The 2015 World Congress on
Advances in Civil, Environmental, and Materials Research (ACEM15)
Incheon, Korea, August 25-29, 2015

Large scale smooth particle hydrodynamics model for analytical fragility curves of a building subject to tsunami

*Fritz Sihombing[1)] and Marco Torbol[2)]

[1), 2)] *School of Urban and Environment Engineering, UNIST, Ulsan, Republic of Korea*
[1)] *fritzharland@unist.ac.kr*
[2)] *mtorbol@unist.ac.kr*

ABSTRACT

This study presents a new method that computes analytical fragility curves of a structure subject to tsunami waves. First, the smooth particle hydrodynamics (SPH) model simulates the propagation of the tsunami waves from shallow water to their impact on the target structure. The advantage of SPH over mesh based finite element method (FEM) is its ability to model wave surface interaction when large deformations are involved, such as the impact of water on a structure. Nowadays, although SPH is computationally more expensive than mesh based FEM the advent of parallel computing on general purpose graphic processing unit overcome this limitation. Second, the impact force is applied to a finite element model of the structure and its dynamic non-linear response is computed. A data-set of tsunami waves is simulated and the structural responses are used to compute the analytical fragility curves. This study proves it is possible to obtain the response of a structure to a tsunami wave using state of the art dynamic models in every stage of the computation at an affordable cost.

1. INTRODUCTION

Tsunami is a word borrowed from Japanese language, it is derived from two words “tsu” and “nami” which means harbor and wave respectively. The name gained global recognition as its occurrences increases and create catastrophic results (e.g. 2004 Aceh Indian Ocean Tsunami, 2006 Pangandaran Tsunami, 2011 Tohoku Tsunami). Tsunami event generally consisted of three phase evolutions: first is the generation of tsunami, second is the propagation over the open ocean, and the last is inundation over the dry land.

The significant disturbance occurred on the sea would likely cause a tsunami wave. The disturbance results on displacement of a body of water in large volume instantaneously, thus generate a new wave in the sea surface. This wave, although looks like normal wave but it is different compared with the wind-generated wave. The normal wind-generated wave will have period around 10 seconds with the wave length of 150 m, while the tsunami wave will have period of one hour and wave length as far as 100 km. However, it is difficult to detect tsunami wave in the vast area of the ocean, as the appearance is not significantly different with wind-generated wave.

Understanding of forces exerted from tsunami impact is important knowledge useful for designing structures in the tsunami-prone area. Structures located near the coastline should be aware of the occurrence of tsunami even, especially if submarine active fault existed near coastline. Some of the building codes already consider the tsunami loading on their calculation such as Coastal Construction Manual by FEMA, City and County of Honolulu Building Code by the Department of Planning and Permitting of Honolulu, Hawaii. The inundation of tsunami and its force are characterized by, 1) the height and period of tsunami wave, 2) the topography of coastline, 3) fluid-solid interaction of tsunami wave. While the forces exerted from the tsunami wave can be estimated by considering, 1) the depth of tsunami inundation, 2) the velocity of tsunami, and 3) the direction of tsunami (Nistor, Palermo et al. 2011).

In this study, smooth particle hydrodynamic (SPH) model (Crespo, Dominguez et al. 2015) is used to compute the tsunami force on a building given the input tsunami wave and coast topography. The forces are then used in a finite element model (FEM) (McKenna 2011) using non-linear dynamic analysis to compute the response of the structure. Both these models allow the inclusion of non-linear behaviors that cannot be included in classic finite difference methods and static analysis at the expense of increase computational effort.

2. METHODS

2.1 Tsunami forces

The following content will discuss the force exerted from the inundation phase of tsunami wave. Most of the content are based on the code suggested by FEMA on their Coastal Construction Manual. There are five forces that can be considered due to tsunami inundation process, 1) hydrostatics force, 2) hydrodynamics force, 3) buoyant force, 4) surge force, and 5) debris impact force (Yeh 2007).

2.1.1 Hydrostatic force

The hydrostatic force is generated when the tsunami inundation raises around the structure. The force is caused by the water gradient between the inside and outside the structure (Figure 1a). The force act perpendicular to the plain surface of structure. It may not fully affect a short length structure, because water will overtop and fill in all the empty space, which reduces the water gradient (Fema 2008). The hydrostatic force is calculated as:

$$F_h = p_c \cdot A_w = \frac{1}{2}\rho_s \cdot g \cdot b \cdot h_{\max}^2 \qquad (1)$$

Where p_c is the hydrostatic pressure, A_w is the wetted area of the panel, ρ_s is the fluid density including sediment (1200 kg/m^3), g is the gravity acceleration, b is the breadth (width) of the wall, and h_{max} is the maximum water height above the base of the wall at the structure location.

2.1.2 Hydrodynamic force

The hydrodynamic force, also known as the drag force, is caused by the friction force of the flowing waves and the pressure force within the flowing mass water (Figure 1b). Drag force is generated when the tsunami waves floods the land and the structures with a moderate to high velocity (Fema 2008). Drag force (F_d) is calculated as:

$$F_d = \frac{1}{2}\rho_s \cdot C_d \cdot B \cdot \left(h \cdot u^2\right)_{\max} \qquad (2)$$

where ρ_s is the fluid density including sediment (1200 kg/m^3 = 2.33 slugs/ft^3), C_d is the drag coefficient, h is the flow depth, and u is the flow velocity at the location of the structure. B is the width of the component over which the friction is exercised. FEMA recommends that the drag coefficient be taken as C_d = 2.0.

2.1.3 Buoyant force

The buoyant force is the hydrostatic forces acting in the vertical direction through the center of mass of the structure when the tsunami wave partially or totally surrounds the structure. Buoyant force is considered as the weight of tsunami water displaced (Fema 2008). The light frame buildings, like wood frame, that are built near the coastline should be of concern about buoyant forces due to its small resistance to the upward force. Buoyant force (F_b) is calculated as:

$$F_b = \rho_s \cdot g \cdot V \qquad (3)$$

where ρ_s is the sea water density including sediment (1200 kg/m^3), and V is the volume of water displaced by the building (Figure 1c).

2.1.4 Surge force

The surge force also known as impulsive force is caused by the impact of the tsunami wave on the structure. The first tsunami wave that arrives on the coastline will not have a significant surge force but the subsequent tsunami waves that flood the coastline will have (Árnason 2005, Ramsden 1996, Yeh 2007). Surge force affects only the edge of the structure that faces the tsunami waves (Fema 2008) (Figure 1d). Surge force (F_s) is calculated as:

$$F_s = 1.5 F_d \qquad (4)$$

2.1.5 Debris impact force

A tsunami wave flooding the land can carry debris of floating pieces of structures, floating automobiles, drift woods, even ships. The impact of floating debris can reduce the strength of the structures (Fema 2008). The debris impact force (F_i) is calculated as:

$$F_i = C_m \cdot u_{\max} \cdot \sqrt{k \cdot m} \qquad (5)$$

where C_m is the added mass coefficient, u_{max} is the maximum flow velocity carrying the debris at the site, and *m* and *k* are the mass and the effective stiffness of the debris. It is recommended that the added mass coefficient be taken as C_m = 2.0.

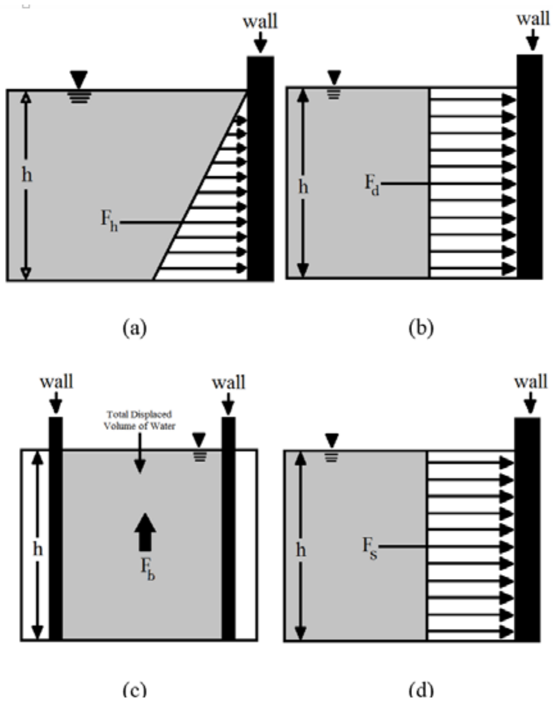


Figure 1. Static forces distribution and location of resultant: (a) hydrostatic, (b) hydrodynamics, (c) buoyant, (d) surge

2.2 Smoothed Particle Hydrodynamic Method

Smoothed particle hydrodynamics (SPH) is a numerical scheme using particle method for the estimation method (Monaghan 1992). The particle method is a numerical method which does not the grid for its numerical operations (mesh-less method). Initially the SPH method originated to account the phenomena of astrophysics (Lucy 1977), however the method can be extended to solve the fluid dynamics problems (Monaghan 1992). The SPH method found successfully simulate the breaking dam problem, waterfalls, flood inundation, and multiphase fluid flow.

The SPH method solve the conservation laws of continuum fluid by introducing the concept of kernel function. The kernel function serves as the interpolation function that provides values of specific particle points given its weighting property due to interactions with other particles. The common kernel function that used in the SPH method is cubic spline and Gaussian function. The integral formulation for SPH method is:

$$F(x) = \int F(x')W(x - x', \mathrm{y})\,\mathrm{dx}' \tag{6}$$

where *W* is the smoothing kernel, and the integration is over the entire interest domain of *x* and *x*`. Some other important aspects of SPH method beside the smoothing kernel are; the derivation of motions, fluid viscosity, and boundary condition (Monaghan 1992).

2.3 Finite element analysis

OpenSees (McKenna 2011) is an open source finite element solver developed in 1999 by Frank McKenna from UC Berkeley. OpenSees is an object-oriented, software framework supported by joint cooperation between Pacific Earthquake Engineering Research Center (PEER) and the George E. Brown Jr. Network for Earthquake Engineering Simulation (NEES), and sponsored by National Science Foundation (NSF). The intention of OpenSees development is to encourage improvement on the nonlinear earthquake engineering research and create an active communities between researchers and practitioners.

In this study, OpenSees is used to compute both the capacity of the structure and the demand of the impact force of the tsunami. The capacity is computed using non-linear static analysis. Moment-curvature analysis to assess the capacity of the reinforced concrete cross-section subject to bending moment. Push-over analysis to assess the capacity of the columns subject to shear force. The demand is computed using non-linear dynamic analysis. The model includes all possible sources of non-linearity and the time history of the impact force, which is recorded in the SPH simulation, is the input.

2.4 Finite element analysis

In this study, the fragility curves were computed using two different methods. Method 1 estimates the parameters of the fragility curves of each damage state independently from each other. The maximum likelihood method is used to compute the median and log-normal standard deviation. Method 2 estimates the parameters of the fragility curves of each damage state concurrently. The fragility curves of the different damage state in method 2 have the same log-normal standard deviation. Because of it they are parallel on a lognormal probability paper and for any value of the intensity measure the correct order of progressive damage is guaranteed: minor, moderate, major, collapse is respected (Shinozuka, Feng et al. 2000).

In method 1, the likelihood function that has to be maximized is:

$$L = \prod_{i=1}^{N} \left[F(h_{w,i}) \right]^{x_i} \left[1 - F(h_{w,i}) \right]^{1-x_i} \quad (7)$$

where $F(h_{w,i})$ represent the fragility curve of the specific damage state, $h_{w,i}$ is the wave height at the point of observation of the simulation *i*, x_i is the realization of the Bernoulli random variable of $h_{w,i}$. x_i=1 if the simulation i causes the structure above the damage state and x_i=0 if the simulation *i* does not cause the structure above the damage state. *N* is the total number of tsunami wave simulations in the data set.

In method 2, at each damage state is assigned one exclusive event: E_0 no damage, E_1 minor, E_2 moderate, E_3 major, E_4 collapse. $P_j=P(X,E_j)$ is the probability of structure to be in the damage state E_j given the intensity measure *X*. The analytical form to estimate the fragility curves in the method 2 is expressed as:

$$F_j(X_i; c_{m,j}; \varsigma_j) = \Phi\left[\frac{\ln(X_i / \mathrm{c}_{m,j})}{\zeta_j}\right] \quad (8)$$

where $c_{m,j}$ and ζ_j are the median and log-standard deviation of the fragility curves for every assigned damage state (i.e., at least minor, at least moderate, at least major, collapse) that is identified by the *j* indices = 0, 1, 2, 3 and 4 respectively. The probability of each damage states can be obtained by the following expressions

$$P_{i,0} = P(a_i, E_0) = 1 - \mathrm{F}_1(a_i; \mathrm{c}_{m,1}, \zeta) \quad (9)$$

$$P_{i,1} = P(a_i, E_1) = \mathrm{F}_1(a_i; \mathrm{c}_{m,1}, \zeta) - \mathrm{F}_2(a_i; \mathrm{c}_{m,2}, \zeta) \quad (10)$$

$$P_{i,2} = P(a_i, E_2) = \mathrm{F}_2(a_i; \mathrm{c}_{m,2}, \zeta) - \mathrm{F}_3(a_i; \mathrm{c}_{m,3}, \zeta) \quad (11)$$

$$P_{i,3} = P(a_i, E_3) = \mathrm{F}_3(a_i; \mathrm{c}_{m,3}, \zeta) - \mathrm{F}_4(a_i; \mathrm{c}_{m,4}, \zeta) \quad (12)$$

$$P_{i,4} = P(a_i, E_4) = \mathrm{F}_4(a_i; \mathrm{c}_{m,4}, \zeta) \quad (13)$$

The likelihood function for the second method can be written as:

$$L(\mathrm{c}_1, c_2, \mathrm{c}_3, c_4, \zeta) = \prod_{i=1}^{N} \prod_{k=0}^{4} P_k\left(a_i; E_k\right)^{x_{ik}} \quad (14)$$

where $x_{ik}=1$ if there is a damage within E_k state occurs in the structural model due to tsunami wave height = a_i and $x_{ik}=0$ if otherwise. A Matlab code is written to solve the numerical procedure of likelihood estimation.

3. RESULTS

3.1 Tsunami simulation

The tsunami simulations were performed using DualSPHysics. Each simulation has its own height of tsunami waves at the coastline and at the point of impact on the structure. The structural response due to forces exerted from the tsunami wave on the structure was computed using the OpenSees, the capacity of the structure is also computed using OpenSees. The damage states of the structure were determined from the moment curvature analysis of the cross-section of the columns and its ductility. The damage states are: minor damage, moderate damage, major damage and collapse. Two different structural models were analyzed with different column width (i.e., 71.2 cm and 50.8 cm respectively) and different reinforcing steel amount.

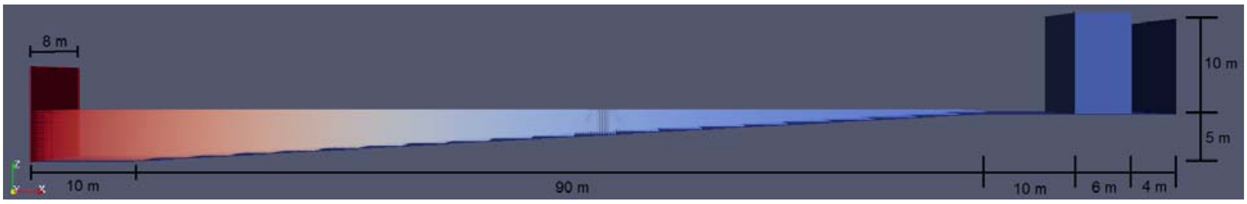


Figure 2. Configuration of tsunami wave model and building model

The computational domain for the tsunami wave simulation was setup with closed boundaries. The domain included 176,849 particles. The time step is t = 0.1 s and the total duration of the simulation is 20 seconds. The distance between particles is 0.25 m and the smoothing length is 0.866 m. A simple coastline was designed and the base of the domain with a gradient height difference. The difference between coastline and the base is 5 m and the length is 90 m, which create an angle $\theta = 3.18^{\circ}$ between the water surface and the coastline. The model of the structure was located 10 m away from the coastline. At t = 0, the water is in stationary position. At t > 0, the wave-maker starts to move pushing the water toward coastline to generate the first tsunami wave and then it move away from the coastline to generate the second tsunami wave. In the different simulations the wave maker moves forward and backward with a different combination of properties, such as speed, and it generates the different tsunami waves breaking at the coastline. During the simulation the height of the waves and the load on the structures are recorded. The height is recorded in two different places: at the coastline and at the structural model (Figure 2 and 3).

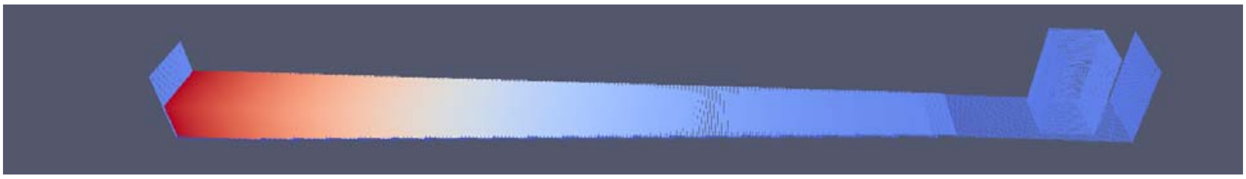
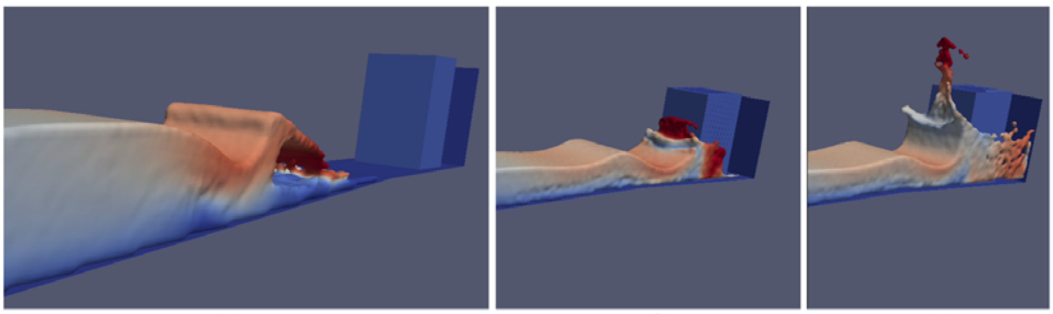


Figure 3. Configuration of tsunami wave model and building model

A total of 96 tsunami simulation were performed on the DualSPHysics. Figure 4 shows how the tsunami wave arrives at the coastline and how it hits the structure. The wave height evolution at the structure was used to calculate the other forces: hydrostatics, and buoyant force



(a) (b) (c)

Figure 4. Side view of tsunami wave simulated on DualSPHysics (a) arriving at coast line and approaching the structural model, (b & c) impacting the structural model.

3.2 Structural model

The prototype model is a three-story building that is 6 m long, 6 m wide, and 3.6 m high each story. It has 4 reinforced concrete square columns (Figure 5). In this study, we built two models of the structure. The differences are the column cross-section and reinforcing steel content. In Model01 the cross-section is 71.2 x 71.2 cm. In Model02 the cross-section is 50.8 x 50.8 cm. The cross-section of the beams is 60.9 x 45.7 cm. Columns have 20 longitudinal rebars with a diameter (ϕ) of 20 mm the yielding stress (σ_y) is 460 MPa.

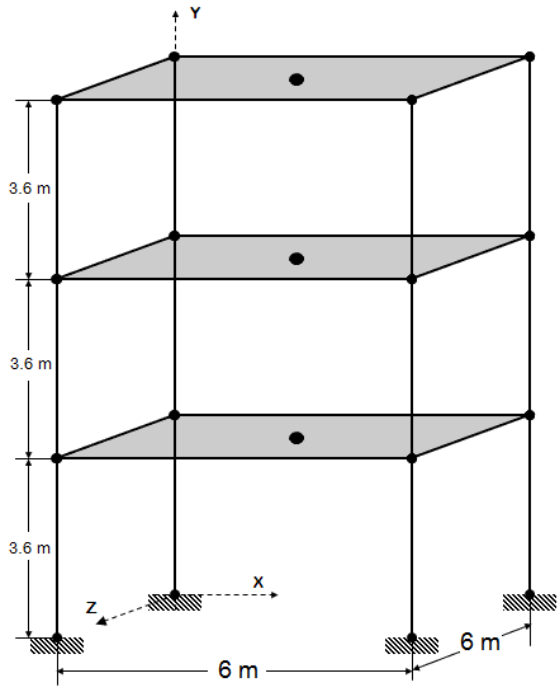


Figure 5. Geometry of structural model

To model the behavior of column a fiber section was used. The core inside the rebars was modeled with confined concrete, the cover was modeled with unconfined concrete. The elastic modulus of the concrete is E_s = 24.85 GPa. The equivalent compressive strength of the confined concrete is σ_{cc} = 859 MPa and the compressive strength of the unconfined concrete is σ_{cu} = 27.5 MPa. The non-linear behavior of the structure is modeled using "nonlinearBeam" elements, "fiber" sections, and non-linear uniaxial behavior models of the materials: core concrete, cover concrete, longitudinal steel rebars. The uniaxial stress-strain (σ–ε) relationship of the concrete uses "Concrete02". Different behavior in the non-linear range is adopted for core concrete, i.e. confined, and cover concrete, i.e. unconfined. The uniaxial stress-strain relationship of the longitudinal steel rebars uses "Steel02" based on Giuffre-Menegotto steel material object with isotropic hardening.

3.3 Fragility curves

The fragility curves computed using Method 2 are shown in Table 1.

Table 1. Fragility parameters estimated by second method

Structure	Reference wave height	Damage state	median (c_m)	std (ζ)
Model 1	Height at the structure	minor	1.30	0.32
		moderate	1.44	
		major	1.52	
		collapse	1.64	
	Height at the coastal line	minor	1.49	0.35
		moderate	1.57	
		major	1.60	
		collapse	1.64	
Model 2	Height at the structure	minor	1.01	0.89
		moderate	1.40	
		major	1.53	
		collapse	1.63	
	Height at the coastal line	minor	1.07	1.02
		moderate	1.43	
		major	1.55	
		collapse	1.64	

4. CONCLUSION

In this study, we demonstrate that it is possible to assess the condition of a structure subject to tsunami waves using dynamic analysis at every stage of the computation. Smooth particle hydrodynamics (SPH) method is nowadays affordable because GPGPU computing and it should be used to compute the hydrodynamics and surge force on the structure. Equivalent static analysis should be avoided because the assumption that the surge force is 1.5 times the hydrodynamic force can underestimate the reality of the non-linear interaction between the wave and the surface. While hydrostatic, buoyant force can be computed using the evolution of the height of the wave, the hydrodynamics and surge force must be extracted directly from the tsunami simulation.

The framework used to compute the analytical fragility curves of a structure subject to tsunami is similar to the framework used to compute the analytical fragility curves of a structure subject to earthquake. In both environment different intensity measures can be the dependent variable of the fragility curves. In this study, we proposed the height at the coastline because it is a parameters common to all the structure in the same area, and the height at the structure. Other intensity measure should be investigated but the amplitude, the shape, and the duration of tsunami waves varies widely between the different cases.

The data set of tsunami simulations was carried out on a single GPU. Our future research focuses on the generation of tsunami waves at their point of origin and their propagation up to the coastline and structures present on it. These SPH models will require the use of billions of particles and multi-GPU systems. However, the analytical fragility curves of this study can and will be used to assess the status of the structures over the entire area affected by the tsunami waves.

ACKNOWLEDGEMENT

This work was supported by the year of 2012-2013 Research Funds of the Ulsan National Institute of Science and Technology (UNIST).

REFERENCES

Árnason, H. (2005). "Interactions between an Incident Bore and a Free-Standing Coastal Structure."
Crespo, A. J. C., Dominguez, J. M., Rogers, B. D., Gomez-Gesteira, M., Longshaw, S., Canelas, R., Vacondio, R., Barreiro, A.Garcia-Feal, O. (2015). "DualSPHysics: Open-source parallel CFD solver based on Smoothed Particle Hydrodynamics (SPH)." *Computer Physics Communications* **187**: 204-216.
Fema (2008). "Guidelines for Design of Structures for Vertical Evacuation from Tsunamis (FEMA P646)". Federal Emergency Management Agency.
Lucy, L. B. (1977). "A numerical approach to the testing of the fission hypothesis." *The astronomical journal* **82**: 1013-1024.
McKenna, F. (2011). "OpenSees: A Framework for Earthquake Engineering Simulation." *Computing in Science Engineering* **13**(4): 58-66.
Monaghan, J. J. (1992). "Smoothed Particle Hydrodynamics." *Annual Review of Astronomy and Astrophysics* **30**: 543-574.
Nistor, I., Palermo, D., Cornett, A.Al-Faesly, T. (2011). "Experimental and numerical modeling of tsunami loading on structures." *Coastal Engineering Proceedings* **1**(32): currents-2.
Ramsden, J. (1996). "Forces on a Vertical Wall due to Long Waves, Bores, and Dry-Bed Surges." *Journal of Waterway, Port, Coastal, and Ocean Engineering* **122**(3): 134-141.
Shinozuka, M., Feng, M. Q., Lee, J.Naganuma, T. (2000). "Statistical analysis of fragility curves." *Journal of Engineering Mechanics-Asce* **126**(12): 1224-1231.
Yeh, H. (2007). "Design Tsunami Forces for Onshore Structures." *Journal of Disaster Research* **2**(6): 531-536.