Articles

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Article

Analytical Rapid Prediction of Tsunami Run-up Heights: Application to 2010 Chilean Tsunami

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Abstract : An approach based on the combined use of a 2D shallow water model and analytical 1D long wave run-up theory is proposed which facilitates the forecasting of tsunami run-up heights in a more rapid way, compared with the statistical or empirical run-up ratio method or resorting to complicated coastal inundation models. Its application is advantageous for long-term tsunami predictions based on the modeling of many prognostic tsunami scenarios. The modeling of the Chilean tsunami on February 27, 2010 has been performed, and the estimations of run-up heights are found to be in good agreement with available observations.

Key words : tsunami run-up height, rapid prediction, analytical theory of long wave run-up, shallow-water system

1. Introduction

The numerical model of tsunami wave propagation is an important tool to forecast the tsunami heights and tsunami risk for coastal populations. The comparable analysis of tsunami characteristics was done in early studies using shallow water models with "no-flux" boundary condition on the coast, which was modeled by the equivalent wall in the last sea points usually with depth of 5 to 10 meters (Sato et al. 2003; Choi et al. 2003; Ioualalen et al. 2006; Schuiling et al. 2007; Zaitsev et al. 2009; Beisel et al. 2009). Runup heights were in some cases corrected with use of simplified formulae of the 1D analytic theory of long wave runup for fixed shape of incident wave, sine wave or solitary wave (Choi et al. 2002; Ward and Asphaug 2003). The runup stage is now included in numerical model taking into account the various assumptions on hydraulic properties (roughness) of the dry land that is important for tsunami risk assessment (Dominey-Howes and Papathoma 2007; Gonzalez et al. 2009; Dall'Osso et al. 2010; Gayer et al. 2010). The direct calculation of tsunami wave propagation from source regions to the coastal zones within the single numerical model provides results with the low accuracy.

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Various nested methods with the different mesh resolution in the open sea and the coastal zone were then applied (Choi et al. 2003; Roger and Hebert 2008; Roger et al. 2010). Near the coast the accurate tsunami computing requires small grid steps of 10 to 100 meters, resulting in the significant increase of computing times. As a result, such numerical models are difficult to use in operational practice. For instance, tsunami waves in the Pacific Ocean usually arrive around 24 hours at the Japanese eastern coast after the earthquake occurrence in Chile and thus the runup height in coastal zones must be predicted well in advance before the tsunami waves arrives. Namely, the runup height in coastal zones must be forecasted quickly, but with high accuracy.

JMA (Japan Meteorological Agency) estimated the runup height at coastal zones by applying Green's theorem to the tsunami wave height obtained from the model at the offshore point. In Chile tsunami occurred on February 27, 2010, JMA warned over the runup height over 3 m in coastal zones, but in fact, the observed runup heights were much less than JMA's forecast at the most of coastal zones.

This study is therefore aimed to develop the combined model based on numerical simulation in sea regions far from the coast and analytical solutions for wave runup for rapid prediction of the tsunami characteristics on the coast required to prevent the tsunami disasters. The analytical approach to compute the runup height at the wall is described in detail. This approach is based on rigorous solution of the 1D linearised shallow-water equations for waves above a plane beach. The shallow water model to simulate tsunami propagation in the Pacific Ocean is first presented, and the numerical simulation for the 2010 Chilean tsunami event is performed. The runup heights in coastal zones are estimated using the analytical approach combined with the model. The prediction capacity of the developed model are presented and discussed along with estimation of runup heights.

2. Analytical Approach to Compute the Runup Height through "Wall" Height of Tsunami Wave

In analytical theory of long wave runup, the rigorous solutions of the 1D nonlinear shallow-water equations were obtained for a plane beach only using the Carrier - Greenspan transformation (Carrier and Greenspan 1958) for various shapes of the incident wave (Pedersen and Gjevik 1983; Synolakis 1987; Kaistrenko et al. 1991; Synolakis 1991; Pelinovsky and Mazova 1992; Tadepalli and Synolakis 1994; Carrier et al. 2003; Kânoğlu 2004; Tinti and Tonini 2005; Kânoğlu and Synolakis 2006; Didenkulova et al. 2006, 2008; Didenkulova and Pelinovsky 2008; Madsen and Fuhrman 2008; Didenkulova 2009). The essential point here is that the linear and nonlinear theories predict the same maximum values for runup height if the incident wave is determined far from the shore. It is why the linear theory can be applied to analyze the runup process. In the framework of linear theory the rigorous solutions are found for various bottom profiles, not a plane beach only. The popular approximation of the bottom profile is a plane beach combined with a flat bottom (such a configuration is usually applied in laboratory modeling). In this case the incident and reflected waves are easily separated on the flat bottom, and the ratio of the runup height to the monochromatic incident wave given by Shuto (1972) is

$$R/A = \frac{2}{[J_0^2(2kL)+J_1^2(2kL)]^2} \tag{1}$$

where R is the maximal runup height, A is the incident wave amplitude, L is a shelf width, k is the wave number of the incident wave, J_0 and J_1 are Bessel's functions. Using the Fourier transformation similar formulas (at least in integral form) could be derived for incident wave of arbitrary shape (Synolakis 1987; Pelinovsky and Mazova 1992). The amplification factor (1) was used to estimate and runup heights on Korean Coast during the 1993 tsunami (Choi et al. 2002).

With application to tsunami, the bottom profile is variable at any depth, and a classic numerical model includes the wall at the distance L with water depth h from the shore (Fig. 1). As a result, numerical simulation allows to compute the oscillation of water level on the wall, $\eta(L, t)$, with respect to time t. To select the incident and reflected waves from the wave records near the wall is not simple, and here we apply another approach based

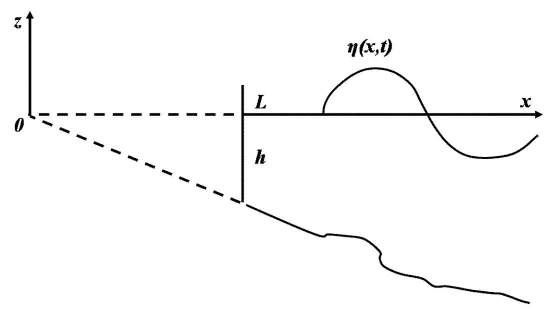


Fig. 1. Schematic presentation of the coastal zone

on rigorous solutions of the wave equation. The shallow-water equations in the linear approximation can be reduced to the wave equation for the water displacement

$$\frac{\partial^2 \eta}{\partial t^2} = \frac{\partial}{\partial x}\left[gh(x)\frac{\partial \eta}{\partial x}\right] \tag{2}$$

where g is the acceleration due to gravity, x is the distance to the offshore from the coast, and $h(x)$ describes the bottom profile. The general solution of (2) can be found using the Fourier transformation

$$\eta(x,t) = \frac{1}{2\pi}\int_{-\infty}^{\infty} \tilde{\eta}(x,\omega)\cdot e^{-i\omega t} d\omega \tag{3}$$

where Fourier transform $\tilde{\eta}(x,\omega)$ is the solution of ordinary differential equation followed from (2)

$$\frac{d}{dx}\left[gh(x)\frac{d\tilde{\eta}}{dx}\right] + \omega^2 \tilde{\eta} = 0 \tag{4}$$

We will assume that $h(x) = \alpha x$ everywhere. In this case an elementary solution of (4) is presented through the Hankel functions

$$\tilde{\eta}(x,\omega) = B(\omega)\cdot H_0^{(1)}(\zeta) + A(\omega)\cdot H_0^{(2)}(\zeta),$$

$$\zeta = 2\omega\sqrt{x/g\alpha} \tag{5}$$

Using the asymptotics of the Hankel functions of zero-order for large values of its argument, it is easy to show that the second term in (5) corresponds to the incident wave with amplitude A (propagated onshore) and the first one corresponds to the reflected wave with amplitude B (propagated offshore). We assume that characteristics of the incident wave are known and therefore $A(\omega)$ can be found from the Fourier presentation of the incident wave.

Let us firstly analyze the wave runup on vertical wall (Fig. 1). The boundary condition on the wall is

$$\left.\frac{d\tilde{\eta}}{dx}\right|_{x=L} = 0 \tag{6}$$

that leads to

$$B(\omega)\cdot H_1^{(1)}(\omega T) + A(\omega)\cdot H_1^{(2)}(\omega T) = 0 \tag{7}$$

where T is the travel time of wave from the wall to the shore

$$T = \frac{2L}{\sqrt{gH}} \tag{8}$$

The equations (5) for $x = L$ and (7) can be considered as a system of equations to find an amplitudes of the incident and reflected wave

$$A(\omega) = \frac{\tilde{\eta}(L)H_1^{(1)}(\omega T)}{H_0^{(1)}(\omega T)H_1^{(2)}(\omega T) - H_1^{(1)}(\omega T)H_2^{(2)}(\omega T)}$$

$$B(\omega) = \frac{\tilde{\eta}(L)H_1^{(2)}(\omega T)}{H_0^{(1)}(\omega T)H_1^{(2)}(\omega T) - H_1^{(1)}(\omega T)H_2^{(2)}(\omega T)} \tag{9}$$

In particular, if the wall is located far from the shore ($\omega T >> 1$), the equations (9) are simplified to

$$A(\omega) = \frac{i\pi\omega T H_1^{(1)}(\omega T)}{4}\tilde{\eta}(L,\omega),$$

$$B(\omega) = -\frac{i\pi\omega T H_1^{(2)}(\omega T)}{4}\tilde{\eta}(L,\omega) \tag{10}$$

Thus, the expressions (9) or (10) can be used to compute the spectral amplitudes of the incident and reflected waves through the Fourier spectrum of the water oscillations on the wall.

Let us consider now the wave runup on the same plane beach with no vertical wall assuming that the incident monochromatic wave has the same amplitude $A(\omega)$ as in "wall" problem. In this case the bounded (on the shore) solution (5) is

$$\tilde{\eta}(x,\omega) = 2\cdot A(\omega)\cdot J_0(\zeta) \tag{11}$$

Eliminating in (11) $A(\omega)$ from (9) we may calculate the wave field on a plane beach versus the wave oscillation on the wall. In particular, the spectral amplitude of the water oscillations on the shore is

$$\tilde{\eta}(0,\omega) = \frac{2H_1^{(1)}(\omega T)}{H_0^{(1)}(\omega T)H_1^{(2)}(\omega T) - H_1^{(1)}(\omega T)H_2^{(2)}(\omega T)}\tilde{\eta}(L,\omega) \tag{12}$$

Using the Fourier transformation of (12) we may compute $\eta(0, t)$ through $\eta(L, t)$. The kernel of this transformation contains the special functions and it is too complicated to simplify the Fourier integral. If the wall is far enough from the shore ($\omega T >> 1$), using an asymptotic expression (10) the formulae (12) is simplified to

$$\tilde{\eta}(0,\omega) = \frac{i\pi\omega T H_1^{(1)}(\omega T)}{2}\tilde{\eta}(L,\omega) \tag{13}$$

The inverse Fourier transformation in this asymptotic case is expressed by the simple integral

$$\eta(x=0,t) = \int_0^{t-T} \frac{t-\tau}{\sqrt{(t-\tau)^2 - T^2}}\frac{d\eta(x=L,\tau)}{d\tau}d\tau \tag{14}$$

Formula (14) can be integrated by parts and transformed to

$$\eta(x=0,t) = \int_0^{t-T} \sqrt{(t-\tau)^2 - T^2} \cdot \frac{d^2\eta(x=L,\tau)}{d\tau^2} d\tau \qquad (15)$$

In both formulas $t = 0$ corresponds to the wave approaching to the vertical wall and in initial moment it is assumed that $\eta(x=L,\ t=0) = d\eta(x=L,\ t=0)/dt = 0$. Extreme of $\eta(x=0,\ t)$ gives the maximal runup height of tsunami waves on the coast.

So, considering two geometries of the nearshore, a plane beach (for runup study) and plane beach with the vertical wall on fixed depth (equivalent boundary condition) it is shown that the runup height can be expressed through characteristics of the water oscillations on the vertical wall. This procedure is rapid and can be simple to realize on computers. As a result, the numerical simulation of the tsunami waves in the basin with vertical wall nearshore can be used for tsunami wave runup estimations.

Several limitations of the proposed approach should be mentioned. First of all, the 1D analytical runup theory is applied here; meanwhile the numerical simulation of tsunami waves in real basins is performed for 2D geometry. The wave field on the wall in general contains from the approaching waves propagated onshore and trapped waves propagated alongshore. It is evident that the first waves in time series near the wall are "onshore" waves (trapped waves approach later), and therefore, the interval of integration in (14) or (15) should be bounded by a few first waves. The second limitation is related with the approximation of the bottom profile near shore and vertical wall as a plane beach with the same slope. The third one is an approximation that a vertical wall is located far from the shore. The fourth limitation is the ignoring of the breaking effects in tsunami waves. And the last one is the linearity of the considered equations. But as it was pointed early, the maximal runup height computed in linear and nonlinear theories is the same and, therefore, this last limitation is not such important. The applicability of other assumptions can be checked in modeling of the historic events.

3. Numerical Model

The finite-difference model (Choi et al. 2003) is constructed to simulate the tsunami generation and propagation using the linear shallow-water equation with a spherical coordinate system (Fig. 2); mesh dimension, 4321 × 2161, mesh size, 5 angular min and time step, 10 sec. The basic equations are

$$\frac{\partial\eta}{\partial t} + \frac{1}{R\cos\phi}\left[\frac{\partial P}{\partial\chi} + \frac{\partial}{\partial\phi}(Q\cos\phi)\right] = 0$$

$$\frac{\partial P}{\partial t} + \frac{gh}{R\cos\phi}\frac{\partial\eta}{\partial\chi} - fQ = 0$$

$$\frac{\partial Q}{\partial t} + \frac{gh}{R}\frac{\partial\eta}{\partial\phi} - fP = 0 \qquad (16)$$

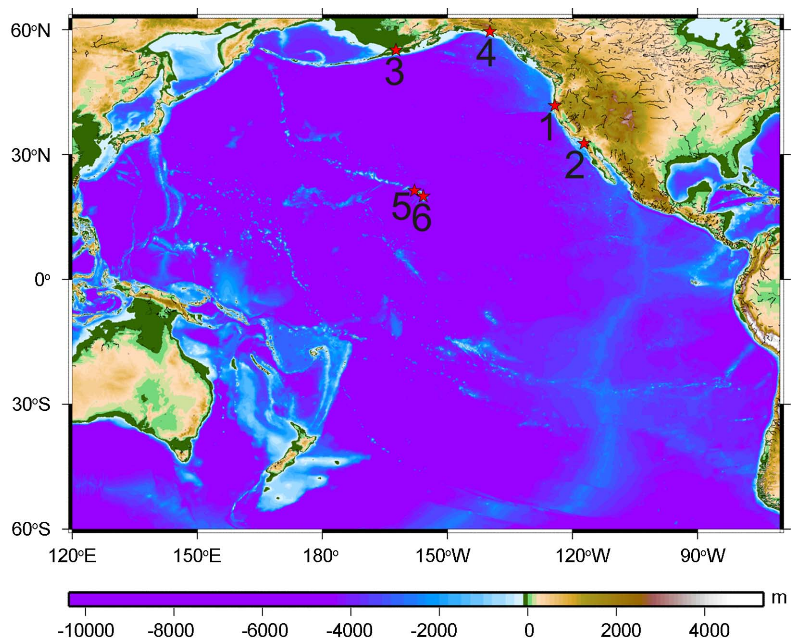


Fig. 2. Topography and bathymetry. Stations marked with a star indicate tide gauge stations. 1: Crescent City, California; 2: San Diego, California; 3: King Cove, Alaska; 4: Yakutat, Alaska; 5: Honolulu, HI; 6: Kawaihae, HI

In the equations above ϕ and χ are latitude and longitude, P and Q are discharge per unit width in the direction of ϕ and χ respectively, R is radius of the earth, and f is the Coriolis parameter.

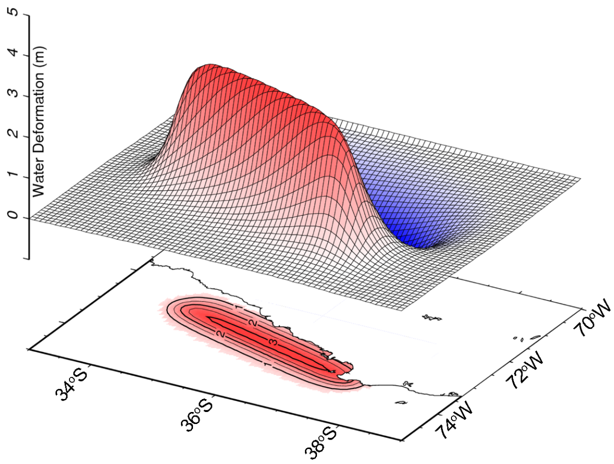


Fig. 3. Location and initial water elevation (unit: m) of 2010 event

We used ETOPO5 (Earth Topography 5-minute) bathymetry dataset. Numerical modeling is done for the Chilean tsunami in 2010. Fault parameters are determined in USGS (2010). The initial surface profile in the source is determined by the method of Manshinha and Smylie (1971). Fig. 3 shows the location of tsunami source.

Fig. 4 shows the comparison of observed and calculated values of water elevation of tsunami at 6 tide gauge stations in the Pacific Ocean (WCATWC 2010). The difference between observed and calculated maximum wave heights is less than 0.2 m and the difference between observed and calculated arrival time is less than 15 minutes except for the tide station of Honolulu, Hawaii. We can say that the model has well reproduced the 2010 Chile tsunami propagation.

Boundary conditions near the coast are "non-reflected", normal component of the particle velocity or flow discharge to boundary is zero; that corresponds to the vertical wall in the last sea points. The numerical model is used for the tsunami waves in the Pacific Ocean and the Japanese

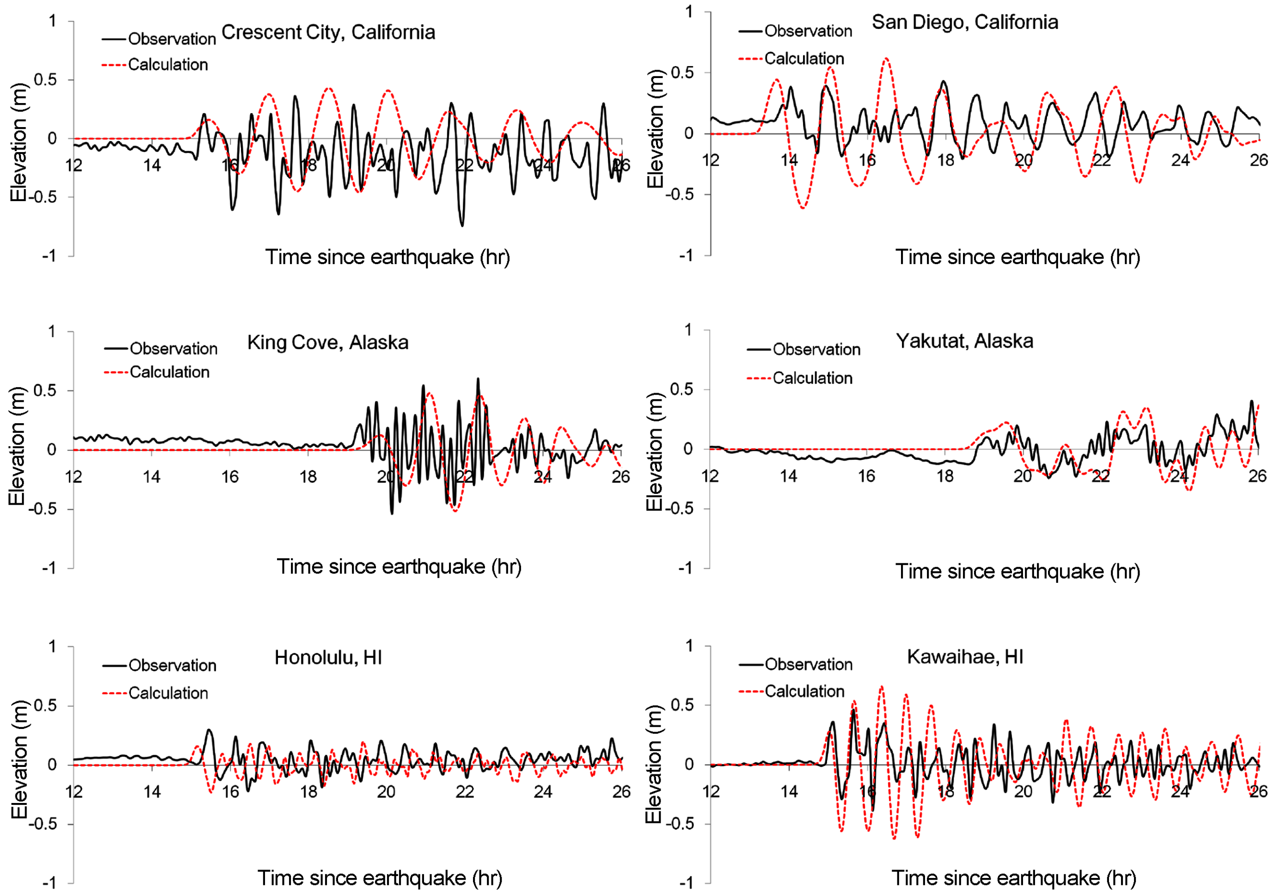


Fig. 4. Observed and computed water elevations of the 2010 tsunami simulations at 6 tide gauge stations shown in Fig. 2

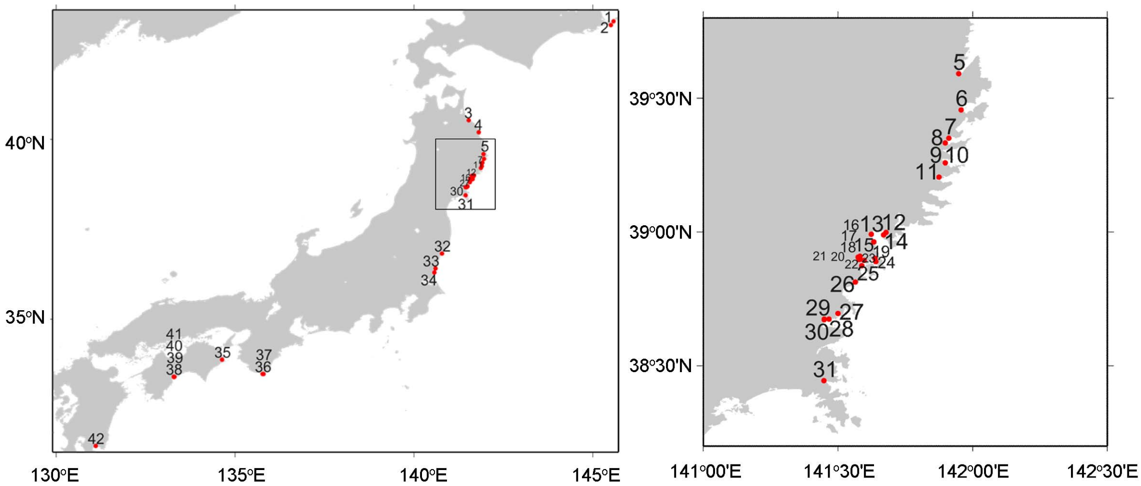
eastern coast, and as a result, the water displacement in the last sea points is calculated. Then, the maximal runup heights are estimated with use of the integral (15).

4. Tsunami Runup Height Distribution Along the Eastern Japanese Coast

After the occurrence of tsunami on February 27, 2010, the tsunami wave height and runup height in the eastern Japanese coast were investigated (JMA 2010). Fig. 5 shows the locations (cities) where the runup heights were measured. We calculated the runup height using the time series of model water elevation and compared with observations. Also, we compared with JMA' runup estimation based on Green's theorem.

Fig. 6 displays the time series of the water displacements along the vertical wall computed by the finite-difference model (dash line) and on a shore (solid line) calculated with use of integral (15) for several coastal locations (shown in Fig. 5). It is seen that the amplification factor of tsunami waves nearshore is about 1.7-3.0. Fig. 7 shows the comparison of observed and computed runup height on 42 points on the eastern Japanese coast. Two computed runup heights are presented, one is the converted runup height obtained using the theory introduced in this study, and the other is estimated by Green's theorem used in JMA.

The computed runup height in this study shows a good



No.	City	No.	City	No.	City
1	Hanasaki	15	Kesennuma1	29	Minamisanriku3
2	Otsiishi	16	Kesennuma2	30	Minamisanriku4
3	Hachinohe	17	Kesennuma3	31	Onagawa3
4	Kiji	18	Kesennuma4	32	Otsu
5	Miyakowan	19	Kesennuma5	33	Hitachinaka
6	Arikasa	20	Kesennuma6	34	Oarai
7	Otsuchi1	21	Onagawa1	35	Anan
8	Otsuchi2	22	Onagawa2	36	Kushimoto
9	Kamaishi	23	Kesennuma7	37	Ojima
10	Rikuzentakata1	24	Kesennuma8	38	Susaki2
11	Shirahama	25	Kesennuma9	39	Susaki1
12	Rikuzentakata2	26	Kesennuma10	40	Susaki3
13	Rikuzentakata3	27	Minamisanriku1	41	Susaki4
14	Rikuzentakata4	28	Minamisanriku2	42	Shibushi

Fig. 5. Location of runup height observation stations on the eastern Japanese coast. The right panel indicates the rectangular region in the left panel. In case of several observations in the same city, the sequential number was affixed to the name of city

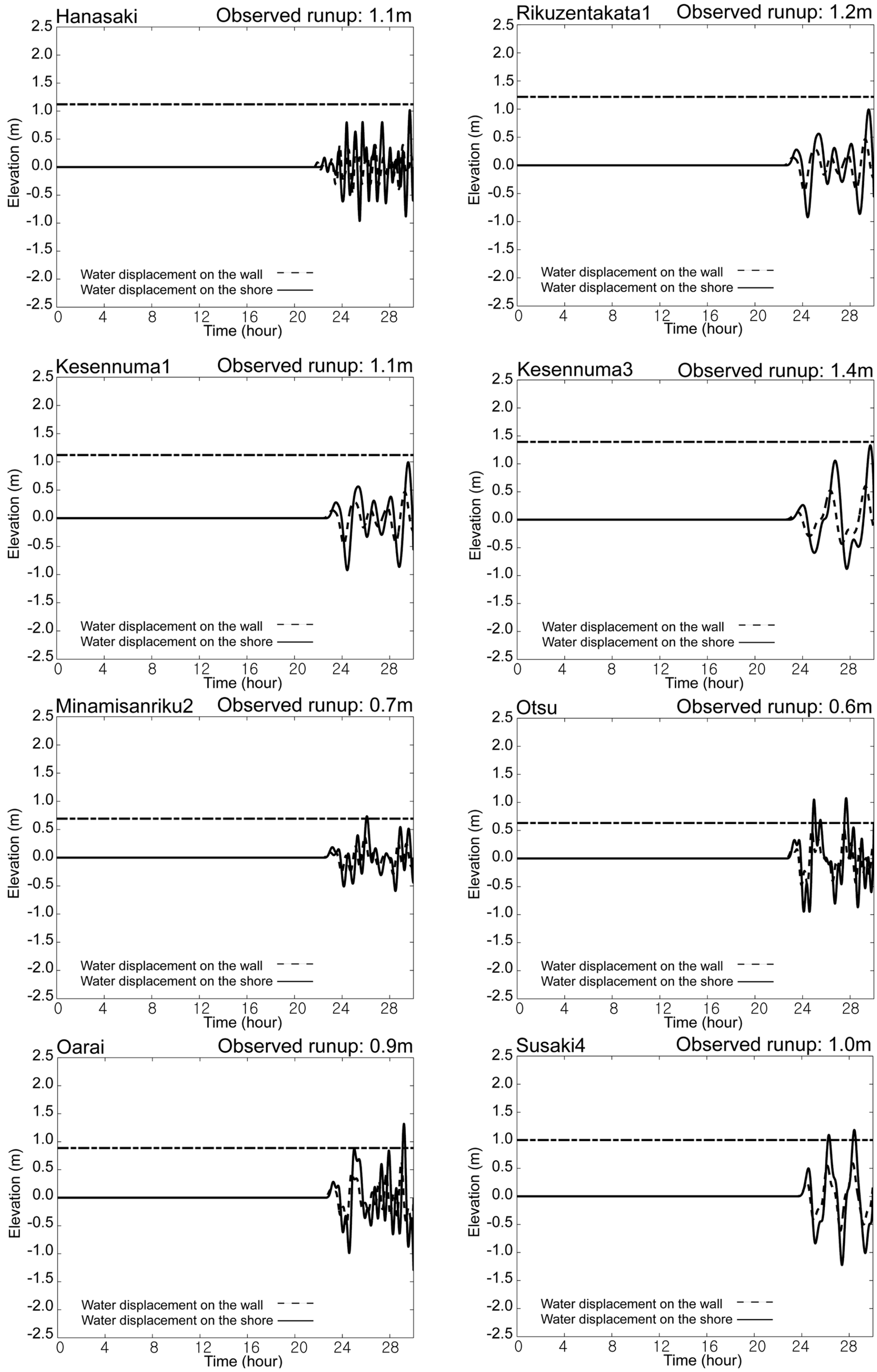


Fig. 6. Computed time series of water displacement on the vertical wall (dashed line) and on shore (solid line). Observed runup heights are shown by dashed-point line

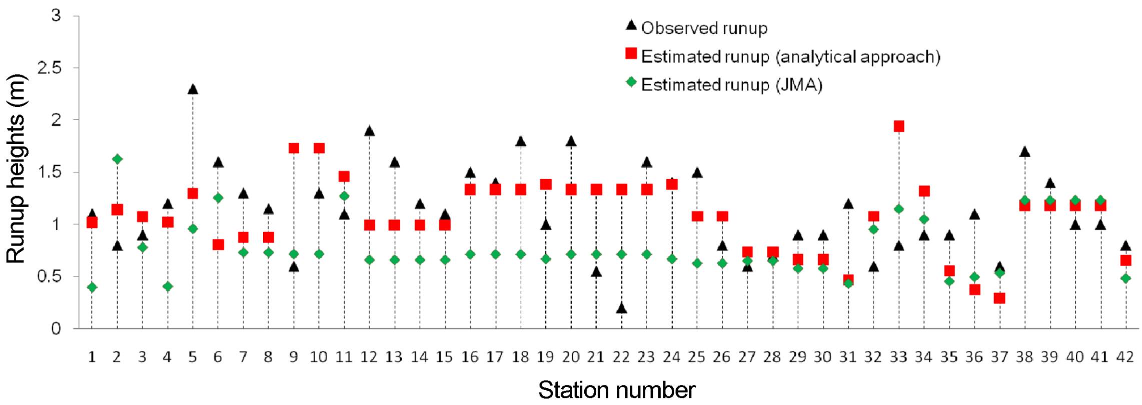


Fig. 7. Comparison of observed and computed runup heights on the eastern Japanese coast. The red squres are estimated runup heights in this study (analytical approach), and the green diamonds are estimated runup height by Green's theory which method is used in Japanese Meteorological Agency (JMA)

agreement with the observation. Comparing with JMA's estimated runup, the RMS (root mean square) error of our estimation is 51.8 cm, while that of JMA was 60.8 cm in all 42 stations. The approach introduced in this study clearly shows better estimation for the tsunami run-up.

5. Conclusions

A rapid forecast method for tsunami runup on coasts based on combined use of 2D numerical model and 1D analytical runup theory is proposed. As the first step the 2D numerical simulations of tsunami generation and propagation are performed using the no-flux boundary conditions on the last sea points. Then the time-series of the water oscillations on the wall are used to calculate the runup heights with the analytical integral expression followed from 1D theory. The applicability of this approach is checked for the 2010 Chilean tsunami event in the Pacific Ocean and the Japanese eastern coast. The predicted runup heights are in good agreement with the observed ones. In addition, predictions in this study have better accuracy than JMA's method. It is believed that this proposed approach is more reasonable for the use of rapid forecast method than using statistical or empirical run-up factor or resorting to complicated coastal inundation model and can be applied to elsewhere.

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