KEYNOTE: ADVANCES IN EVALUATING TSUNAMI FORCES ON COASTAL STRUCTURES

Tiziana ROSSETTO[1] Ian EAMES[2] and Tristan O. LLOYD[3]

Abstract: This paper presents a brief overview of the current knowledge and research gaps in the evaluation of tsunami forces on coastal structures. It presents the need for a systematic analysis of the physics of tsunami flows in and around buildings and the forces and pressures they produce on structures as a function of time. The first steps towards such a study are presented. Through a combination of large-scale physical experiments reproducing the forces generated by extremely long, tsunami-like, waves on instrumented building models, and small-scale tests of steady flows around rectangular cylinders, it is shown that steady-state approximations of drag force can potentially represent the unsteady case of tsunami flows around buildings. Significant limitations surround this observation and hence, plans to continue the study are presented.

Introduction

Tsunami are water waves caused by earthquakes, volcanic eruptions, meteorite and underwater or aerial landslides occurring in relatively shallow waters. At source, tsunami waves have relatively small wave heights (typically 0.5-2m), but very long wavelengths. As these waves approaches the shoreline and enter the shallower waters, their wavelength reduces and their wave height increases dramatically. The resulting waves can cause violent impacts on infrastructure and structures, and the long wavelengths lead to extensive inundation inland causing destruction over large areas of coast as seen recently in Japan (2011). Community and infrastructure exposure to coastal floods across the world is forecast to increase to 150 million people and £20 trillion in assets by 2070 (Nicholls et al. 2007). Also, climate change scenarios over the 21st Century predict an increase in sea-level rise (IPCC,2007), which will lead to increased severity of coastal flooding from tsunami when they happen.

Tsunami risk to coastal areas is composed of: the tsunami hazard, and the vulnerability of the natural and built environment to this hazard. Good understanding, representation and modelling of both elements are necessary in order to produce useful and reliable damage scenarios and loss estimates. There are however, large gaps in knowledge in both risk components. For example, from the hazard perspective there are large uncertainties regarding nearshore processes of tsunami, inundation prediction and tsunami loading on buildings. From the vulnerability standpoint it is not yet clear how different structural types perform under tsunami. No reliable method exists for the analysis of buildings under tsunami onshore flows; existing analyses are limited to looking at building resistance under peak forces, poorly estimated due to lack of aforementioned knowledge. Despite these gaps, tsunami are entering design guidance, and tsunami risk analysis required for special structures (e.g. USNRC, 2009).

Around the world, virtually all coastal cities or major infrastructure require some degree of shoreline protection/coastal defence, most of which are configured to handle storm waves. Only a few regions have invested into the design and building of tsunami specific defences, however even these may be inadequate. Whilst some defences will indeed mitigate the impacts of many tsunami by reducing their inundation characteristics, this may not always be the case. When a tsunami defence wall fails, it may do so suddenly, discharging flows that

[1] Professor in Earthquake Engineering, EPICentre, University College London, London, t.rossetto@ucl.ac.uk
[2] Professor in Fluid Mechanics, University College London, London, i.eames@ucl.ac.uk
[3] AIR Worldwide Ltd., London, tlloyd@air-worldwide.com

have accumulated at the defence onto assets that may have been expected to be defended (hence not appropriately designed). An inundation wave arising from sudden failure of tsunami defence may present a deeper and more violent bore than would have arisen in the absence of the defence. It is therefore important to quantify the effects of tsunami defences up to and including their 'design' level of performance, quantify their failure limits, and their post-failure contribution to coastal protection.

This paper presents preliminary observations obtained from sets of unique physical experiments designed to study the impact of tsunami-like waves on coastal structures towards the development of tsunami design/assessment guidance. The experiments demonstrate a significant difference in the behaviour of very long waves (typical of tsunami) and their interaction with structures compared to shorter waves.

Loads on buildings from tsunami onshore flows

Experiments relating to the loading of structures from waves are extensive. The work of Morison et al. (1950), Goda (1974) and later Takahashi and Shimosako (1994) made large contributions to the design equations used in offshore structures and sea walls, respectively. Loading induced by short-period inundating waves on structures has been examined by Camfield (1980), Camfield (1991), Asakura et al. (2002), Yeh (2007), and Lukkunaprasit et al. (2009b). Much of this literature has led to the development of recent design guidance; Okada et al. (2006), and FEMA (2008), which are beginning to be used in real world applications. All this guidance is however based on experiments carried out for solitary waves of short period as compared to tsunami.

Guidance on forces from tsunami that exists (e.g. FEMA, 2008), commonly split the flood loads into components: hydrostatic force (dependent on flow depth, *d*), hydrodynamic force (dependent on onshore flow velocity, *v*) and impulse load (initial overshoot associated with the impact of the leading tongue of a wave or surge). The latter component is commonly presented as an empirical factor multiplied by the hydrostatic (e.g. 1.5 x hydrostatic force in FEMA, 2008), where the empirical factor is based on expert judgement and limited experimental observations. Onshore flow depth from tsunami can be calculated from existing numerical models of inundation, but velocities are poorly predicted. Hence, the guidance documents provide simplified formulae for determining tsunami flow velocities onshore. But, a problem with most design codes is that their methodologies have been modified for use with tsunami directly from fluvial flooding manuals (e.g. FEMA 2000, Camfield 1980). Tsunami and fluvial flooding are inherently different phenomena; fluvial flooding is generally considered as open-channel flow where velocity is proportional to the square root of the flow depth (as seen in the Chézy equation) whereas the same is not true of tsunami. The peak inundation for tsunami generally occurs at the transition between run-up and draw-down (Lukkunaprasit et al., 2009b), a time when the flow is slowing and beginning to reverse, so at a minimum. Shallow water theory also predicts that the maximum tsunami velocity occurs at the leading tip of the incoming run-up (Yeh, 2006; Shen and Meyer, 1963), a time when the depth is at a minimum or theoretically zero. The complete opposite to a flood. Despite this, velocity equations in current guidance are all based on an empirical factor multiplied by the square root of the flow depth. Hydrodynamic force equations found in past guidance combine empirical factors with a drag coefficient (dependent on the structure geometry, size and orientation) and either the maximum velocity squared (v_{max}^2) or more recently, the maximum momentum flux, $(d.v^2)_{max}$, (FEMA, 2008) in recognition that the maximum flow depth and velocity may not coincide. However, in all existing guidance a structure is supposed to be assessed for a peak tsunami force, assuming the peak hydrostatic, hydrodynamic and impulse loads occur at the same time.

Although these design guides represent a first attempt to deal with the tsunami aspects of structural design, very little verification of these design equations has been conducted (Lukkunaprasit et al., 2009a, Asakura et al., 2002, Fujima et al., 2009), and that which has been done adopts experimental setups similar to those on which the equations were based i.e. use short-period waves that are not representative of tsunami in the field. This is true even of those studies carried out at large-scale, (Arikawa, 2009).

Limitations of numerical and experimental simulation of tsunami onshore flows

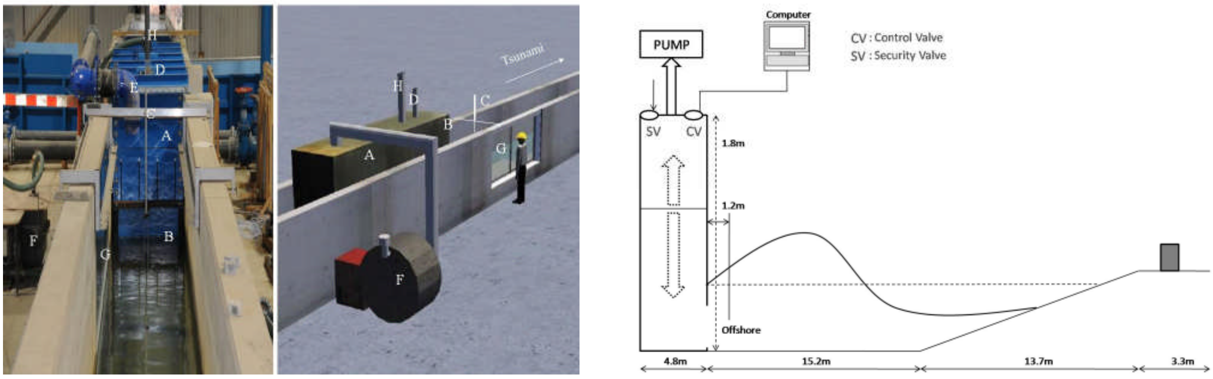
Generation and propagation of tsunami can be simulated numerically. Tsunami transformations into coastal margins can be simulated by many well-known numerical models such as Non Linear Shallow Water or Boussinesq models e.g. MOST (Titov and Synolakis, 1998) and FUNWAVE (Grilli et al. 2007). However, critical gaps in knowledge exist in the modelling of nearshore and onshore processes, which are of interest for the determination of design/assessment loads on structures in coastal regions or coastal defences. Numerical models are able to simulate offshore wave characteristics of tsunami wave forms. However, the physics of the wave form, as it enters the shallow water and encroaches onshore, becomes more complex and requires much higher bathymetric and topographic resolutions in order for the numerical model to provide a realistic simulation of the flow. For example, Mader (2004), found grid resolutions as small as 10m were needed to represent local flooding in his study of the inundation of Hilo, Hawaii during the 1946 tsunami. In low tidal areas, typical coastal structure near the shoreline will have vertical heights often as small as 2-4m, so vertical resolutions of order 0.2m may be desirable. Unfortunately, the most widely available elevation datasets have a horizontal resolution of 1 minute e.g. (BODC, 2008). When the grid resolution required to model local flooding is extremely fine, the total number of grid cells covering a given area of study is much greater and computing times become cumbersome. Multiple core computers are required to run one simulation, the multiple simulations required for fragility analysis would therefore require supercomputing resources. Also, the models are unable to cope with the changes in flow condition and resolution.

In general, physical modelling of wave - structure processes is commonly used to analyse fluid flow processes and responses for which complexities are too great to model numerically. In the design of any physical model tests, it is essential to establish which processes are being reproduced correctly and hence those that are not correctly reproduced. Most wave/structure problems studied in physical models, such as direct wave loads, armour movement etc, are dominated by wave inertia/momentum. The ranges of scales (or strictly the size of model wave) that can be used without significant scale effects are relatively well-established (Wolters et al, 2009) so that quite small scales (for example 1/50 to 1/100) can be used for those processes that are dominated by wave inertia or momentum. An inherent complication in the physical modelling of large/long waves is accurate wave generation, especially because few facilities have been constructed to deal with such relatively rare phenomena. Many studies have modelled generation and propagation of large waves, but they have mainly concentrated on idealised cnoidal and solitary waves (e.g. Synolakis, 1987, Jensen et al., 2003), which have limited similarity to Tsunami (Madsen et al. 2008).

Conventional piston wave generators can recreate solitary waves (often used to approximate tsunami, but simply do not have the stroke to reproduce realistic tsunami wavelengths and periods; an immediate limitation. For example, the tsunami facility at Oregon State University (Yim et al. 2004) can generate waves which at a scale of 1/50 in the Tsunami Wave Basin would have a period of 3.5s to 71s, and at a scale of 1/5 in the Long Wave Flume would have a period of 1.1s to 22.4s. For some events this may be sufficient, but most tsunamis have typical periods ranging from 2 to 200min. For example, the “Mercator” trace (Siffer 2005) recorded during the 2004 tsunami displayed a main direct wave which had a period of approximately 20min (Figure 2). Most worldwide facilities adopt piston wave-makers, hence are limited to the generation of solitary waves with periods <10s, and are also unable to reproduce stable leading depression waves that can characterise tsunami. The only way they could generate such a wave is for the piston to start part-stroke and then be pulled back in its first cycle. This method has not been shown to produce stable wave forms as highlighted by the experimental results of Schmidt-Koppenhagen et al. (2006).

The UCL-HR Wallingford Tsunami Tests

Through a UCL-HR Wallingford collaboration an innovative method for generating tsunami in the laboratory was developed that that uses a pneumatic, rather than a paddle system. In brief, the generator consists of a sealed tank, which sits at one end of a long flume, with a submerged opening facing shorewards. A fan extracts air from the top of the tank, drawing water from the test flume. A valve releases air to generate a wave from the tank. Control of the air valve in the top of the tank gives the desired wave shape. This form of wave generation is ideally suited to simulating tsunami as it allows the controlled movement of large volumes of water in a confined space without high discharge water pumps, which are expensive in both capital and operational costs. Schematics and photographs of the tsunami generator in the flume and the tank are shown in Figure 1. Tests carried out using the new tsunami generator demonstrate that it is the only facility worldwide currently able to produce wavelengths long enough to represent tsunami and generate stable trough-led waves (see Rossetto et al. 2011). The maximum wavelength generated to date corresponding to the Mercator recording (2004 tsunami) with wavelength of 23km reproduced at scale 1/50.



(a) (b) (c)

Fig. 1. (a) tsunami generator and (b) schematic diagram of the generating system, (c) schematic diagram of the experimental setup with main dimensions: A: Wave tank, B: gate, C: “Offshore 1” probe, D: control valve, E: water supply, F: pump, G: glass window and H: security valve

The original aim of this study was to model accurately the propagation of earthquake-generated Tsunami through the surf zone and to the inundation of buildings behind the shoreline. From observation of these physical experiments it was hoped to better quantify tsunami run-up and / or loading regimes on typical buildings, providing essential research input for the future up-grading of structures in areas at risk from tsunami. New tsunami runup equations have been produced, following a better understanding of the tsunami evolution onshore (Charvet et al. 2013).

A better understanding of the evolution of forces and pressures over time is also arising from the results of a limited number of experiments carried out on structures in the flume using the tsunami generator (Lloyd and Rossetto, 2012) and a number of small scale tests carried out at UCL (see Fig. 2) to better characterise steady flows around rectangular cylinders (Lloyd, 2014 and Qi et al. 2014). In particular, the latter show that for a single configuration and blockage ratio, that once a critical Froude Number is surpassed the flow regime around the square cylinder passes from being sub-critical (where drag forces dominate) to choked (where hydrostatic forces dominate). In recognition of the fact that the majority of numerical models cannot represent buildings explicitly in their simulations, Qi et al (2014) propose a set of equations for describing the forces on the rectangular cylinder from only knowledge of the flow velocity, depth and Froude number in front of the cylinder and the ratio of the cylinder width to that of the flume. When these steady state equations are applied to the unsteady case of the rectangular buildings tested under tsunami, Figure 3 results; i.e. the measured force time-histories seem to agree well with those predicted by the steady flow equations.

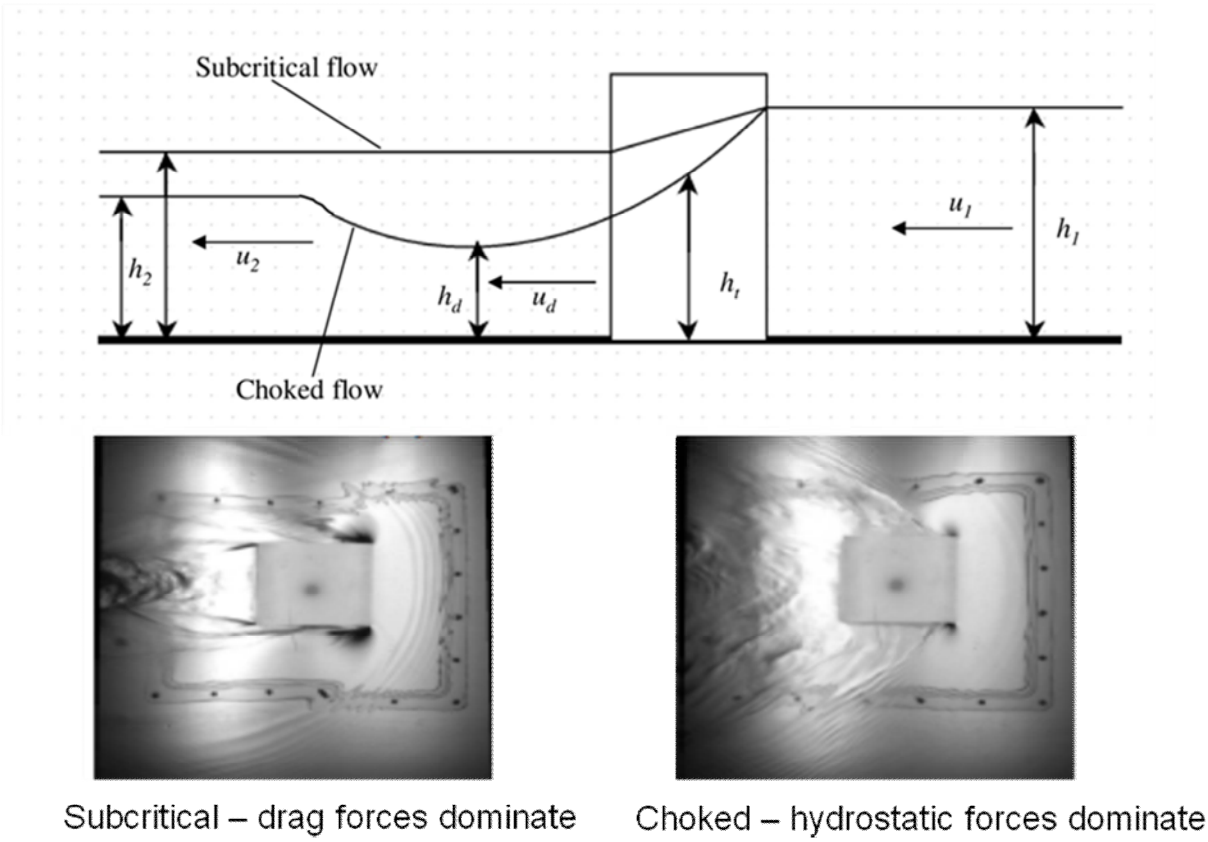


Fig. 2. Schematic diagram and photos of the steady flow tests at UCL showing the identified Choked and Subcritical flow regimes (adapted from Lloyd 2014 and Qi et al. 2014)

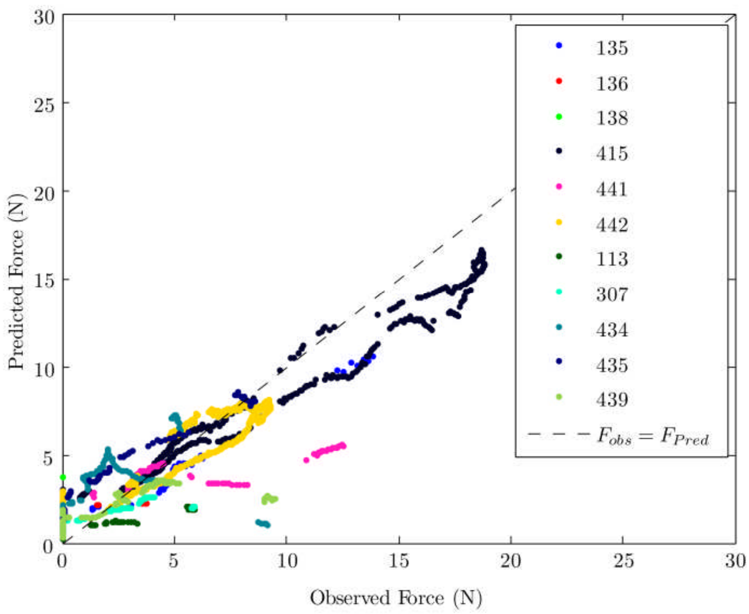


Fig. 3. UCL-HRW tests of forces on a rectangular body subjected to 13 different tsunami-like waves: Observed forces versus those predicted by the Qi et al. (2014) equations.

These results show strong promise and suggest that a steady flow assumption may be applied to the unsteady case of tsunami onshore flow. However, it is recognised that the UCL-HRW tests for forces on a rectangular body subjected to tsunami onshore flow are few

(13 waves repeated 3 times each) and pertain to a single structural configuration. Also the length of the test flume was insufficient for the waves generated (even though the flume was 40m long), meaning that only a limited range of wave steepness/height were reproduced and issues were seen with the accurate generation of the full wave profiles of the longest waves generated.

Conclusions and Next Steps

This paper presents research on tsunami forces that is very much a work in progress. Clearly there is a need for a systematic analysis of the physics of tsunami flows in and around buildings and the forces and pressures they produce on structures as a function of time**,** of which the above measurements are only a first step. Furthermore, the few velocity readings taken of onshore flow during these tests show that the code equations do not appropriately represent these, and that there is acceleration of the flow along the shore, especially for very long waves and depression-led waves (Charvet, 2012). These are not aspects that can be seen in experiments carried out using traditional paddle generators but have been observed in real tsunami (Fritz et al. 2011).

On the basis of the work presented here, the Author was successful in obtaining an ERC Starting Grant called “URBAN WAVES” for the continued collaboration with HR Wallingford and the experimental and numerical modelling of tsunami flows around buildings but also for the study of tsunami impact on coastal defences. This project sees an improved version of the pneumatic tsunami generator built and placed in a 100m x 1.8m flume located at HR Wallingford. The improved design includes increasing the height and capacity of the tank, modifying the opening where the wave is generated to reduce eddies/back flow, and making the opening adjustable, so as to allow a larger range of wave heights and steepness’ to be generated. Use of the 100m long flume will overcome issues identified as regards the reliable reproduction of very long waves.

Using the new facility, three phases of experiments will be carried out during the 5 years of the grant. Phase 1, is to be carried out in Spring/Summer 2015, and will focus on coastal defence structures. Preliminary observations from these experiments will be presented in the Keynote address that accompanies this paper. These experiments will be accompanied by extensive numerical analysis, using numerical models validated against the experiments. These will allow observations made in the laboratory to be extended to real sceniarios.

Acknowledgements

The research presented in this paper derives from the work of several people. In particular William Allsop, David Robinson and Ian Chandler at HR Wallingford, and EPICentre staff and researchers past and present: Dr Tristan Robinson, Dr David McGovern, Dr Ingrid Charvet and Joshua Macabuag. This research has been funded by The European Research Council, the UK Engineering and Physical Sciences Research Council, Willis Re and Arup.

REFERENCES

Arikawa, T. (2009). structural behavior under impulsive tsunami loading, *J.Disaster Research*. 4:6. 377–381.

BODC (2008). Gridded Bathymetry Data (GEBCO); 14-1-2008

Camfield, F. E. (1980). *Tsunami Engineering*. Special Report No. 6, US Army Coastal Engineering Research Center, Fort Belvoir, Virgina.

Camfield, F. E. (1991). Wave Forces on Wall. *J. Waterway, Port, Coastal and Ocean Engg.* 117:1,76–79.

Charvet, I. (2012). *Experimental modelling of long elevated and depressed waves using a new pneumatic generator.* PhD Thesis, University College London, January 2012.

Charvet, I., Rossetto, T., Eames, I. (2013). New Tsunami Runup Relationships Based on Long Wave Experiments. *Ocean Modelling.* 69: 79-92.

FEMA (2005). *Coastal Construction Manual, third edition.* FEMA 55, Federal Emergency Management Agency, Washington D.C.

FEMA (2008). *Guidelines for Design of Structures for Vertical Evacuation from Tsunamis*. Technical Report P646, Federal Emergency Management Agency, Washington D.C.

Fritz HM, Phillips DA, Okayasu A *et al.* (2012) The 2011 Japan tsunami current velocity measurements from survivor videos at Kesennuma Bay using LiDAR.*Geophysical Research Letters* 39.

Fujima, K., et al. (2009). Estimation of Tsunami Force Acting on Rectangular Structures, *J. Disaster Research* 4:6, 404–409.

Goda, Y. (1974). New wave pressure formulae for composite breakwaters, *Proc. of the 14th International Coastal Engineering Conference*, 3, 1702–1720.

Grilli ST, Ioualalen M, Asavanant J, Shi F, Kirby JT, Watts P. (2007). Source constraints and model simulation of the December 26, 2004, Indian Ocean Tsunami. *Journal of Waterway, Port, Coastal and Ocean Engineering* 2007; 133:414-428.

IPCC (2007). *Climate Change 2007: The Physical Science Basis* (eds Solomon, S. *et al.)* (Cambridge Univ. Press, Cambridge, UK, and New York, 2007).

Jensen A, Pedersen GK, Wood DJ. (2003) An experimental study of wave runup at a steep beach. *J. Fluid Mechanics* 2003; 486:161-188.

Lloyd, T. (2014). *PhD Thesis*. Submitted.

Lloyd, T., Rossetto, T. (2012). A comparison between existing tsunami load guidance and large-scale experiments with long-waves. *15th World Conference on Earthquake Engineering*, Lisbon, Portugal, September 24-28, 2012. Paper No.1092. Oral Presentation.

Lukkunaprasit, P., Thanasisathit, N., Yeh, H. H. (2009a). Experimental Verification of FEMA P646 Tsunami Loading, *Journal of Disaster Research* 4:6, 410-418

Lukkunaprasit, P., Ruangrassamee, A., Thanasisathit, N. (2009b). Tsunami loading on buildings with openings, *Science of Tsunami Hazards* 28:5, 303–310.

Mader CL. (2004). *Numerical Modeling of Water Waves*. 2nd ed. London: CRC Press; 2004.

Madsen PA, Fuhrman DR, Schäffer HA (2008). On the Solitary Wave paradigm for Tsunamis. *Journal of Geophysical Research 2008; 113:C12012.*

Morison, J. et al (1950). The force exerted by surface waves on piles, *Petroleum Transactions* 189,149–154.

Nicholls R.J., et al. (2007). Ranking port cities with high exposure and vulnerability to climate extremes: Exposure estimates. *OECD Environment Working Papers,* No.1, OECD publishing.

Okada, T., Ishikawa, T., Tateno, T., Sugano, T., Takai, S. (2006). *Tsunami loads and structural design of tsunami refuge buildings*. Technical report, The Building Centre of Japan.

Qi, Z.X., Eames, I., Johnson, E.R. (2014), Forces acting on a square cylinder fixed in a free-surface channel flow. *Journal of Fluid Mechanics*, 756:716-727.

Rossetto, T., Allsop, W., Charvet, I., Robinson, D. I. (2011). Physical modelling of tsunami using a new pneumatic wave generator. *Coastal Engineering* 58(6), 517-527.

Schmidt-Koppenhagen R., et al (2006). Tsunami wave decay in near and onshore areas. *ICCE*: 1665-1676

Shen, M. C., Meyer, R. E. (1963). Climb of a bore on a beach : Run-up. *J. Fluid Mechanics.* 16 (01), 113.

Siffer, T. (2005). “Mercator" depth gauge recording of 26 December 2004 tsunami. Ref Type: Data File from the Meteorological Database of the Netherlands. Available at http://www.knmi.nl/onderzk/seismo

Stilwell A. (2009) *State of the Nation: Defending Critical Infrastructure,* Institution of Civil Engineers.

Synolakis CE. (1987) The runup of solitary waves. *Journal of Fluid Mechanics* 1987; 185:523-545.

Takahashi, S., Shimosako, K. (1994). Wave pressure on a perforated wall, *Proc., Int. Conf. on Hydro-Technical Engineering for Port and Harbor*, Japan.

Titov VV, Synolakis CE (1998). Numerical modeling of tidal wave runup. *Journal of Waterway, Port, Coastal and Ocean Engineering*. 1998; 124:157-171.

USNRC (2009). *Tsunami hazard assessment at nuclear power plant sites in the United States of America*. Technical Report NUREG/CR-6966, United States Nuclear Regulatory Commission, USA.

Wolters G, et al. (2009) HYDRALAB III: Guidelines for physical model testing of rubble mound breakwaters, *Proc ICE Conf. on Coasts, Marine Structures & Breakwaters*, Edinburgh, September 2009

Yeh, H. H., (2006). Maximum Fluid Forces in the Tsunami Runup Zone. *Journal of Waterway, Port, Coastal, and Ocean Engineering* 132 (6), 496.

Yeh, H. H. (2007). Design Tsunami Forces for Onshore Structures*, J.Disaster Research* 2:6, 531–536.

Yim S, Yeh H, Cox D, Pancake C. (2004). A shared-used large-scale multidirectional wave basin for tsunami research. *Proc. of the 13th World Conference on Earthquake Engineering*: Vancouver 2004; Paper 1517.