Modelling of Tsunami Waves Using an Existing Hydraulic Model

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Abstract

The 26 December 2004 Sumatra tsunami disaster has triggered the need for all relevant government authorities to develop better disaster management and prevention plans. These include the construction of tsunami warning systems, defining flood impact and hazard to local populations, and considering future building and planning.

A two-dimensional hydraulic model developed for flood analysis of a Southeast Queensland coastal city has been utilised to assess the possible flood impacts caused by a direct hit from a tsunami wave. Tsunami wave time series data from the Sumatra Tsunami for Phuket, BandaAceh, Ahungalle, and Kaolak have been used as ocean boundaries in the hydraulic model.

This analysis has assessed broadly how a tsunami wave of sufficient (and known) magnitude can traverse and penetrate into a typical Australian coastal city and the degree of hazard and impact that results. Through this application, the applicability of existing hydraulic models to broadly analyse Tsunami waves have also been assessed.

Introduction

The devastating tsunami triggered by the 9.0 Ritcher scale earthquake off north-western coast of Sumatra on 26 December 2004 has caused more than 290,000 casualties (170,000 deaths, 120,000 missing) in countries around the Indian Ocean including Indonesia, Thailand, Sri Lanka, India, Maldives and Myanmar (WHO, 2005). Figure 1 presents the approximate earthquake centre (red dot) of this devastating event. It has been estimated that the total energy carried by the 2004 tsunami wave equivalent to an explosion of 100 Megatons of TNT. The kinetic energy of the wave was then released through turbulence and friction losses when it reached the coasts, sweeping masses of water, boats, debris kilometres in-land the shore and caused huge damages and human casualties to the affected area (Annunziato & Best, 2005).

As reported, when the tsunami reached the coastal area, the following maximum run-up wave heights have been observed:

- Western coast of the Sumatra Island, directly facing to the earthquake centre, highest run-up of 49 metres;
- Kaolak of Thailand, 500 km from earthquake centre, highest run-up of 11 metres; and
- Eastern coast of Sri Lanka, 1,600 km from earthquake centre, highest run-up of 15 metres (Shuto, 2005).
The shocking high casualty caused by this tragedy is mainly attributed to inadequate knowledge in tsunamis among local coastal population and lack of tsunami warning systems throughout the region.

Immediately after this tragic event, hydraulic modellers carried out numerous hydrodynamic modelling to study the behaviour of the 2004 tsunami across the Indian Ocean. However, most of the models built covered the extent of the Ocean with a grid size as large as 200 Km (Thaicharoen et al, 2005) and as such, these large scale models do not have enough high spatial resolution to represent local coastal properties. WorelyParsons (WP) has utilised an existing two-dimensional (2D) flood model with high spatial resolution (10 metre grid size) developed for a Southeast Queensland coastal city to carry out modelling of the propagation of tsunami waves derived from the 2004 tsunami event. This was utilised to assess the possible flood impacts to the city caused by the hit of tsunami. WP believes that this approach could provide an affordable and effective platform for various authorities to establish disaster prevention management programmes such as hazard map preparation, disaster response education for local populations and tsunami warning systems.

Background on Tsunamis

A tsunami wave is typically generated by vertical displacement of seawater due to submarine fault movement of the sea bottom. Figure 1 shows the earthquake centre (red dot) which triggered the tsunami. The dash line represents the demarcation line between Eurasian and the Indo-Australian plates. It is believed that a violent slippage occurred along this line between Sumatra and the Andaman Islands (Annunziato & Best, 2005) in the morning of 26 December 2004, which triggered a vertical displacement of 100s of cubic kilometres (Km$^3$) of water and generated the devastating 2004 tsunami.

Tsunami Wave Profile in Open Ocean

When travelling across the open oceans, the tsunami propagates as a far-field tsunami wave with a wave length of several hundred kilometres but with
amplitude in the order of only a few centimetres to a few metres. Therefore, the wave height of a tsunami travelling across the open oceans is hardly noticeable (Shuto, 2005). Figure 2 depicts a conceptual tsunami wave profile travelling in the ocean. The travelling velocity of the tsunami generally follows the following equation (Annunziato & Best, 2005):

\[
V = \sqrt{g \times d}
\]

where \(V\) = the tsunami velocity (m/s),
\(g\) = gravitational constant (m/s\(^2\)),
\(d\) = ocean depth (m)

Figure 2 Tsunami in Deep Ocean
(Source: Annunziato & Best, 2005)

**Tsunami Wave Approaching Shore**

At the shallow water region, the leading edge of the tsunami is slowed down by the shallow sea bottom of the shore, the crest of the trailing water moves faster than the front and as such increasing the height of the tsunami wave (Figure 3).

Figure 3 Tsunami Approaching Shore
(Source: Annunziato & Best, 2005)

**Tsunami Run-up**

When a tsunami wave enters very shallow coastal waters and propagates into further inland, the wave is described as run-up. In this location, the tsunami is subject to a series of wave transformations where the tsunami front becomes a vertical wall to a multiple of the height in the open ocean and water rushes out continuously and propagates in the form of breaking bores.

In open oceans, a tsunami is often no taller than a wind wave but is much more dangerous because a wind wave will come and go on the shore without flooding higher areas; whereas a tsunami runs quickly over the land as a wall of water (Shuto, 2005; Guard et al, 2005). Figures 4 and 5 illustrate the difference between waves generated by wind and tsunami.
The run-up of waves on a coast is the most important stage of the life of a tsunami to evaluate the level of tsunami hazard for the coastal population (Dotsenko (2005)). WP has utilised an existing two-dimensional (2D) flood model developed for a Southeast Queensland coastal city to carry out modelling the run-up behaviour of tsunamis and to assess the possible flood impacts to the coastal city. The following sections of this paper describe these works in further detail.

Hydrodynamic Model Setup

Tsunami propagation has been undertaken utilising an existing two-dimensional MIKEFLOOD (2005 version) model. MIKEFLOOD integrates the one-dimensional (1D) MIKE11 modelling component and the two-dimensional (2D) MIKE21 modelling component into a single, dynamically coupled modelling system.

The MIKEFLOOD model has been developed for comprehensively determining flooding throughout the floodplain area of a Southeast Queensland coastal city. Since the model was developed for modelling the floodplain, it was necessary to extend the model boundary two (2) kilometres into the ocean from the land to include ocean bathymetry for tsunami simulations. The extended 2D model has a grid spacing of 10 metres with approximately 420,000 grid cells which covers a total area of 42 Km². Ocean bathymetry information was obtained from Australian Bathymetry and Topography Grid (Geoscience Australia, 2005).

Key culvert structures across the floodplain have been prescriptively modelled within the hydraulic model using MIKE11 and coupled to the MIKE21 component. In order to avoid tsunami wave ‘hit’ back of model, a large dummy 1D storage has been included in the MIKE11 component coupling to the upstream end of the MIKE21 boundary, opposite to the ocean boundary of the tsunami time series. The time step interval setting for the simulation is one (1) second.
Four (4) Tsunami wave time series derived by DHI Water and Environment from the Sumatra Tsunami have been utilised as ocean boundaries in the hydraulic model. DHI has carried out a number of simulations to assess propagation of tsunami wave immediately following the Sumatra tsunami event (Pedersen et al, 2005). These wave time series represent the tsunami waves hitting the coasts of Phuket, BandaAceh, Ahungalle and Khaolak. Locations of these time series were believed relevant to the ocean bathymetry applicable on the east coast of Australia (between -4 to -6 mAHD). Information of the tsunami time series are summarised in Table 1 and a plot of the time series is illustrated in Figure 6.

**Table 1  Summary of Tsunami Time Series**

<table>
<thead>
<tr>
<th>Time Series</th>
<th>Country</th>
<th>Depth at location</th>
<th>Maximum Level</th>
<th>Distance from Earthquake (hours)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ahungalle</td>
<td>Sri Lanka</td>
<td>-6.60m</td>
<td>5.25m</td>
<td>03:18</td>
</tr>
<tr>
<td>Khaolak</td>
<td>Thailand</td>
<td>-4.47m</td>
<td>8.49m</td>
<td>02:25</td>
</tr>
<tr>
<td>BandaAceh</td>
<td>Indonesia</td>
<td>-6.00m</td>
<td>12.24m</td>
<td>00:01</td>
</tr>
<tr>
<td>Phuket</td>
<td>Thailand</td>
<td>-5.36m</td>
<td>4.10m</td>
<td>02:10</td>
</tr>
</tbody>
</table>

![Figure 6 Profiles of Tsunami Waves](image)

**Modelling Results**

The four (4) tsunami series were simulated in the revised MIKEFLOOD model as the downstream boundary condition. No rainfall was applied to the model. The results were used to determine extents of inundation predicted from each tsunami time series:
Animations were produced to allow visualisation of a tsunami wave over time;
Velocities, depths and levels are available from the model output to assist with emergency/disaster management and building safety; and
The force on coastal structures due to a tsunami run-up event may be estimated by calculating the momentum flux in terms of water depths and velocities to predict the potential damage of tsunami to the coastal environment. The momentum flux per unit breadth can be written (after Guard et al, 2005):

\[ F = \left( \rho \times h \times u^2 \right) / 1000 \]

where
- \( F \) = momentum flux (KN/m)
- \( \rho \) = density of water (Kg/m³)
- \( h \) = water depth (m)
- \( u \) = water velocity (m/s)

Figure 7 illustrates the momentum flux map simulated from the Banda Aceh tsunami time series. Table 2 summaries the peak momentum flux, peak velocities and peak water depths calculated from the four tsunami time series at various key locations across the study area.
<table>
<thead>
<tr>
<th>ID</th>
<th>Peak Momentum Flux (KN/m)</th>
<th>Peak Velocity (m/s)</th>
<th>Peak Water Depth (m)</th>
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<tr>
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<td>KL</td>
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<td>498</td>
<td>74</td>
</tr>
</tbody>
</table>

Note: BA – Banda Aceh, AH – Ahungalle, KL – Khao Lak, PH – Phuket

Discussions

To accurately simulate how far inland and how fast the inundation occurs when a coastal city is directly hit by a tsunami is of great importance for the planning of emergency management including the evacuation of population.

The modelling procedure and results described above confirm the feasibility of this approach to utilise an existing 2D hydraulic model and use a tsunami time series with known magnitude to broadly estimate the impact of tsunami on a coastal city with dense population.
To build a model for these kinds of simulations is expensive and time consuming, in particular because of the additional requirement of high spatial resolution (in the order of 100 m or less) to resolve coastal properties, bathymetric features, and the tsunami signal itself. For this reason, the strategy of utilising the existing available 2D hydraulic model is able to provide an affordable and effective tsunami modelling platform for various authorities to establish disaster prevention management programmes including hazard map preparation, disaster response education for local population and tsunami warning systems.

Take Home Message

The establishment of tsunami disaster prevention management programmes are crucial for every Australian coastal city. This paper provides an example of utilising an established flood model to predict the impact of tsunami on a coastal city. This approach has resulted in the fine scale modelling of a tsunami wave in a time and cost efficient way. The results have assisted the understanding of tsunami behaviour within a coastal city (where no information was previously available) and can be used for emergency management and planning. There are many coastal towns where this methodology may be suitable to provide useful tsunami modelling information to floodplain engineers, council officers, disaster management authorities and town planners.

Acknowledgements

We would like to thank Mr Peter Rasch of DHI Water and Environment Australia for providing the four tsunami time series that enable us to complete this study.

References

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