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Tsunami flood modelling for Aceh & west Sumatra and its application for an early warning system

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SUMMARY

For implementation of a regional Tsunami Early Warning System (EWS) in Sumatra island in Indonesia, a set of detailed and accurate tsunami propagation and flooding models using Delft3D were developed. The purpose of the models was not only to reproduce the 2004 Indian Ocean tsunami, but also to determine tsunami flood hazard maps with different return periods. The model outputs have then been used to build a tsunami flooding database covering 1250 hypothetical sources for different earthquake parameters along the Sunda Trench for an EWS called RiskMap. The model simulations produced detailed information of near-shore tsunami wave height, tsunami inundation length and run-up. Smart storage of computational results, in a geo-referenced database, allows quick access to the requisite information. The result is a system capable of issuing a warning within few minutes after a detection of an earthquake. The system has been successfully installed and tested in the last two years at national and regional emergency coordination centres, National Agency for Meteorology, Climatology and Geophysics (BMKG) and at Tsunami Disaster Mitigation Research Centre (TDMRC) in Banda Aceh.

1. Introduction

Tsunami restoration and recovery activities in the Aceh province in Indonesia, caused by the Indian Ocean tsunami of 26th December 2004, have been concluded by the closure of the responsible agency, known as the 'Agency for Rehabilitation and Reconstruction' (BRR, Badan Rehabilitasi dan Rekonstruksi). The Agency coordinated all the recovery activities/projects of the Government of Indonesia, local governments, NGO's, foreign donors and UN organisations. One of the projects coordinated by the BRR was a project that had a primary objective of putting in place an appropriate strategy for coastal protection, flood protection, multifunction refuge construction and a regional early warning system that is to linked to the national EWS. The project was funded by the Netherlands government and carried out by a consortium called Sea Defence Consultants (SDC), consisting of DHV Consultants, Witteveen+Bos and Deltares. The project focused, among others, on:

- Developing a set of models to reproduce the tsunami event of 2004.
- Producing tsunami flood hazard maps with different return periods.
- Studying different coastal/tsunami protection options for the city of Banda Aceh.
- Implementing a regional tsunami EWS that is to be linked with the national tsunami EWS.

Tsunami Early warning systems in other places in the world, such as PTWC, are principally based on two steps approach:

- Issue an alert when an earthquake event is recorded that has a potential to generate tsunami and
- issue a warning in all countries bordering the ocean when a tsunami has been confirmed by one or more data buoys and or tidal gauges.

This method works when areas are located are far away from the tsunami source and sufficient time is available to evaluate the data before taking the decision to issue a warning. Tsunamis in Aceh and West-Sumatra arrive form nearby source with arrival times in the order of 15–30 min, just like in Japan. So evaluation of tsunami hazard can only be based on earthquake information available shortly after the event occurred.

The national system in Indonesia evaluates the tsunami hazard potential based on various information sources leading to two types of warning levels at provincial levels: 'tsunami watch' or 'tsunami warning'. The system in Aceh and West-Sumatra

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described here provides a more detailed warning on village complements the national system.

2. Tsunami modelling

Initially in 2005 and early 2006 the project was requested to develop a strategy and determine priorities for reconstruction after taking the vulnerability of the coast for future tsunami occurrences into account. As inundation data were then scarcely available, except at larger cities, flooding simulations generated by numerical model were deemed necessary to get a good overall picture of areas that had been hit in the province.

2.1. 2004 Case

A comprehensive set of models using Delft3D, online coupled, were then set-up to compute the tsunami propagation and inundation caused by the earthquake of 2004. These set of models contained over a million grid points covering the entire Indian Ocean, with a resolution of 1000 m and above, and the coastal areas in the province of Aceh and Nias with a resolution of 50–200 m (SDC (2007)), (see also). The digital elevation model is based on SRTM data; SRTM data has a vertical error of upto +/−16 m (Berthier et al. (2006)). In the city of Banda Aceh the data was supplemented by surveyed spot heights data. Experiments with preliminary models, with similar coverage but containing fewer amounts of grid cells, were able to yield very good approximations of the initial tsunami source (Vatvani et al. (2005a)), which is essential for the reproduction of the tsunami wave, arrival times and flooding pattern (Fig. 1).

The tsunami wave heights simulated by the propagation model compared well with sea level heights measured by the radar altimeter satellites that recorded the running tsunami wave in the Indian Ocean on December the 26th 2004 as shown in Fig. 2 (Vatvani et al. (2005a)). Similarly this also holds for the computed arrival times when compared to observed data at various sites in Indian Ocean (see Table 1 and Vatvani et al., 2005b).

Furthermore the simulated tsunami flooding in the city of Banda Aceh has been compared with the surveyed data (see Fig. 3). Overall the resuts compare well with observed data, with under prediction of the flooding east of the city (near the village of LhokNga). Overall, we can conclude that results obtained are quite accurate. Most of the inaccuracies could be afterwards primarily attributed to inaccurate DEM and bathymetry. This is especially true for the stretch of coast near the village of LhokNga.

Accurate inundation was obtained due to application of a special numerical scheme in solving the Non-Linear Shallow Water equations (NLSW) (Stelling and Duinmeijer (2003); Hesselink et al. (2003)). This solver is a finite difference scheme that combines the efficiency of staggered grids with momentum conservation properties to ensure accurate results for rapidly varying flows. The Delft3D model has been validated against numerous laboratory experiments with very good results (Apotsos et al. (2010)). The models have also been applied to simulate sediment transport and morphological changes near Calang (West Aceh) due to the tsunami with encouraging results (Gelfenbaum et al. (2007)).

With respect to the neglection of the dispersive effects, despite earlier indication from Horrillo et al. (2006) on the importance of this effect, later studies (Shigihara and Fujima (2006); Pujiraharjo and Hosoyamada (2008)) have concluded that the dispersion effect is negligible. They also show that run-up computation with NLSW models (at least in Northern Sumatra) is more reliable for practical computation purposes as they give more consistent results (to observed data) compared to Boussinesq type of models.

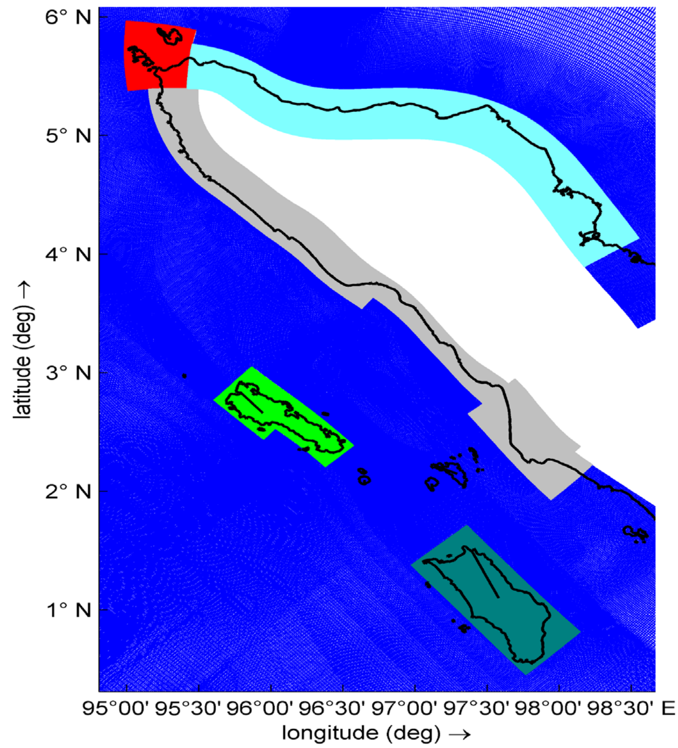

Fig. 1. Flooding model area embedded in the overall Indian Ocean model (blue coloured, with a resolution of approximately 1 km near the coast). Other colours separate the different inundation models. All inundation models have a resolution of 200 m except in the city of Banda Aceh (red coloured area) that has a resolution of 50 m). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

2.2. Flood hazard maps

The next challenge for the project was the determination of the hazard of the Aceh and Nias coasts for future tsunami events. Various preliminary studies then suggest a return period of a tsunami with a magnitude comparable to the Indian Ocean tsunami as being anywhere between 500 and 1000 years (Gelfenbaum et al. (2007); Wilkinson (2005); Stein and Okal (2005); Bellier et al. (1997)). Based on these articles it was concluded that occurrence of earthquakes with magnitudes (Mw) of 7.5, 8.0, 8.5, 9 and 9.5 could be associated with return periods of approximately 100, 150, 200, 500 and 1000 years respectively.

Subsequently, tsunami sources for these hypothetical earthquakes with different epicentres and focal depths were compiled using an adapted version of the programme RNGCHN by Feigl and Dupré (1999), which is based on the Okada model (Okada (1985)). For these sources uniform slip distribution is assumed, which is the commonly accepted practise when no actual data is available. These sources were defined by specifying epicentres of potential earthquakes along the Sunda Trench in such a manner that two succeeding earthquake scenarios overlap each other by about half a rupture length. By overlapping the earthquake sources it is ensured that a maximum flood impact along the entire coast can be computed. In total approximately 400 scenarios were simulated for earthquakes with magnitudes (Mw) of 6.5, 7.0, 7.5, 8.0, 8.5, 9.0 and 9.5. The maximum flooding computed for scenarios with equal magnitude were then combined to produce flood hazard maps for the province of Aceh and Nias that can be associated with the assumed recurrence intervals of an earthquake magnitude.

The computed tsunami wave heights along the coast using this approach compared very well with the results computed using an entirely different method (Thio et al. (2005)). The computed