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THE TSUNAMI OF CAMANA 2001

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Abstract: On 23 June 2001, at 15:33 local time, the Camaná city and all the peruvian southern region were hit by a strong earthquake of magnitude 8.4 Mw and maximal intensity VIII in Mercalli scale, the epicenter was located on the sea in the forefront of Ocoña (Arequipa). 15 minutes later a localized tsunami was generated, which destroyed the seaside town of Camana and caused the death of 24 people and 62 missing people. With the help of numerical modeling TIME and the use of computers, it is possible to make the numerical simulation of tsunami and to obtain parameters such as arrival times, run up (maximal height of flooding), synthetic tidal gage recordings and flooding maps, which will be useful for disaster mitigation for the corresponding authorities.

1. INTRODUCTION

A tsunami is a series of water waves of great length (with periods ranging from 5 to 60 minutes, or higher), generated by mechanisms such as volcanic explosions on islands, underwater landslides, falling rocks or bays ocean and tectonic movements associated with earthquakes. An earthquake tsunami generator is usually associated with subduction zones. Since many of these areas are along the Pacific Rim, the vast majority of tsunamis occur in the Pacific Ocean.

Tsunamis are classified in the place of arrival to the coast, according to the distance (or travel time) from their place of origin, in:

a) Local Tsunami, if the place of arrival on the coast is very near or within the area of generation (defined by the area of seafloor displacement) of the tsunami, or less than one hour travel time from the beginning.

b) Distant Tsunamis, if the place of arrival is more than 1000 km away from the zone of generation or end-opposite shores across the Pacific Ocean and about half a day or more of the tsunami travel time from that area (Jimenez, 2008).

According to the testimonies of survivors, shortly before the earthquake a refolding of the sea in some places and then the earthquake on 15 minutes started the tsunami destroyed the resort of Camaná. This was a small local tsunami that affected only Camaná coastal resorts. The height of the waves reached up to 7 m in some places, with a run-up to 7 m and a maximum flooding distance of 1350 m. There were 24 dead and 2 missing and large losses. This tunamigenic earthquake is the strongest since 1868 in the southern region of Peru. The period of recurrence of this type of event for the region of Peru and northern Chile is of 100 years (Kulikov et al., 2005).

The parameters obtained by the Geophysical Institute of Peru (IGP) were:

Local Time = 15h 33m 23 June 2001
Latitude = -16.20 º
Longitude = -73.75 º
Depth = 29 km
Magnitude Mw = 8.4
Intensity = VIII Ocoña, Camana
Location: 82 miles north west of Ocoña (Arequipa)

1.1 Area of study

Camana province is located in the Midwestern part of the Arequipa region to 172 km from the capital of the Department of Arequipa, and has about 56 thousand inhabitants. This is the first city that sent the conqueror Francisco Pizarro founded. Predominant economic activity is agriculture. Bounded on the north by the province Condesuyos, province of Castilla, Arequipa province (San Juan de Siguas) for the north-west province Caravelí and Penthouse, on the south by the Pacific Ocean on the east by the province of Islay. In 2001 a strong earthquake rocked the region and a tsunami devastated the coastal resorts of the city of Camana.

2. FOCAL PARAMETERS CALCULATION

From the empirical relationship of Papazachos 2004, between the seismic moment magnitude Mw and the focal parameters: length L (km), width W (km), and displacement

U (cm) of the failure to subduction zones :

$$\log(L) = 0.55M - 2.19$$
$$\log(W) = 0.31M - 0.63 \qquad (1)$$
$$\log(U) = 0.64M - 2.78$$

The following results were obtained for Mw = 8.4:

Rupture length	L = 269 km
Rupture width	W = 94 km
Fault displacement:	U = 3.9 m

The seismic moment Mo is defined as: Mo = μLWU = $4.9*10^{21}$ Nm, where μ = 4.5*1010 N/m2 is the modulus of the medium. Talandier 1993, provides a relationship between seismic moment Mo and the destructive potential of a tsunami. The value of Mo indicates that the Camana earthquake generated a small tsunami (Talandier, 1993). However, it was destructive in the area of the coastal resorts due to the vulnerability of buildings.

Table 1. Classification of tsunamis according Talandier.

Value range	Tsunami type
$Mo < 10^{21}$ N.m	No tsunami was generated
$10^{21} < Mo < 5*10^{21}$ N.m	Small tsunami
$5*10^{21} < Mo < 2*10^{22}$ N.m	Potencially destructive
$Mo > 2*10^{22}$ N.m	Great and destructive

3. DATA AND SELECTION OF THE DOMAIN OF INTEGRATION

To model the tsunami flood zones need the following information:

a) Global bathymetry grid.- To simulate the largest where the tsunami spread. The data are taken Etopo2 model with a resolution of 3.6 km (Smith, 2006).

b) Local bathymetry.- These fine details are obtained from drilling conducted in the area.

c) Local topography.- To model the flooding caused by the tsunami. Data are taken on-site survey and satellite survey data SRTM 90 (Jarvis et al., 2006).

With all these data we obtain a digital elevation model and proceeds to draw 4 nested grids: A, B, C and D (see Figure 1). Where grid A is the largest and contains the area of rupture. The grid D is the smallest, but the data are finest and contains the region where we want to evaluate the flood. The boundaries of the grid are:

region_a = [-20 -13 282.0 290.0];
region_b = [-17 -15.8 285.5 287.5];
region_c = [-17 -16.2 286.5 287.5];
region_d = [-16.85 -16.59 287.258 287.373];

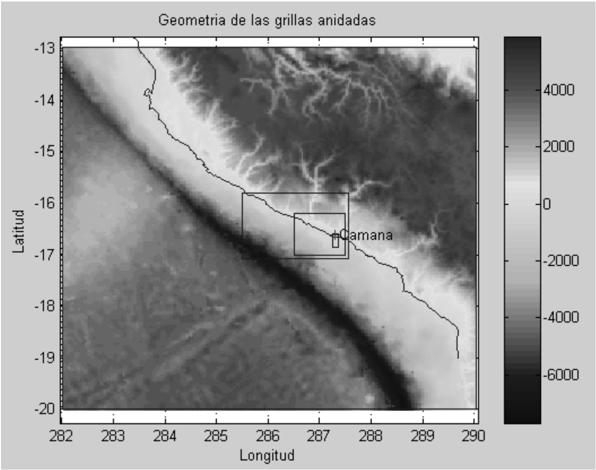

Fig. 1 Nested grids for the present model

4. TSUNAMI GENERATION PHASE

For an earthquake generates a tsunami is necessary to meet the following requirements:

a) The epicenter of the earthquake, or a majority of its rupture area, is under the seabed at a depth less than 60 km (shallow earthquake).

b) Occurring in a sink edge of tectonic plates in the sea, ie the failure to have vertical movement and is not just lateral strike slip motion.

c) The earthquake releases enough energy in a certain period of time and this is efficiently transmitted. In general, magnitude Mw > 7.0.

The initial condition of tsunami (strain field due to displacement or fault line) is determined using the model of Mansinha and Smylie (1971) assuming an instantaneous deformation of the ocean's surface equal to the vertical component of the strain field of the bed ocean. This is a model of fracture and requires knowledge of the earthquake focal mechanism (Okal, 2002). It has been considered the following values:

Strike angle = 301º
Dip angle = 20º
Slip angle = 90º

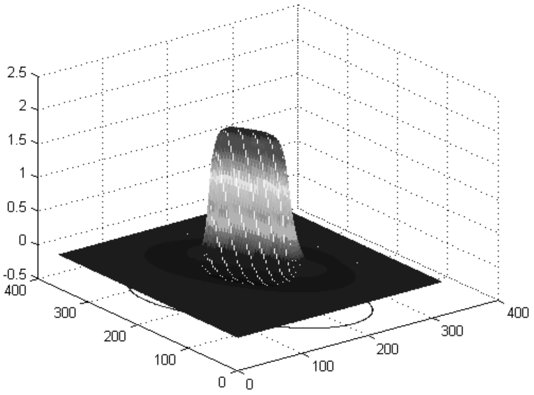

Fig. 2 Model of initial co-seismic deformation.

For this model the maximum height of the deformation is of 2.04 m. This creates the "piston effect" that destabilizes the water column causing tsunami waves.

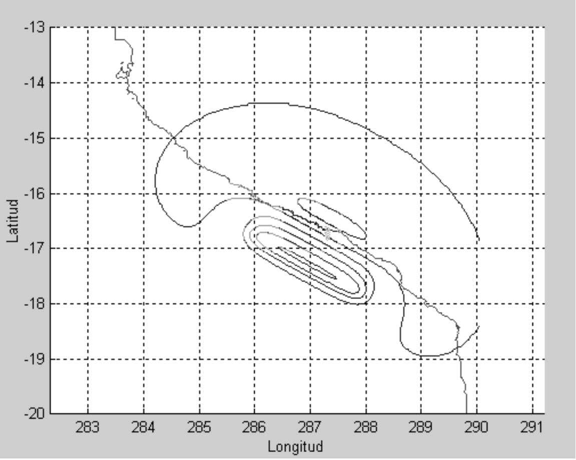

Fig. 3 Contours of initial co-seismic deformation.

Using the inversion of the tsunami waveforms from tidal gauge stations is possible to get the source parameters for a heterogeneous slip model as shown in Figure 4 (Adriano, 2010).

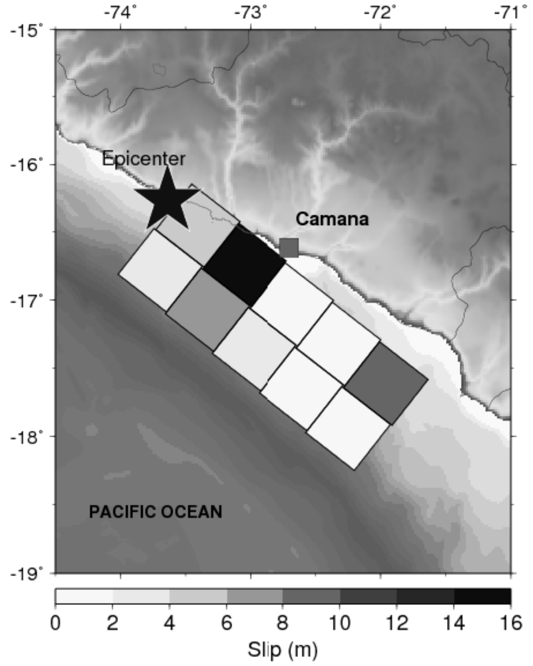

Fig. 4 Heterogeneous slip model from inversion of tsunami waveform data (Adriano, 2010).

5. PROPAGATION PHASE OF TSUNAMI

The propagation of the tsunami is simulated with the model of Goto and Ogawa (1982) that integrates the shallow water equations by the numerical method of finite differences. The TIME model (and other models) uses the linear equations for the propagation of the tsunami through the ocean floor in shallow water:

$$\frac{\partial \eta}{\partial t} + \nabla.\vec{U} = 0 \qquad (2)$$

$$\frac{\partial \vec{U}}{\partial t} + gh\nabla \eta = 0 \qquad (3)$$

where η is the disturbance of sea level, U represents the velocity field, g is the acceleration of gravity, h is the depth and t is time. In Figure 5 shows the initial stage of propagation of tsunami waves for the homogeneous slip model.

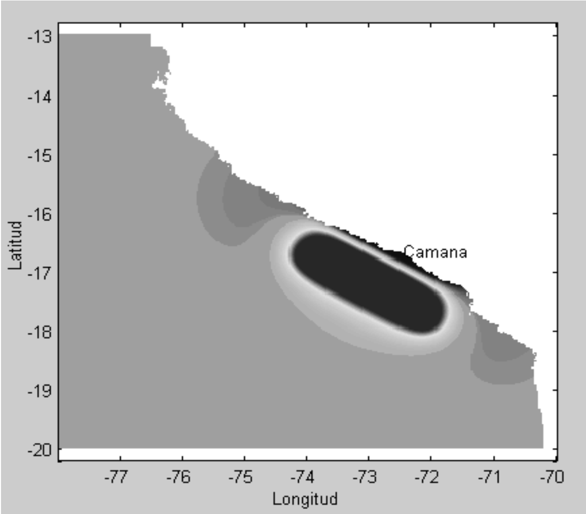

Fig. 5 Start time of Tsunami Propagation

6. INUNDATION PHASE OF TSUNAMI

The height reached by a tsunami, upon reaching the coast is due to the interaction of various physical and morphological factors such as characteristics of waves at sea, bathymetry, seabed slope, configuration of the sea boundary, diffraction, refraction, reflection, dispersion of the normal modes of resonance of the coastal formations and the formation of bores on beaches, estuaries and coastal lagoons. These factors determine that the arrival of the tsunami on the coastline is a complex process, which generates significant differences in height of the tsunami even over short distances along the coast.

In Figure 6 shows that the maximum wave height (according to model) to the shoreline was 9 m at the position corresponding to -72.75 degrees longitude (outside the area of interest: grid D). The maximum wave height is 7 m.

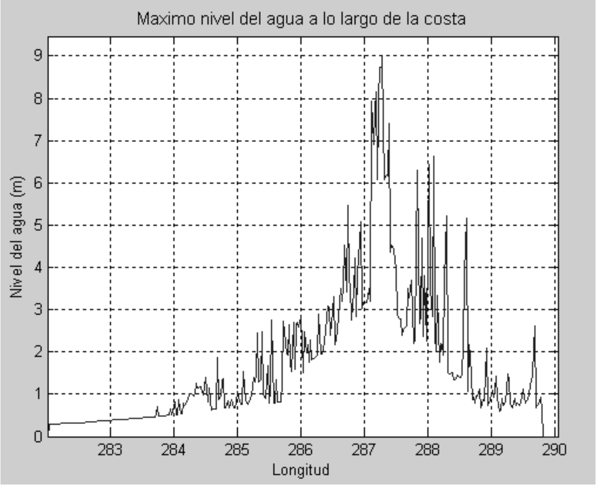

Fig. 6 Maximum wave height along the coast.

In Figure 7, we can see a tsunami inundation map according to the homogeneous slip model for Camana area. The narrow strip for the seaside resort (right side) is completely flooded, with the South Panamerican highway and the adjacent hills as boundary. The maximum horizontal inundation distance is about 1350 m, according to this model.

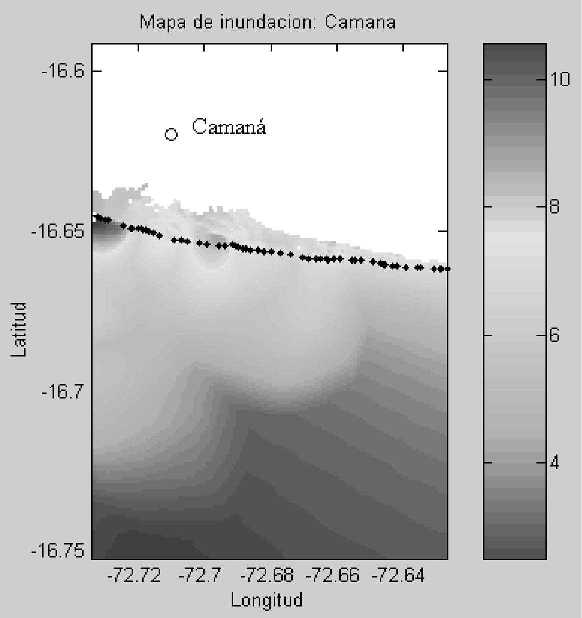

Fig. 7 Flooding map from the homogeneous slip model (scale in meter).

In Figure 8, we can see the inundation map for the heterogeneous slip model. This means that the tsunami would reach to Camana city, that did not happen, and this is because the values obtained for the slip amount on the northern part of the fault in the Tsunami waveform inversion model (for to get the heterogeneous slip model) are overestimated (Adriano, 2010).

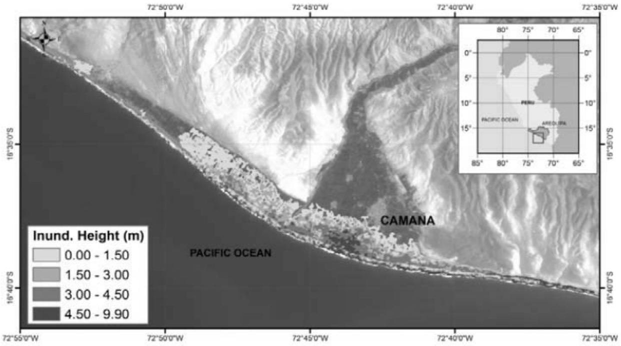

Fig. 8 Flooding map from the heterogeneous slip model (Adriano, 2010).

Figure 9 shows an aerial photograph in which is traced the flooding observed, it appears that the homogeneous slip model agrees quite closely with the observation in situ, thus validating this modeling tsunami inundation.

Fig. 9 Flooding map as in-situ (Source: DHN)

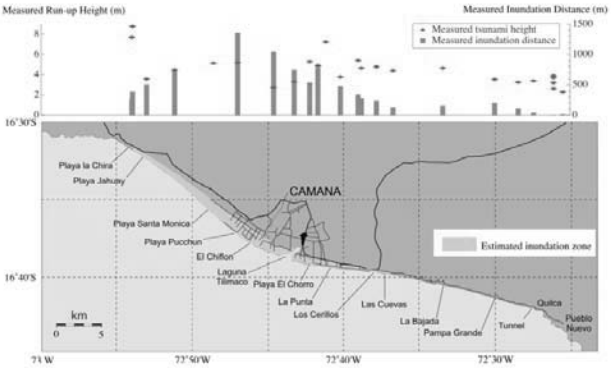

Fig. 10 Measured inundation distances (ITST)

In Figure 11 shows a synthetic waveform (tidal meter) located in the region of the grid D. The peak of the first wave arrives about 12 minutes and the next largest wave arrives at 28 min. The maximum wave height is about 7 m (which is consistent with the observation in situ). After 3 hours the wave amplitude has been reduced to little more than 1 m.

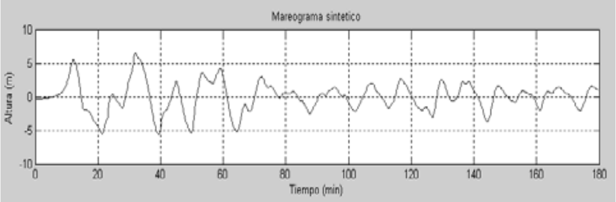

Fig.11 Synthetic waveform tsunami from a virtual tidal station located in the coastline of the flood region.

7. CONCLUSIONS

Camana City is well located, but not the coastal resort in an area that is highly vulnerable to the occurrence of a tsunami, which means that in future similar event may occur as in 2001.

The value of seismic moment Mo = $4.9*10^{21}$ Nm calculated in this work indicates that the earthquake of Camana 2001 generated small but destructive tsunami.

For a local tsunami, the arrival time of the first wave will be about 12 minutes, which provides little time for evacuation. However, not always the first wave is the largest.

The run-up (maximum flood height) reached a height of 7 m on average, implying that some places like the resort, would be potential flood spots.

The results in this paper are a mathematical physical model to some extent validated by field data and evidence.

The relevant authorities should develop plans for disaster mitigation in the event of an earthquake and tsunami. The coastal population must learn to be forewarned before the occurrence of these events.

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