# TSUNAMI HAZARD ASSESSMENT FOR THE CENTRAL COAST OF PERU USING NUMERICAL SIMULATIONS FOR THE 1974, 1966 AND 1746 EARTHQUAKES

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## ABSTRACT

A comprehensive study of tsunami simulation for the two recent events in 1974 (Mw8.0), 1966 (Mw8.1) and one historical event in 1746 (Mw8.5-9.2) was carried out in order to constrain the tsunami source and evaluate the tsunami hazard in the central coast of Peru. We propose a seismic source for each event in 1974 and 1966 and evaluate the tsunami heights and arrival time by performing a tsunami simulation using a TUNAMI-N2 code that solves non-linear long wave equation. Also, in order to reproduce the historical tsunami in 1746, we carried out a simulation for scenarios with Mw of 8.5, 8.8, 9.0 and 9.2. Through a comparison among the historical tsunami descriptions, the scenarios with Mw 8.8-9.0 were found to be more representatives, which is consistent with the maximum tsunami heights observed from Huarmey to Barranco stations. Moreover, we adopt a more realistic future tsunami scenario using a predicted slip model from an interseismic coupling using GPS data provided by Pulido et al. (2011). This scenario shows an important coupling area facing Huacho Lima and Pisco cities and according to the moment deficit a repetitive event of the 1746 earthquake could occur. Also this model shows that the events in 1940, 1966, 1974 and 2007 have not released the total energy accumulated since 1746. From this scenario, the maximum tsunami height could be 7.8 m in Huacho station with a minimum arrival time of 25 min after the earthquake. In all the cases, we found that the tsunami travels faster to the south and slower to the north of Peru. The tsunami simulation using the bathymetry data of 30 arc-second resolution showed longer travel time and higher amplitude compared with the 1 arc-minute resolution, giving the former better results in the comparison between the synthetic and observed tide gauge records for the 1974 and 1966 events.

**Keywords:** Tsunami hazard in Peru, Tsunami simulation, Tsunami height, Tsunami arrival time.

## 1. INTRODUCTION

Recent catastrophic tsunamis in Sumatra 2004 (Mw9.0), Chile 2010 (Mw8.8) and Japan 2011(Mw9.0) have shown the potential of the tsunami hazard, more destructive than the ground shaking by the earthquakes. These three earthquakes demonstrate the necessity of considering different scenarios and historical events, taking the most extreme cases into account in order to avoid an underestimation as the last tsunami in Japan 2011. In this study, we estimate a more realistic tsunami hazard in the Central coast of Peru using numerical simulations of two instrumentally recorded events in 1974, 1966 and historical one in 1746. Moreover, we adopt a realistic tsunami scenario using the interseismic plate coupling facing Huacho, Lima and Pisco cities. The estimated moment deficit could produce an earthquake of Mw 8.7 in the future.

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## 2. DATA

In order to perform numerical tsunami simulation, we use three kinds of data. The first one is the bathymetry data from the General Bathymetry Chart of the Ocean (GEBCO), which is useful to know the morphology of the sea bottom, taking into account that the velocity of the tsunami depends on sea bottom depth. Also, in order to compare the accuracy of bathymetry, we use GEBCO 1 arc-minute and 30 arc-second resolution data. The second one is the tide gauge record which is important in order to validate our result in tsunami simulation and get a better approximation of the tsunami source. For the 1966 event we use the tide gauge records of Chimbote (09°14'S; 79°00'W), Callao (12°03'S; 77°09'W) and San Juan (15°21'; 75°10'). For the 1974 event we use Callao and San Juan records. All tide gauges are operated by the Directorate of Hydrography and Navigation (DHN), the Navy of Peru, which is responsible for the National Tsunami Warning System. Moreover, in order to estimate the height and arrival time of the tsunami along the central coast of Peru, we consider the location of the actual tide station and we assume some stations in important places along the study area. In order to compare the synthetic tsunami waveforms with the observed ones we digitize the tide gauge records provided by Kuroiwa (2004) and Murty and Wigen (1975) and removed the tide effect fitting a polynomial function and subtracting the tide from the original signal for the 1974 and 1966 events.

## 3. METHODOLOGY

### 3.1. Computational Area

For the instrumental 1966 and 1974 events, the computational domain ranges from 84.0°W to 74.0° W and from 17°S to 7°S (600 x 600 for 1 arc-minute and 1200 x 1200 for 30 arc-second grid nodes). For the historical 1746 event, the computational domain ranges from 91°W to 72°W and from 20°S to 4°S (1140 x 960 for 1 arc-minute and 2280 x 1920 for 30 arc-second grid nodes). Time step of 2s for 1 arc-minute and 3s for 30 arc-second were chosen considering the CFL (Courant-Friedrichs-Lewy) criteria, in order to avoid numerical instabilities. The propagation time of 3 hours has been chosen in order to simulate enough duration of waves for comparison with the tide gauge records for all the three cases.

### 3.2 Tsunami Source

In order to calculate the static deformation of the seafloor, which is used as an initial condition, we use the algorithm by Okada (1985) based on the assumption of an isotropic media with a half-space. Using nine source parameters we can calculate the seafloor deformation due to the fault motion. These parameters are latitude, longitude, depth of fault top, length, width, strike, dip, rake angle and slip amount. In order to get the best parameters for our simulation, we consider the geometry of the Nazca plate subduction in the central region between 10°S and 15°S on which the seismicity distribution shows a dip of 10° at a depth of 20-25 km and increases to 30° until a depth of about 100 km, where it became sub-horizontal (Barazangi and Izacks, 1976).

## 4. RESULTS AND DISCUSSION

### 4.1. Tsunamis on 3 October 1974 and 17 October 1966

#### 4.1.1 Tsunami Source

In order to find a good source model for the 1974 and 1966 events we perform a tsunami simulation and stimate the tsunami height and arrival time. In both cases we use the scaling law proposed by Papazachos et al. (2004) in order to know the size of the fault considring the estimated moment magnitude for this events. Since it is a rough estimation of the source model, we refer previous studies such as aftershock distribution, rupture distribution (Hartzell and Langer, 1994; Langer and Spence,

1995) to improve the source models as the resoult of comparison between synthetic tsunami waveforms and recorded ones.

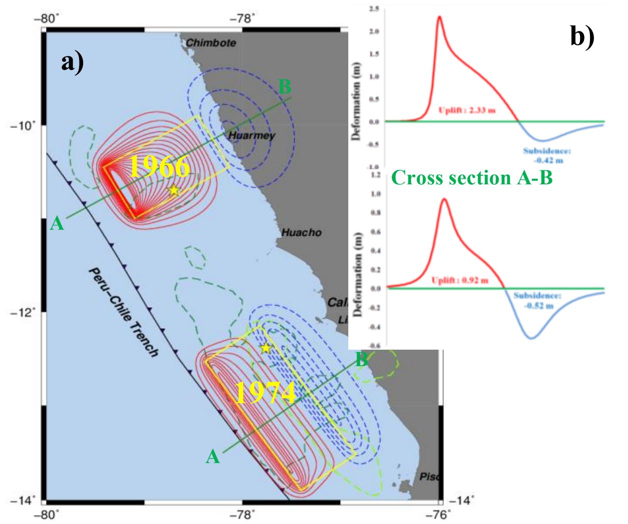


Figure 1: a) Seismic fault models proposed for 1974 and 1966 events and projection to the surface (yellow rectangle), the epicentral location by USGS (yellow star), the uplift and subsidence areas with the contour interval of 0.1 m and aftershocks and rupture areas (dark green and light green dashed lines). b) Cross section of the vertical deformation along A - B.

After numerous simulations we find a good agreement between the synthetic and recorded waveforms, and propose source models for the event in 1974 and 1966 located to the south and north of Lima city, respectively (Table 1). According to these parameters the calculated seafloor deformation showed an uplift of 0.92 m and a subsidence of 0.52 m for the 1974 event, and 2.33 m and 0.42 m for the 1966 event. In both cases we compare the proposed source models with the aftershock distribution areas determined by Langer and Spence (1995). The aftershock and rupture area in both cases are located within our proposed sources indicating good agreement with our result (Figure 1a and b). Moreover, the proposed model for the 1966 event with a small length and large width is in good agreement with the model proposed by Abe (1972) using long period surface wave data recorded in far field stations.

### 4.1.2 Tsunami arrival time and maximum height

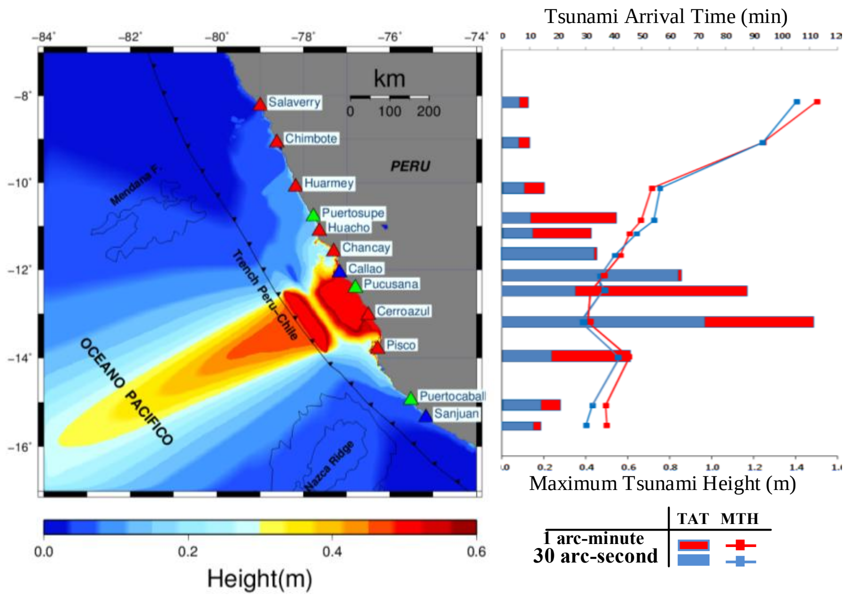


Figure 2: Distribution of the maximum tsunami height (left) and comparison of the tsunami arrival time for the first wave and maximum tsunami height (right) using the bathymetry data of 30 arc-second (red) and 1 arc-minute (blue), for the 1974 event.

The tsunami arrival times calculated by using the bathymetry data of 30 arc-second tend to be larger than the ones obtained by using the bathymetry data of 1 arc-minute. Figure 2 for the 1974 event the maximum tsunami heights were estimated at the stations of Callao (0.8 m), Pucusana (1.14 m) and Cerro Azul (1.46), since the maximum directivity of the tsunami energy is perpendicular to the strike angle (Figure 2). The minimum tsunami arrival time is 30 min after the earthquake in the Cerro Azul station.

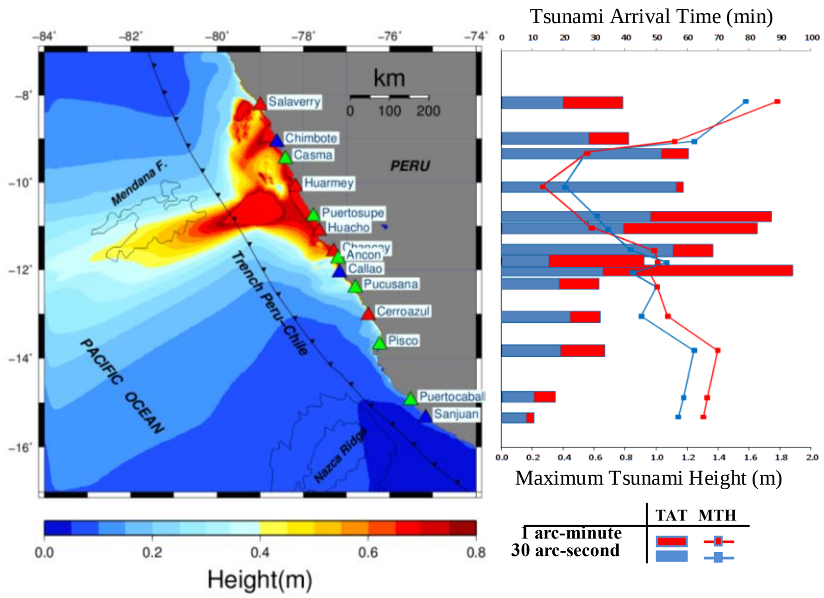


Figure 3: Same as Figure 2 but for the 1966 event.

For the 1966 event, between Salaverry (8.5°S) and Callao (11.5°S), the maximum tsunami height of 1.1 - 1.9 m was calculated, with the exception of the maximum tsunami height of 0.8 m at Ancon station (Figure 3). This characteristic shows a good agreement with the survey between Ancon and Huacho where low amplitude of tsunami was observed (Lomnitz and Cabre, 1968). The high amplitude of tsunami in Callao station (1.9 m) gives us an important factor of amplification in front of Callao city. Finally, small waves (<0.8 m) are calculated to the south.

In both cases, the maximum tsunami height calculated by using the bathymetry data of 30 arc-second tends to be higher than the one obtained by using the bathymetry data of 1 arc-minute.

Table 1: Proposed fault parameters for the 1974 and 1966 earthquake using tsunami simulation.

| *Year* | *Lat. (° S)* | *Long. (° W)* | *Slip (m)* | *Length (km)* | *Width (km)* | *Strike (°)* | *Dip (°)* | *Rake (°)* | *Top depth (km)* |
|---|---|---|---|---|---|---|---|---|---|
| 1974 | 13.9 | 77.4 | 2.4 | 185 | 75 | 325 | 10 | 90 | 9 |
| 1966 | 11.0 | 79.0 | 4.9 | 70 | 130 | 330 | 20 | 90 | 7 |

### 4.2 Historical Tsunami on 28 October 1746

A study of historical events after the 2011 tsunami in Japan is more important considering that the large events have some degree of cyclicality in terms of frequency and magnitude. We perform a tsunami numerical simulation for the historical 1746 event as a possible event in the future. We carried out a rough validation of the tsunami model using the historical descriptions of the damages. Moreover, the estimated moment magnitude for this event according to previous studies is between 8.5 to 9.5. In order to find more precise magnitude and fault model we performed the tsunami simulation for four scenarios, considering the moment magnitude of 8.5, 8.8, 9.0 and 9.2 (Table 2). Dorbath et al. (1990) indicate that this event ruptured along 350 km and produced a tsunami with local height of 15 m to 20 m, destroying Lima completely.

Table 2: Fault parameters of the four scenarios for the 1746 earthquake

| *Mw* | *Lat. (° S)* | *Lon. (° W)* | *Slip (m)* | *Length (km)* | *Width (km)* | *Strike (°)* | *Dip (°)* | *Rake (°)* | *Top depth (km)* |
|---|---|---|---|---|---|---|---|---|---|
| 8.8 | -78.0 | -13.3 | 14 | 330 | 100 | 328 | 10 | 90 | 0 |
| 9.0 | -78.0 | -13.3 | 25 | 350 | 100 | 328 | 10 | 90 | 0 |

However, according to a historical tsunami description it could have a height of around 7 m. The more preferable scenarios could be the case of Mw=8.8 with the calculated tsunami height of 6.5 m at

Callao or the cases of Mw=9.0 with the one of 9.8 m at Callao. For these two scenarios, the maximum tsunami height more than 3 m can be shown between Huarmey to Cerro Azul stations.

## 4.3 Scenario from GPS interseismic coupling

### 4.3.1 Slip distribution and vertical seafloor deformation

A slip distribution model was provided by Pulido et al. (2011) from the interseismic coupling model using GPS data. Figure 4a shows the slip distribution with two nearest asperities. The first one is to the north between 11°S-12.5°S and the second one is to the south between 12.5°-15°S. According to the deficit of the estimated seismic moment (12 x $10^{21}$ Nm), both asperities could produce an earthquake of Mw=8.7. In order to identify the contribution of each asperity to tsunami height and arrival time, we perform the tsunami simulations for both two asperities and only the asperity to the north. Figure 4b shows the total vertical deformation for the two asperities, which produce an uplift of 4.6 m and a subsidence of 2.2 m. The distribution of the two rupture areas proposed in this study for the events in 1974 and 1966 are located around the asperity to the north (in a low coupling area) and the earthquake in 2007 is located over the south asperity in front of Pisco city.

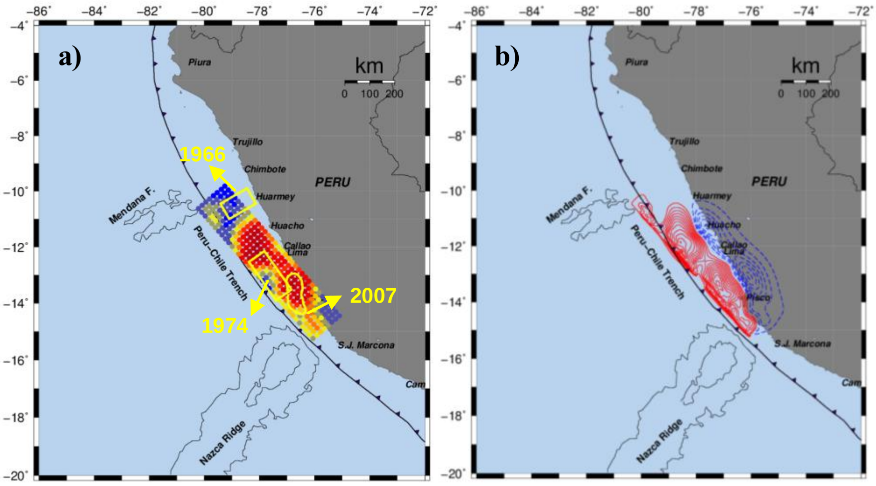


Figure 4: a) Slip distribution from GPS data provided by Pulido et al. (2011), the rectangles and polygon show the source model for the 1966 and 1974 events proposed in this study and the 2007 proposed by Sladen et al. (2010). b) Uplift and subsidence areas with contour interval of 0.3

### 4.3.2 Tsunami arrival time and maximum height

Figure 5 shows the maximum tsunami amplitude and arrival time considering the two asperities. According to this scenario, the stations facing the source area will be greatly affected. In both scenarios the computation results are similar in the north of the rupture area from Eten to Barranco stations with the minimum arrival time of 20 min after the earthquake and the maximum tsunami height of about 7.8 m in Huacho station.

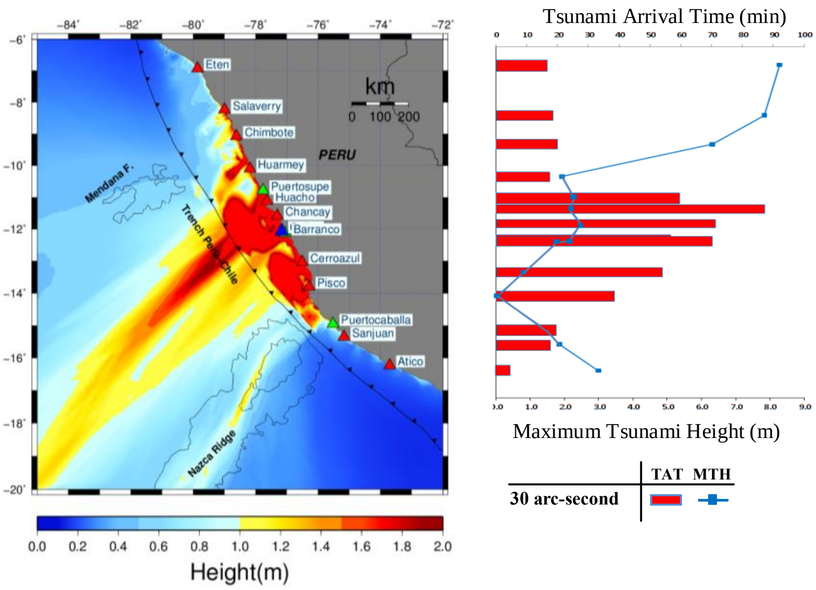


Figure 5: Same as figure 2 but for the two asperity model from GPS data.

For the places to the north and south of the two asperities, the tsunami will be relatively small, less than 2 m. For the scenario without considering the asperity in the south, the maximum tsunami wave decreases to 2.5 m and 1 m in Cerro Azul and Pisco stations, respectively. The scenario considering the two asperities, the tsunami arrival time in the Pisco station is almost at the same time with the earthquake occurrence, this characteristic is due to location of the south asperity under the Pisco station. The scenario considering only the asperity to the north, the first tsunami wave will reach the coast along the Huarmey station within 18 min and from Huarmey to Barranco between 20 and 30 min after the earthquake. The places to the south, from the Cerro Azul to Atico stations the first tsunami waves arrive in 35 min and later. The places to the north of Lima between Chimbote and Eten have enough time more than 1 hour to evacuate. The tsunami propagation shows the same behavior with the previous cases, which the tsunami propagation to the north takes more time with respect to the south of Peru. The tsunami arrival time is more than one hour for the stations located to the north (Chimbote and Salaverry), but it is less than one hour for the stations located to the south (Puerto Caballa and San Juan).

## 5. CONCLUSIONS

We assessed the tsunami hazard in the central coast of Peru using two recent (1974, Mw8.0; 1966, Mw8.1) and one historical tsunami (1746, Mw 8.5-9.2). The historical 1746 events, according to the tsunami simulation and historical description of the tsunami damages in Callao city, could have been the earthquake of Mw 8.8-9.0. Moreover, we adopted more realistic tsunami scenarios, based on the slip distribution from the interseismic coupling predicted from GPS data (Pulido et al., 2011). In order to analyze the accuracy of the tsunami amplitude and arrival time, we used two bathymetry data from GEBCO with 1 arc-minute and 30 arc-second grid intervals. We simulated the tsunamis in 1974 and 1966 and we proposed the best solutions of the tsunami sources based on the comparison of the synthetic and recorded tsunami waveforms. According to their locations, both events are emplaced near Lima city and around the predicted coupling area. This characteristic seems that these two events released the accumulated energy to the north and south of the coupling area. In this sense, we performed the tsunami simulation using the slip distribution model in order to evaluate two realistic scenarios of the future tsunami which could be used to construct a tsunami hazard map and evacuation plan in the Callao city. According to these scenarios, the most affected areas are located between Puerto Supe and Barranco with maximum tsunami height of 7.8 m in Huacho station. The minimum time to evacuate for those places near the source is about 15 min in average.

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