Numerical simulations of tsunami waves impacts on Ulee Lheue Harbour in Banda Aceh-Indonesia

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Abstract. This paper reports the effects of 2004 Indian Ocean tsunami onto the Ulee Lheue harbour facility, Banda Aceh – Indonesia. The breakwater that had damaged after tsunami were rebuilt into its original design once more due to UNDP funding source. As the existing construction knowing how much the chance it stands again ts the tsunami in various terms would be decent for further improvement. This research aim is to measure the capabilities of the breakwater against the various tsunami scenario. Performing the numerical simulation to analyze the hydrodynamics we used both COMCOT and Delft3D-flow for tsunami propagation in line with the hydrodynamics. Several observation points were deployed representing each part of the breakwater. The process revealed that the breakwater only able to hold 8.0 Mw induced wave from overtopping. uniquely when 8.2 Mw tsunami wave strikes the breakwater till overtopped but not giving enough energy to move the boulder aside. Potential movement of the boulder occurred when the 8.4 Mw tsunami wave come through the breakwater produced 77.12 m (5.88 %) damaged structure. The 8.6 Mw single fault highest magnitude gave 209.32 m long (15.97%) destruction upon this Ulee Lheue Harbour breakwater.

1. Introduction
The 2004 Indian Ocean tsunami left many lessons learned. Among the most important lessons were the destructions of harbour area around Banda Aceh where their images were often used to describe the tsunami prowess. One study also revealed that large shear stresses generated by the 2004 tsunami were able to detach a portion of land creating a new island as in the case of Ujong Seudeun of Aceh Jaya District, located about 70 km to the western part of Banda Aceh [1]. Despite the firm evidence, future development of the coastal area in Banda Aceh is questioned regarding its resiliency toward future tsunamis. Smaller magnitude of tsunamis than 2004 have higher possibility to hit the coastal zone. Nonetheless, no study have been conducted to assess the possibility of the impacts of the future tsunami on coastal area in Banda Aceh. The reasons inspired this study, to evaluate the possible effects of the smaller tsunami generated by earthquakes smaller than 8.6 Mw that could happen around the same rupture area, as in the 2004 Indian Ocean Tsunami. The Ulee Lheue Ferry Port is one of the most...
important complexes in Aceh that connect the mainland of Sumatra Island to some small islands around Aceh Besar and Sabang Districts. During the 2004 Indian Ocean tsunami reconstruction process, this harbor was frequently used to deliver aids and other emergency supports for the affected area. Considering its important status, this study was performed to see the impacts of the future tsunami regarding of wave heights, time of arrivals, and shear stresses.

Figure 1. Satellite images of the Ulee Lheue Harbor taken in 2004 before the tsunami (left), after the tsunami taken in 2005 (center), and after reconstruction taken in 2015.

2. Study Area
Ulee lheue harbour became the site where the research took place. Massively destructed, the harbour area wears a 8 hectares, which consists of the passenger terminal as the main building, parking area, ferry port, harbour basin etc. After the 2004 mega disaster, almost all the facility in the harbour area were seriously damaged with almost nothing left except the ruins. This unexpected damage also occurred in the breakwater. It had destructed along 699 m from 1311 m in total, representing 53.32% of damage (according to breakwater line comparations on Google Earth images taken on June 23th, 2003 and January 25th, 2004). As the people will always try to learn and do better, the facilities were rebuilt with the UNDP’s fund with no modification in the former design. The breakwater rebuilt with 464 m long on the left side, and 847 m on the other side. The construction built of the big stones that assembled with 1 m diameter in average. The study area is shown in figure 2.

Figure 2. The map of Ulee Lheue Harbour.
3. Methods

Two numerical models were used in this research, namely COMCOT (Cornell Multi-grid Coupled Tsunami Model) and Delft3D-FLOW. COMCOT was used to perform tsunami propagation from the sources since the Delft3D-FLOW has a limitation to generate a linear shallow water equation and to include initial waves produced by presumably rupture areas. At the innermost layers of the simulation, we impose Delft3D-FLOW where its open boundary condition was adopted from the wave heights produced by COMCOT simulations. The Delft3D FLOW is able to simulate non-linear shallow water equation with the small size of the grid. This gives the advantage to create grids that represent breakwaters and another type of facilities in the harbour area.

3.1 Grid setup

Due to this research, the COMCOT model proposed 5 horizontal layer to complete the process (figure 3). The fault rupture will be accommodated in the first outer layer while the 2nd, 3rd and 4th layer were smaller in area and grid size. The GEBCO data were used as the bathymetry which updated first with the available chart from DISHIDROS TNI – AL (Indonesia Navy). All 4th outer layer were using the spherical coordinate system while the finest one using the cartesian. The latest field measurement in 2014 data was applied for the innermost domain which consists of 5x5m grid size. The domain consists the detail measurement of both topography and bathymetry from 2014 field survey. After compilation, the grid was resampled to produce the final modelling grids. Simulating the flow, the 0.013 roughness coefficient were applied in the wet area while 0.02 determined in the dry area. As a focus the grid that represents breakwater had 0.035 value for roughness coefficient. Bathymetry model used in this study is shown in Figure 3.

![Figure 3. Simulation domain in Delft3D-Flow.](image)

3.2 Fault model

Using the same historical data as based on 2004 megathrust earthquake, some modification on the fault scenario applied to represent the different magnitude. The model varied with single fault scenario from 7.8 Mw, 8.0 Mw, 8.2 Mw, 8.4 Mw, to 8.6 Mw. The adjustment of the fault parameter was calculated in scale based on well Coppersmith equation by follows a finite rectangular rupture area [10]. started at 01.00 UTC (08.00 am local time) on December 26, 2004, the megathrust earthquake which located at 95.982° E and 3.295° N had produced a significant dislocation an amount volume of water moved dynamically. This event caused by the duration of the earthquake within 8 to 10 min which caused the western coast of northern Sumatra Island ruptured as far as 1200–1300 km from the...
Andaman–Sunda Sea. The complex fault mechanism of the rupture process is completed to explain in
detail. Okada had purposed a theory which explains tsunamis are generated by the deformation of the
sea floor, which is instantly reproduced at the sea surface [5]. This theory is also known as the
deformation model. Several researchers later on also have proposed earthquake source parameters to
describe the complexity of the multi-fault mechanism, one of them was developed by Romano [6].
This model was also used by Liu et al. [3] to investigate the morphological changes in Aceh due to the
2004 Indian ocean tsunami.

![Figure 4](image)

**Figure 4.** Initial waves produced by various single fault scenario in comparison with 2004 event.

A multi-fault model as proposed by Romano [6] was used to generate the tsunami waves around
the rupture area of the 2004 Indian Ocean tsunami. Each of the nine faults was used to calculate the
waveforms around the faults using Masinha and Smyle Theories combined with Okada analytical
solutions for waveforms produced by a fault [4]. The model also had been validated by Syamsidik et al
[7] using a transect line captured by Satellite Jason 1 about two hours after the first earthquake [2].
The fault was divided into nine segments of rupture area. The initial waves around the sources based
on this scenario can be seen in figure 4. Negative waves were observed in the eastern part of the
source. This multi fault scenario used as a comparison for the variation of magnitude wave that
generated the tsunami and affecting the coastal protection (table 1).
Table 1. Fault mechanism variation parameter.

| Event | Long, Lat | Depth | Strike,Dip;Rake | Mo Width | Length | Dislocation |
|-------|-----------|-------|----------------|----------|--------|-------------|
| 7.8   | 95.98° E  | 3.29° N | 309°; 8°; 110° | 6.31 x 10²⁰ | 145211.16 | 4.05 |
| 8.0   | 3.29° N   | 3.29° | 309°; 8°; 110° | 2.51 x 10²¹ | 250034.54 | 6.98 |
| 8.2   | 3.29° N   | 3.29° | 309°; 8°; 110° | 5.01 x 10²¹ | 328095.29 | 9.16 |
| 8.6   | 3.29° N   | 3.29° | 309°; 8°; 110° | 1.00 x 10²² | 430526.61 | 12.02 |
| 9.1   |           |       |                | [6]       | [6]    | [6]         |

3.3 Numerical simulations

Two model were used to performed the simulation, i.e. Cornell Multi-grid Coupled Tsunami Model (COMCOT) which generated the hydrodynamic condition during the tsunami waves propagation and Delft3D continued the sediment transport process that later produces morphological changes around the domain of the simulations. The Delft3D was applied at the innermost layer of the simulation.

COMCOT uses Shallow Water Equations (SWE), i.e. Linear SWE and Nonlinear SWE. The linear SWEs are as follows.

\[ \frac{\partial \eta}{\partial t} + \frac{1}{R \cos \varphi} \frac{\partial P}{\partial \psi} \left( \frac{\partial \eta}{\partial \psi} + \frac{\partial \varphi}{\partial \psi} \cos \varphi Q \right) = -\frac{\partial h}{\partial t} \]  
\[ \frac{\partial P}{\partial t} + \frac{gh}{R \cos \varphi} \frac{\partial \eta}{\partial \psi} - f Q = 0 \]  
\[ \frac{\partial Q}{\partial t} + \frac{gh}{R} \frac{\partial \eta}{\partial \psi} + f P = 0 \]

The nonlinear equations that include friction factors can be seen in Eqs 4-6 as follows.

\[ \frac{\partial \eta}{\partial t} + \frac{1}{R \cos \varphi} \left( \frac{\partial P}{\partial \psi} + \frac{\partial \varphi}{\partial \psi} \cos \varphi Q \right) = -\frac{\partial h}{\partial t} \]  
\[ \frac{\partial P}{\partial t} + \frac{1}{R \cos \varphi} \left( \frac{\partial \eta}{\partial \psi} \left( \frac{P^2}{H} \right) + \frac{1}{R} \frac{\partial Q}{\partial \psi} \left( \frac{PQ}{H} \right) \right) + \frac{gH}{R \cos \varphi} \frac{\partial \eta}{\partial \psi} - f Q + F_x = 0 \]  
\[ \frac{\partial Q}{\partial t} + \frac{1}{R \cos \varphi} \left( \frac{\partial \eta}{\partial \psi} \left( \frac{Q^2}{H} \right) + \frac{1}{R} \frac{\partial P}{\partial \psi} \left( \frac{PQ}{H} \right) \right) + \frac{gH}{R \cos \varphi} \frac{\partial \eta}{\partial \psi} + f P + F_y = 0 \]

where,

\[ H = \eta + h \]  
\[ f = 2\Omega \sin \varphi \]  
\[ F_x = \frac{gn^2}{H^{7/3}} P \sqrt{P^2 + Q^2} \]  
\[ F_y = \frac{gn^2}{H^{7/3}} Q \sqrt{P^2 + Q^2} \]
\[ P = \int_{-h}^{\eta} udz = u(h + \eta) = uH \]  
(11)

\[ Q = \int_{-h}^{\eta} vdz = v(h + \eta) = vH \]  
(12)

Here, \( g \) is gravitational acceleration, \( f \) is Coriolis coefficient, \( P \) is discharged flux at x-axis (west-east), \( Q \) is discharge flux at x-axis (north-south). Meanwhile, \( \phi, \psi \) are latitude and longitude respectively, \( R \) is the earth radius; \( h \) is depth, \( \eta \) is water elevation \( H \) is total depth, \( \Omega \) is the earth rotational speed (7.292 x 10^{-5} \text{ rad/s}) ; \( F_x, F_y \) are friction at x- and y-dimensions respectively, \( n \) is manning coefficient, and \( u, v \) are velocity at x- and y- directions, respectively. The equations were schematized using Leap-Frog Method of Finite Different Method. Details of the COMCOT model development were released in 2004 and 2009 [8,9].

3.4 Observation Point

In objective to observe the hydrodynamic process due to the tsunami in affecting the coastal protection in this case breakwater, several observation point were applied. The observation points represented the breakwater as the object that receiving the tsunami energy. There was two side of the breakwater which on the south-east and north-west. 119 observation point were deployed to represent each grid on breakwater area as shown in figure 5. Wave height, velocity and shear stress were recorded during the simulation process in time series.

![Figure 5](image)

**Figure 5.** Locations of the numerical observation points and cross sections.

3.4 Critical shear stress

Shear stress is the force that gave by current, wave or both of them combined. As a fuel for sediment transport, shear stress gave the force which hold by critical shear stress as a reaction. Critical shear stress represents the ability of a particle to react and holds the stand against the external forces. Particle start moving (initial movement) when the bed shear stress (\( \tau_b \)) produced by current or waves
exceeds its critical shear stress ($\tau_c$), in other words, $\tau_b > \tau_c$. But mathematically it only explains whether it was potential to move or not. In the harbour case, the particle was substitute with boulder-size (diameter) while the calculation produced the indication of the boulders respond whether it moved or not. Producing the velocity and waves for fueling the shear stress, Delft3D-Flow using tsunami wave input from COMCOT get the job done. The following equation was used to determine critical shear stress for stone motion:

Komar and Miller 1974,

$$\tau_{cr} = \theta^* (\rho_s - \rho) g d_{50}$$  \hfill (12)

$$\theta^* = \frac{0.30}{1 + 1.2D_s} + 0.055[1 - \exp(-0.020D_s)]$$  \hfill (13)

With,

$$D_s = \left[ \frac{g(s - 1)}{v^2} \right]^{\frac{1}{3}} d_{50}$$  \hfill (14)

Here, $\tau_c$ is the critical bed shear stress (N/m$^2$), $\theta^*$ is parameter for the given particle size (dimensionless), $s$ is the specific gravity of the particles and is calculated as the ratio of specific weight of stone $\rho_s$, to specific weight of water $\rho$ (kg/m$^3$), $g$ is the constant for acceleration of gravity (m/s$^2$), $D_s$ is grain size (dimensionless), $d_{50}$ is median boulder size (m).

4. Results

As the construction that had a submerged part while other part didn’t, breakwater as potential protection due to the tsunami, but how far it stands again tsunami was the question about to answer. Creating the tsunami wave COMCOT had produced the water level in the outer finest layer as an input to Delft3D-flow boundaries as shown in figure 6. Different wave height had produced due to different magnitude waves of the earthquake. The difference of the water volume movement had contributed to the tsunami waves height. The result shows the waves started to peak rapidly exceed 1 meter after 8.0 Mw scenario applied and keep raising until the highest magnitude waves of single fault mechanism which represent by 8.6 Mw. 0.72 m high peak wave released from 7.8 Mw scenario which follows by 2.06 m from 8.0 Mw. The next scenario 8.2 Mw gave further gap with 4.18 m high wave which continues higher, even twice with 8.4 m high in peak. The higher single fault scenario produces the highest wave with 13.28 m.
The tsunami waves came and amplified inside the harbour mouth and circling inside the harbour basin. The hydrodynamic condition inside the basin gave the destruction around the southern part of the basin and also the north, which are perpendicular with the waves direction.

4.1 Tsunami hydrodynamic

Interacting with a shallower depth, the wave getting higher on the break water. The result revealed that after all scenario waves going through breakwater, only with 8.2 Mw minimum the waves succeed overtopped the breakwater. Three scenarios which 8.2 Mw, 8.4 Mw, and 8.6 Mw each of them produced 8 m, 13.9 m and 19.2 m wave height when interacting with the breakwater. Beside all the differences with the wave height, the arrival time was also different for each of the scenario. The higher magnitude wave gave, the sooner time to arrive for the tsunami waves.

Tsunami continues waving from the Delft3D boundary and interacting with the bathymetry around the harbour. The first 7.8 Mw scenario didn’t give any significant wave run up while the next 8.0 Mw scenario gave the tsunami wave run-up although did not overtop the breakwater construction. Deducing the propagation and the run up the 8.0 scenario become the furthest limit for the breakwater
to be able in facing the tsunami wave run-up. The breakwater construction couldn’t do much for the higher magnitude wave, started from 8.2 Mw the breakwater were not able to hold the tsunami wave from amplifying and flooding far inland.

4.2 Bed shear stress

Complementing the former process which was the wave run up, the bed shear stress explained how the breakwater interacted with massive tsunami energy that varies due to the proposed scenario. The respond, the ability of the breakwater to stand agains the tsunami wave will be described with the process of forces which worked around the harbour. As the calculation went the critical shear stress were done by using the boulder size (diameter) regarding 25 degree which gave $0.89 \times 10^{-3}$ kg/ms of viscosity value. While 2600 kg/m$^3$ were the value of the boulder density and 1 m of diameter the calculation induce 873.814 N/m$^2$ for the internal force that holds the particle alias critical shear stress as shown in figure 8.

![Figure 8](image)

**Figure 8.** Bed shear stress maximum on left breakwater.

The similar process with wave run-up happened during the shear stress analysis. But the overtopping didn’t always mean enough energy to move the boulder. This conclusion came from the 8.2 scenario which had overtopped the construction, but in the shear stress that induced didn’t have enough energy to exceed the critical shear stress. Its appealed that 8.2 Mw scenario became the limit for the 1 m diameter of the boulder to hold the tsunami energy from 2004 historical fault parameter. The exceeded value in the next scenario confirmed that in 8.4 Mw the maximum shear stress that induced, 1530 N/m$^2$ had overtaken 873.814 N/m$^2$ of boulder critical shear stress.
Figure 9. Bed shear stress maximum on right breakwater.

Uniquely the shear stress only exceeds on the south-east part of breakwater while leaving the southwestern part remain save from the energy. It happened to be the current that produced the shear stress amplified around the corner of the south-east part while the wave and current were directed into that spot and had nowhere to go, then turn back. When the wave that turns and circling back met the wave that keeps coming from the mouth of the breakwater in harbour basin, it amplified the waves and the current, produced the massive energy of shear stress that exceeds the limit of boulder critical shear stress. The spot that located in the corner of the harbour basin were accommodating the amplification through the propagation and run-up the process. The spot where the exceeding value of shear stress against its critical limit was getting wider in 8.6 scenario. The breakwater couldn’t hold the wave and the energy any longer in the southwest part. The spot is wider and it amplified both southeast and northwest part of the breakwater. This simulation shows that the placement and the design of the breakwater gave an effect for the tsunami wave to interact with the construction and how it will be after getting through the construction.

Table 2. Breakwater damage of several tsunami scenario

| Description                                      | Event        |
|--------------------------------------------------|--------------|
|                                                  | 7.80 Mw  | 8.00 Mw  | 8.20 Mw  | 8.40 Mw  | 8.60 Mw  |
| Total Observation Points (Obs)                   |            |          |          |          |          |
| Exceed Critical Shear Stress (Obs)               | No Overtopping | 119     | 119     | 119     |
| Percentage of Fail (%)                           | No Overtopping | 0       | 7       | 16      |
| Breakwater Failed (m)                            | No          | No       | 77.12   | 209.32  |

5. Conclusion

COMCOT had produced the tsunami waves along with 1-hour numerical simulation. A 4.18 m high tsunami wave continued and overtopped through the breakwater. In the boulder case, the overtop not always can be transferred to movement (transport) of the boulder with 1 m diameter which produced 873.814 N/m² critical shear stress. The shear stress started exceeding its critical shear stress in 8.4 Mw
scenario which brought 8.4 m high wave into the boundary which later on produced 1530 N/m² which exceed its critical shear stress and so on with 8.6 scenario. With the limitation, design whom still old style harbour, the breakwater could sustain a tsunami generated by an earthquake smaller than 8.2 Mw but started in 8.4 Mw the damage began to happen 5.88 % and followed by 8.6 Mw that gave 13.45 % damage (table 2). Presumably, the source is the same with the recent 2004 tsunami. However, with bigger earthquakes, the breakwater could be detached and failed as in the 2004 Indian Ocean tsunami case.

6. References

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