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SOURCE INVERSION AND INUNDATION MODELING TECHNOLOGIES FOR TSUNAMI HAZARD ASSESSMENT, CASE STUDY: 2001 PERU TSUNAMI

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ABSTRACT

The source of the Peru 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 3.7x1021Nm (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.

INTRODUCTION

Peru has experienced some of the largest tsunamis that have occurred around the world. As an 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 US Geological Survey, USGS) on June 23, 2001 generated a tsunami that as stated by the post-tsunami report done by the Directorate of Hydrography and Navigation (DHN), Peru Navy, the coastal cities of Ocoña, 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 event 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.

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DATA AND METHOD

Bathymetry and Topography Data

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 and second domains are re-sampled from General Bathymetry Chart of the Ocean (GEBCO) 30 arc-seconds grid data. The bathymetry data for the third and fourth domains are 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 (see Fig. 1ab). In order to conduct the tsunami waveform inversion the bathymetry data are taken from GEBCO 30 arc-seconds grid data for the computation domain (see Fig. 1c).

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 is used in this study to validate the tsunami inundation model.

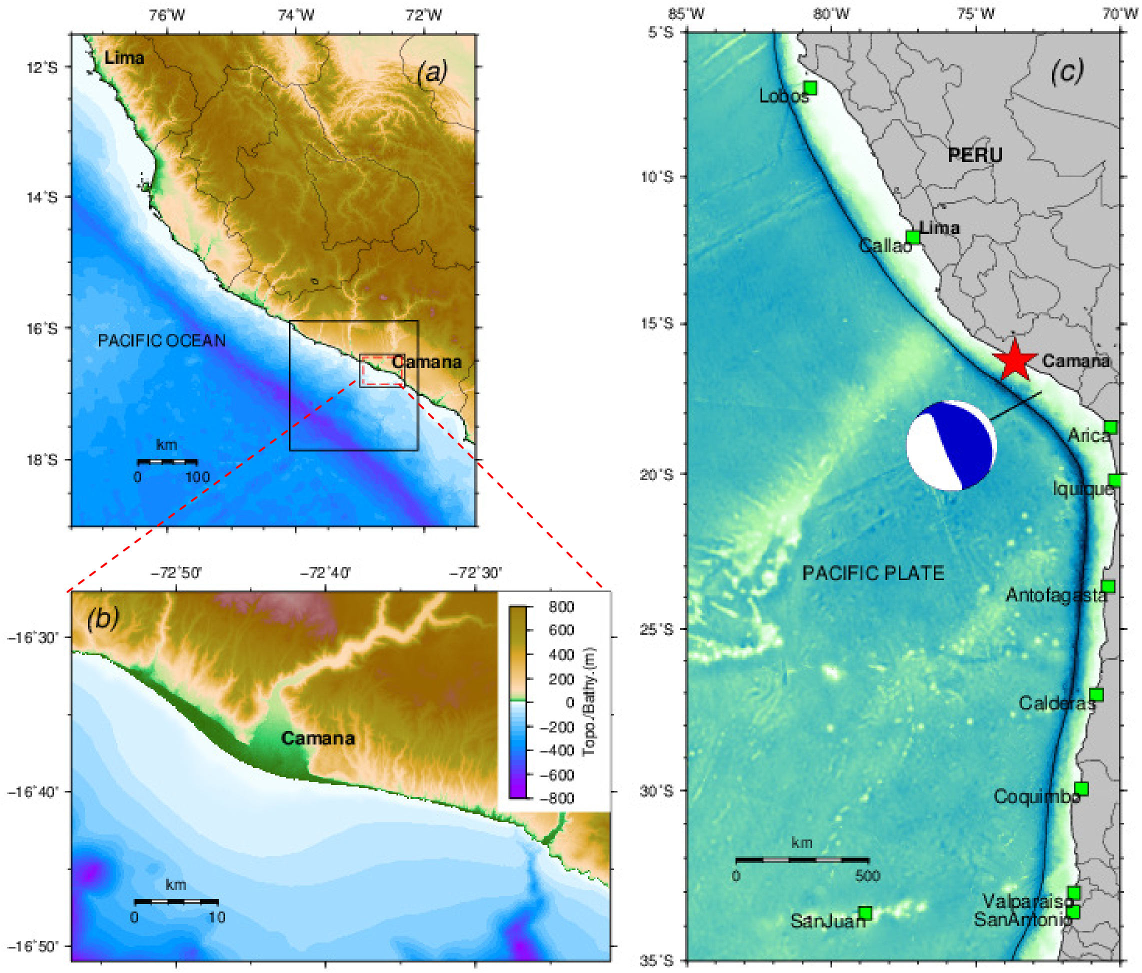

Fig. 1 **(a)** Domains scheme to construct the nested grid system. **(b)** Smaller domain used in the tsunami inundation modeling **(c)** Computational domain used in the tsunami waveform inversion. Green rectangles indicate the location of the tide gauge stations. Red star shows the epicenter (USGS). Lower hemisphere projection is the Global Centroid Moment Tensor (GCMT) solution.

Tsunami Source Models

The source model of the 2001 Peru earthquake has been estimated from two different seismological analyses, the Global Centroid Moment Tensor (GCMT) and Kikuchi and Yamanaka [1]. The results of these studies are used for two different source models Uniform Slip Model (USM) and Heterogeneous Slip Model (HSM), respectively. In addition, in this study a third model called Tsunami Waveform Inversion Model (TWIM) is estimated. It is the result of the inversion of observed tsunami waveforms.

Tsunami Waveform Inversion

In order to estimate the extent of the rupture area and the slip amount distribution, we divided the source into 12 sub-faults that cover the aftershock area during one month after the mainshock (see Fig. 2). The sub-fault size is 50 km x 50 km. The top depths are 14.15 km and 29.60 km for shallow and deep, respectively. The epicenter is located on the northern sub-fault. The focal mechanisms for all the sub-faults 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 sub-fault, the lineal shallow-water or long-wave equations were numerically solved by finite-difference method (Satake [2]). The governing equations are described in Fujii and Satake [3]. The previous Fig 2c 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 [4]). We also take into consideration the effect of the seismic horizontal displacement in region of steep bathymetry slope (Tanioka and Satake [5]).

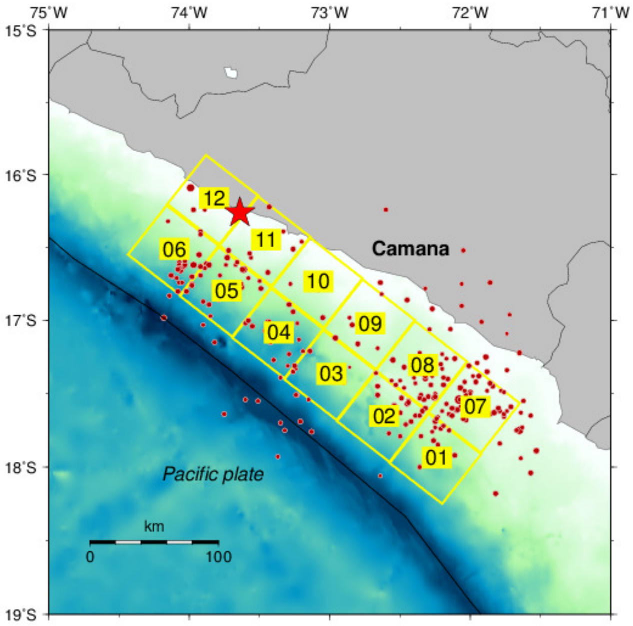

Fig. 2 Spatial locations and order numbers of sub-fault planes. Red star shows the mainshock epicenter. Red circles indicate aftershocks within one month after the mainshock.

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, which was developed by Disaster Control Research Center (DCRC), Tohoku University, Japan. The set of nonlinear shallow water Eqns. (1)-(3) is discretized using a staggered leap-frog finite difference scheme (Imamura [6]). 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. The value of the Manning's roughness coefficient is assumed to be equal to 0.025 (Koshimura [7]).

$$\frac{\partial \eta}{\partial t}+\frac{\partial M}{\partial x}+\frac{\partial N}{\partial y}=0 \tag{1}$$

$$\frac{\partial M}{\partial t}+\frac{\partial}{\partial x}\left(\frac{M^2}{D}\right)+\frac{\partial}{\partial y}\left(\frac{MN}{D}\right)=-gD\frac{\partial \eta}{\partial x}-\frac{g\eta^2}{D^{7/3}}M\sqrt{M^2+N^2} \tag{2}$$

$$\frac{\partial N}{\partial t}+\frac{\partial}{\partial x}\left(\frac{MN}{D}\right)+\frac{\partial}{\partial y}\left(\frac{N^2}{D}\right)=-gD\frac{\partial \eta}{\partial y}-\frac{g\eta^2}{D^{7/3}}N\sqrt{M^2+N^2} \tag{3}$$

Therein, the follow definitions are used:

$$M = \int_{-h}^{\eta} u dz \quad (4)$$

$$N = \int_{-h}^{\eta} \upsilon dz \quad (5)$$

$$D = \eta + h \quad (6)$$

In these equations, M and N are the discharge flux of x- and y-directions, respectively; η is the water level, and h is the water depth to the mean sea level.

RESULTS AND DISCUSSION

Source Models

The USM is a single fault based on the GCMT solution which proposes the magnitude, strike, slip angles and centroid latitude/longitude for this event. The slip amount, length and width of the fault are estimated through scale law proposed by Papazachos [8]. Table 1 shows the magnitude and source parameters for this model. Fig. 3.1a shows the spatial location of the fault area

Table 1 Sub-fault parameters obtained by tsunami waveform inversion of tide gauge data.

Magnitude (Mw)	Strike angle	Dip angle	Slip angle	Length (km)	Width (km)	Slip (m)	Top depth (km)
8.4	310º	18º	63º	270	95	4.0	29.6

The source parameters for the HSM are taken from the seismic inversion results of Kikuchi and Yamanaka [1] available at http://wwweic.eri.u-tokyo.ac.jp/EIC/EIC_News/105E.html. 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 sub-fault segments in the rupture area of 150 km by 240 km and each sub-fault segment area is 30 km x 30 km. Fig. 3b shows the slip distribution for the HSM. The dislocation value reach up to ~5 m and the largest slip amounts are located on the southern area. However, the fault plane proposed does not include the location of the mainshock which correspond to the epicenter.

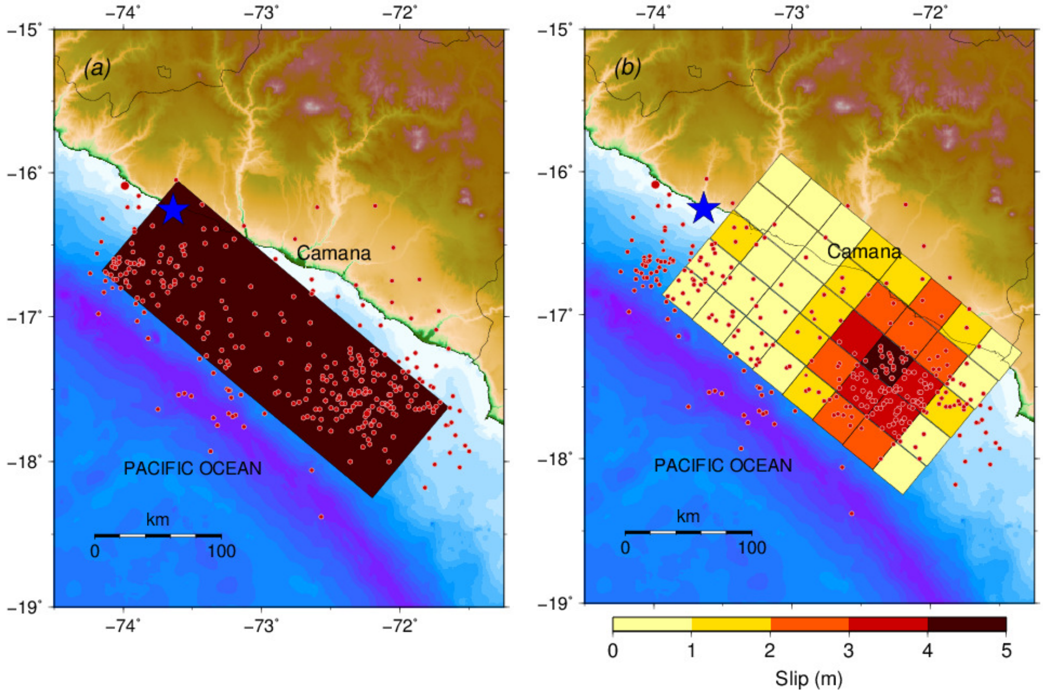

Fig. 3 (a) Location of the fault plane for the USM. **(b)** Slip distribution estimated by inversion analysis of teleseismic record by Kikuchi and Yamanaka [1]. Blue star shows the mainshock epicenter. Red circles indicate aftershocks within one month after the mainshock.

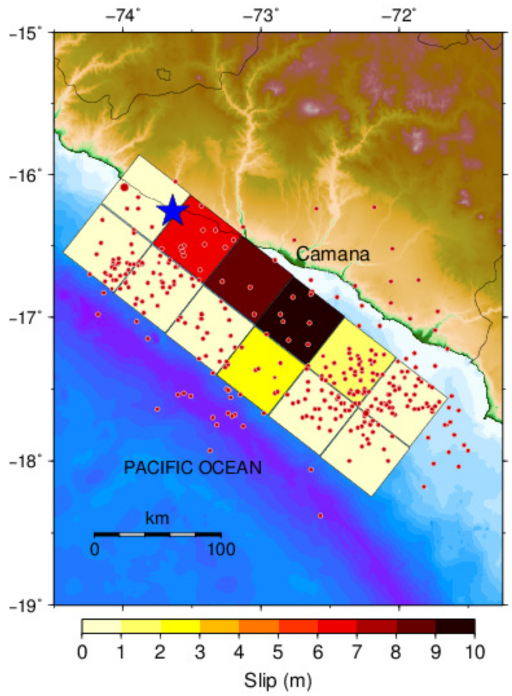

Fig. 4 Slip distribution estimated by inversion analysis of tide gauge data. Blue star shows the mainshock epicenter. Red circles indicate aftershocks within one month after the mainshock.

The source model of the 2001 Peru earthquake has been estimated by a tsunami waveform inversion from tide gauge data (Satake [9]). We used non-negative least square method and delete-half jackknife method to estimate the slip and error, respectively (Fujii and Satake [3]). 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 Fig. 4. The largest slips are estimated on the southern part of the source region, at the deeper region of the fault. The two largest slip amounts (8.72 m 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 3.7x1021Nm (Mw 8.3) for 12-subfault model.

The obtained slip distribution is similar to the proposed by Kikuchi and Yamanaka [1]. Their result (seismic moment is calculated as 2.2x1021 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 sub-faults 3, 8 and 9 may correspond to their asperities.

Tsunami Inundation Modeling

The inundation result from our source models are validated through the comparison with field survey data from ITST [10], [11] and [12] in terms of the run-up height. It is performed by using K and k proposed by the equations (7), (8) and (9) (Aida [13]). Where R_i and H_i are the measured and modeled values of tsunami runup height at point i, respectively.

$$K_i = \frac{R_i}{H_i} \tag{7}$$

$$\log K = \frac{1}{n}\sum_{i=1}^{n}\log K_i \tag{8}$$

$$\log k = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(\log K_i)^2 - (\log K)^2} \tag{9}$$

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[10], [11] and [12] approximately 20 points were obtained for tsunami run-up height. JSCE [14] 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.

Based on the previous analysis, our best source model is the TWIM, this model satisfies the K and k values (K=1.00 and k=1.40) recommended by JSCE [14], excluding the higher values which might be the result of the lack of bathymetry and topography data in the tsunami modeling. Fig. 5 and Table 2 show the analysis results between observed and computed tsunami run-up for our three source models where it is conclusive that The TWIM's result are better approximation compare with the rest two models.

Table 2 Numerical model results validation in term of tsunami run-up.

Model	*K*	*k*
USM	0.85	1.53
HSM	1.18	1.83
TWIM	1.00	1.40

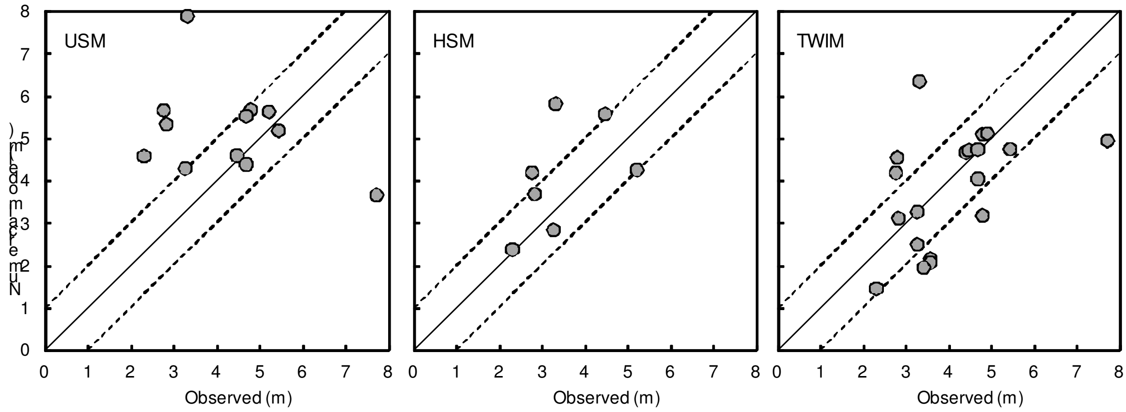

Fig. 5 Comparison between the observed and the numerical model results in term of tsunami run-up height around Camana city.

Fig. 6 shows the inundation result map using our best source model. 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).

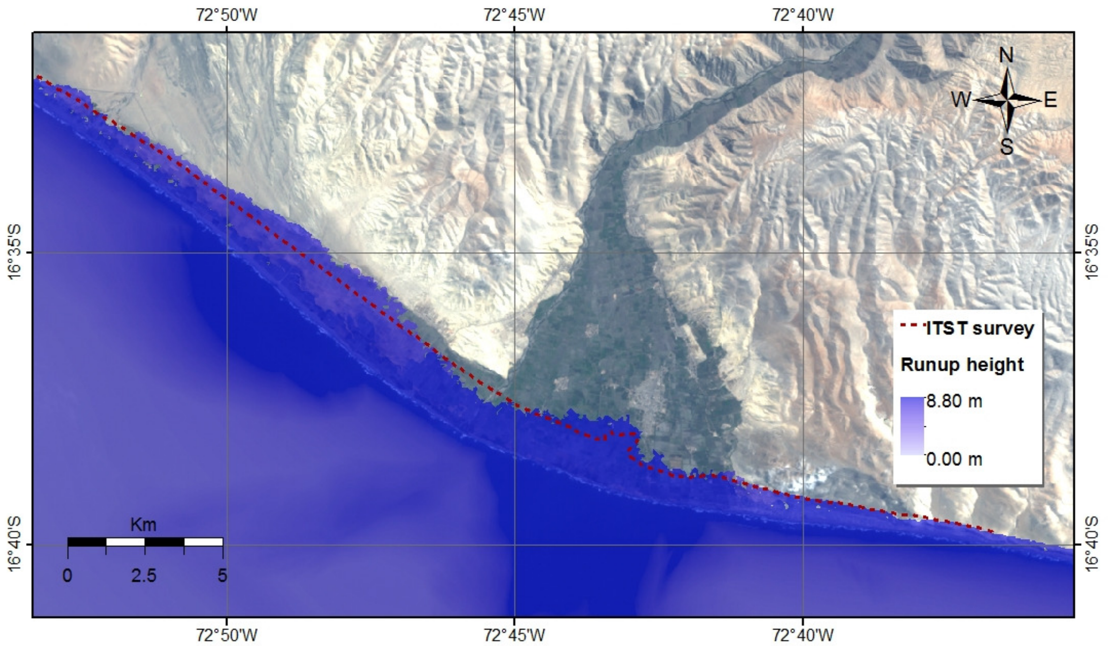

Fig. 6 Maximum computed tsunami run-up height based on the TWIM. Background satellite image LandSsat (path=4, row=71)

CONCLUSIONS

We performed tsunami inundation modeling based on the shallow water approximation and by using four computational domains that are connected with nested grid system and three different source models, which two of them were estimated by seismological analysis and the third model calculated by the inversion of tsunami waveform 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 $3.7x10^{21}$Nm (Mw = 8.3) for 12-subfault model. The inundation modeling result based in the TWIM is more appropriate approximation compared to the field survey in terms of the run-up height compared with the USM and HSM. Considering the accuracy of the bathymetry and topography data, the third model can be used as tsunami source of June 23, Peru earthquake.

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