3520	-77.9295	8.00	17.50
3	-12.5040	-78.4390	8.00	17.00
4	-11.6561	-78.9485	8.00	07.00
5	-10.8082	-79.4580	8.00	07.00

great historical earthquakes have been reported in northern Peru since at least the 17th century, it is reasonable to assume that great earthquakes at Lima correspond to a rupture between latitudes 15°S to 9°S. We have chosen a fault length $L = 550$ km, a distance encompassing to these latitudes.

We have assumed that Peruvian seismicity distribution is located on a fault plane from the trench. We have chosen a dip angle for subduction plane $\delta = 20°$ corresponding to mean dip of CMT solutions in the selected area. Width W of the fault in the direction of the dip angle is chosen as $W = 140$ km and corresponds to depth limit $W \sin(\delta) + H$ of 58 km, a depth consistent with the extension of seismicity with depth. The lower limit of the horizontal projection of the fault corresponds approximately to the position of the coast, often seen to be the limit of great subduction earthquakes.

To simulate historical tsunami information we have divided the total rupture area into five fragments (see **Fig. 3**). Slip distribution is obtained by the forward method by trial and error until the model agrees with historical observations. The present model may be appropriate for explaining available tsunami information, but not necessarily the observed intensities due to shaking of the ground. This slip distribution is given in **Table 4**, wherein the mean slip value corresponds to 11.5 m (see **Figs. 3** and **4**).

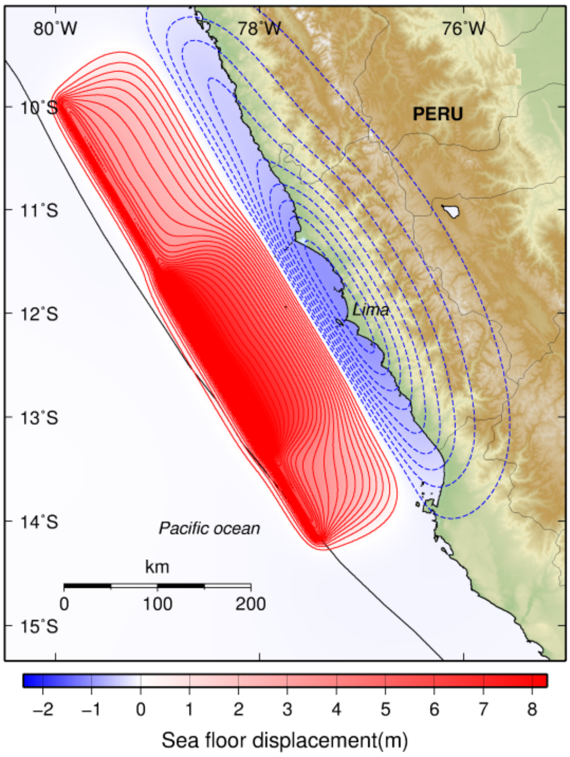

Fig. 4. Initial deformation of the seabed [19].

To calculate initial coseismic deformation of our source model (see **Fig. 4**) we used the model of Okada [17], which will be used to set the initial condition of the tsunami propagation phase.

5.2. Tsunami Propagation Model

We have used the numerical model TUNAMI [18], which numerically solves using a finite difference scheme (the leapfrog method) equations of conservation of linear momentum and the continuity equation of fluid dynamics to simulate the propagation (linear model in spherical coordinates) and inundation (nonlinear model in Cartesian coordinates for inundation grid) of the tsunami, with the initial condition of coseismic deformation given by the seismic source model.

To fit the requirement of "tsunami waves arriving at Callao after half an hour from the northwest," we must take into account a source rupture directivity from north to south for a total rupture time of about 3 minutes ($v_r = 3$ km/s). This implies that the rupture could start from fault 01 (north) consecutively until fault 05 (south), (**Fig. 5**). This is in agreement with the North-West to South-East unilateral rupture propagation that has characterized most great earthquakes in Peru, such as the 1996 Nazca, 2001 Camaná and 2007 Pisco earthquakes. This probably means that the rupture began north of the rupture area and then propagated south-east.

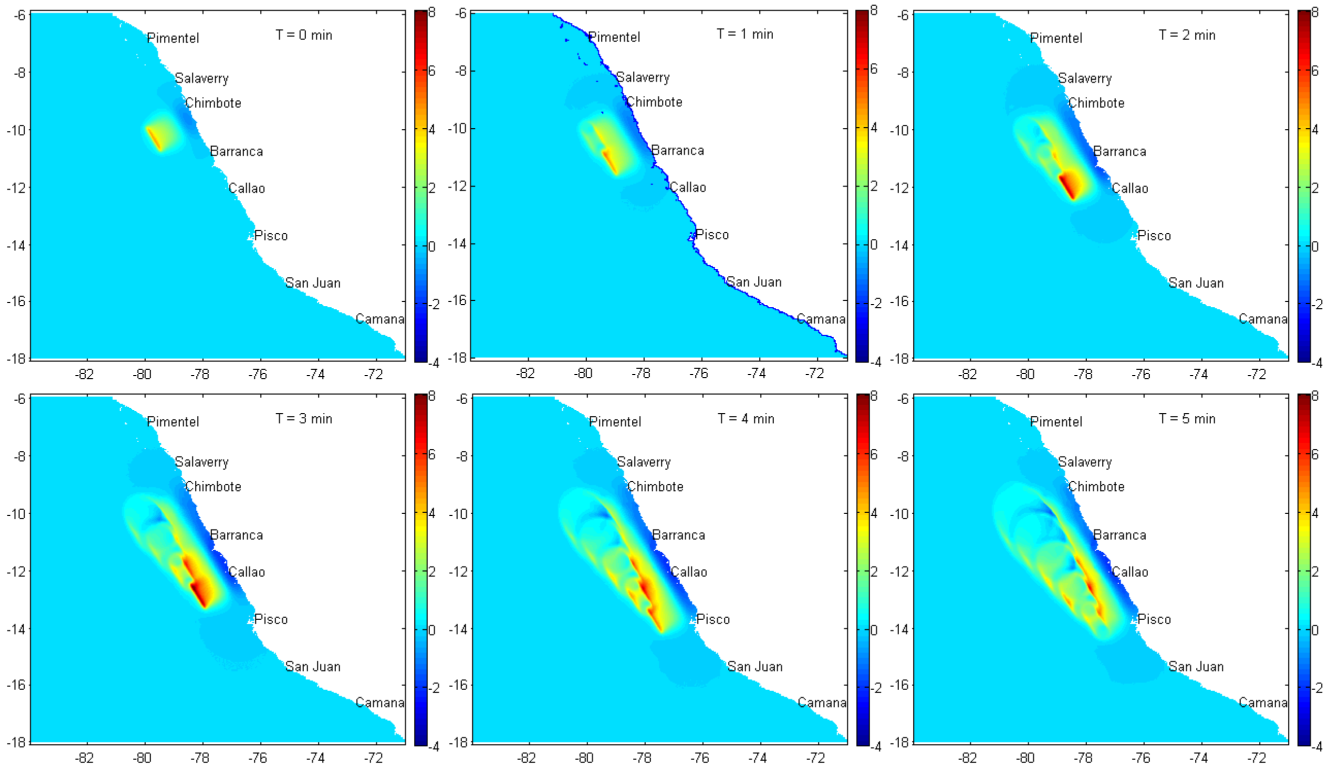

Fig. 5. Kinematic model of the seismic source for the 1746 Callao earthquake and tsunami.

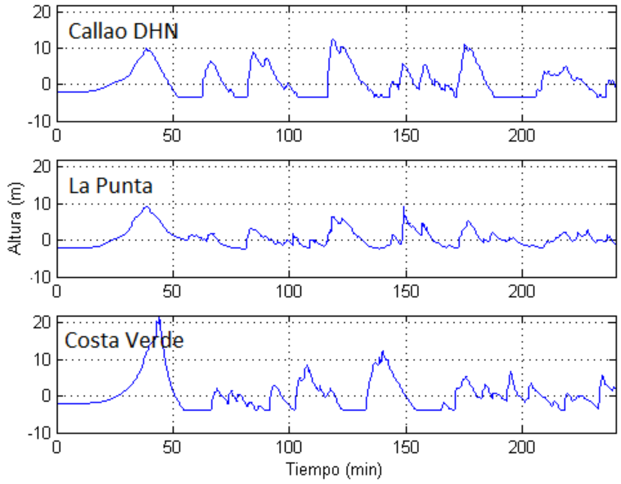

Fig. 6. Virtual tidal gauges. Notice lower saturation due to the proximity of virtual gauges to the shoreline. The height of the first wave in Callao was 10 m while the maximum runup was 22 m at Costa Verde.

5.3. Tsunami Inundation Model

For simulation of this phase, we have used a non-linear model to take into account friction between fluid and ground through the Manning roughness coefficient. As a result of non-linear simulation of tsunami dynamics, we have obtained parameters such as arrival time and wave height.

Figure 6 shows that in a virtual gauge, adjacent to the Lima port area (Callao DHN), the first wave had a height of 10 m with an arrival time of 23 minutes. In the area of La Punta, the first wave was less than 10 m, while in the area of the Costa Verde, the height of the first wave was greater than 22 m. These differences are due to the bathymetry, topography and morphology of each particular area.

We also observe a peculiarity of the coseismic subsidence phenomenon that started after the earthquake, i.e., a decrease in the sea level as evidenced by virtual gauges before the arrival of the first tsunami wave. This is due to the geometry of the subduction zone and the focal mechanism of the earthquake.

Figure 7 shows an inundation map for Callao. Inundation would arrive at 4 km from La Punta to the landmark of Plaza Vea. In the airport zone, inundation would arrive at 1.8 km inland, the airport is located 3.6 km inland, so the airport would not be affected. It is also noted that at Costa Verde, waves may be more than 22 m high, which is consistent with historical information.

6. Conclusions

The seismic source parameters modeled in this study are derived from historical documents and information from seismic catalogs based on macroseismic parameters.

The magnitude of 1746 Callao earthquake is estimated at Mw9.0, a value obtained quantitatively by the forward process of trial and error through numerical modeling of tsunamis.

Heterogeneous initial deformation or slip distribution indicates greater asperity from Cañete to the south to Barranca to the north. This agrees with the total destruction

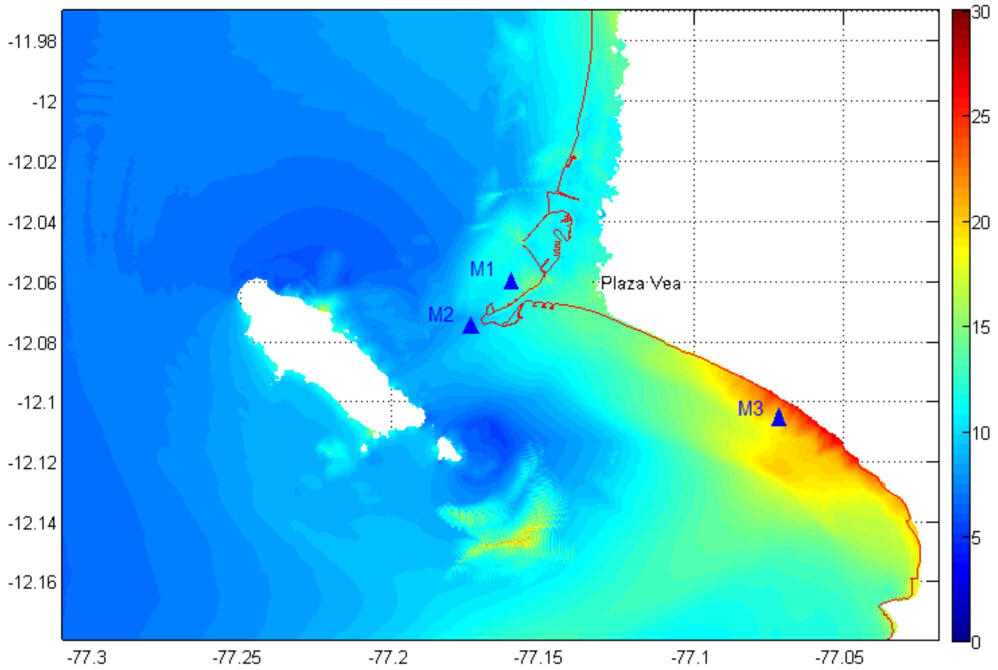

Fig. 7. Tsunami inundation map for Callao and Miraflores Bay. Note the height (red) reached by the tsunami waves in Costa Verde. Blue triangles correspond to virtual gauges: M1 = Callao-DHN, M2 = La Punta, M3 = Costa Verde.

reported in this region.

For great earthquakes or for very slow rupture velocity, it is necessary to apply a kinematic source model. This affects the values of tsunami arrival time, depending on the directivity of the rupture process.

For a near field tsunami at Lima and Callao, the arrival time of the first wave would be 23 minutes (at Callao) according to the nonlinear inundation model.

According to the numerical model, the height of the first wave at virtual gauge M1 (Callao DHN) is 10 m. The maximum vertical inundation height or run-up is 22 m at virtual gauge M3 (Costa Verde), (**Fig. 7**).

Results obtained by this paper correspond to a numerical model and, to some extent, are validated by data from historical documents.

Acknowledgements

The authors acknowledge support from: the project of the Science and Technology Research Partnership for Sustainable Development supported by JST-JICA, Dirección de Hidrografía y Navegación of the Peruvian Navy and the Universidad Nacional Mayor de San Marcos - Fenlab.

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Academic Societies & Scientific Organizations:
- Japan Society of Civil Engineers (JSCE)
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