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TSUNAMI SOURCE AND INUNDATION MODELING OF THE JUNE 2001 PERU EARTHQUAKE

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Abstract: The source of the Camana tsunami of June 23, 2001, which was generated due to a large earthquake (Mw = 8.4 by USGS) at the southern part of Peru, is estimated by the inversion of 10 tsunami waveforms that were recorded at ten tide gauge stations around the Pacific Ocean. Then, we perform the tsunami numerical inundation modeling to investigate the validity of this source model through comparison in term of the run-up height with field survey data measured around Camana city. As a results, the waveform inversion shows that large slips were estimated at the deeper part (> 29 km) of the fault plane, located more than 50 km from the trench axis, with a largest slip value about 9.96 m. The total seismic moment is calculated as 3.7×10^{21}Nm (Mw = 8.3) for 12-subfault model. The inundation modeling result is consistent in terms of the run-up height data measured around Camana city.

1. INTRODUCTION

Peru has experienced some of the largest tsunamis that have occurred around the world. For example, an earthquake off the southern coast of Peru (16.265°S 73.641°W, Mw = 8.4 at 20:33:14 UTC according to United State Geological Survey, USGS) on June 23, 2001 generated a tsunami that according to the post-tsunami report done by the Directorate of Hydrography and Navigation (DHN), Peru Navy, the coastal cities of Oconha, Camana, Quilca and Matarani, located at the southern part of Peru, were significantly affected. In Camana the tsunami wave penetrated more than one kilometer causing destruction and death. This tsunami was recorded in several tide gauge stations placed in Hawaii, Japan, Australia, New Zealand and Chile with tsunami heights between 5 m and 20 cm. At the tide gauge station located at Callao, Lima-Peru, the tsunami wave was recorded 90 minutes after the mainshock with an initial tsunami height of 40 cm.

The purpose of this study is to estimate the tsunami source model of the June 23, 2001 Peru earthquake by performing an inversion analysis from tsunami waveforms and then perform a tsunami inundation modeling to investigate the validity of this source model through comparison in term of the run-up height with field survey data measured around Camana.

2. DATA AND METHOD

2.1 Bathymetry and Topography Data

In order to perform the tsunami waveform inversion the bathymetry data are taken from the General Bathymetry Chart of the Ocean (GEBCO) 30 arc-seconds grid data for the computation domain.

To perform the tsunami inundation modeling the computational area is divided into four domains to construct the nested grid system. The bathymetry/topography data for the first to the third domains are resampled from GEBCO 30 arc-seconds grid data. The bathymetry data for the fourth domain is constructed from the nautical chart provided by DHN and the topography data are merged from the Thermal Emission and Reflection Radiometer (ASTER) 1 arc-second resolution and 50 m resolution contour line data from Camana Local Government. The grid size varies from 810 m to 30 m.

2.2 Tide Gauge Data

The June 23, 2001 Peru tsunami was recorded in several tide gauges around the world. In this study the tide gauge data are taken from the National Oceanic and Atmospheric Administration (NOAA)/Pacific Marine Environmental Laboratory (PMEL), Center for Tsunami Research and are provided by the National Oceanic Services (NOS)/NOAA, Field Operation Division, Pacific Regional Office.

Among all tide gauge stations data, only ten tide gauges are used as input data which has 1 minute data sampling, two tide gauge stations located in Peru and the rest of them located in Chile. In order to obtain the tsunami signal from each tide gauge data, firstly the initial time of the earthquake must be subtracted (T_0 = 06/23 20:33:14 UTC, according to USGS. After that the astronomical signal could be estimated by fitting a polynomial regression model using the entire data thus it can be removed from the original data. Finally these observed tsunami signals can be compared with the synthetic tsunami signal obtained in the tsunami propagation. Figure 1 shows the locations of the tide gage stations used for the tsunami waveform inversion analysis.

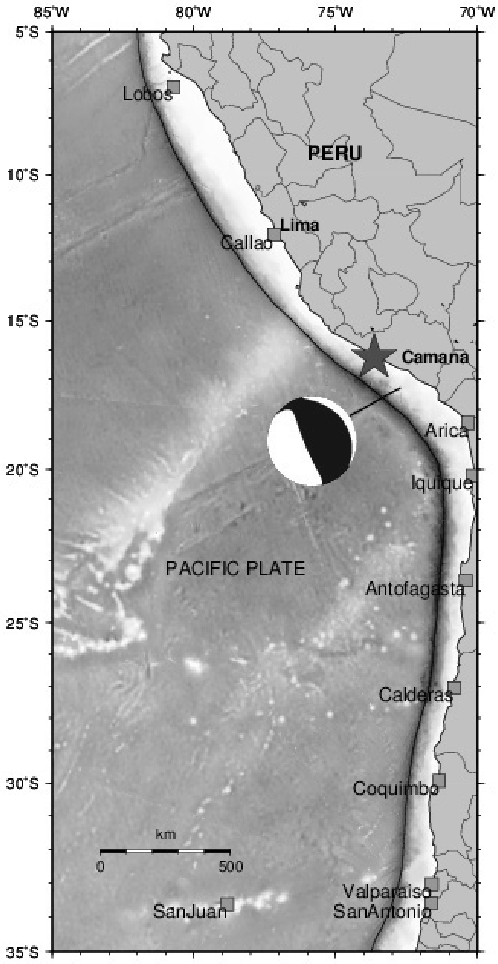

Figure 1 Green rectangles indicate the location of the tide gauge stations. Red star shows the epicenter (USGS). Lower hemisphere projection is the Global Centroid Moment Tensor (GCMT) solution.

2.3 Field Survey Data

The International Tsunami Survey Team (ITST) conducted a field survey along the area affected by the tsunami with the main purpose to examine the tsunami damage, to measure the tsunami run-up height and the extent of inundation and also to interview the eyewitnesses of the event. The measured tsunami run-up around Camana city done by the ITST (2001abc) is used in this study to validate the tsunami inundation model.

2.4 Tsunami Waveform Inversions

In order to estimate the extent of the rupture area and the slip amount distribution, we divided the source into 12 subfaults that cover the aftershock area during one month after the mainshock (Figure 2). The subfault size is 50 km x 50 km. The top depths are 14.15 km and 29.60 km for shallow and deep subfaults, respectively. The epicenter is located on the northern subfault. The focal mechanisms for all the subfaults are strike = 308°, dip angle = 18° and slip angle = 63° from the GCMT solution of the mainshock (Table 1).

To calculate the tsunami propagation initiated at each subfault, the lineal shallow-water or long-wave equations were numerically solved by finite-difference method (Satake, 1995). The governing equations are described in Fujii and Satake (2006). The previous Figure 1 shows the computation area, there are 1800 x 3600 grid point along the longitude and latitude, respectively. For the initial condition, static deformation of the seafloor is calculated by using the rectangular dislocation model (Okada, 1985). We also take into consideration the effect of the seismic horizontal displacement in region of steep bathymetry slope (Tanioka and Satake, 1996).

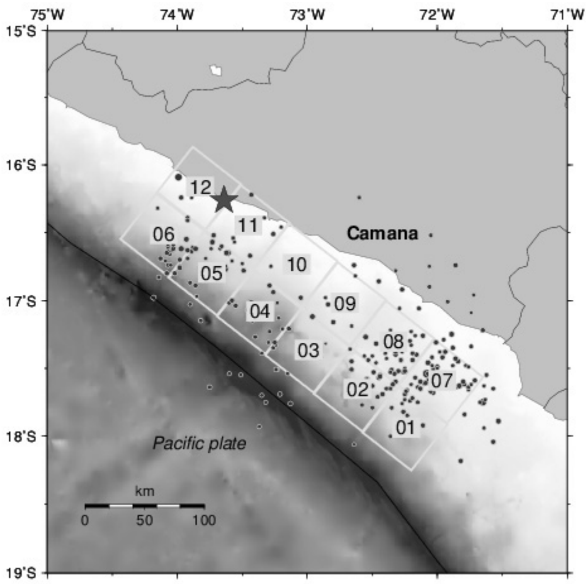

Figure 2 Subfaults location and numbers. Red star shows the mainshock epicenter. Red circles indicate aftershocks within one month after the mainshock.

2.5 Tsunami Inundation Modeling

The numerical simulation is conducted by using TUNAMI-N2 (Tohoku University's Numerical Analysis Model for Investigation of Near-filed tsunami No.2) code based on shallow water theory and Cartesian coordinate system (Imamura, 1995), which was developed by Disaster Control Research Center (DCRC), Tohoku University, Japan. The computation time for the tsunami propagation is 3.5 hour. In order to satisfy the stability condition the time step is 0.2 s. The tsunami inundation is calculated on the fourth domain using 1 arc-second of bathymetry and topography grid data, and in this domain there are 1200 x 900 grid points along the longitude and latitude directions, respectively, for which the total computation time is 3.5 hours. The value of the Manning's roughness coefficient is assumed to be equal to 0.025 (Koshimura et al, 2009).

3. RESULTS AND DISCUSSION

3.1 Tsunami Source Model

The source model of the 2001 Peru earthquake has been estimated by a tsunami waveform inversion from tide gauge data (Satake, 1987). We used non-negative least square method and delete-half jackknife method to estimate the slip and error, respectively (Fujii and Satake, 2006). The observed tsunami waveforms at tide gauge were sampled at 1 min interval, hence the synthetic waveform are also computed at 1 min interval. We used the first cycle of tsunami waveform because the spatial resolution of the bathymetry data may prevent accurate modeling of later phases such as reflected waves.

The inversion results are shown in Table 1 and Figure 3. The largest slips are estimated on the center of the source region, at the deeper region of the fault. The two largest slip amounts (8.72m and 9.96 m) are located in front of coastal area of Camana city, less than 50 km, which is responsible for generating abnormal large tsunami in this area. The total seismic moment is calculated from this slip distribution as 3.7×10^{21}Nm (Mw = 8.3) for 12-subfault model.

The synthetic waveforms generally agree well with the observed tsunami waveform at most of the tide gauge stations (Figure 4). Although, the amplitudes at Calderas and Callao stations are greater than the observed, this might occur due to the poor bathymetry data around their locations. The tsunami waveforms at Arica, Antofagasta, Coquimbo, Valparaiso, San Antonito and San Juan are well reproduced in terms of amplitude and arrival time. The tide gauge data at Lobos is not used for inversion due to the poor quality of the tsunami signal.

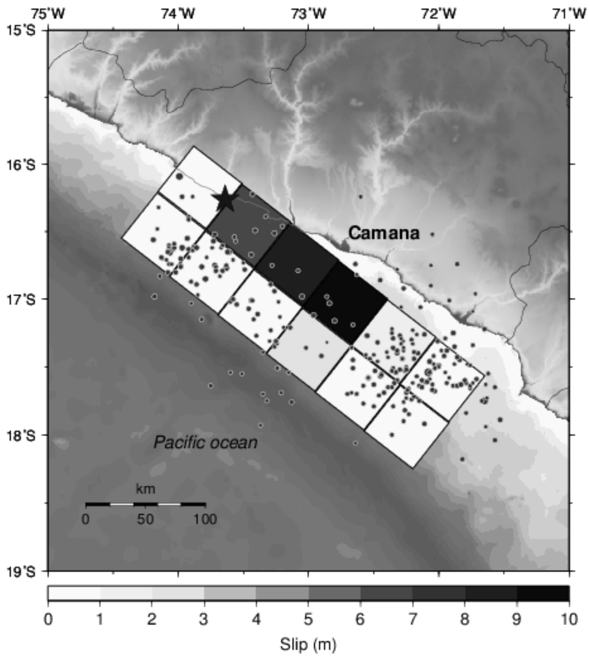

Figure 3 Slip distribution estimated by inversion analysis of tide gauge data. Blue star shows the mainshock epicenter. Red circles indicate aftershocks within one month after the mainshock.

Table 3 Subfault parameters obtained by tsunami waveform inversion of tide gauge data.

No.	Strike	Dip	Slip angle	Length (km)	Width (km)	Slip (m)	Top depth (km)
1	308°	18°	63°	50	50	0.01	14.15
2	308°	18°	63°	50	50	0.00	14.15
3	308°	18°	63°	50	50	2.66	14.15
4	308°	18°	63°	50	50	0.00	14.15
5	308°	18°	63°	50	50	0.00	14.15
6	308°	18°	63°	50	50	0.00	14.15
7	308°	18°	63°	50	50	0.00	29.60
8	308°	18°	63°	50	50	1.51	29.60
9	308°	18°	63°	50	50	9.96	29.60
10	308°	18°	63°	50	50	8.72	29.60
11	308°	18°	63°	50	50	6.83	29.60
12	308°	18°	63°	50	50	0.12	29.60

The obtained slip distribution is similar to those of Kikuchi and Yamanaka (http://wwweic.eri.u-tokyo.ac.jp/EIC/EIC_News/105E.html). Their result (seismic moment is calculated as 2.2×10^{21} Nm, Mw = 8.2) shows that the largest slip of 3 m to 5 m is located at the southern part of the epicenter approximately 75 km south of Camana city. Our subfaults 3, 8 and 9 may correspond to their asperities.

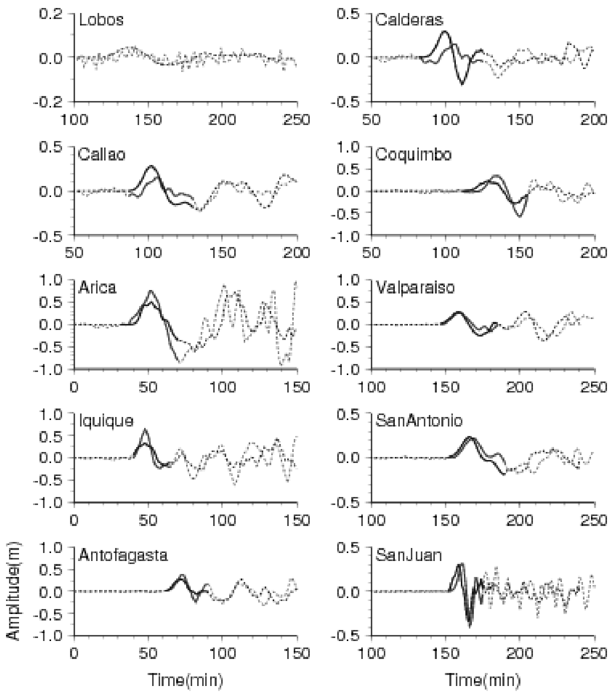

Figure 4 Comparison of observed (red lines) and synthetic (blue lines) tsunami waveforms. The ranges shown by the solid lines are used for the inversion while the dashed lines parts are not used for the inversion but are shown for comparison. The tide gauge data at Lobos is not used for inversion due to the poor quality of the tsunami signal.

3.2 Seafloor Deformation due to the Source Model

The initial seafloor deformation due to our source model of 12 subfaults is calculated by using rectangular dislocation model (Okada, 1985). Figure 5 shows the deformation result where the maximum uplift value is ~2.40 m and the minimum subsidence value is ~1.03 m. The spatial distribution of the uplift part is located offshore; consequently the subsidence part is extended towards the land area.

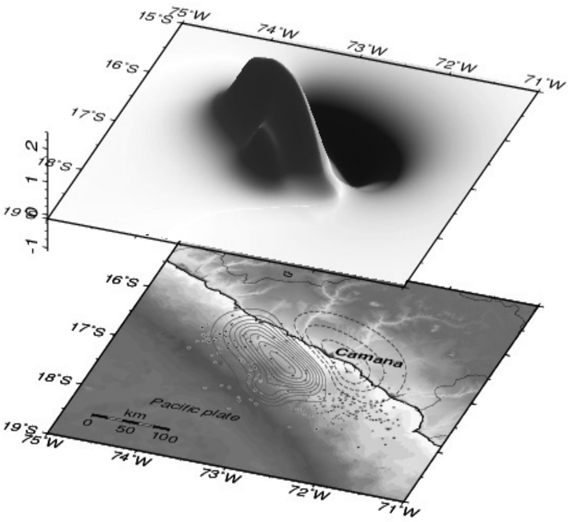

Figure 5 Calculated seafloor deformation due to the fault model. (Above) The 3D views of the deformation result. (Below) The red contours indicate uplift with the contour interval of 0.25 m, while the blue contours indicate subsidence with the contour interval of 0.25 m.

3.3 Tsunami Inundation Modeling

In general, the computed tsunami inundation area along the coastline of Camana city agrees well with the observed inundation area. Although, on the northern part the inundation results are slightly overestimate the field survey data. This might indicate the limitation of the tsunami inundation model using the shallow water approximation, and the possibility that the field data represents the extreme feature of tsunami run-up height, or lack of bathymetry and topography features in the model (Koshimura et al, 2009).

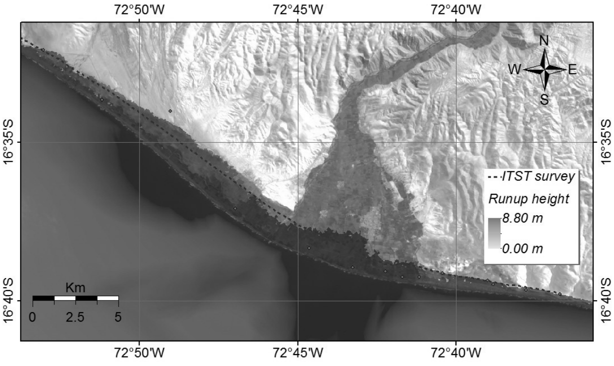

Figure 6 Computed maximum tsunami runup height. Background satellite image LandSsat (path=4, row=71)

The inundation result from our source model is validated through the comparison with field survey data from ITST (2001abc) in terms of the run-up height. It is performed by using K and k proposed by the equations (1), (2) and (3) (Aida, 1978). Where R_i and H_i are the measured and modeled values of tsunami runup height at point i, respectively.

$$K_i = \frac{R_i}{H_i} \tag{1}$$

$$\log K = \frac{1}{n}\sum_{i=1}^{n}\log K_i \tag{2}$$

$$\log k = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(\log K_i)^2 - (\log K)^2} \tag{3}$$

The local inundation depth is the result of measuring water marks on structures or debris on trees above the ground while the inundation height is the result of measuring water marks or debris above the astronomical tide level when the tsunami arrived. We calculate the computed runup height based on the local inundation depth result and the topography data used in the inundation modeling. According to the ITST (2001abc) approximately 20 points were obtained for tsunami run-up height. JSCE (2002) empirically provides the guideline for a tsunami numerical modeling suggesting that $0.95 < K < 1.05$ and $\kappa < 1.45$ as the threshold of valid tsunami source to develop the tsunami hazard assessment. Figure 7 shows the comparison between observed and computed tsunami runup. Our model satisfies the K and k values (K=1.0 and k=1.4) recommended by JSCE (2002), excluding the higher values which might be the result of the lack of bathymetry and topography data in the tsunami modeling.

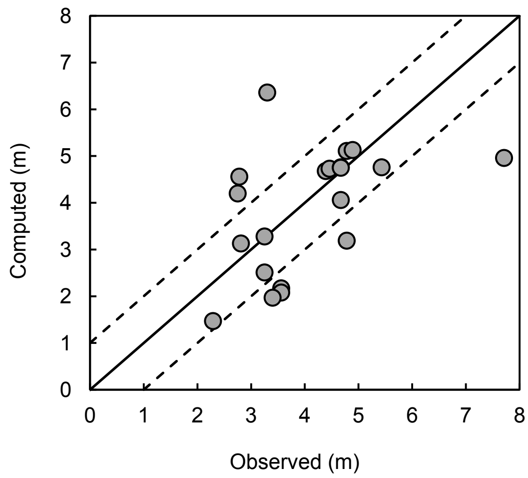

Figure 7 Comparison between observed tsunami runup height and computed tsunami runup height around Camana city.

3. CONCLUSIONS

The tsunami source based in 12 subfaults for the June 23, 2001 Peru earthquake is estimated by tsunami waveform inversion from tsunami tide gage records and then we performed tsunami inundation modeling based on the shallow water approximation and by using four computational domains that are connected with nested grid system. The waveform inversion result shows that large slips were estimated at the deeper part of the fault plane, with a largest slip value as 9.96 m. The total seismic moment is calculated as 3.7x1021Nm (Mw = 8.3) for 12-subfault model. The inundation modeling result is consistent in terms of the run-up height and inundation area measured around Camana city. Considering the validation result through the inundation modeling, our source model can be used as tsunami source of June 23, Peru earthquake.

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