VALIDATION OF TSUNAMI INUNDATION MODELLING FOR THE JUNE 23, 2001 PERU EARTHQUAKE

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ABSTRACT

The validation of the tsunami inundation modeling for the June 23, 2001 Peru earthquake is carried out by using three different tsunami source models. The source parameters for this event have been estimated from seismological analyses by two different studies. We use the Global Centroid Moment Tensor solution, and apply the scaling law proposed by Papazachos et al. (2004) to estimate the fault length, width and slip amount, as the first model called Uniform Slip Model. Kikuchi and Yamanaka's (2001) results are used for the second model called Heterogeneous Slip Model. They analyzed teleseismic broadband P waves retrieved from 24 seismic stations to determine the general source parameters and estimated the slip distribution in detail of 40 subfault segments (30 km x 30 km) in the rupture area of 240 km by 150 km. The third model, called Tsunami Waveform Inversion Model, is constructed in this study by using tsunami waveforms that were recorded at eleven tide gauge stations around the source region. In this model we determined the slip distribution in detail of 10 subfault segments (50 km x 50 km) in the rupture area of 250 km by 100 km.

The numerical simulation of tsunami inundation is carried out using TUNAMI-N2 code developed by Disaster Control Research Center (DCRC), Tohoku University, Japan, which is based on Cartesian coordinate for nested grid system of four domains. The inundation results from the three models are validated through comparison in terms of the run-up height and inundation distance with the field survey data measured around Camana city by the International Tsunami Survey Team (ITST, 2001abc). The tsunami inundation modeling results in terms of the run-up height shows that the third model is a more appropriate approximation compared to the field survey data, and in terms of the inundation distance the first model is a more appropriate approximation.

Keywords: June 23, 2001 Peru tsunami, Tsunami source models, Tsunami waveform inversion, Inundation modelling.

1. INTRODUCTION

Due to the location in a highly seismic area, Peru has experienced some of the largest tsunamis that have occurred in the world. For example, the tsunami that occurred on June 23, 2001 in the southern part of Peru was generated by the earthquake of Mw 8.4.

The purpose of this study is to validate the tsunami inundation modelling of the June 23, 2001 Peru earthquake, in order to use it as model to create future tsunami hazard maps for the hazard assessment along the coastal area of Peru. In this study three different tsunami source models are simulated by tsunami inundation modeling and the results are validated through a comparison with field survey data in terms of the run-up height and inundation distance recorded along the coastal area of Camana city.

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2. DATA AND METHOD

2.1 Bathymetry and Topography Data

In order to perform tsunami numerical modeling the computational area is divided into four domains to construct the nested grid system. The bathymetry data for the first to the third domains are interpolated from the General Bathymetry Chart of the Ocean (GEBCO) 30 arc-seconds grid data and for the fourth domain the bathymetry is generated from the nautical chart of Directorate of Hydrography and Navigation (DHN), Navy of Peru. The topography data for the first and second domains are interpolated from GEBCO, and for the third domain it is taken from the Shuttle Radar Topography Mission (SRTM) 3arc-second resolution data and for the fourth domain it was taken from the Thermal Emission and Reflection Radiometer (ASTER) 1 arc-second resolution data. Table 1 shows the boundary, resolution, location and data source for each domain.

Table 1. Boundary, resolution and data source for each computational domain.

| Domain | Longitude | | Latitude | | Resolution | Data source | |
	Min	Max	Min	Max	arc-second	Bathymetry	Topography
1	-78.00°	-70.00°	-19.00°	-11.00°	27	GEBCO 30c	GEBCO 30c
2	-74.00°	-72.00°	-18.00°	-16.00°	9	GEBCO 30c	GEBCO 30c
3	-73.15°	-72.40°	-17.00°	-16.25°	3	GEBCO 30c	SRTM
4	-72.92°	-72.58°	-16.75°	-16.50°	1	DHN	ASTER

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.

2.2.1 Extracting Tsunami Signal from Tide Gauge Data

Among all tide gauge stations data, only eleven tide gauges are used as input data which has 1 minute data sampling, three 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 (T0 = 06/23 20:33:14 UTC, according to USGS). After that the astronomical signal must be estimated by fitting a polynomial regression model using the entire data. Then it can be removed from the original data. Finally these observed tsunami signals are compared with the synthetic tsunami signal obtained in the tsunami simulations.

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 height, and inundation distance around Camana city done by the ITST (2001abc) are used in this study to validate the tsunami inundation model.

2.4 Tsunami Simulation

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 (Table 2), 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 Models

The source parameters of the 2001 Peru earthquake have been estimated from two different seismological analyses, the Global Centroid Moment Tensor (GCMT) and Kikuchi and Yamanaka (2001). The results of these studies are used for two different models of Uniform Slip Model (USM) and Heterogeneous Slip Model (HSM). Another model called Tsunami Waveform Inversion Model (TWIM), estimated from tsunami waveform in this study is also used.

3.1.1 Uniform Slip Model
This model is a single fault based on the GCMT solution which proposed some parameters of the seismic source (magnitude, strike, slip angle, centroid latitude and centroid longitude). By using the magnitude, it is possible to estimate the slip, length and width of the fault (Papazachos et al, 2004). Table 2 shows the magnitude and the source parameters for this simple model.

Table 2. Magnitude and source parameters for the Uniform Slip Model.

Magnitude (Mw)	Strike	Dip	Slip angle	Length (km)	Width (km)	Slip (m)	Top depth (km)	Southern left corner of fault	
								Longitude	Latitude
8.4	310°	18°	63°	270.0	95.0	4.0	29.6	72.20°W	18.25°S

3.1.2 Heterogeneous Slip Model
The source parameters for this model are taken from the seismic inversion results by Kikuchi and Yamanaka (2001). They analyzed teleseismic broadband P waves retrieved from 24 seismic stations to determine the general source parameters. They determined the slip distribution in detail of 40 subfault segments in the rupture area of 150 km by 240 km. Each subfault segment has an area of 30 km x 30 km. The large asperity is concentrated at southern part of the rupture area.

3.1.3 Tsunami Waveform Inversion Model
The source parameters for this model are estimated by the inversion of the tsunami waveforms from tide gauge data (Satake, 1987). The computation area extends from 70°W to 85°W and 5°S to 35°S using GEBCO 30 arc-seconds bathymetry grid data, and consequently, there are 1800 x 3600 grid points along the longitude and latitude direction, respectively.

The computation time for the tsunami numerical propagation is 4 hours. The time step is 2.0 s to satisfy the stability condition. The initial seafloor deformation for each subfault is calculated based on Okada (1985) and Tanioka and Satake (1996).

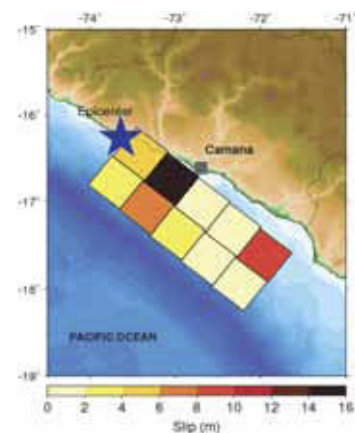Figure 1 shows the spatial slip distribution obtained

Figure 1. Results obtained from the tsunami waveform inversion.

by the tsunami waveform inversion which is divided into ten subfault segments. The subfault size is 50 km x 50 km. The rupture area is 250 km by 100 km. Because of the spatial distribution of the stations around the fault area, the accuracy of the result in the southern part is better comparing to the northern part. Therefore, this result is used to compute the initial seafloor deformation for the tsunami inundation model on Camana city that is located in the central part of the fault area. Table 3 shows the fault parameters from the tsunami waveform inversion model.

Table 3. Subfault parameters obtained from the tsunami waveform inversion.

No.	Strike	Dip	Slip angle	Length (km)	Width (km)	Slip (m)	Error (m) +/-	Top depth (km)	Southern corner of subfault	
									Longitude	Latitude
1	308°	18°	63°	50.0	50.0	1.15	0.91	14.15	72.20°W	18.25°S
2	308°	18°	63°	50.0	50.0	0.35	0.43	14.15	72.56°W	17.96°S
3	308°	18°	63°	50.0	50.0	2.84	1.78	14.15	72.92°W	17.67°S
4	308°	18°	63°	50.0	50.0	7.78	4.79	14.15	73.29°W	17.38°S
5	308°	18°	63°	50.0	50.0	3.8	1.83	14.15	73.65°W	17.09°S
6	308°	18°	63°	50.0	50.0	8.38	4.18	29.60	71.91°W	17.92°S
7	308°	18°	63°	50.0	50.0	0.36	0.22	29.60	72.27°W	17.63°S
8	308°	18°	63°	50.0	50.0	0.68	2.01	29.60	72.64°W	17.34°S
9	308°	18°	63°	50.0	50.0	14.18	6.56	29.60	73.00°W	17.05°S
10	308°	18°	63°	50.0	50.0	5.92	2.89	29.60	73.36°W	16.76°S

3.2 Seafloor Deformation due to the Source Models

The initial seafloor deformation for each model was calculated by using the Okada (1985) formula (Figure 2). The spatial distribution of the uplift part is located offshore, while the subsidence part is extended towards the land area for all models.
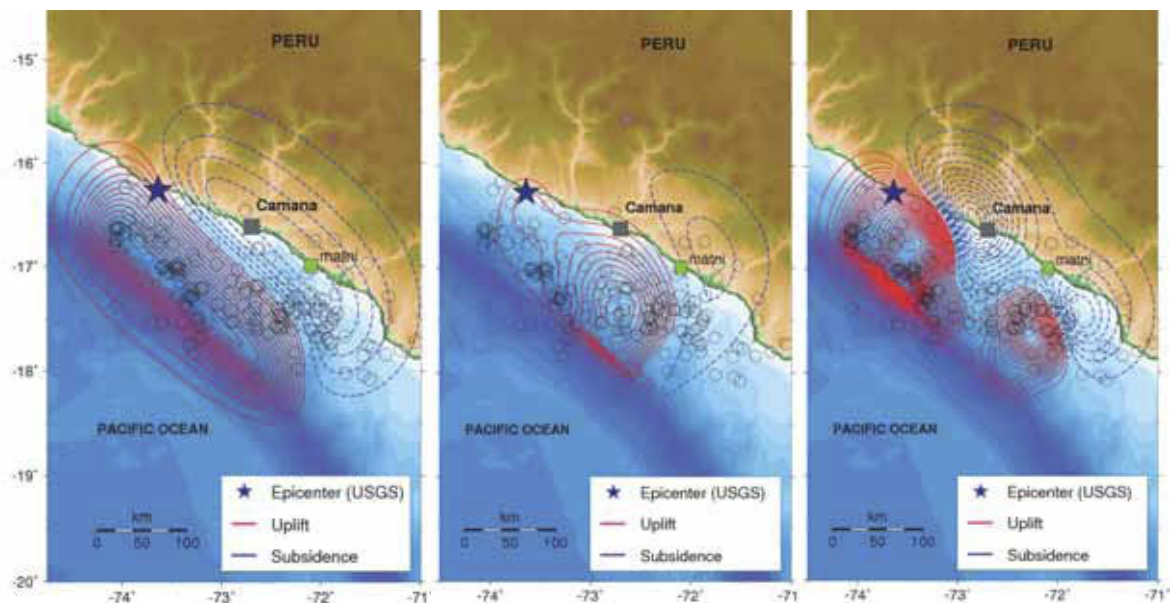

Figure 2. Seafloor deformation for each model left: USM, center: HSM and right: TWIM. Contour lines are drawn in every 0.1 m for uplift (solid line in red) subsidence part (dotted line in blue).

3.3 Run-up Height and Inundation Distance

The calculated inundation results from each model are validated through a comparison with field survey data from ITST (2001abc) in terms of the run-up height and inundation distance. According to the ITST (2001abc), approximately 15 points were obtained for tsunami run-up height and inundation distance from the field survey.

The comparison between the computed and observed tsunami run-up height is shown in Figure 3. In general the computed tsunami run-up height along the coastline of Camana city from each model is underestimated compared to the measured run-up height. 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). However, the computed tsunami run-up height from the TWIM shows a better approximation on the southern part of Camana city from 72.61°W to 72.76°W.
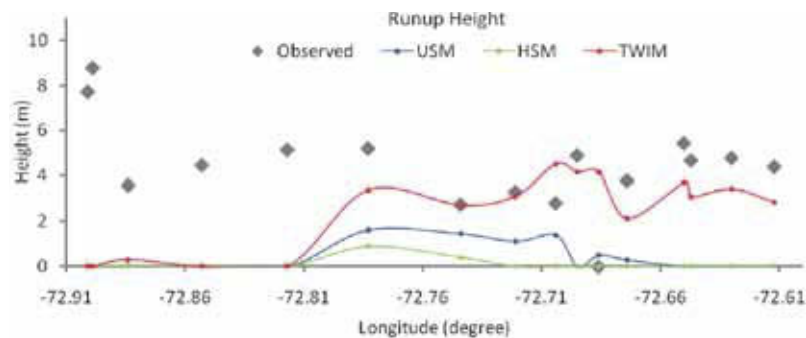

Figure 3. Comparison between the observed tsunami run-up height (gray diamond) and the computed tsunami run-up height from each model (line in blue: USM, line in green: HSM and line in red: TWIM).

The comparison between the computed and observed inundation distance is shown in Figure 4. It shows that the result from the HSM is underestimated on the entire area around Camana city. Figure 4, also shows that the result from the TWIM is overestimated predominantly on the south from 72.61°W to 72.81°W. However, the result from the USM fitted better, this is predominantly shown on the southern part of coastline of Camana city from 72.61°W to 72.81°W. This also might indicate the possibility that the field survey data represents the extreme feature of the tsunami inundation distance in the northern part of Camana city (from 72.81°W to 72.91°W).
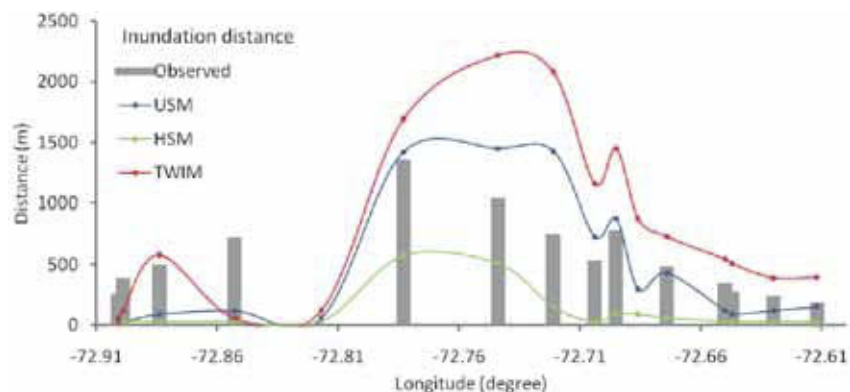

Figure 4. Comparison between observed tsunami inundation distance (gray bar) and computed tsunami inundation distance, from each model (line in blue: USM, line in green: HSM and line in red: TWIM).

I order to investigate the reason of underestimation of run-up height and inundation distance, we compare the real topography image and the topography data used in this study. The cross section shown in Figure 5 covers from 16.54°S, 72.91°W to 16.53°S, 72.90°W on the northern part of Camana city and shows a hill that is approximately 10 m height which does not exist in the real topography. This represents an incompatibility between the real topography and topography data used in this study, indicating that calculated tsunami waves less than 6 m at the coast line cannot pass through the hill.
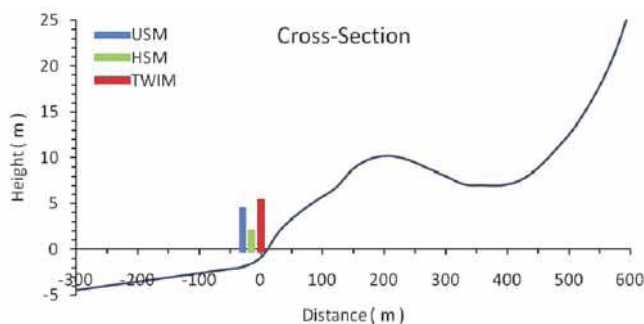

Figure 5. Cross section of topography and bathymetry data on the northern part of Camana. Blue, green and red bars show calculated tsunami height al coast from USM, HSM and TWIM, respectively.

4. CONCLUSIONS

The tsunami numerical modeling is performed using three different models for the June 23, 2001 Peru earthquake, based on the shallow water approximation and by using four computational domains that are connected with nested grid system. The results of tsunami inundation modeling in terms of the run-up height around Camana city shows that the third model from the Tsunami Waveform Inversion Model is more appropriate approximation compared to the field survey. In terms of the inundation distance the first model of the Uniform slip model is more appropriate approximation. Considering the accuracy of the bathymetry and topography data, the third model can be used as tsunami source of June 23, Peru earthquake. However, we may need to improve the tsunami source inversion results. And also, topography and bathymetry data should be investigate and be improved.

ACKNOWLEDGEMENT

REFERENCES

Imamura, F., 1995, Word Science, 25-42.
ITST, 2001a, http://www.usc.edu/dept/tsunamis/peru01/web%20pages/peru2001tsunhtml.
ITST, 2001b, International Tsunami Symposium Proceedings, 409.
ITST, 2001c, International Tsunami Symposium Proceedings, 377-378.
Kikuchi, M. and Yamanaka, Y., 2001, EIC seismological note: 105.
Koshimura, S. et al., 2009, Coastal Engineering Journal, Vol. 51, No. 3, 243-273.
Okada, Y., 1985, Bulletin Seismological Society of America. Vol. 75, No. 4, 1135-1154.
Papazachos, et al., 2004, Bulletin of the Geological Society of Greece, Vol. XXXVI, Proceedings of the 10th International Congress, Thessaloniki, April 2004.
Satake, K. 1987, Journal of Physics of the Earth 35, 241-254.
Tanioka, Y., and Satake K., 1996, Geophysical Research Letters, Vol. 23, 891-894.