REAL-TIME TSUNAMI INUNDATION FORECAST STUDY IN CHIMBOTE CITY, PERU

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ABSTRACT

For rapid forecast of tsunami inundation during a tsunamigenic event, we constructed pre-computed tsunami inundation database for Chimbote (north-central Peru). 165 fault model scenarios were used to build a database which consists of tsunami waveforms and tsunami inundation areas from Mw 8.0 to 9.0. We evaluated the reliability of NearTIF algorithm using two hypothetical thrust earthquake scenarios: Mw 9.0 (worst-case event), Mw 8.5 (high probability of occurrence), and a finite fault model of the 1996 tsunami earthquake (Mw 7.6) offshore Chimbote. The linear tsunami propagation and nonlinear inundation were simulated with the JAGURS code implemented in a high-performance computer at Earthquake Information Center (EIC), Earthquake Research Institute, The University of Tokyo. This study demonstrated that NearTIF algorithm worked well even for tsunami earthquake scenario. Finally, we evaluated the lead time with NearTIF algorithm for purpose of tsunami warning in Chimbote. Comparison of computation time indicated that NearTIF only needed less than 20 seconds while direct numerical forward modeling required 27-45 minutes. We demonstrated that NearTIF was a suitable algorithm for developing a future tsunami inundation forecasting system in Chimbote and would give useful contribution to improve and strengthen the Peruvian Tsunami Warning Center in terms of obtaining in short time a forecast of tsunami inundation maps for analysis of evacuation and reduction of loss of life.

Keywords: Real-time tsunami inundation forecast, Chimbote Peru.

1. INTRODUCTION

Regarding tsunami risk in Peru, the main problem is the exposure to near-field tsunami in the coastal area, where expected travel time is between 15 to 30 minutes. The Peruvian Tsunami Warning Center (CNAT, in Spanish) belonging to the Directorate of Hydrography and Navigation (DHN) is in charge of issue tsunami warning bulletins to the National Institute of Civil Defense which spreads the tsunami warning information to citizens along the coast and provides assistance immediately in case of natural disasters. Since real-time forecast of tsunami inundation maps has not been implemented in Peru (even by any Tsunami Warning Center in South America). The main goal of this study is a proposal of real-time tsunami inundation forecast based on a pre-computed tsunami inundation database with the NearTIF (Near-Field Tsunami Inundation Forecasting) algorithm developed by Gusman et al. (2014). The study area is Chimbote city, Ancash Department, Peru.

2. DATA

To perform simulation of tsunami propagation, topography and bathymetry data are needed. Bathymetry and topography for coarse domains were obtained from General Bathymetric Chart of the Oceans (GEBCO 2014) (Weatherall et al., 2015) with a resolution of 30 arc-second to be resampled to resolution

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of each domain (D1=27 arc-sec, D2=9 arc-sec and D3=3 arc-sec). The finest domain (D4=1 arc-sec) to perform tsunami inundation is from bathymetry survey taken in 2015 and the Nautical Chart No. 2123 by DHN map scale of 1:20,000 taken in 2009 and topography data from field survey taken in 2015 by DHN and from the Shuttle Radar Topography Mission by NASA.

3. METHODOLOGY

3.1. Introduction to NearTIF Algorithm

Near-Field **T**sunami **I**nundation **F**orecasting (NearTIF) is an algorithm and a methodology developed by Gusman et al. (2014) based on the assumption that if different earthquakes produce the similar tsunami waveforms at nearshore sites, then tsunami inundations in coastal areas will have similar characteristics independent of their arrival time, location or source mechanism (Setinoyo et al., 2017). Three main components constitute the NearTIF algorithm: (1) the pre-computed tsunami database for tsunami waveforms and tsunami inundation, (2) the tsunami numerical model that solves the linear shallow water equations, and (3) the tsunami database search engine (Figure 1).

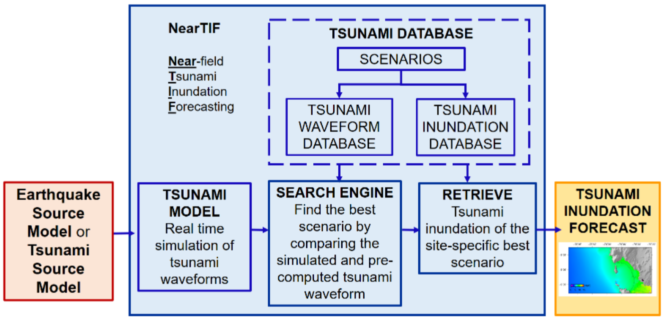

Figure 1. Scheme of NearTIF method, redrawn from Gusman et al. (2014).

3.2. Fault Model Scenarios (FMS) for Tsunami Database

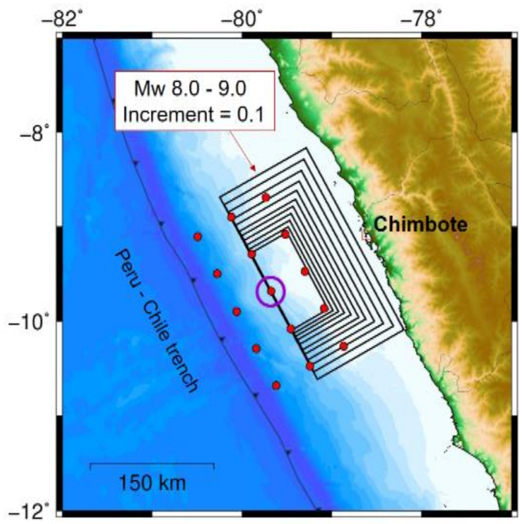

Figure 2. Fault model scenarios for constructing pre-computed tsunami waveform and tsunami inundation database. Red dots represent the 15 referent points. Black rectangles are examples of fault models with different fault sizes from Mw 8.0-9.0 A purple circle is on the top center of each fault model scenario.

To construct a tsunami database, we started by setting 15 reference points and specify the top and center of the fault plane, along the subduction zone off western Chimbote city (Figure 2). To construct the fault scenarios, we need the seismic parameters for each fault model, which are length (L), width (W), top depth, strike, dip, rake, slip, latitude and longitude of top left corner (or center) of the fault plane. L and W were derived from Hanks and Bakun (2002) scaling relation, whose formula is Mw=4/3 log A + 3.03, where A is the fault area given by L=2 x W. Depth and dip angles were derived from interpolation of Slab Model for Subduction Zone (SLAB 1.0) of the South America region (Hayes et al., 2012).

The slip amount was calculated from the seismic moment (Mo) using the formula of Mo=μAD (Hanks and Kanamori, 1979), where A is the area of the rupture in m^2, D is the displacement in m and μ is the rigidity along the plate interface. In this study we assumed the rigidity of 4 x 10^{10} Nm^{-2} for thrust earthquakes. We assumed a rake of 90° and a strike of 331°. The magnitude range used for each scenario is from Mw 8.0 to Mw 9.0 with increment of 0.1 on moment magnitude scale. A total of 165 scenarios at 15 reference points with 11 different sizes were built.

3.3. Selection of Virtual Observation Points

A distribution of nine Virtual Observation Points (VOPs) was selected in front of Chimbote Bay (Figure 3) for the purpose of precompute tsunami waveform database using linear waves for tsunami propagation. The deepest VOP is No. 3 and its corresponding depth is 67 m (78.75° W, 9.127° S), and the shallowest VOP is No.7 at 25 m (78.674°W, 9.075° S). The distance between respective observation points is 50 km. These VOPs are all virtual points and no actual instrumentation is required.

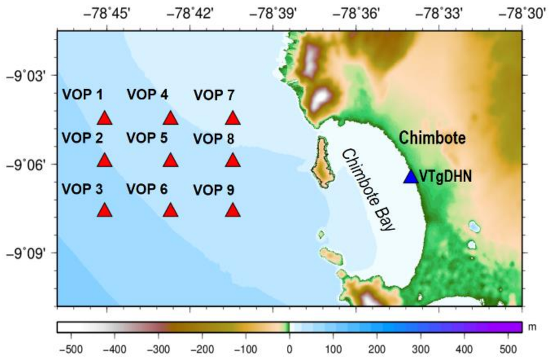

Figure 3. Distribution of nine VOPs (red triangles) off Chimbote Bay.

3.4. Numerical Model for Construction of Tsunami Waveform and Tsunami Inundation Database

Tsunami waveforms at nine VOPs off the coast of Chimbote Bay were computed by solving linear long wave equations with a finite-difference scheme for a coarse domain No. 1 (D1) of 1 arc-min (~1853 m) resolution. 165 fault model scenarios were used as input files. The output is a pre-computed tsunami waveform database (Figure 4a) which is used in the NearTIF algorithm to search the best-fit fault model scenarios. Tsunami inundation database was computed by solving nonlinear shallow wave equations with a finite-difference scheme. The finest domain (D4) of 1 arc-sec (~ 30 m) resolution corresponds to Chimbote city as a target area. The output is a pre-computed tsunami inundation database (Figure 4b) which is used in the NearTIF algorithm to produce the tsunami inundation forecast map selected from the best site-specific fault model scenario. The JAGURS code (Baba et al., 2015) in serial version was used for simulation of tsunami propagation (linear) and inundation (nonlinear).

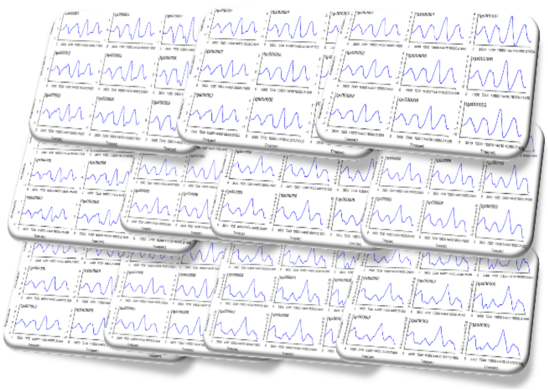

Figure 4a. Pre-computed tsunami waveform database.

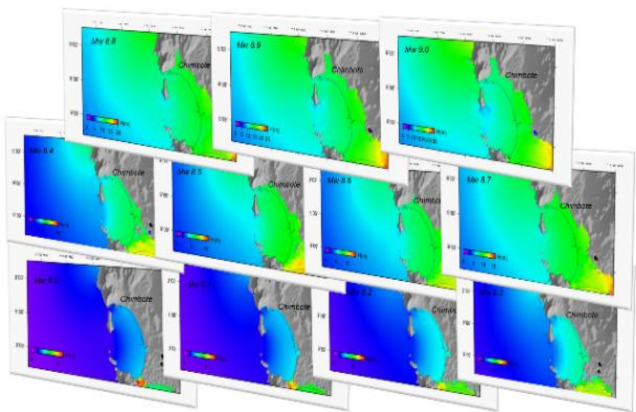

Figure 4b. Pre-computed tsunami inundation database.

3.5. Earthquake Scenarios and Tsunami Database Search Engine

To validate the NearTIF algorithm, we adopt three earthquakes scenarios as input fault model, case 1: hypothetical megathrust earthquake Mw 9.0 (worst-case scenario); case 2: hypothetical thrust earthquake Mw 8.5 (high probability of occurrence) and case 3: finite fault model of the 1996 Chimbote tsunami earthquake (Mw 7.6) by Jimenez et al. (2015). Tsunami waveforms at the VOPs can be simulated by solving the linear shallow water equations using a finite difference scheme on the 1 arc-min for a coarse domain (D1) in less than 20 seconds by computation of JAGURS tsunami code on the

EIC high-performance computer. The candidate for the best site-specific scenario among 165 scenarios should give the most similar tsunami waveforms from earthquakes scenarios. The comparison is made by RMS (root-mean-square) misfit/error analysis. The scenario which gives the smallest RMS error value is selected as the best site-specific scenario among the NearTIF database. Finally, the pre-computed tsunami inundation of the best site-specific fault model scenario (FMS) is selected as the tsunami inundation forecast, in this study for Chimbote city.

4. RESULTS AND DISCUSSION

4.1. Computation Time Comparison of NearTIF and Numerical Forward Modeling (NFM)

In this study, the total time required to obtain tsunami inundation forecast map using the NearTIF algorithm is less than 20 seconds as shown in Table 1.

Table 1. Computational times for NearTIF and NFM.

Seismic Event	Numerical Forward Modeling (NFM)	NearTIF			
		Tsunami Model (Lineal computation)	Search Engine	Total time	Speed of NearTIF relative to NFM
Mw 9.0	45 min	19 sec	0.8 sec	19.8 sec	135 times faster
Mw 8.5	40 min	18 sec	1.5 sec	19.5 sec	120 times faster
Mw 7.6	27 min	14 sec	0.8 sec	14.8 sec	108 times faster

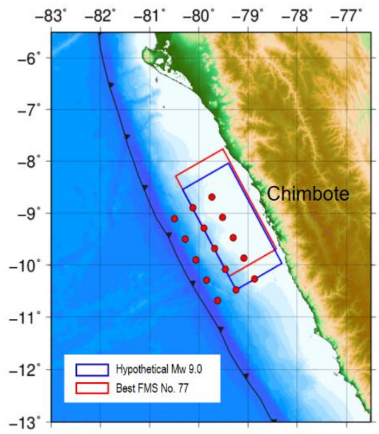

Figure 5a. Case 1: Location of hypothetical megathrust earthquake Mw 9.0 (blue rectangle) and the best FMS No. 77 (red rectangle).

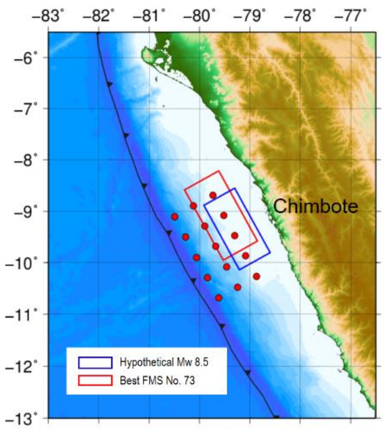

Figure 5b. Case 2: Location of hypothetical megathrust earthquake Mw 8.5 (blue rectangle) and the best FMS No. 73 (red rectangle).

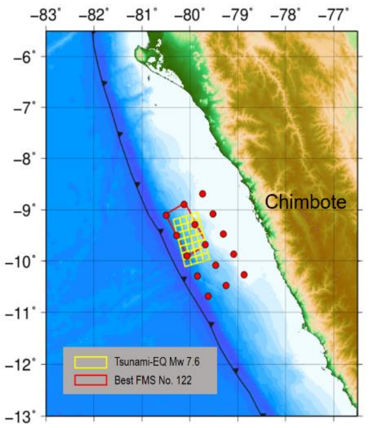

Figure 5c. Case 3: Location of tsunami earthquake scenario Mw 7.6 (yellow rectangle) and the best FMS No. 122 (red rectangle).

4.2. Case 1: The Offshore Chimbote Hypothetical Megathrust Earthquake (Mw 9.0)

A hypothetical megathrust earthquake (Mw 9.0) was used as a simple fault model scenario 27 km off the coast of Chimbote as a near-field tsunami case (Figure 5a). The best site-specific scenario selected with the NearTIF algorithm is FMS No. 77 (Mw 9.0). Comparison of inundation forecasting for domain D4 in case 1 is shown in Figure 6a and 6b.

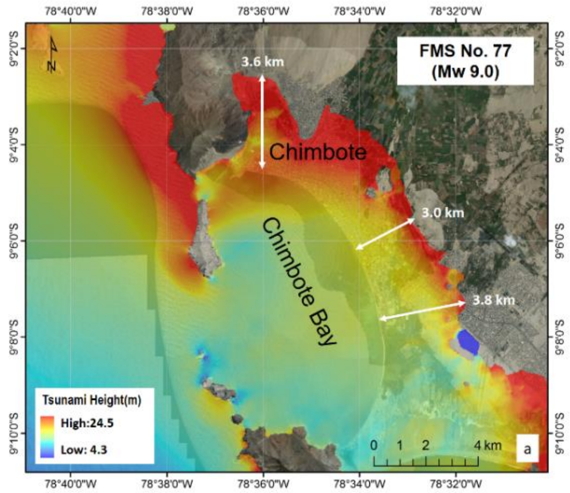

Figure 6a. Tsunami inundation forecasting of the best FMS No. 77.

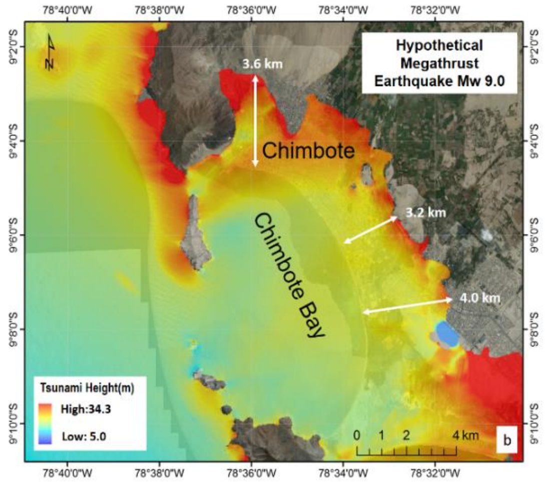

Figure 6b. Tsunami inundation forecasting from direct numerical forward modeling (Mw 9.0).

4.3. Case 2: The Offshore Chimbote Hypothetical Thrust Earthquake (Mw 8.5)

A hypothetical thrust earthquake (Mw 8.5) was used as a simple fault model scenario for offshore Chimbote (53 km off the coast of Chimbote) as a near-field tsunami case (Figure 5b). The best site-specific FMS selected with the NearTIF algorithm is FMS No. 73 (Mw 8.6). Comparison of inundation forecasting for domain D4 in case 2 is shown in Figure 7a and 7b.

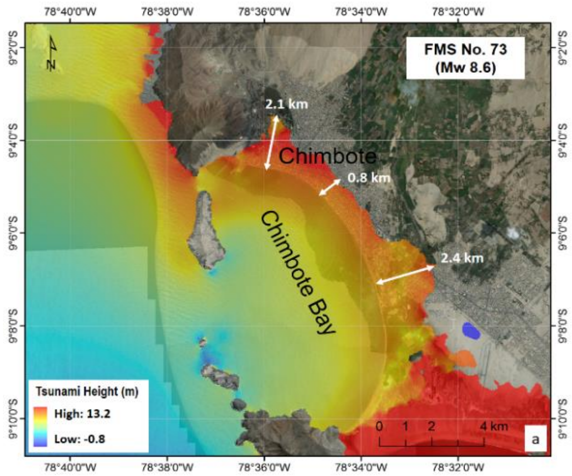

Figure 7a. Tsunami inundation forecasting of the best FMS No. 73.

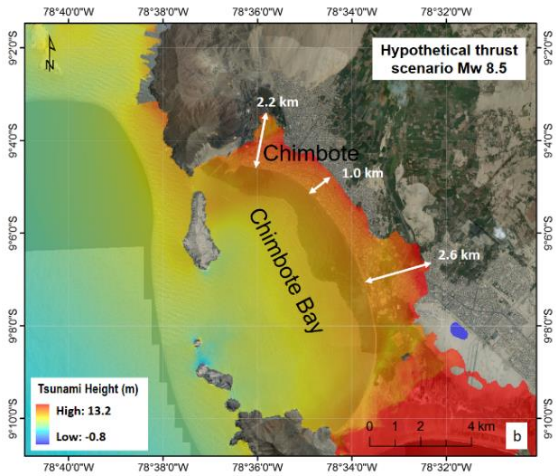

Figure 7b. Tsunami inundation forecasting from direct numerical forward modeling (Mw 8.5).

4.4. Case 3: The 1996 Chimbote Tsunami Earthquake (Mw 7.6)

There is a finite fault model of tsunami earthquake (Mw 7.6) which occurred in 1996 offshore Chimbote (Figure 5c). The best site-specific scenario from the NearTIF algorithm is FMS No. 122 (Mw 8.0). Comparison of inundation forecasting for domain D4 in case 3 is shown in Figure 8a and 8b.

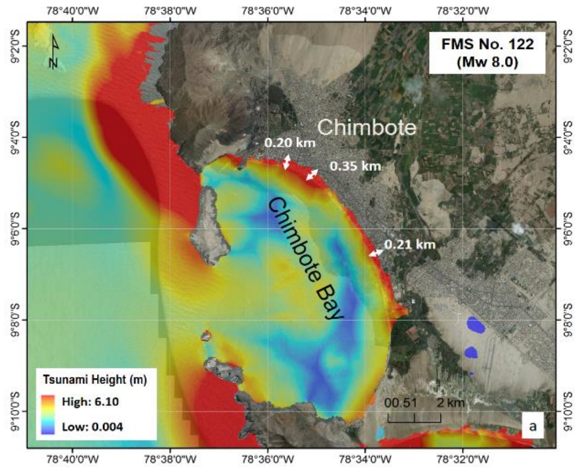

Figure 8a. Tsunami inundation forecasting of the best FMS No. 122.

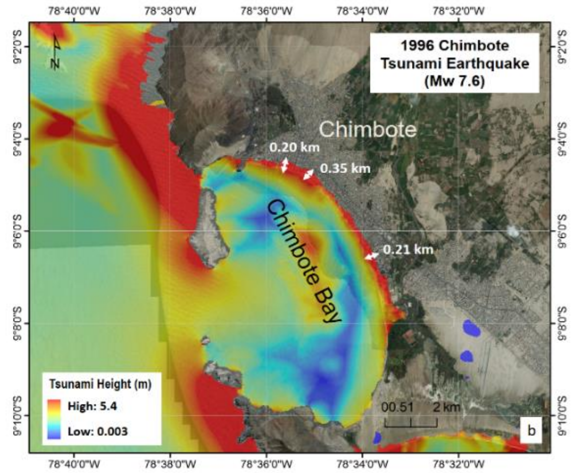

Figure 8b. Tsunami inundation forecasting from direct numerical forward modeling (Mw 7.6).

5. CONCLUSIONS

We performed a real-time tsunami inundation forecast focused on Chimbote city using the NearTIF algorithm. The pre-compute tsunami waveform and tsunami inundation database was built for 165 fault model scenarios from Mw 8.0 to 9.0. We tested the effectiveness of NearTIF algorithm during 6 hours of tsunami propagation time using the JAGURS tsunami code with three types of earthquakes scenarios (Mw 9.0, Mw 8.5 and Mw 7.6). The forecasted tsunami height and inundation distances in Chimbote are similar between NearTIF and direct numerical forward modeling (NFM).

We evaluated the lead time with NearTIF algorithm for the three earthquake scenarios. The speed of the NearTIF algorithm to obtain the tsunami inundation forecast is remarkably (hundreds of times) faster than that by NFM computed in EIC high-performance computer, Earthquake Research Institute, The University of Tokyo. We demonstrate that this methodology is reliable and useful for purpose of tsunami early warning in Chimbote and applicable in the Peruvian Tsunami Warning Center, owing to a rapid estimation of tsunami inundation forecast maps during a tsunamigenic event.

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