PROPOSAL OF NEW PROCEDURES FOR IMPROVED TSUNAMI FORECAST BY APPLYING COASTAL AND OFFSHORE TSUNAMI HEIGHT RATIO

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ABSTRACT

Regression analysis was performed using observed tsunami height at offshore and coastal tidal station pairs, which were within 20 km each other, for the 2010 Chile earthquake tsunami. We used 26 sets initial and 33 sets maximum tsunami height data obtained from the Real-Time Kinematic Global Positioning System (RTK-GPS) buoys, wave stations and coastal tidal stations throughout Japan. We obtained the formulas for initial and maximum tsunami height as

$$H_{c,init} = 1.005 H_{o,init} \left(\frac{h_o}{h_c} \right)^{\frac{1}{4}} \quad \text{and} \quad H_{c,max} = 1.180 H_{o,max} \left(\frac{h_o}{h_c} \right)^{\frac{1}{4}},$$

where $H_{o,init}$ and $H_{o,max}$ are the initial and maximum tsunami height observed at an offshore station, $H_{c,init}$ and $H_{c,max}$ are the initial and maximum tsunami height observed at a coastal tidal station, h_o and h_c are the water depth at an offshore and coastal tidal station from the mean sea level. In the previous study, similar proportional parameters have been derived. Tsunami simulation of the 1896 Sanriku earthquake tsunami was performed as a case study of application of these equations to real time tsunami forecast and tsunami database. Then, we conclude that the former formula is reliable and valuable enough to be applied in real time tsunami forecast using detected initial tsunami wave at offshore RTK-GPS buoy, because of the potentially increased leading time to issue tsunami warning. In addition, preparing maximum tsunami height data by applying the latter formula and using synthetic tsunami waveforms at forecast points or RTK-GPS buoys should improve the accuracy of tsunami database.

Keywords: Tsunami height ratio, Offshore and coastal points, Green's law, Real time forecast, Tsunami database.

1. INTRODUCTION

Japan Meteorological Agency (JMA) as a national government has responsibility to issue tsunami forecast including warnings and advisories immediately after occurrence of an earthquake. Information about tsunami caused by a near-field earthquake is based on a tsunami scenario database and seismic observation. The database includes estimations of maximum tsunami heights and arrival times at coastal points for each scenario. To estimate tsunami height at coastal areas, firstly, JMA applies numerical tsunami simulation to calculate tsunami height at forecast points at which water depths are about 50 m; and then tsunami heights at forecast points are converted into tsunami height at coastal points by applying Green's law under assumption that water depth at coastal point is 1 m. If actually utilized offshore observation data and measured water depth values were used instead, the

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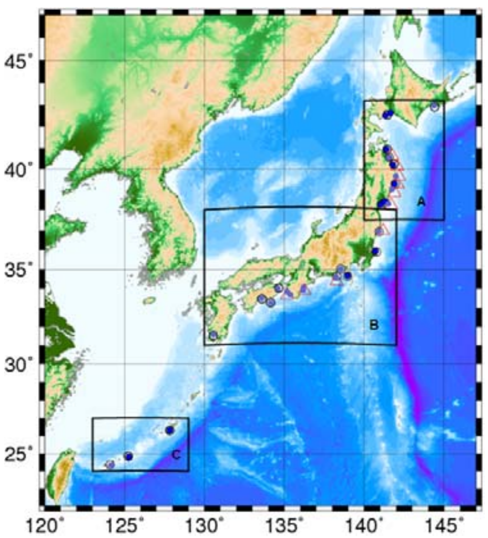
method would have been more accurate. The purpose of this study is to improve relationship and develop a new procedure on tsunami forecasting using tsunami simulation. A case study of the 1896 Sanriku earthquake will be introduced.

2. DATA



We collected the 2010 Chile earthquake tsunami waveforms observed at tidal stations along the Pacific Coast of Japan operated by JMA or Ministry of Land, Infrastructure and Transport (MLIT). Among these stations, pairs which consist of offshore (RTK-GPS buoys or wave stations) and coastal tidal stations are selected. In this study, the pairs are selected according to the criterion that the distance between both composing stations of a pair must be within 20 km (Figure 1). Water depth at offshore are referred to Nationwide Ocean Wave information network for Ports and HArbourS (NOWPHAS) station catalogue and Hayashi (2010). Water depths at coastal tidal stations are obtained by reading sea charts and getting average water depth within 100 m from the coastal tidal station.

Figure 1. Locations of station pairs which consist of an offshore and a coastal tidal station. Blue dots, red triangles, and black circles indicate tidal station, RTK-GPS buoys and wave stations, respectively.

3. THEORY AND METHODOLOGY

3.1. Relationship between Offshore and Coastal Tsunami by the 2010 Chile Earthquake

3.1.1. Initial and Maximum Tsunami Height

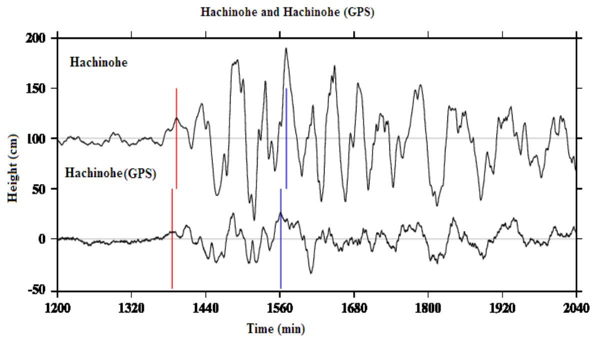


Figure 2. Examples of band-pass filtered waveforms for a station pair at Hachinohe (coastal tidal station) and Hachinohe (RTK-GPS Buoy). Sea-level anomalies at red and blue lines were defined as initial tsunami heights and maximum tsunami heights, respectively.

Raw data of sea-level height in time-series are contaminated with short period variation accompanied by wind waves as well as long-period variation such as tidal components. To eliminate noise and extract tsunami component, band-pass filter of 2-209 min is applied to tsunami waveform data (Figure 2). Also we used the calculated tsunami travel times as references in order to avoid misreading of initial tsunami wave.

In this study, regression analysis was performed to calculate proportional parameters (α_{init}, α_{max}) in

$$H_{c,init} = \alpha_{init} H_{o,init} \left(\frac{h_o}{h_c} \right)^{\frac{1}{4}} \qquad (1) \text{ and,}$$

$$H_{c,max} = \alpha_{max} H_{o,max} \left(\frac{h_o}{h_c} \right)^{\frac{1}{4}} \qquad (2),$$

where α_{init}, α_{max} are ratios of initial and maximum tsunami height affected by reflected wave from coast at offshore station.

3.2. Tsunami Simulation for Case of the 1896 Sanriku Earthquake

TUNAMI-N2 (Tohuku University's Numerical Analysis Model for Investigation of Near-field tsunami No.2) code developed by the Disaster Control Research Center (DCRC), Tohoku University, Japan was used for tsunami simulation for the case study of the 1896 Sanriku earthquake tsunami. TUNAMI-N2 is based on a tsunami numerical simulation with the staggered leap-frog scheme which is applied to a shallow water theory in shallow and deep sea to investigate near-field tsunami.

The fault parameters are presented by Tanioka and Satake (1996). Bathymetry data are prepared by using the General Bathymetry Chart of the Oceans (GEBCO) one arc minute grid data. Bathymetry grid intervals were of Δx=1521.2311 m and Δy=1848.7197 m, maximum bathymetry depth *(h_{max})* was 8,135.68 m in the computation area. We set the time step of computation as 3 sec which is less than the Courant Friedrics Lewy (CFL) condition. The dimension of computation area is 480 grid points for longitude and also for latitude. In the bathymetry grid for tsunami simulation, we set 12 coastal stations and 32 offshore stations which consist of 7 RTK-GPS buoy stations, 22 JMA forecast points and 3 wave stations (Figure 3).

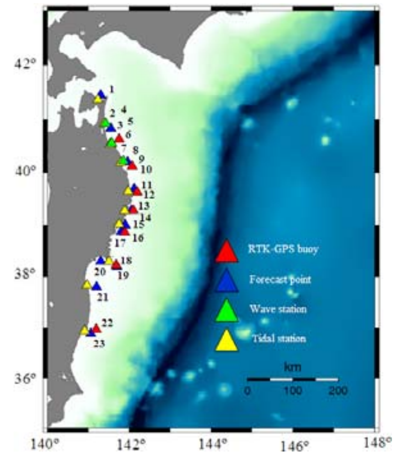


Figure 3. Locations of offshore and coastal stations. Red, blue, green and yellow triangles indicate RTK-GPS buoy, JMA forecast points, wave stations and tidal stations, respectively.

4. RESULTS

4.1. Relationship between Initial and Maximum Tsunami Height

We read initial and maximum tsunami height of the 2010 Chile earthquake tsunami from each waveform. Then, we obtained the ratio of the initial and the maximum tsunami height observed at coastal tidal stations toward offshore stations (Figure 4). The linear initial and maximum tsunami height relationship has been derived as follow,

$$H_{c,init} = 1.005 H_{o,init}\left(\frac{h_o}{h_c}\right)^{\frac{1}{4}} \quad (3), \qquad H_{c,max} = 1.180 H_{o,max}\left(\frac{h_o}{h_c}\right)^{\frac{1}{4}} \quad (4).$$

The standard deviation of the log-scaled residual error of the proportional constant is 0.156 and 0.161. When the standard deviation of the log-scaled residual error is considered, the accuracy of forecasting the initial and maximum tsunami height is 70% to 143% and 69% to 145% of the corrected tsunami height calculated by Equations (3) and (4) with offshore observation data ($H_{o,init}$ or $H_{o,max}$), respectively.

4.2. Comparison of Initial and Maximum Tsunami Height

The initial and maximum tsunami heights observed at coastal stations, and calculated heights were compared by applying Equations (3), (4) and conventional equations (Hayashi 2010) to the data recorded at RTK-GPS buoys and wave stations. The calculation shows that at some stations tsunami height are overestimated or underestimated of about 0.1 m; especially maximum tsunami height at Kuji coastal station was underestimated as much as 0.7 m. The underestimations at coastal tidal stations are also found at Hachinohe, Miyako and Onahama. These might be because of local characteristics of coastal stations. The tsunami height is also affected by the shape of a bay; tsunami becomes much larger in areas with a V-shaped bay (Earthquake Research Committee 1998)

a) b)

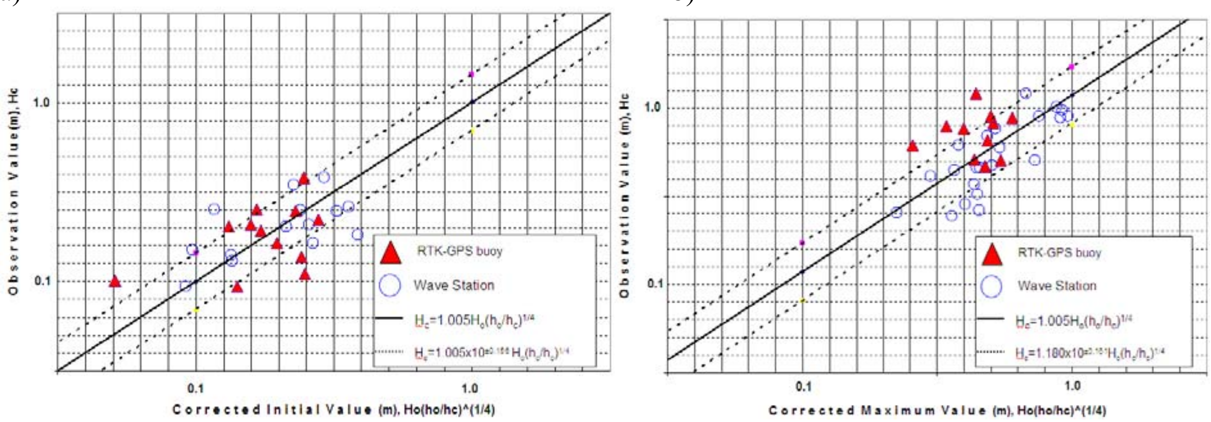


Figure 4. Log scaled relationship of (a) initial and (b) maximum tsunami height of offshore and coastal stations. The horizontal axis indicates corrected initial or maximum tsunami heights. The corrected value is defined as the observed offshore initial or maximum tsunami height multiplied by the fourth root of the ratio of the water depth at offshore and coastal stations. The vertical axis indicates initial or maximum tsunami heights observed at coastal tidal stations. The thick line indicates the regression function derived by this study. The pair of dotted lines indicates the range of the single standard deviations.

4.3. Synthetic Tsunami Waveform

After the tsunami simulation, we obtained synthetic waveform for each station pair of offshore and coastal station. We read the initial and maximum tsunami heights of synthetic waveform at all the stations pairs.

5. DISCUSSION

5.1. Application to Real Time Tsunami Forecast

The Equation (3) derived in this study can be applied to realize real-time forecasting of initial tsunami heights at nearby coastal area with high accuracy if offshore RTK-GPS buoys or wave stations detect the initial tsunami heights on the real time-basis. Leading time means time difference between the time issuing or upgrading tsunami warning and occurrence time of first crest at coastal area. In order to enlarge leading time, it is essential to issue tsunami advisory or tsunami warning before the arrival of the first crest. H_{coast} is tsunami height at the coast by applying the equation. H_{th} is the threshold value corresponding to the categories of tsunami warning or tsunami advisory. Threshold values between tsunami advisory and major tsunami are assumed to be 0.75 m and 2.5 m. By this method the tsunami warning can be issued when the estimated tsunami height at the coast using the equation become larger than the threshold value. This condition is,

$$H_{offshore}(t) \geq \left(\frac{H_{th}}{\beta_{init}}\right) \quad (5), \qquad \beta_{init} \equiv \alpha_{init}\left(\frac{h_o}{h_c}\right)^{\frac{1}{4}} \quad (6),$$

where $H_{offshore}(t)$ is offshore tsunami height at the time t, β_{init} is a tsunami height ratio for initial wave. Example of calculation is shown in Table 1. Here, P is defined as the time when the estimated tsunami height at the coast reaches the threshold value (e.g. H_{th} = 0.75). If tsunami warning is issued at P, the leading time of tsunami warning increase greater than the time in case when it is issued at the detection of initial crest (Q). According to this case, RTK-GPS buoy has larger leading time than the others (forecast point or wave station). By using RTK-GPS buoy and applying the Equation (3) in real time has possibility to upgrade tsunami warning timely and then the accuracy of tsunami warning could be improved.

Table 1. Example of initial tsunami height application to real time forecast by case study of the 1896 Sanriku earthquake tsunami.

No	Offshore						Coastal				
	Station Name		WD (m)	Q (min)	H (m)	P (min)	Station Name	WD (m)	Init. Time (min)	H (m)	Leading Time (min)
7	FP	109	142.2	26.2	1.8	24.5	Kamaishi	4.7	31.7	2.4	7.2
10	WS	Kuji	50.0	41.8	2.7	40.0	Kuji	5.4	44.6	3.2	4.6
11	GPS	Miyako	200.0	24.4	1.6	22.7	Miyako	7.3	37.3	2.8	14.6

No: Pair number, WD: Water depth, Q: time of initial crest in offshore stations. H: Maximum height of initial wave, P: time when the estimated tsunami height at the coast reaches the threshold value (e.g. H_{th} = 0.75). Init. Time: Time of maximum tsunami height of initial wave. FP: Forecast point, WS: Wave station, GPS: RTK-GPS buoy,

5.2. Application Proposal of New Procedure to Calculate Maximum Height

We apply a numerical tsunami simulation to calculate the tsunami height at offshore forecast points or RTK-GPS buoy locations. Then, tsunami amplitudes at the coast are estimated by using Equation (4) with measured water depth values at coastal points as,

$$H_{CP} = \beta_{\max} H_{FP} \quad (7), \qquad \beta_{max} \equiv \alpha_{max}\left(\frac{h_{FP}}{h_{CP}}\right)^{\frac{1}{4}} \quad (8),$$

where β_{max} is a coastal and offshore tsunami height ratio for maximum height, α_{max} is a proportional parameter defined in Equation (2) (α_{max}=1.180 in Equation (4)), h_{FP} and h_{CP} are water depths at a forecast point and a coastal point, H_{FP} and H_{CP} are calculated maximum tsunami height at a forecast point from tsunami simulation and the predicted maximum tsunami height at a coastal point. Table 2 shows the calculation of maximum tsunami height at coastal points by present JMA's method and proposed method in this study (Equation (8)). To estimate maximum tsunami height at coastal area, by applying the method in this study, the predicted tsunami heights are close to directly simulated ones at coastal points.

Table 2. Example of calculation of maximum tsunami height at coastal points by case study of the 1896 Sanriku earthquake tsunami.

No	Offshore					Coastal					
									Sim.	EQ	JMA
	Station Name		WD (m)	Max. Time (min)	H_{max} (m)	Station Name	WD (m)	Max. Time (min)	H_{max} (m)	H_{max} (m)	H_{max} (m)
4	GPS	Hachinohe	87.0	40.3	1.4	Hachinohe	6.7	57.6	1.9	3.0	4.1
10	WS	Kuji	50.0	41.1	2.7	Kuji	5.4	44.6	3.2	5.7	7.3
22	FP	127	99.0	43.2	0.2	Onahama	10.2	70.7	0.2	0.3	0.5

No: Pair number, WD: Water depth, Max. Time: Time of maximum tsunami height, H_{max}: Maximum tsunami height, Sim.: Simulated tsunami waveform, EQ: Equation (4), JMA: Green's law which is adopted by JMA, GPS: RTK-GPS buoy, WS: Wave station, FP: Forecast point.

6. CONCLUSIONS

Regression analysis was performed using observed tsunami height at offshore and coastal tidal station pairs, which were within 20 km each other, for the 2010 Chile earthquake tsunami. Tsunami simulation of the 1896 Sanriku earthquake tsunami was performed as a case study of application of the derived equations for real time tsunami forecast and tsunami database. We conclude that Equation (3) derived in this study is reliable and valuable enough to be applied in real time tsunami forecast using detected initial tsunami wave at offshore RTK-GPS buoy because of the potentially increased leading time before of issuing tsunami warning. In addition, preparing maximum tsunami height data by applying Equation (4) and using synthetic tsunami waveform at forecast points or RTK-GPS buoy should improve the accuracy of tsunami database.

7. ACTION PLAN

The 2010 Chile earthquake tsunami reached the north of Papua, eastern part Indonesia at almost same time to Japan which is 21 hours after the earthquake with amplitude of about 5 cm. This tsunami gave lesson to technical operational work in InaTEWS especially to BMKG, to generate advisory bulletin which is needed by local governments and also about requirement of a new Standard Operational Procedure (SOP) for distant tsunami (National Report Submitted by Indonesia 2010).

The accuracy of tsunami warning and earthquake bulletin could improve if we utilize offshore data. Although InaTEWS buoy is located at more offshore area and water depth is deeper than 1000 m compared with RTK-GPS buoy in Japan, we will apply equation derived in this or previous studies and also use tsunami simulation after setting forecast points along the Indonesian coastal area.

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