Ocean Engineering 163 (2018) 369–376

Contents lists available at ScienceDirect

Ocean Engineering

journal homepage: www.elsevier.com/locate/oceaneng

Effect of continental and nearshore slopes on tsunami height

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ARTICLE INFO

Keywords:
Tsunami
Shallow water equation
Crank-Nicolson method
Run-up
Continental slope
Nearshore slope

ABSTRACT

In the present study, an attempt is made to understand the effect of continental and nearshore slopes on the transmission, propagation and run-up of tsunami. A numerical model study is carried out using shallow water equations that are solved using Crank-Nicolson finite difference approximation method on a staggered grid. A rectangular solitary wave is considered to propagate over typical continental slopes and nearshore profiles available along the Indian coast. The amplification or attenuation of tsunami characteristics over these cross-sections was studied. It was observed that the tsunami run-up is altered with varying continental slope, water depth on continental shelf and nearshore slope. The study suggests that tsunami height on the continental shelf increases for shallow continental shelf depths. The percentage increase in tsunami height with decrease in continental shelf depth from 200 m to 50 m is found to be 31%. Higher tsunami run-up was observed for deeper continental shelf and steeper continental slope, whereas lower tsunami run-up for deeper continental shelf and flatter continental slope. It was observed that for a steep continental slope (1:0.1), a reduction in nearshore slope (steep to flat) increases tsunami run-up up to a slope of 1:632 and then decreases.

1. Introduction

Tsunamis, earthquake-generated waves, are created in the deep portion of the ocean and propagate towards the shore. Tsunami, a shallow water wave, undergoes transformation as it propagates along the continental slope towards the coast. This transformation is in the form of reduction in speed which leads to increase in wave height (Kowalik et al., 2006; Sriram et al., 2006). After reaching the shore, tsunami will break and travel over the land with huge energy which creates severe impact and disaster in the society (Sriram et al., 2006). It is necessary to understand the effect of near shore bathymetry on tsunami characteristics and prediction of run-up (Behera et al., 2011), which will help in adopting appropriate measures to reduce the tsunami effect on society. In the past, various studies had been carried out to investigate the tsunami run-up on different beach slopes and empirical formulae were suggested for computation of tsunami run-up. Gjevik and Pedersen (1983) developed a numerical model based on a Lagrangian description for studying run-up of long water waves on beach slopes varying from 0° to 45°. Synolakis (1987) studied the run-up of solitary wave on plane beaches by conducting various laboratory experiments over different beach slopes varying from 2° to 45°. The author observed that run-up variation will behave differently for breaking and non-breaking waves. Grilli et al. (1997) had reported that waves will not break on beach with slope steeper than 1:4.7. They have also concluded that shoaling rate decreases for slopes steeper than 1:15. At the same time, waves may break very close to the shore line for moderately steep slopes. Postacioglu et al. (2017) have investigated the resonance aspect of coastal run-up as a response to incident tsunami. They have observed that the resonance is highly dependent on the discontinuity in depth at the toe of the slope. In case of no discontinuity in depth, the run-up amplitude increases steadily with negligible resonance. Similarly, long wave run-up on a segmented beach slope was investigated by Ezersky et al. (2013) and reported that resonance effects lead to the sufficient increase of run-up heights for the weakest earthquakes.

Gedik et al. (2005) observed that armor units used for beach protection cause 50% reduction in run-up height. If wave steepness (H/L) is greater than 0.015, the run-up decreases with increasing value of bed friction (Borthwick et al., 2006). Hsiao et al. (2008) conducted laboratory experiments and developed a formula to compute maximum run-up height for beach slopes varying from 1:15 to 1:60. Madsen and Fuhrman (2008) observed that the impact of run-up on flat beaches (with slope 1:100) is much higher than that on steep beaches (with slope 1:15). The reflection coefficient decreases when run-up height and wave steepness increase (Gedik et al., 2011). Lin et al. (2014) had concluded that the maximum run-up velocity increases gradually along the slope before the solitary wave reaches its breaking point. Zhao et al. (2017) carried out numerical and experimental study to investigate the effect of submarine gentle slopes and coastal cliffs on the nearshore tsunami characteristics and concluded that critical cliff angle is 45°.

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https://doi.org/10.1016/j.oceaneng.2018.05.069
Received 12 November 2017; Received in revised form 20 March 2018; Accepted 28 May 2018

There were numerous experimental, analytical and numerical model studies carried out on behavior of tsunami along the coast (Gjevik and Pedersen, 1983; Grilli et al., 1997; Lin et al., 2014). Most of the studies were based on the analysis of solitary wave propagation over different beach profiles and the subsequent run-up. Beach slopes are more flatter than continental slopes and expected to affect the tsunami characteristics differently. The effect of continental slopes on tsunami characteristics and subsequent run-up along the coast has not been investigated in the past studies. The tsunami characteristics in the continental shelf region is of great importance as they are going to affect large number of offshore structures present in these regions. Thus, a 1D numerical study is carried out to investigate the effect of continental and nearshore slopes on tsunami characteristics.

2. Numerical model

Although tsunami is generally simulated using 2D or 3D models for realistic modelling, in the present study, a 1D model is used to understand the effect of continental and nearshore slope profiles on the tsunami characteristics. The 1D model study also helps in avoiding the effect of lateral energy transfers due continental shelf geometry. Thus, using the 1D model study, we intend to quantify the effect of continental slope and nearshore slope alone. Tsunami being a shallow water wave can be simulated using shallow water equations.

2.1. Governing equations and boundary conditions

In the present study, a numerical model is developed using 1D shallow water equations (SWE) and are given as

$$\frac{\partial \eta}{\partial t} + \frac{\partial q}{\partial x} = 0 \tag{1}$$

$$\frac{\partial q}{\partial t} + \frac{\partial (uq)}{\partial x} = -\frac{H}{\rho}\frac{\partial p_a}{\partial x} - gH\frac{\partial \eta}{\partial x} + \frac{\tau_b}{\rho H} \tag{2}$$

$$\tau_b = \rho k_b H^{-2}|q|q \tag{3}$$

where, η is sea surface elevation, H is total depth of water (still water depth from mean sea level (d) + sea surface elevation (η)), u is average velocity of the water particle, q is the flow discharge in the x direction (uH), g is acceleration due to gravity, ρ is density of sea water, τ_b is bottom stress and k_b is dimensionless bottom friction coefficient. The value of friction coefficient (k_b) varies from 1.0×10^{-3} to 3.0×10^{-3} (Dotsenko, 1998). In this study $k_b = 2.0 \times 10^{-3}$ is considered as suggested by Behera et al. (2011). Here, P_a is atmospheric pressure and the gradient equals to 0. Then, the modified momentum equation can be written as,

$$\frac{\partial q}{\partial t} + \frac{\partial (uq)}{\partial x} = -gH\frac{\partial \eta}{\partial x} + \frac{\tau_b}{\rho H} \tag{4}$$

The shoreline boundary is assumed as an abrupt end of the coast with finite water depth and no flow condition is applied. Open boundary is imposed with radiation condition given by (Flather, 1976). The velocity of tsunami at the open boundary is given by

$$u = -\sqrt{\frac{g}{H}}(\eta) \tag{5}$$

2.2. Solution of SWE

Equations (1) and (4) can be solved by using Crank-Nicolson finite difference method on a staggered grid (Fig. 1) with first order difference in time and space. The staggered grid arrangement is shown in Fig. 1, where the sea surface elevations (η) are defined by filled circles and discharges (q) are defined by empty circles. The staggered grid requires either sea level or velocity as boundary condition input (Kowalik and Murty, 1993).

The continuity and momentum equations in central difference form are given as,

$$\frac{\eta^{n+1} - \eta^{n-1}}{2\Delta t} + \left(\frac{{q_{i+1}}^{n} - {q_{i-1}}^{n}}{2\Delta x}\right) = 0 \tag{6}$$

$$\frac{q^{n+1} - q^{n-1}}{2\Delta t} + u_i\left(\frac{{q_{i+1}}^{n} - {q_{i-1}}^{n}}{2\Delta x}\right) + q_i\left(\frac{{u_{i+1}}^{n} - {u_{i-1}}^{n}}{2\Delta x}\right) + gH_i\left(\frac{{\eta_{i+1}}^{n} - {\eta_{i-1}}^{n}}{2\Delta x}\right) = \frac{k_b|q_i|q_i}{{H_i}^3} \tag{7}$$

Here, n is time level, Δt is time step, i is spatial node number and Δx (dx) is the grid size (Fig. 1). The unknown value of η and q at all the nodes except at the boundary are obtained by solving the above equations.

3. Validation of the numerical model

In general, a numerical model is validated with standard numerical model or physical model results. The 1D numerical model developed using the shallow water equations, is validated with the results of Kowalik et al. (2006) who have studied the tide-tsunami interaction for Gulf of Alaska region. A numerical model domain, same as of Kowalik et al. (2006) is considered for the study. The model domain consists of 1000 km long channel with constant water depth up to 875 km from the open boundary (0 km) and varying depth for a stretch of 125 km towards the shore (Fig. 2(a)). The water depth in the domain is 3000 m from the open boundary to 875 km and then reduces from 3000 m to 5 m at the truncated shoreline boundary. In the present model, the shoreline boundary is assigned with finite water depth of 5 m for numerical stability, unlike the wet-dry boundary condition used in the study of Kowalik et al. (2006).

Simulation of tsunami was carried out by generating a perturbation with uniform bottom uplift of height 2 m and length 200 km located between 200 km and 400 km (Kowalik et al., 2006) (Fig. 2(b)). The model was initialized with zero elevation and zero velocity all through the domain except the tsunami perturbation given in Fig. 2 (b). The simulation was carried out and tsunami elevation profiles were recorded at 2min, 16.67min, 39min, 57.6min, 1hr 16min and 1hr 27min intervals. The extracted tsunami profiles were compared with that of Kowalik et al. (2006) and are found to be in acceptable agreement. However, the comparison plot for T = 1hr 27min (Fig. 3(f)) show higher values for present numerical model results compared to Kowalik's results. This difference is expected as the shoreline boundary, in the present study, is imposed with no flow condition unlike the wet-dry boundary condition used in the study of Kowalik et al. (2006). It was observed that the tsunami splits into two waves of 1 m height travelling in opposite direction (T = 16.67min). The wave travelling towards the open boundary travels across and moves out of the domain, whereas the wave travelling towards the shore propagates with constant amplitude (T = 39min) and is considered as incident wave. At 57.6min, the tsunami strikes on the shore, following which the reflection of tsunami from the shore is observed. The tsunami attains maximum run-up height when the complete wave hits the shore as seen in Fig. 3(f).

The tsunami elevation and velocity at open and shoreline boundary were obtained and compared with results obtained by Kowalik et al. (2006) (Figs. 4 and 5). In Fig. 4, the elevations and velocities obtained from the present model are found to be in good agreement with the results of Kowalik et al. (2006) up to the arrival of initial tsunami, whereas an over estimation is observed in the case of reflected wave recorded around 4 h of the simulation. This difference is due to the reflection from the wall boundary condition imposed at the shoreline in the present model in comparison the wet-dry boundary imposed in the Kowalik et al. (2006) model. Similarly, Fig. 5 shows the elevation and velocities close to the shoreline. A finite depth is considered at the