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Title: OPEN SOURCE TSUNAMI SIMULATION MODELS: A SYSTEMATIC REVIEW
Author/Co-Authors: Retno Utami Agung Wiyono
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Technical Session Timeline and Poster

(Taken and edited from https://iahrapd2018.ugm.ac.id/events-tours/technical-session-timeline-and-poster/)

TECHNICAL SESSION 1, Monday 3 September 2018 (13:00-15:00)

Room 6 (Pasewakan 2) – Subtheme 7: Water-related Disaster Risk Reduction

No.	Time	Ref.No.	Paper Title Author/Co-Authors
1	13:00 – 13:15	IAHR1510806401	DEVELOPMENT OF FLOOD INUNDATION MAP USING UAV-BASED DEM ON RESIDENTIAL AREA (Sarino, Helmi Haki, Reini S. Ilmiaty)
2	13:15 – 13:30	IAHR1507899494	RISK TO A VEHICLE IN A FLOOD IN CONSIDERATION OF FLOW DIRECTION (Hideo Oshikawa, Takashi Oshima, Akihiro Hashimoto, Koichiro Ohgushi, Toshimitsu Komatsu)
3	13:30 – 13:45	IAHR1511190105	OPEN SOURCE TSUNAMI SIMULATION MODELS: A SYSTEMATIC REVIEW (Retno Utami Agung Wiyono, Agung Wiyono, Gusfan Halik)
4	13:45 – 14:00	IAHR1511176367	A METHOD TO SPECIFY CRITICAL RAINFALL CONDITIONS FOR SEDIMENT DISASTERS AND THEIR REGIONALITY (Yusuke Yamasaki, Shinji Egashira)
5	14:00 – 14:15	IAHR1508044819	PROBABILISTIC TSUNAMI HAZARD ASSESSMENT FOR JAVA (SUNDA) TRENCH USING MONTE CARLO SIMULATION METHOD (Cuneyt Yavuz, Elcin Kentel)
6	14:15 – 14:30	IAHR1508066325	RELATIONSHIP OF THREE HOURS OF CUMULATIVE RAINFALL DURING CONCENTRATION TIME OF SLOPE AND COLLAPSED AREA OF LANDSLIDE (Toshiyuki MORIYAMA, Muneo HIRANO)
7	14:30 – 14:45	IAHR1511096051	THE EFFECTIVENESS OF DETENTION POND FOR REDUCING PROPERTIES FLOOD DAMAGE (Agus Suharyanto, Diah Susilowati)
8	14:45 – 15:00	IAHR1508058519	A STUDY ON THE 2016 AUGUST FLOOD AND LEVEE BREACHES IN THE SORACHI RIVER, HOKKAIDO, JAPAN (Jun Okuda, Yasuyuki Shimizu, Tomoko Kyuka, Toshiki Iwasaki, Yoshiaki Ishida)

OPEN SOURCE TSUNAMI SIMULATION MODELS: A SYSTEMATIC REVIEW

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ABSTRACT

Tsunami has less frequency of occurrence compared to other disasters such as flood, landslide, earthquake, and volcanic eruptions. Nevertheless, tsunami has caused significantly higher casualties compared to other disasters. It is therefore extremely important for researchers as well as local governments to conduct tsunami simulation to predict the tsunami potentials by generating tsunami hazard map for their local areas. Further, to make the model accessible by different stakeholders, open source tsunami simulation model is highly necessary. In this study, a systematic review of open source tsunami simulation models that have been widely used in literature during the last decade will be presented. Each model will be reviewed based on a number of aspects such as governing equation, discretization method, computation method, availability of parallel running, availability of slip distribution input, stability criterion, and the complexity of necessary input files. The ability to conduct inundation simulation, which is critical for tsunami mitigation system, will be especially examined in each model. Further, availability of pre-processing and post-processing tools will be described. Tools for bathymetry and topography input, mesh generator, initial surface elevation generator, and visualization tools will be reviewed. Finally, the performance of each model will be assessed from validation point of view including analytical cases, experimental cases, and real cases.

Keywords: *Tsunami, simulation, model, open source*

1. INTRODUCTION

Tsunami is one of the most destructive disasters in the world. The 2011 Japan Tsunami caused about 28,000 casualties while the 2004 Indian Ocean Tsunami caused more than 225,000 casualties (Doocy et al., 2013). Although tsunami has less frequency than other disasters do, it is highly important to understand the mechanism of tsunami especially in coastal area.

In order to understand hydrodynamic phenomena, laboratory experiments and numerical simulations are widely used. By conducting laboratory experiments, actual behavior of hydrodynamic phenomena could be obtained. However, laboratory experiments cost longer time and higher resources. On the other hand, numerical simulations cost lower resources. Thus, it is highly necessary to use numerical simulations to model tsunami.

Review of tsunami simulations have been done by several researchers. Imamura (1996) reviewed tsunami simulations with Finite Difference Method (FDM). He reviewed governing equations, numerical scheme, stability, truncation error and accuracy of tsunami simulations with FDM. TUNAMI (Tohoku University Numerical Analysis for Investigation of tsunamis) was mentioned as an example of tsunami simulation using FDM.

Walters and Takagi (1996) reviewed tsunami simulation with Finite Element Methods (FEM). They discussed governing equations, boundary and initial conditions, numerical approximations, grid generation methods and applications of FEM on tsunami simulations. TELEMAC was taken as example of tsunami model using FEM.

While other studies reviewed tsunami simulations based on the discretization method, Wiyono (2015) reviewed unstructured grid tsunami models. She highlighted that unstructured grid models are preferable for tsunami simulations because the spatial scale of inundation area is much smaller than that of the major propagation area. Recently, Teng et al. (2017) reviewed flood inundation models including 1D, 2D and 3D hydrodynamic model. Proprietary, open source and research stage models are also reviewed.

For researcher who started studying tsunami simulation, open source tsunami models are preferable than the proprietary one. Thus, this study focused in reviewing open source tsunami models.

2. METHOD

In this study, the literature review was conducted through several steps. The first step is to find out the names of open source tsunami models. Several websites such as Science Direct, Springer, and Directory of Open Access Journals (DOAJ) are accessed to find articles which had been published since 2008 until 2018. The key words include “open source”, “tsunami”, “hydrodynamics”, “simulation”, and “model”. Articles having no relation to tsunami modeling using open source model are excluded. The output of the first step is a list of open source tsunami models such as “Delft3D-FLOW”.

The second step is to find out the papers using the name of open source tsunami model obtained from the first step as keywords. The last step is model classification based on grid system, governing equations, discretization method, availability of parallel running, and tsunami initialization. In order to understand details of the models, official websites and user manual of each tsunami model were also checked.

3. OPEN SOURCE TSUNAMI MODELS

List of open source tsunami models is shown in the Table 1 while details are shown afterwards.

Table 1. Open Source Tsunami Models

No	Software	Grid System	Governing Equation	Discretization Method	Parallel Running	Tsunami Generation
1	Delft3D-FLOW	Curvilinear	Three dimensional shallow water equations	Finite Difference Method	Available	Initial water surface elevation
2	GeoClaw	Adaptive Mesh Refinement (AMR) rectangular	Two dimensional shallow water equations	Finite Volume Method	Available	Dynamic fault model or static initialization
3	FVCOM	Unstructured	Three dimensional Navier-Stokes Equations	Finite Volume Method	Available	Initial water surface elevation
4	ANUGA	Unstructured	Two dimensional shallow water equations	Finite Volume Method	Available	Initial surface elevation (constants, numeric arrays, expressions involving quantities, functions, or arbitrary data points)
5	TELEMAC-2D	Unstructured	Two dimensional shallow water equations	Finite Element Method	Available	Initial water surface elevation?
6	SELFE	Unstructured	Three dimensional shallow water equations	Finite Volume Method	Available	Initial water surface elevation
7	COMCOT	Rectangular	Two dimensional shallow water equations	Finite Difference Method	Unknown	Instant fault model, transient floor motion, water surface disturbance and wave maker.

3.1 Delft3D-FLOW

Delft3D-FLOW is a part of Delft3D which is a product from Deltares. It had been proprietary software until the pre-compiled version was open for free access. Delft3D-FLOW is able to simulate tides, storm surges, river flow, tsunamis, hydraulic jumps, sediment transport, morphological changes, non-hydrostatic flows, and simulations in deep lakes and reservoirs (Deltares, 2014). Delft3D has capability to perform propagation and inundation simulation, which is very important to examine tsunami effects to coastal areas. Navier Stokes Equation is the governing equation in Delft3D while the Finite Difference Method is the discretization method. Currently the code is written in Fortran.

Input files for simulation using Delft3D-FLOW include the extent of modeling area, definition of location, extent and types of open boundaries, definition of the land and water boundary, definition of grid details, definition of time frame, open boundary conditions, wind speed and direction, discharges and salinity, or substances which will be transported.

In order to maintain stability and accuracy for the time integration of the shallow water equations, there are different settings in time-step limits of Delft3D-FLOW. The limits are based on length and velocity scale, with or without density-coupling, and other factors. MPI-based parallel calculations using Delft3D are possible although do not work in combination with Delft3D-WAVE online, Z layer models, and other specific conditions.

Although available in the proprietary version, the open source version of Delft3D does not include complete pre-processing tools (grid generation and initial surface elevation modules). However, Delft Dashboard, a graphical user interface tool to generate simple model input, which is also a pre-processing tool, is available both in the proprietary and open source software. The official website mentions that other pre-processing modules will become open source in the near future. Post-processing tools for visualization (QUICKPLOT) and graphical user interface for plot designing and animations (MUPPET) are freely available for both proprietary and open source software.

According to Gerritsen et al. (2008), Delft3D-FLOW has been benchmarked to analytical tests (e.g. simple channel flow, standing wave, wind driven channel flow), laboratory tests (e.g. tidal flume, water elevation in a flume, one-dimensional dam break), schematic tests (e.g. drying and flooding, wind over a schematized lake, tsunami), and real applications (3D North Sea, Zegeeplas, Lake Grevelingen, Sea of Marmara, and South China Sea).

3.2 GeoClaw

GeoClaw is a subset of Clawpack (Conservation Laws Package) able to model numerous flooding problems including generation, propagation, and inundation of tsunami. Geoclaw solves the two-dimension, depth-averaged shallow water equations with Finite-Volume Method (Berger et al., 2011). It is written in Fortran 77. Geoclaw is capable to perform parallelization running through MPI and OpenMP.

As a tsunami generator, GeoClaw is capable of using either dynamic fault models or static initialization as the inputs. For the dynamic model case, time-dependent seafloor displacement in some region should be described. Pre-processing tools for file conversion from subfaults to seafloor movement results, by applying Okada model, is provided in Python module.

GeoClaw adopted a block-structured Adaptive Mesh Refinement (AMR) algorithm, which is absent in other models under review. As the tsunami propagates across the ocean, the grid resolution increases, whereas the time-step decreases around the tsunami and in pre-defined regions of interest (Baranes, 2015). GeoClaw automatically chooses temporal refinement ratios to achieve a desired Courant number, while spatial refinement ratios are specified by the user.

Input files for running GeoClaw code includes number of space dimensions, bathymetry and topography data, initial time, time-step, restart file (for restart simulation), boundary condition, output time and format. Regarding visualization tools of the output of GeoClaw, VisClaw provides tools needed for animating and browsing simulation results in Google Earth.

GeoClaw has been validated to analytical solutions e.g. single wave on a simple beach and solitary wave on a composite beach; laboratory experiments e.g. saucer landslide, single wave on simple beach, solitary wave on composite beach, solitary wave on a conical island, Monai valley beach, and old 3D-landslide; and filed result of tsunami in Okushiri Island (Gonzales et al., 2011). GeoClaw has also been applied for many applications such as radially-symmetric tsunami and sloshing water in parabolic bowl, hurricane Ike, Chile 2010 tsunami and the 2011 Tohoku tsunami (The Clawpack Development Team, 2017).

3.3 FVCOM

Finite Volume Community Ocean Model (FVCOM) is an unstructured grid coastal ocean circulation model developed by joint efforts of University of Massachusetts-Dartmouth (UMASSD) and Woods Hole Oceanographic Institution (WHOI). The governing equations of FVCOM consist of momentum, continuity, temperature, salinity, and density equations. Written in Fortran 90, FVCOM is able to run parallel computation using MPI. In order to maintain numerical stability, the Courant-Friedrich Levy (CFL) stability criterion is adopted in this model (Chen et al., 2013).

The pre-processing and post-processing tools are available in fvcom-toolbox, a group of Matlab and Fortran 90 scripts. The codes include scripts for preparing input files for FVCOM (open boundary forcing, river forcing, etc.), scripts for converting meshes from SMS to FVCOM, and scripts for post-processing FVCOM results using Matlab. FVCOM visualization can also be done using Visit, an open source visualization tool.

Necessary input files include coordinates of grid system, bathymetry and topography of grid system, tidal amplitudes at open boundary, initial surface elevation, and initial field of currents. Other necessary parameters are specified in run file.

FVCOM was originally developed for hydrodynamics problems. By slightly modifying the FVCOM code to treat initial surface elevation, Sasaki et al. (2011) applied FVCOM to tsunami problem. Since then, FVCOM has been validated to analytical case (wave run up on a uniform plane beach) and experimental cases (influence of macro-roughness on tsunami run up and tsunami inundation modeling in constructed environments) by Wiyono (2015). FVCOM has also been applied to propagation and inundation of real tsunami cases e.g. the 2006 Indian Ocean Tsunami and the 2011 Tohoku Tsunami.

3.4 ANUGA

ANUGA is an unstructured mesh hydrodynamic inundation model developed by Geoscience Australia and the Australian National University. It is based on a finite-volume method to solve the shallow water equation. It is a Python package with some C extensions. The time-step should satisfy Courant-Fredrichs-Levy (CFL) condition to maintain numerical stability.

Necessary input files include computational domain, boundary conditions, and initial condition. Initial conditions can be set using several ways as follow: constants, numeric arrays, expressions involving quantities, functions, or arbitrary data points with associated values. ANUGA provides several pre- and post-processing tools for example tools for mesh generation and domain creation, code providing coordinate transforms between projections, code providing ability to load an ASCII mesh, and anuga_viewer as visualization tool. ANUGA is also capable to run parallelization computation (Roberts et al., 2013).

ANUGA has been validated to analytical validation of the dam break problem and experimental validation of force on a column in a simulated dam break situation. ANUGA has also been applied to case studies, for example, tsunami case study in Patong City and flood model in Towradgi Creek (Roberts et al., 2015).

3.5 TELEMAC-2D

TELEMAC-2D is a part of TELEMAC system developed by the the Laboratoire National d’Hydraulique, a department of the Division for Research and Development of the French Electricity Board (EDF-DRD). TELEMAC employed unstructured grid mesh system to calculate dynamic flows in a lake, a river, an estuary and coastal area including tsunami propagation and inundation.

The governing equations of TELEMAC are two dimensional shallow water equations which are discretized using Finite Element Method. The main codes are developed in Fortran 90. In order to maintain numerical stability, it is recommended to adopt a time-step so that the Courant number is not larger than 3 in general (EDF-DRD, 2015).

In addition to the primary codes, TELEMAC supplied several pre- and post- processing modules for example FUDAA. Input files of TELEMAC-2D include mesh and bathymetry files, the boundary conditions, and the steering parameters (input/output file names, time-step, friction, viscosity formulations, etc).

TELEMAC-2D has been validated to analytical validation of flow over a bump on the bed and theoretical dam break wave, real case simulation of the Malpasset dam break wave, and transient flood flow in the valley of river Culm (EDF-DRD, 2015), analytical validation of wave refraction and diffraction around a circular island, and experimental validation of Monai tsunami (Cooper et al., 2012). TELEMAC-2D has also been utilized to simulate tsunami propagation in the Sea of Marmara (Kilinc et al., 2009).

3.6 SELFE

SELFE is an open source 3D unstructured grid hydrodynamic model, which is able to model propagation and inundation. The governing equations used in this model are 3D shallow water equations. Due to the hydrostatic assumption, vertical velocity term is solved using Finite Volume Method. SELFE is written in Fortran 90 and parallelization of the code is available using the MPI (Message Passing Interface) protocol. In order to design a stable simulation, the local Courant-Friedrichs-Lewy (CFL) criterion and dimensionless wavelength numbers are used in developing grid system.

Mandatory input files of SELFE includes horizontal and vertical grid, interpolation mode and other input parameters such as initial condition for salinity and temperature, bottom drag, wind, time history input, spherical coordinates, boundary forcing, and bed deformation input (CMOP, 2018).

SELFE has been benchmarked to many cases for example analytical validation of wave run up on a uniform plane beach, experimental validation of wave run up on a complex 3-D beach (Zhang and Baptista, 2008), and analytical validation of tidal propagation in simple domain. SELFE has also been applied for tsunami-tide interaction modeling in 1964 Prince William Sound Tsunami (Zhang et al., 2011).

3.7 COMCOT

Cornell Multi-grid Coupled Tsunami Model (COMCOT) is an open source tsunami modeling package developed by the research group the research group led by Prof. Phillip L. –F. Liu at the School of Civil and Environmental Engineering in Cornell University, USA. Tsunami generation, propagation and run-up are capable to be modeled by COMCOT.

COMCOT used Finite Difference Method to solve Shallow Water Equations using Fortran 90 as a programming language. It used an equally spaced grid system. Cluster applications of Shallow Water Equations and nesting system are capable to be done by COMCOT. In a deep ocean, when the tsunami amplitude is much smaller than the water depth, linear Shallow Water Equations in Spherical coordinates can be applied. Meanwhile, when simulation is employed to relatively small coastal regions and non-linear effects increase significantly; non-linear Shallow Water Equations in Cartesian Coordinates can be implemented.

COMCOT allows the user to select various tsunami-generating mechanisms, including instant faulting, transient floor motion, water surface disturbance and wave maker mechanism. Fault model is already included in COMCOT. In order to apply the function, nine parameters of fault are entered to calculate initial surface elevation. Other pre-processor module to convert matrices bathymetry data is available in Matlab script. Input files for simulation include general aspects e.g. the total runtime, output time interval, initial and boundary conditions, parameters for tsunami generating mechanism, coordinate system, governing equations, grid size, and bottom friction.

Experimental validation of COMCOT has been done by Zhou et al. (2009) to solitary wave run-up case on smooth plane beaches. In addition, Hsu (2014) inferred that systematic validation of COMCOT has been carried out. COMCOT has also been applied to real cases e.g. 2002 Hua-lien tsunami, 2003 Algerian tsunami, 2004 and 2005 Indian Ocean tsunamis, and 2006 Java tsunami (Wang, 2009; Syamsidik, 2015).

4. CONCLUSIONS

A literature review has been carried out to gather state-of-the-art open source tsunami models in the last decade. From the literature review, seven open source tsunami models are found. Each model has been reviewed based on grid system, governing equations, discretization method, availability of parallel running, tsunami generation input, and required input files.

From the seven open source models, four models are unstructured grid models while other three models employ curvilinear, rectangular, and Adaptive Mesh Refinement (AMR) rectangular grid system. One model utilized three dimensional Navier-Stoker equations as the governing equations, other two models utilized three dimensional shallow water equations, while other four models utilized two dimensional shallow water equations. Regarding discretization method, two models utilize Finite Difference Method, one model employ Finite Element Method, while other four models utilize Finite Volume Method. All the reviewed models have been validated to analytical solutions, experimental results and applied to real cases. From the reviewed models, it is observed that the two dimensional shallow water equations with Finite Volume Method are the most utilized method.

The review on many aspects of the models shows that no model outperforms other models in all aspects. Accuracy to the results, complexity of codes, input files, and supporting tools may become the considerations for choosing a specific model. Many improvements and corrections will be carried out by the model's community.

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REFERENCES

Baranes, H. (2015). Sedimentological Records and Numerical Simulations of the C.E. 1707 Hoei Tsunami in Southwestern Japan. *Master Thesis,* University of Massachusetts.

Berger, M.J., George, D.L., LeVeque, R.J., and Mandli, K.T. (2011). The GeoClaw software for depth-averaged flows with adaptive refinement. *Advances in Water Resources*. Vol. 34 (9). pp. 1195-1206.

Chen, C., Beardsley, R.C., Cowles, G., Qi, J., Lai, Z., Gao, G., Stuebe, D., Liu, H., Xu, Q., Xue, P., Ge, J., Hu, S., Ji, R., Tian, R., Huang, H., Wu, L., Lin, H., Sun, Y., and Zhao, L. (2013). An Unstructured Grid, Finite-Volume Community Ocean Model FVCOM User Manual Fourth Edition. Retrieved from http://fvcom.smast.umassd.edu/download/. Accessed February 15, 2018.

Center for Coastal Margin Observation and prediction (CMOP). (2018). Selfe v4.0 User Manual. Retrieved from http://www.stccmop.org/knowledge_transfer/software/selfe/v3manual. Accessed February 15, 2018.

Cooper, A., Cuomo, G., Bourban, S., Turnbull, M., and Roscoe, D. (2012). Testing TELEMAC-2D suitability for tsunami propagation from source to near shore. Proc. XIXth *TELEMAC-MASCARET User Conference*.

Deltares. (2014). Delft3D-FLOW User Manual. Version 3.15.34158. Retrieved from https://oss.deltares.nl/documents/183920/185723/Delft3D-FLOW_User_Manual.pdf. Accessed February 15, 2018.

Doocy S, Daniels A, Dick A, Kirsch TD. (2013). The Human Impact of Tsunamis: a Historical Review of Events 1900-2009 and Systematic Literature Review. *PLOS Currents Disasters*. Edition 1.

EDF-DRD. (2015). TELEMAC Modelling System TELEMAC-2D Software Version 7.0 Validation Document. Retrieved from http://www.opentelemac.org/downloads/VALIDATION/telemac2d_validation_v7p0.pdf. Accessed February 15, 2018.

Gerritsen, H., de Goede, E. D., Platzek, F. W., van Kester, J. A. Th. M., Genseberger, M., and Uittenbogaard, R. E. (2008). Validation Document Delft3D-FLOW. Retrieved from https://oss.deltares.nl/c/document_library/get_file?uuid=39169f8f-4ab0-4f7b-9771-c3f7d0ddd61f&groupId=183920. Accessed February 15, 2018.

Gonzales, F. I., LeVeque, R. J., Chamberlain, P., Hirai, B., Varkovitzky, J., and George, D. L. (2011). Validation of the GeoClaw Model. *NTHMP MMS Tsunami Inundation Model Validation Workshop*.

Hsu, C.A. (2014). Comparative Validation of SEC-HY21 and COMCOT Models for Tsunami Inundation. *Sinotech Engineering*. Vol. 124.

Imamura,F. (1996). Review of tsunami simulation with a finite difference method, Long-wave Runup Models edited by H.Yeh, P.Liu and C.Synolakis, World Scientific publishing, Singapore, pp.25-42.

Kilinc, I., Hayir, A., and Cigizoglu, H.K. (2009). Wave dispersion study for tsunami propagation in the Sea of Marmara. *Coastal Engineering*. Vol. 56. pp. 982-991.

Roberts, S.G., Oishi, Y., and Li, M. (2013). High Resolution Tsunami Inundation Simulations. *20th International Congress on Modelling and Simulation*. pp. 310-316.

Roberts, S.G., Nielsen, O., Gray, D., Sexton, J., and Davies, G. (2015). ANUGA User Manual Release 2.0. Retrieved from https://anuga.anu.edu.au/. Accessed February 15, 2018.

Sasaki, J., Komatsu, Y., Matsumaru, R., and Wiyono, R. U. A. (2011). Unstructured Model Investigation of 2004 Indian Ocean Tsunami Inundation in Banda Aceh , Indonesia. *Journal of Coastal Research* SI64: 941–945.

SELFE website http://www.stccmop.org/knowledge_transfer/software/selfe. Accessed on February 15, 2018.

Syamsidik, Rasyif, T.M., and Kato, S. (2015). Development of Accurate Tsunami Estimated Times of Arrival for Tsunami-Prone Cities in Aceh, Indonesia. *International Journal of Disaster Risk Reduction*. Vol. 14(4). pp 403-410.

Teng, J., Jakeman, A. J., Vaze, J., Croke, B. F. W., Dutta, D., and Kim, S. (2017). Flood inundation modeling: A review of methods, recent advances and uncertainty analysis. *Environmental Modelling and Software*. Vol. 90, pp. 201-216.

The Clawpack Development Team. (2017). Gallery of GeoClaw applications. Retrieved from http://www.clawpack.org/gallery/gallery_geoclaw.html. Accessed February 15, 2018.

Walters, R.A. and Takagi, T., (1996). Review of finite element methods for tsunami simulation, Long-Wave Runup Models edited by H.Yeh, P.Liu and C.Synolakis. World Scientific publishing, Singapore, pp.43-87.

Wang, X. (2009). User Manual for COMCOT Version 1.7. Retrieved from http://223.4.213.26/archive/tsunami/cornell/comcot_down.htm. Accessed February 15, 2018.

Wiyono, R. U. A. 2015. Unstructured mesh tsunami simulation using FVCOM considering the fine structure of land use. *Ph.D Dissertation*, Yokohama National University.

Zhang, Y.J., and Baptista, A.M. (2008). An Efficient and Robust Tsunami Model on Unstructured Grids. Part I: Inundation Benchmarks. *Pure and Applied Geophysics*. Vol. 165. pp 2229-2248.

Zhang, Y.J., Witter, R.C., and Priest, G.R. (2011). Tsunami-tide interaction in 1964 Prince William Sound tsunami. *Ocean Modelling*. Vol. 40. pp 246-259.

Zhou, H., Teng, M. H., Lin, P., Gica, E., and Feng, K. (2009). Predicting run-up of breaking and nonbreaking long waves by applying the Cornell COMCOT model. *Nonlinear Wave Dynamics*. pp. 147-163.