Numerical Simulations of Tsunami Wave Properties on Coastal Slopes using One Piston-Wavemaker Method

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Abstract. Most of the coastal area in the Ulee Lheue Bay of Aceh Besar was affected by a tsunami wave during the 2004 Indian Ocean Tsunami. Such area has an inclined bed floor which varies in slope. Variations of slope can affect tsunami wave properties such as tsunami arrival time, wave height and velocity. With those variations, the degree of the tsunami effects is highly unpredictable. Therefore, it is important to conduct a research to understand the effects of coastal slopes on tsunami waves propagation and wave deformation. Google SketchUp was used for designing the coastal slopes’ 3 Dimensional models. For the tsunami waves, solitary waves were generated by using smoothed particle hydrodynamics numerical models through the DualSPHysics software. The computation was based on the meshless method. From the simulations, the waves’ properties were obtained and were analyzed how coastal slopes affect the arrival time of tsunami waves, also for their height and velocity. Results show that the steepest coastal slope has the highest velocity, but shortest wave height and longest arrival time. Conversely, the flattest coastal slope has the lowest velocity, but highest wave height and shortest arrival time. Longer tsunami arrival times will benefit people in the evacuation process during the hazard.

Keywords: DualSPHysics, Solitary Waves, Meshless Method, Coastal Slopes

1. Introduction
On December 26th, 2004, a tsunami devastated Aceh, Indonesia. This event generated major loss, especially in terms of human casualties and properties, since it caused over 200,000 fatalities and almost 20 billion USD of economic damage. So far, it has also been the deadliest natural disaster of the 21st century.

Since Aceh is located in very active subduction zones, this area is prone to numerous earthquakes and tsunamis [1]. After 2004, people started to realize how vulnerable Indonesia, especially in coastal cities. This vulnerability highlights the need for developing several strategies to reduce the impact of natural hazards.

Numerical simulations have become one of the main methods which is used in coastal research. Furthermore, numerical modeling is able to provide more economic solutions in terms of funds and preparation time, compared, for instance, to physical modeling. Hence, numerical modelling has become the best option for running tsunami simulations and other coastal studies.

The purpose of this study is to show the interaction between tsunami waves and coastal slopes with multiple slope variations; as well as to present the effect of the slope on the wave’s height, velocity...
and arrival time. The results could then be used as a reference for designing coastal structures that would be able to mitigate future tsunamis. The height and velocity of the wave could become standards to take into account in the building of future coastal structures. Finally, tsunami arrival times could be used to determine the best evacuation route according to the area’s geophysical configuration.

2. Methods
Numerical simulations were conducted using the DualSPHysics software. This software is based on a Smoothed Particle Hydrodynamics named SPH. It is used to study free-surface flows such as tsunami-like waves. DualSPHysics uses the meshless method for hydrodynamic and other types of fluid simulations. SPH can be run by using CPU (Central Processing Unit) or GPU (Graphics Processing Units). GPU is able to process more data and in a faster way compared to CPU [2]. In this simulation, DualSPHysics was executed by using GPU of NVIDIA® GeForce GTX 1080 8GB. The distance between the particles (DP) was set to 0.01 m.

2.1. Model setup
Ten simulation cases were run according to different volumes of water and variation of coastal slopes. The simulation time of each case was 10.0 seconds with a time step of 0.01 seconds. Every case took about 12 hours of running time. All of the cases were using 0.5 m as the sea width with the horizontal length consisted of 2 m of flat area and 10 m of inclined slope. The coastal slopes with multiple variations had ratios of 1:80, 1:100, 1:120, and 1:150. These slopes have variation of water levels regarding on the slope, which are 0.11 m, 0.09 m, 0.08, and 0.06 m. These 16 cases are shown in Table 1.

| Cases  | Designed Wave Height (m) |
|--------|--------------------------|
| Slopes | Water Level (m)          |
| 1 : 80 | 0.11                     |
|        | 0.06                     |
|        | 0.05                     |
|        | 0.04                     |
|        | 0.03                     |
| 1 : 100| 0.09                     |
|        | 0.06                     |
|        | 0.05                     |
|        | 0.04                     |
|        | 0.03                     |
| 1 : 120| 0.08                     |
|        | 0.06                     |
|        | 0.05                     |
|        | 0.04                     |
|        | 0.03                     |
| 1 : 150| 0.06                     |
|        | 0.05                     |
|        | 0.04                     |
|        | 0.03                     |

This research used a 3D DualSPHysics model, where the domain resembles a flume. This flume appeared to be a boundary describing the coastal area of Ulee Lheue Bay, Aceh Besar. This coastal area was designed in 3D models with a 1:10 scale. The design had a 5 meters length of inclined area, and a meter land area, with varied elevation on the even level of the surface in the land/lee side. The
varied elevation height on the lee side depended on the coastal slopes, varying among 0.125 m, 0.1 m, 0.083 m, and 0.067 m. The slope model was placed 2 meters from the start of the flume.

The paddle was used as a solitary wave generator, and it was placed at the start of the flume with a square-shaped dimension of 0.5 m x 1 m and a thickness of 0.2 m. Sensors as Wave Gauges (WG) were placed in four locations. WG #1 was placed in the Deep Ocean (2 m from the start), WG #2 was placed on the Nearshore (9 m from the start), WG #3 was placed on the Shoreline (12.1 m from the start), and WG #4 was placed on the Land Side/Lee Side (12.6 m from the start). The complete dimension of the design is shown in Figure 1.

![Figure 1. Flume design](image1)

For the coastal slopes, Google SketchUp was used for designing these 3D models. The model consisted of coastal slopes with multiple variations of: 1:80, 1:100, 1:120, and 1:150. Furthermore, the models were saved in *.stl format for further use in DualSPHysics as coastal slopes. The SketchUp model is shown in Figure 2.

![Figure 2. Google SketchUp slope model for the coastal slope](image2)

2.2. Solitary Wave

The DualSPHysics cannot generate tsunami wave from an earthquake source, thus the tsunami wave was assumed to be a solitary wave, which is a single wave that travels from the deeper part of the ocean and starts breaking through the shallower area. The best ratio for perfect solitary waves should be 1:10 on the designed wave height (H) over the depth of the sea (h). The wave was generated from a paddle movement start, with a distance (x) equal to 0 m and a time (t) equal to 0 s until time is equal to 5 s. The solitary wave was generated based on a Goring equation which was calculated using Visual
Basic, and converted into Paddle Movement Data in *.txt format. The solitary wave equation was calculated as follows [3]:

\[ u(x_s, t) = \frac{dx_s}{dt} \]  
\[ u(x_s, t) = \frac{c \cdot \eta(x_s, t)}{h + \eta(x_s, t)} \]  
\[ x_s(t) = \frac{2H}{kh} \tan h \left[ k(c \cdot t - x_s(t)) \right] \]  
\[ c \cdot \eta(x_s, t) = H \cdot sech^2 \left[ k(c \cdot t - x_s) \right] \]  

Equation (1) defines the movement formula, where \( x_s \) is the paddle displacement (in meters) and \( t \) is the movement time (in seconds). In Equation (2), the average velocity of the wave was calculated, where \( c \) is the wave velocity, \( h \) is the water depth, and \( \eta \) is the surface elevation. After that, the paddle displacement over time can be calculated with Equation (3). Finally, the solitary wave can be generated using Equation (4), where \( H \) is the designed wave height (in this study equal to 0.03 m) and \( k \) is the Ouskirt Coefficient.

After the solitary wave data were calculated, the back and forth wavemaker piston type in DualSPHysics was used as the paddle. The paddle moves for 5 seconds. In \( t=0 \) s, the paddle moves until \( t = 2.5 \) s for 1.25 m of displacement. Finally, the paddle returns for another 2.5 s to its original position (0 m). The paddle movement graph of 0.06 m designed wave is shown in Figure 3.

![Wavemaker - Solitary Wave](image)

**Figure 3.** Time series of paddle displacement for solitary wave generation of 0.06 m. Within a 5 s displacement time, the paddle moves horizontally as far as 1.25 m.

### 2.3. Current Velocity Profile

Wave Gauges (WG) were placed in four places as observers. These wave gauges observed the wave velocity and height at every point. WG #1 was placed in the deep ocean for observing the travel of solitary wave. WG #2 was placed on the nearshore for observing the hydrodynamic process when the wave was going to break. WG #3 and WG #4 were placed in the elevated land area for comparing the differences in wave height between every variation of the case. These sensors recorded wave height and wave velocity data for every 0.1 m of elevation.

The wave travels as a profile of water column. The velocity increases as the water level rise. It starts from zero in the sea bed until it hits the maximum velocity on the surface. This phenomenon is
called current velocity profile. To determine the current velocity profile at certain times and places, the depth averaged velocity formula by Soulsby was used as follow [4]:

$$\bar{U} = \frac{1}{h} \int_{0}^{h} U(z) \, dz \tag{5}$$

Where $\bar{U}$ is depth averaged velocity (m/s), $h$ is water depth (m), $U(z)$ is the current speed at $z$-depth (m/s), and $z$ is the observed depth point (m). From Equation (5), trapezoidal rules are used as a mathematical approach to obtain $\bar{U}$. The velocity in the sea bed is assumed to be zero (at $z=0$) and the maximum value on the surface (at $z=h$). Thus, if the current speed in the depth of $z_1$, $z_2$, $z_3$, ..., $z_n$ (ascending) are $U_1$, $U_2$, $U_3$, ..., $U_n$, then the Equation (5) becomes [4]:

$$\bar{U} = \frac{0.5}{n} \left[ U_1 z_1 + (U_1 + U_2)(z_2 - z_1) + (U_2 + U_3)(z_3 - z_2) + \ldots + (U_{n-1} + U_n)(z_n - z_{n-1}) + 2U_n(h - z_n) \right] \tag{6}$$

3. Results
3.1. Paraview animations
The DualSPHysics has *.vtk and *.csv files as its outputs. From the *.vtk files, video animations can be rendered using Paraview. Subsequently, snapshots from animations at certain time steps can be obtained. Those images are presented in Figure 4.

![Figure 4. Snapshots of a travelling tsunami wave at certain times, rendered with Paraview](image)
From the snapshots in Figure 4, at t=0 s, the solitary wave doesn’t exist yet since the paddle is still in sedentary state and the water volume is still at its initial condition. Afterward, the paddle starts moving based on the solitary wave generation data in Figure 3. At t=2 s, the wave travels and reaches its maximum peak at t=2.5 s. After that, at t=3 s, the wave still travels through the flume from the deeper part of the sea to the nearshore area at t=4 s. Finally, at t=5 s, the wave hits the shoreline and the lee side of the flume.

3.2. Time series graph of flow depth and wave velocity

From the *.csv files (obtained from wave gauge sensors), wave height and the velocity data can be collected and analyzed. Then time series graphs can be made. Those graphs are shown in Figure 5 and Figure 6.

![Figure 5](image)

**Figure 5.** Flow Depth -Wave Height time series graph.
(a. Deep Ocean, b. Nearshore, c. Shoreline, d. Land Side)

From the flow depth–wave height graph (Figure 5) maximum flow depth is obtained. In Figure 5.a, the maximum flow depth formed is 0.48 m. After that, the wave starts breaking through the shallower area near to the shore with a maximum flow depth of 0.29 m (see Figure 5.b). Finally, the wave hits the shoreline and the land side area forming a massive force upon the impact with maximum flow depths of 0.32 m and 0.35 m (see Figure 5.c and 5.d).

Also, based on the velocity graph (see Figure 6), the maximum velocities from each wave gauge are collected. The maximum velocities that occurred in WG #1, WG #2, WG #3, and WG #4 are 1.99 m/s, 3.00 m/s, 2.53 m/s, and 2.35 m/s respectively.
3.3. Depth averaged velocity

Since the wave moves as a water column/profile, the maximum velocity does not represent its significant values. Therefore, the depth averaged velocity ($\bar{U}$) for every time step was calculated by using Equation 6. From these results, the Maximum value of $\bar{U}$ ($\bar{U}_{\text{max}}$) can be obtained as the significant velocity of the wave. $\bar{U}_{\text{max}}$ in the Land Side of the case is used as a reference for the comparison to $\bar{U}_{\text{max}}$ in the Nearshore area in the same time steps. The maximum wave height in the land side is also compared to the wave height in the nearshore area with the same time steps as the $\bar{U}_{\text{max}}$. The graphs are presented in Figure 7.

![Figure 6. Wave Velocity time series graph. (a. Deep Ocean, b. Nearshore, c. Shoreline, d. Land Side)](image)

![Figure 7. Comparison between two values in the land side and near shore area. (a. $\bar{U}_{\text{max}}$ and b. $H_{\text{max}}$)](image)
Based on the graph, the highest $U_{max}$ value in the land side area is 1.69 m/s with the steepest coastal slope of 1:80. The minimum value is 0.74 m/s with the flattest coastal slope of 1:150 (see Figure 7.a). On the contrary, the lowest wave height that occurs in the land side area came from the steepest slope of 1:80 with the value of 0.07 m, and the highest wave height came from the flattest slope of 1:150 with the value of 0.16 m (see Figure 7.b).

3.4. Graph summary and Estimated Time of Arrival (ETA)

The maximum values of the case parameters are summarized into Table 2. Those parameters are flow depth maximum, depth averaged velocity maximum, and the arrival time of the wave (see Table 2). The maximum values of flow depth and velocity parameters have already been mentioned in the previous section. From Table 2, averaged value of each parameters was calculated based on each slope. So, the averaged parameter values represent every slope it had. The averaged value is shown in Table 3.

The steeper coastal slopes have bigger advantages in diminishing wave velocity compared to flatter slopes. Weaker velocity will benefit most infrastructures from massive damages caused by Tsunami waves. On averages, Banda Aceh and Aceh Besar have coastal slopes of 1:150 [5].

| Slopes | Water Level (m) | Designed Wave Height (m) | Wave Height Maximum (m) | Depth Averaged Velocity Maximum (m/s) | Arrival Time (s) |
|--------|----------------|--------------------------|-------------------------|--------------------------------------|------------------|
|        |                |                          | WG #1 | WG #2 | WG #3 | WG #4 | WG #2 | WG #4 | WG #2 | WG #4 |                 |
| 1 : 80 | 0.11           | 0.06                     | 0.480 | 0.284 | 0.274 | 0.303 | 1.622 | 1.691 |         | 4.72 | 6.24 |
|        |                | 0.05                     | 0.425 | 0.268 | 0.245 | 0.269 | 1.346 | 1.427 |         | 4.99 | 6.73 |
|        |                | 0.04                     | 0.357 | 0.252 | 0.224 | 0.213 | 1.157 | 1.241 |         | 5.30 | 7.33 |
|        |                | 0.03                     | 0.297 | 0.239 | 0.209 | 0.205 | 0.930 | 0.963 |         | 5.76 | 8.07 |
| 1 : 100| 0.09           | 0.06                     | 0.480 | 0.280 | 0.286 | 0.301 | 1.528 | 1.340 |         | 4.68 | 6.27 |
|        |                | 0.05                     | 0.424 | 0.270 | 0.269 | 0.284 | 1.275 | 1.124 |         | 4.98 | 6.71 |
|        |                | 0.04                     | 0.355 | 0.253 | 0.229 | 0.259 | 1.210 | 1.051 |         | 5.27 | 7.22 |
|        |                | 0.03                     | 0.295 | 0.231 | 0.221 | 0.204 | 0.945 | 0.815 |         | 5.73 | 7.91 |
| 1 : 120| 0.08           | 0.06                     | 0.480 | 0.278 | 0.317 | 0.329 | 1.546 | 1.380 |         | 4.70 | 6.23 |
|        |                | 0.05                     | 0.422 | 0.263 | 0.304 | 0.309 | 1.222 | 1.130 |         | 4.96 | 6.65 |
|        |                | 0.04                     | 0.353 | 0.251 | 0.287 | 0.336 | 1.166 | 1.080 |         | 5.29 | 7.16 |
|        |                | 0.03                     | 0.294 | 0.227 | 0.215 | 0.203 | 0.938 | 0.852 |         | 5.73 | 7.79 |
| 1 : 150| 0.06           | 0.06                     | 0.480 | 0.288 | 0.323 | 0.351 | 1.451 | 1.392 |         | 4.70 | 6.17 |
|        |                | 0.05                     | 0.423 | 0.263 | 0.294 | 0.338 | 1.268 | 1.124 |         | 4.97 | 6.59 |
|        |                | 0.04                     | 0.353 | 0.246 | 0.299 | 0.354 | 1.095 | 0.922 |         | 5.28 | 7.08 |
|        |                | 0.03                     | 0.294 | 0.225 | 0.220 | 0.213 | 0.972 | 0.739 |         | 5.70 | 7.71 |
Table 3. Averaged parameter summaries.

| Cases   | Averaged Wave Height on Land Side (m) | Averaged Ūmax (s) | Averaged Arrival Time (s) |
|---------|-------------------------------------|-------------------|--------------------------|
|         | Slopes                              | WG #4             | WG #2                    | WG #4             | WG #2             |
| 1 : 80  | 0.25                                 | 1.26              | 1.33                     | 5.19              | 7.09              |
| 1 : 100 | 0.26                                 | 1.24              | 1.08                     | 5.17              | 7.03              |
| 1 : 120 | 0.29                                 | 1.22              | 1.11                     | 5.17              | 6.96              |
| 1 : 150 | 0.31                                 | 1.20              | 1.04                     | 5.16              | 6.89              |

Estimated Time of Arrival (ETA) can be obtained from the *.csv data. The longest times for a wave to get to the nearshore and land side came from the steepest slope of 1:80 which are 5.19 s and 7.09 s. On the other side, the shortest times came from the flattest slope of 1:150 which the averages are 5.16 s and 6.89 s.

4. Conclusion

This study was conducted to investigate numerical simulation results to obtain the role of coastal slope variations to reduce tsunami waves energy; in term of tsunami wave heights, tsunami wave velocity, and wave arrival time. The maximum values recorded were: 0.351 m wave height on land side of a 1:150 slope, 1.691 m/s of velocity on land side of a 1:80 slope, and 7.09 s of arrival time on a 1:80 slope.

The study shows that steeper coastal slopes have longer wave travel times to the shoreline than flatter coastal slope areas. However, wave height in steeper coastal slopes is slightly shorter than in flatter coastal slopes. Steeper slopes also have higher velocities than flatter areas. This would benefit most infrastructures from damage caused by tsunami waves. Longer arrival times would benefit people in evacuation times, and smaller velocities would reduce the impacts of future potential tsunamis in this area. Nevertheless, topography and other related factors are the most critical in influencing tsunami wave impacts.

5. References

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