

Inundation Modelling of the December 2004 Indian Ocean Tsunami

J.D. Jakeman¹ and O. Nielsen² and K. VanPutten² and R. Mleczko² and S.G Roberts¹

¹The Australian National University, Canberra, Australia

²Geoscience Australia, Canberra, Australia

Email: john.jakeman@anu.edu.au

Keywords: ANUGA, Finite Volume Method, Natural Hazards, Indian Ocean Tsunami, Inundation, Thailand, Phuket, Patong Bay

ABSTRACT

Geoscience Australia, in an open collaboration with the Mathematical Sciences Institute, The Australian National University, is developing a software application, ANUGA, to model the hydrodynamics of tsunamis, floods and storm surges. The open source software implements a finite volume central-upwind Godunov method to solve the non-linear depth-averaged shallow water wave equations. This paper investigates the veracity of ANUGA when used to model tsunami inundation. A particular aim was to make use of the comparatively large amount of observed data corresponding to the Indian ocean tsunami event of December 2004, to provide a conditional assessment of the computational model's performance. Specifically a comparison is made between an inundation map, constructed from observed data, against modelled maximum inundation. This comparison shows that there is very good agreement between the simulated and observed values. The sensitivity of model results to the resolution of bathymetry data used in the model was also investigated. It was found that the performance of the model could be drastically improved by using finer bathymetric data which better captures local topographic features. The effects of two different source models was also explored. Notes: * Model source developed independently of inundation data. * Patong region was chosen because high resolution inundation map and bathymetry and topography data was available there

1 INTRODUCTION

Tsunamis are a potential hazard to coastal communities all over the world. These 'waves' can cause loss of life and have huge social and economic impacts. The Indian Ocean tsunami killed around 230,000 people and caused billions of dollars in damage on the 26th of December 2004 (Synolakis *et al.* 2005). Hundreds of millions of dollars in aid has been donated to the rebuilding process and still the lives of hundreds of thousands of people will never be the same. Fortunately, catastrophic tsunamis of the

scale of the 26 December 2004 event are exceedingly rare (Jankaew *et al.* 2008). However, smaller-scale tsunamis are more common and regularly threaten coastal communities around the world. Earthquakes that occur in the Java Trench near Indonesia (e.g. Tsuji *et al.* 1995) and along the Puysegur Ridge to the south of New Zealand (e.g. Lebrun *et al.* 1998) have potential to generate tsunamis that may threaten Australia's northwestern and southeastern coastlines.

For these reasons there has been an increased focus on tsunami hazard mitigation over the past three years. Tsunami hazard mitigation involves detection, forecasting, and emergency preparedness (Synolakis *et al.* 2005). Unfortunately, due to the small time scales (at the most a few hours) over which tsunamis take to impact coastal communities, real time models that can be used for guidance as an event unfolds are currently underdeveloped. Consequently current tsunami mitigation efforts must focus on developing a database of pre-simulated scenarios to help increase effectiveness of immediate relief efforts. Firstly areas of high vulnerability, such as densely populated regions at risk of extreme damage, are identified. Action can then be undertaken before the event to minimise damage (early warning systems, breakwalls etc.) and protocols put in place to be followed when the flood waters subside. In this spirit, Titov *et al.* (2001) discuss a current Short-term Inundation Forecasting (SIFT) project for tsunamis.

Several approaches are currently used to solve these problems. They differ in the way that the propagation of a tsunami is described. The shallow water wave equations, linearised shallow water wave equations, and Boussinesq-type equations are commonly accepted descriptions of flow. But the complex nature of these equations and the highly variable nature of the phenomena that they describe necessitate the use of numerical simulations.

Geoscience Australia, in an open collaboration with the Mathematical Sciences Institute, The Australian National University, is in the final stages of completing a hydrodynamic modelling tool called ANUGA to simulate the shallow water propagation

and run-up of tsunamis. Further development of this tool requires comprehensive assessment of the model. In particular the model must be validated and tested to ensure it is sufficiently robust and that the interactions and outcomes demonstrated are feasible and defensible, given the objectives. These objectives include: simulating flow over dry beds and the appearance of dry states within previously wet regions; accurately describing steady state flows and small perturbations from these steady states over rapidly-varying topography; and accurately resolve shocks. Applications of ANUGA include, but are not limited to, dam-breaks, storm surges, and tsunami propagation.

The process of validating the ANUGA application is in its early stages, but initial indications are encouraging. As part of the Third International Workshop on Long-wave run-up Models in 2004¹, four benchmark problems were specified to allow the comparison of numerical, analytical and physical models with laboratory and field data. One of these problems describes a wave tank simulation of the 1993 Okushiri Island tsunami off Hokkaido, Japan (Matsuyama *et al.* 2001). The wave tank simulation of the Hokkaido tsunami was used as the first scenario for validating ANUGA. The dataset provided bathymetry and topography along with initial water depth and the wave specifications. The dataset also contained water depth time series from three wave gauges situated offshore from the simulated inundation area. Although good agreement was obtained between the observed and simulated water depth at each of the three gauges (Roberts *et al.* 2006) further validation is needed.

Although appalling, the devastation caused by the 2004 Indian Ocean tsunami has heightened community, scientific and governmental interest in tsunami and in doing so has provided a unique opportunity for further validation of tsunami models. Enormous resources have been spent to obtain many measurements of phenomenon pertaining to this event to better understand the destruction that occurred. Data sets from seismometers, tide gauges, GPS stations, a few satellite overpasses, subsequent coastal field surveys of run-up and flooding and measurements from ship-based expeditions, have now been made available (Vigny *et al.* 2005, Ammon *et al.* 2005, Kawata *et al.* 2005, and Liu *et al.* 2005).

An aim of this paper is to use this relative abundance of observed data corresponding to this event to further validate the use of ANUGA for modelling the inundation of tsunami. The specific intention is to test the ability of the model to reproduce an inundation survey of maximum runup constructed in the aftermath of the 2004 tsunami. A further aim

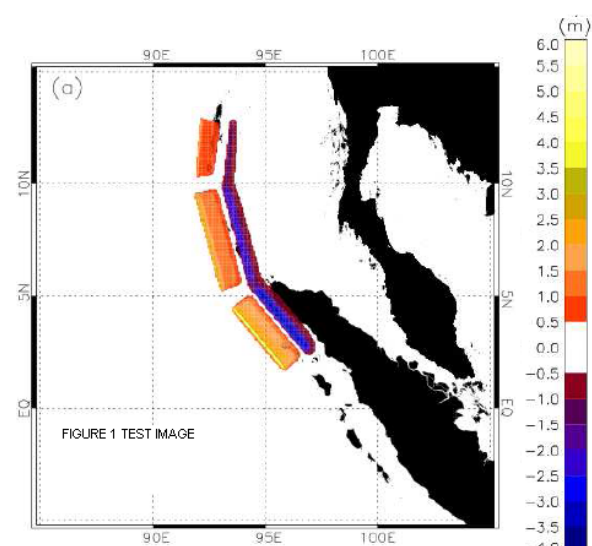


Figure 1. Comparison of ANUGA simulation against the wave tank simulation of the 1993 Okushiri Island tsunami off Hokkaido, Japan

is to test the sensitivity of the model predictions to bathymetry and tsunami source used.

2 MODELLING THE TSUNAMI OF 24TH DECEMBER 2004

The evolution of earthquake-generated tsunamis has three distinctive stages: generation, propagation and run-up (Titov and Gonzalez, 1997). To accurately model the evolution of a tsunami all three stages must be dealt with. Here we investigate the use of two different source models, URS and the Method of Splitting Tsunamis Model (MOST) and to model the generation of a tsunami and open ocean propagation. The resulting data is then used to provide boundary conditions for the inundation package ANUGA (see below) which is used to simulate the propagation of the tsunami in shallow water and the tsunami run-up.

Here we note that the MOST model was developed as part of the Early Detection and Forecast of Tsunami (EDFT) project (Titov *et al.* 2005). MOST is a suite of integrated numerical codes capable of simulating tsunami generation, its propagation across, and its subsequent run-up. The exact nature of the MOST model is explained in (Titov and Synolakis 1995, Titov and Gonzalez 1997, Titov and Synolakis 1997, and Titov *et al.* 2005).

ANUGA is an inundation tool that solves the depth integrated shallow water wave equations. The scheme used by ANUGA, first presented by Zoppou and Roberts (1999), is a high-resolution Godunov-type method that uses the rotational invariance property

¹<http://www.cee.cornell.edu/longwave>

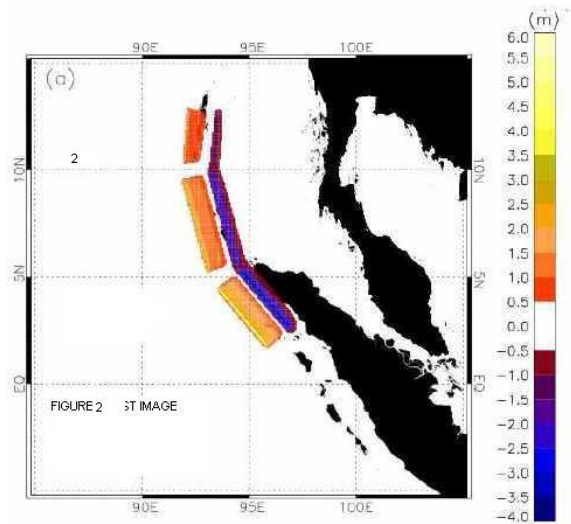


Figure 2. Triangular elements in the 2D finite volume method.

of the shallow water equations to transform the two-dimensional problem into local one-dimensional problems. These local Riemann problems are then solved using the semi-discrete central-upwind scheme of Kurganov *et al.* (2001) for solving one-dimensional conservation equations. The numerical scheme is presented in detail in (Zoppou and Roberts 1999, Zoppou and Roberts 2000, and Roberts and Zoppou 2000, Nielsen *et al.* 2005). An important capability of the software is that it can model the process of wetting and drying as water enters and leaves an area. This means that it is suitable for simulating water flow onto a beach or dry land and around structures such as buildings. It is also capable of adequately resolving hydraulic jumps due to the ability of the finite-volume method to handle discontinuities.

2.1 Tsunami Generation

The Indian Ocean tsunami of 2004 was generated by severe coseismic displacement of the sea floor as a result of one of the largest earthquakes on record. The $M_w=9.2-9.3$ mega-thrust earthquake occurred on the 26 December 2004 at 0h58'53" UTC approximately 70 km offshore North Sumatra. The disturbance propagated 1200-1300 km along the Sumatra-Andaman trench time at a rate of 2.5-3 km.s^{-1} and lasted approximately 8-10 minutes (Ammon *et al.* 2005). At present ANUGA does not possess an explicit easy to use method for generating tsunamis from coseismic displacement, although such functionality could easily be added in the future. Implementing an explicit method for simulating coseismic displacement in ANUGA requires time for development and testing that could not be justified given the aims of the project and the

time set aside for completion. Consequently in the following we employ the URS model and the MOST model to determine the sea floor deformation.

The URS code uses a source model based on Wang (Wang *et al.* 2003) which is an elastic crustal model. The source parameters used to simulate the 2004 Indian Ocean Tsunami were taken from Chlieh (2007). The resulting sea floor displacement ranges from about - 5.0 to 5.0 metres and is shown in figure 3.

The solution of Gusiakov (1972) is used by the MOST model to calculate the initial condition. This solution describes an earthquake consisting of two orthogonal shears with opposite sign. Specifically we adopt the parameterisation of Greensdale (2007) who modelled the corresponding displacement by dividing the rupture zone into three fault segments with different morphologies and earthquake parameters. Details of the parameters associated with each of three regions used here are given in the same paper. The resulting sea floor displacement is shown in Figure 3 and ranges between 3.6 m and 6.2 m.

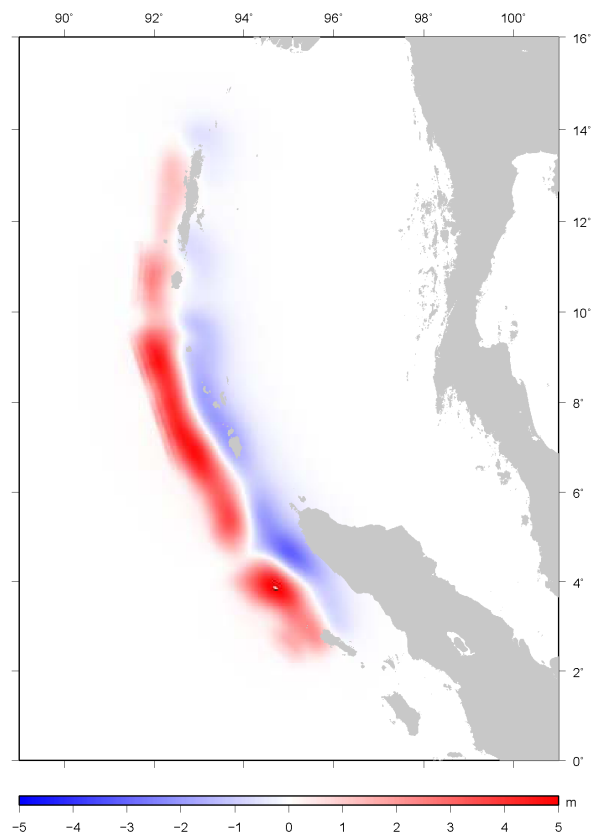


Figure 3. Location and magnitude of the sea floor displacement associated with the December 24 2004 tsunami. Source parameters taken from Chlieh *et al.* (2007)

2.2 Tsunami Propagation

We use both the URS model and the MOST model to simulate the propagation of the 2004 Indian Ocean tsunami in the deep ocean, based on a discrete representation of the initial deformation of the sea floor, described above.

The URS code models the propagation of the tsunami in deep water using the finite difference method to solve the non-linear shallow water equations in spherical co-ordinates with friction and coriolis terms. The code is based on Satake (1995) with significant modifications made by the URS corporation (Thio et al. 2007) and Geoscience Australia (Burbidge et al. 2007). The tsunami is propagated via a staggered grid system starting with coarser grids and ending with the finest one. The URS code is also capable of calculating inundation.

Most models the propagation of the tsunami using a numerical dispersion scheme that solves the non-linear shallow-water wave equations in spherical coordinates, with Coriolis terms. This model has been extensively tested against a number of laboratory experiments and was successfully used for simulations of many historical tsunamis (Titov and Synolakis 1997, Titov and Gonzalez 1997, Bourgeois *et al.* 1999, and Yeh *et al.* 1994).

The computational domain for the MOST simulation, was defined to extend from ...E to ...E and from ...S to ...S. The bathymetry in this region was estimated using ...

The output of the URS and MOST models were produced for the sole purpose of providing an approximation of the tsunami's size and momentum that can be used to estimate the tsunami run-up. ANUGA could also have been used to model the propagation of the tsunami in the open ocean. The capabilities of the numerical scheme over such a large extent, however, have not been adequately tested. This issue will be addressed in future work.

2.3 Tsunami Inundation

The utility of the URSGA model decreases with water depth unless an intricate sequence of nested grids is employed. On the other hand, while the ANUGA model is less suitable for earth quake source modelling and large study areas, it is designed with detailed on-shore inundation in mind. Consequently, the Geoscience Australia tsunami modelling methodology is based on a hybrid approach using models like URSGA (or the MOST model) for tsunami generation and propagation up to a 100m depth contour where the wave is picked up by

ANUGA and propagated on shore using the finite-volume method on unstructured triangular meshes.

In this case the open ocean boundary of the ANUGA study area was chosen to roughly follow the 100m depth contour along the west coast of Phuket Island. The other boundaries were chosen to maximise the number of locations for which run-up depths were measured, whilst keeping the computational domain 'small enough' to avoid excessively large computational time. The computational domain is shown in Figure 5

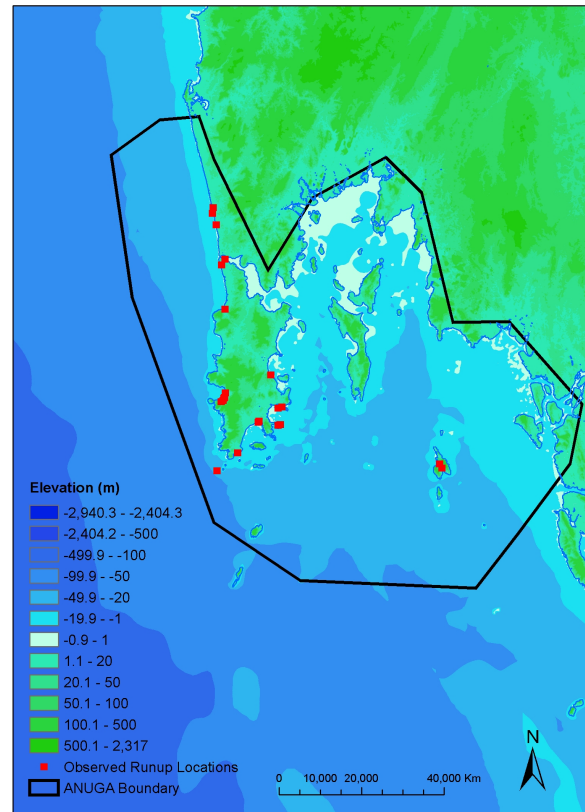


Figure 4. Computational Domain. Can we easily create picture like this one for our new scenario

The domain was discretised into approximately ...,000 triangles. The resolution of the grid was increased in certain regions to efficiently increase the accuracy of the simulation. The grid resolution ranged between a maximum triangle area of $\dots \times 10^5 \text{ m}^2$ near the Western ocean boundary to $\dots \text{ m}^2$ in the small regions surrounding the run-up points and tide gauges. The triangle size around islands and obstacles which "significantly affect" the tsunami was also reduced. The authors used their discretion to determine what obstacles significantly affect the wave through an iterative process.

The bathymetry and topography of the region was

estimated using...

2.3.1 Boundary Conditions

The boundary of the computational domain comprises $N=...$ linear segments. Those segments which lie entirely on land were set as reflective boundaries. The segments that lie in depths greater than 50m were set as Dirichlet boundary conditions with the stage (water elevation) equal to zero. Finally all other segments were time varying boundaries. The value at these boundaries was interpolated from the estimates of the wave depth and momentum obtained from the URS and MOST simulation.

2.4 Bathymetric and Topographic Data

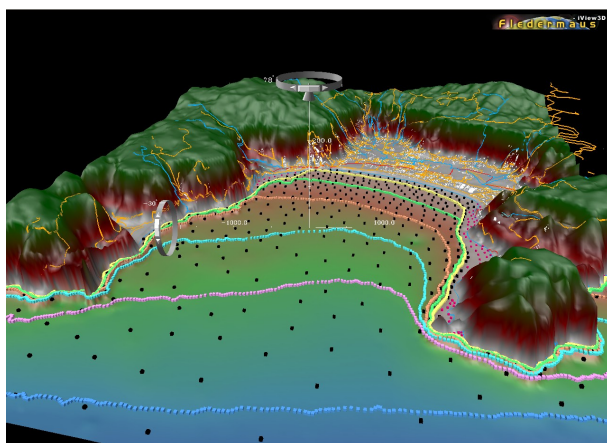


Figure 5. Is there a new picture with river included???

Both the source models MOST and ... require the input of bathymetric data describing the geometry of the sea floor. The data used ...

The URS code employed 5 nested grids and their creation and data source are described below:

DBDB2 2 minute of arc grid from the US Naval Research Labs.

This grid was also interpolated to 27 sec of arc and used in a nested grid scheme.

Indian Ocean 27 sec of arc grid created by:

Interpolating the DBDB2 2 minute of arc grid. In the region where the 9 sec grid sits the data was cut out and replaced by the 9 sec data. Any points that deviated from the general trend near the boundary were deleted. The data was then re-gridded.

Andaman Sea 9 sec of arc grid created by:

Sub-sampling the 3 sec of arc grid from NOAA. In the region where the 3 sec grid sits the data was cut out and replaced by the 3 sec data. Any points that deviated from the general trend near the boundary were deleted. The data was then re-gridded.

Thailand off-shore 3 sec of arc grid created by:

cropping a much larger 3 sec of arc grid covering the whole of the Andaman Sea which itself was based on Thai charts 45 and 362.

This grid was obtained from NOAA.

In the region where the 1 sec grid sits the data was cut out and replaced by the 1 sec data. Any points that deviated from the general trend near the boundary were deleted. The data was then re-gridded.

Patong Bay 1 second of arc grid created from:

elevation data contained in a GIS of Patong Bay supplied by Niran Chaimanee, Geo-environment Sector Manager, CCOP T/S, Bangkok.

Digitised Thai Navy bathymetry chart no 358.

3 RESULTS

Table ?? also highlights the misrepresentation of the local coastline. Large discrepancies, in the order of metres, exist between the modelled and observed elevation. Furthermore, three run-up observation sites were deemed to be initially underwater. This suggests that results could be improved further by employing finer bathymetric data when it becomes available. Yet, despite the poor bathymetric data there is still a moderate correlation between the observed and modelled run-up values suggesting that local variations in the energy of the tsunami are being approximated reasonably well.

4 DISCUSSION AND CONCLUSIONS

We have simulated the inundation of the tsunami of a small irregular region of the west Thailand coast surrounding Phuket using the inundation tool ANUGA. The tsunami size and position at the boundaries of this region were estimated using the MOST model which was used to simulate the generation and propagation of the tsunami in the deep ocean. Specifically the parameterisation of Greensdale *et al.* (2007) was used to describe the tsunami source and the subsequent wave elevation and momentum required by the inundation simulation were interpolated from the MOST simulation at each time step.

Comparison between observed and modelled run-up at 18 sites show reasonable agreement. We also find a modest agreement between the observed and modelled tsunami signal at the two tide gauge sites. The arrival times of the tsunami is approximated well at both sites. The amplitude of the first trough and peak is approximated well at the first tide gauge (Taphao-Noi), however the amplitude of the first wave was underestimated at the second gauge (Mercator yacht). The amplitude of subsequent peaks and troughs, at both gauges, are underestimated and a phase lag between the observed and modelled arrival times of wave peaks is evident after the first peak. Grilli *et al.* (2006) also could not reproduce the correct arrival time at the Taphao-Noi tide gauge or reproduce the signal at the Mercator yacht.

The performance of the model could be improved by using finer bathymetric data, which at present cannot be obtained by the authors, and by a more accurate estimation of the initial tsunami source. The wave height observed at a particular point along the coast is strongly influenced by relatively small scale bathymetric and coastal features which may be under-resolved by the current computational mesh or poorly represented by the sparse bathymetry and topography data set. These problems may also cause errors in simulated arrival times in coastal areas adjacent to regions consisting of inaccurate bathymetry data. Titov and Gonzalez (1997) state that for most cases 10-50m horizontal resolution of bathymetry data is essential. As mentioned above we could only obtain 2 arc minute (3.6km) bathymetry which is most likely insufficient. Topography is approximated using a 3 arc second (90m) grid which is much more appropriate. However, when combined, these data sets do not reproduce the position of coastline well. If a finer resolved bathymetric data set could be obtained for the shallow waters of the Thai coast (say in regions with important bathymetric features) a much better result could be expected.

The approximation of the tsunami source also affects the near shore amplitude of the tsunami wave. As the graphs and tables above show, the amplitude of the tsunami is at times misrepresented and this is partly due to an suboptimal reproduction of the initial coseismic displacement. Grilli *et al.* (2006) obtain improved reproduction of tsunami amplitude when they optimise the parameters of the tsunami source based on the model's ability to reproduce certain observed behaviour. We would like to think, and will explore, that it is this optimisation that yields more accurate results rather than any deficiency of the ANUGA model.

5 ACKNOWLEDGEMENTS

This project was undertaken at Geoscience Australia and the Department of Mathematics, The Australian National University. The authors would like to thank Niran Chaimanee from the CCOP, Thailand for providing the post 2004 tsunami survey data and the elevation data for Patong beach.

6 REFERENCES

- Ammon, C.J., C. Ji, H. Thio, D. Robinson, Sidao Ni, V. Hjorleifsdottir, H., T. Lay, S. Das, D. Helmburger, G. Ichinose, J. Polet, and D. Wald (2005), Rupture process of the 2004 Sumatra-Andaman earthquake, *Science*, **308**, 1133.
- Bourgeois, J., C. Petroff, H. Yeh, V. Titov, C. Synolakis, B. Benson, J. Kuroiwa, J. Lander, and E. Norabuena (1999), Geologic setting, field survey and modeling of the Chimbote, northern Peru, tsunami of 21 February 1996, *Pure and Applied Geophysics*, **154(3/4)**, pages 513-540.
- Burbidge, D., P. Cummins, and R. Mleczko (2007), A Probabilistic Tsunami Hazard Assessment for Western Australia, Report to the Fire and Emergency Services Authority of Western Australia.
- Chlieh, M., J. P. Avouac, et al. (2007). Coseismic slip and afterslip of the great Mw 9.15 Sumatra-Andaman earthquake of 2004. Bulletin of the Seismological Society of America, **97(1A)** , S152-S173.
- Greensdale, D., M . Simanjuntak, D. Burbidge, and J. Chittleborough (2007), A first-generation real-time tsunami forecasting system for the Australian region. BMRC Research Report 126, Bureau of Meteorology Australia.
- Grilli, S.T., M. Ioualalen, J. Asavanant, F. Shi, J.T Kirby, and P. Watts (2006), Source constraints and model simulation of the December 26, 2004 Indian Ocean tsunami, *Journal of Waterways, Port, Ocean and Coastal Engineering*. In press.
- Gusiakov, V.K. (1972), Static displacement on the surface of an elastic space. Ill-posed problems of mathematical physics and interpretation of geophysical data, *Novosibirsk, VC SOAN SSSR*, 23-51. In Russian.
- Jankaew, K., B. F. Atwater, et al. (2008). Medieval forewarning of the 2004 Indian Ocean tsunami in Thailand, *Nature*, **455(7217)**, 1228-1231.
- Kawata, T. et XIV alia (2005) Comprehensive analysis of the damage and its impact on coastal zones by the 2004 Indian Ocean tsunami disaster. Technical report, Disaster Prevention Research Institute. <http://www.tsunami.civil.tohoku.ac.jp/sumatra2004/report.html>.

- Kurganov, A., S. Noelle, and G. Petrova (2001), Semidiscrete central-upwind schemes for hyperbolic conservation laws and Hamilton-Jacobi equations, *SIAM Journal of Scientific Computing*, **23**(3), 707-740.
- Lebrun, J.F., G.G. Karner, and J.Y. Collot. Fracture zone subduction and reactivation across the Puysegur ridge trench system, southern New Zealand, *Journal of Geophysical Research*, **103**, 7293-7313.
- Liu P. L.-F., P. Lynett, H. Fernando, B.E. Jaffe, H. Fritz, B. Higman, R. Morton, J. Goff, and C. Synolakis. Observations by the international tsunami survey team in Sri Lanka, *Science*, **308**, 1595.
- Matsuyama, M. and H. Tanaka (2001) An experimental study of the highest run-up height in the 1993 Okkaido Nansei-Oki earthquake tsunami. In *National Tsunami Hazard Mitigation Program Review and International Tsunami Symposium (ITS)*, pages 879-889. U.S. National Tsunami Hazard Mitigation Program.
- Merrifield, M.A., et XXIII alia (2005), Tide gauge observations of the Indian Ocean tsunami, December 26, 2004, *Geophysical Research Letters*, **32**, L09603.
- National Geophysical Data Center (NGDC). Indian ocean december 26, 2004: run-ups. <http://www.ngdc.noaa.gov/seg/hazard/tsu.shtml>
- Nielsen, O.M, S.G Roberts, D. Gray, A. McPherson, and A. Hitchman (2005), Hydrodynamic modelling of coastal inundation. In A. Zerger and R.M. Argent, editors, *MODSIM 2005 International Congress on Modelling and Simulation*, pages 518-523. Modelling and Simulation Society of Australia and New Zealand. <http://www.mssanz.org.au/modsim05/papers/nielsen.pdf>.
- Roberts, S.G., O.M. Nielsen, and J.D. Jakeman (2006), Simulation of tsunami and flash flood. Accepted for publication in the refereed proceedings of the International Conference on High Performance Scientific Computing: Modeling, Simulation and Optimization of Complex Processes, March 6-10, 2006, Hanoi Vietnam.
- Roberts, S.G. and C. Zoppou (2000), Robust and efficient solution of the 2d shallow water wave equation with domains containing dry beds, *The ANZIAM Journal*, **42**(E), C1260-C1282.
- Satake, K. (1995). Linear and nonlinear computations of the 1992 Nicaragua earthquake tsunami. *Pure and Applied Geophysics*, **144**(3), 455-470.
- Synolakis, C., E. Okal, and E. Bernard (2005), The megatsunami of December 26 2004, *The Bridge, National Academy of Engineering Publications*, **35**(2), 36-35.
- Titov, V.V., F. González E. Bernard, M. Eble, H. Mofjeld, J. Newman, and A. Venturato (2005), Real-time tsunami forecasting: Challenges and solutions, *Natural Hazards*, **35**, 41-58.
- Titov, V.V. and C. Synolakis (1995), Modeling of breaking and nonbreaking long wave evolution and run-up using VTCS-2, *Journal of Waterways, Port, Ocean and Coastal Engineering*, **121**(6), 308-316.
- Titov, V.V. and F.I. Gonzalez (1997), Implementation and testing of the method of splitting tsunami (MOST) model, *NOAA Technical Memorandum*.
- Titov, V.V., F.I. Gonzalez, H.O. Mofjeld, and J.C. Newman (2001), Project SIFT (short-term inundation forecasting for tsunamis), In *ITS Proceedings*.
- Gica, E., M. Spillane, V.V. Titov, C.D. Chamberlin, and J.C. Newman (2008): Development of the forecast propagation database for NOAA's Short-term Inundation Forecast for Tsunamis (SIFT). NOAA Tech. Memo. **OAR PMEL-139**, 89 pp.
- Titov, V.V. and C.E. Synolakis (1997), Extreme inundation flows during the hokkaido Nansei-Oki tsunami, *Geophysical Research Letters*, **24**(11), 1315-1318.
- Tsuji, T., S. Matsutomi, F. Imamura, and C.E. Synolakis (1995), Field survey of the east Java earthquake and tsunami, *Pure and Applied Geophysics*, **144**(3/4), 839-855.
- Vigny, C., W.J.F. Simons, S. Abu, R. Bamphenyu, N. C. Satirapod, C. Subarya Choosakul, A. Socquet, K. Omar, H.Z. Abidin, and B.A.C. Ambrosius (2005), Insight into the 2004 Sumatra-Andaman earthquake from GPS measurements in southeast Asia, *Nature*, **436**, 201-206.
- Wang, R., F. L. Martin, et al. (2003). Computation of deformation induced by earthquakes in a multi-layered elastic crust - FORTRAN program ED-GRN/EDCMP. *Computers and Geosciences*, **29**, 195-207.
- Yeh, H., V.V. Titov, V. Gusiakov, E. Pelinovsky, V. Khrumushin, and V. Kaistrenko (1994), The 1994 Shikotan earthquake tsunami, *Pure and Applied Geophysics*, **144**(3/4), 569-593.
- Zoppou, C., and S.G Roberts (1999), Catastrophic collapse of water supply reservoirs in urban areas, *Journal of Hydraulic Engineering*, **125**(7), 686-695.
- Zoppou, C. and S.G Roberts (2000), Numerical solution of the two-dimensional unsteady dam break, *Applied Mathematical Modelling*, **24**, 457-475.