A UNIQUE TSUNAMI GENERATOR FOR PHYSICAL MODELING OF VIOLENT FLOWS AND THEIR IMPACT

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ABSTRACT :

Tsunami waves travel across oceans with quite small vertical displacements, but shoal up dramatically in coastal and nearshore depths, and can cause extensive loss of life and infrastructure. Propagation of tsunami waves in the nearshore, across the shoreline, and then inland is not well modeled by many current techniques. Physical modeling can be used to study flow and force processes, but correct generation of the tsunami wave(s) is essential and conventional wave paddles simply do not have adequate stroke to reproduce the required wavelength. A collaboration between University College London (UCL) and HR Wallingford (HRW) is working to eliminate obstacles to physical modeling of tsunamis and their effects. Within this project, HRW has constructed an innovative Tsunami Generator which is capable of generating multiple waves, an initial draw-down and ensure realistic wavelengths. The Tsunami Generator is mounted within a 45m wave flume and is able to generate tsunami waves which have been previously transformed from deeper water (approx -200m) to shallow water (approx -20 to -50m) using any suitable numerical model. Bathymetry in the wave flume shoals the tsunami waves over a representative coastal slope though the shoreline and inland, covering a suitable inland inundation area. Several stages of modeling are required to validate details of the Tsunami Generator design and control system. The modelling team will then measure flow / wave driven loadings on representative (model) buildings. This paper presents a summary of these and outlines opportunities for international teams to carry out participative testing using this unique facility.

KEYWORDS: Tsunami, physical testing, hydraulic models, waves, overtopping, violent flows

1. INTRODUCTION

Tsunamis are water waves caused by earthquakes, underwater landslides, volcanic eruptions or major debris slides. In deep water, tsunami waves have relatively small heights (typically 0.5-2m), but very long wavelengths (i.e. 5-20km). As these waves enter the shallower waters of coastal areas, their length reduces sharply and their wave height increases dramatically. The resulting steep waves may cause violent wave impacts onto shoreline structures, and the very long wave lengths may lead to extensive inundation inland. Most tsunamigenic seismic sources cause multiple waves, which on one side of the fault may be preceded by a leading depression wave, but not on the other side. Where the seismic slip is long, the tsunami waves are strongly directional without substantial spreading (reduction with distance). For shorter slips, the resulting waves will be reduced by radial dispersion. At approximately 1,200 km long (estimates differ between 1,000 and 1,600km), the December 2004 Indian Ocean tsunami was one of the longest generating fronts, and therefore least directionally spread tsunamis.

Tsunami risk to coastal areas can be considered to be composed of two main elements: the tsunami hazard, and the vulnerability of the natural and built environment to this hazard. Good understanding, representation and modeling of both elements are necessary in order to produce useful and reliable damage scenarios and loss estimates. Governments require such estimates to make decisions as to if and how to intervene to mitigate potential tsunami induced losses, and where to locate critical facilities or emergency resources to ensure effective post-disaster relief and recovery. 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. Indeed current state-of-the-art treats tsunami loading on buildings as equivalent to that of a flood with appropriate velocity and inundation height (e.g. FEMA, 2005 and 2008). From the vulnerability standpoint it is not yet clear how different structural types perform under tsunami actions, nor to what extent different coastal protection measures mitigate tsunami effects.

This paper provides an outline of the “Violent Flows” project being undertaken by HR Wallingford (HRW), Arup and UCL’s Earthquake and People Interaction Centre (EPICENTRE). This project looks to answer a number of the following questions: given a certain tsunami, bathymetry and beach topography:

- Can we predict the onshore flow?
- What are the tsunami loads on coastal structures?
- Are existing guidelines (e.g. FEMA, 2005) adequate?
- What are the criteria of design acceptability?

In particular this paper describes the first phase of the project, which looks to answer the first two questions above through the development of a physical modeling facility capable of generating a train of tsunami waves within a 2-D flume at a scale of between 1:75 and 1:150.

2. MODELING TSUNAMI ONSHORE FLOW

A characteristic of Tsunami waves is their very large ratio of wavelength to wave height. Even the biggest Tsunami may only have a wave height of about 5m, whilst their wavelength could be 10 to 20km. As these waves move into coastal and nearshore depths, they shoal up dramatically, creating a hazardous wall of turbulent water. It is often mistakenly assumed that Tsunami waves occur singularly. Actual events often generate a series of waves, which interact significantly as they propagate shoreward. This is important when studying the effect of Tsunami onshore, as the combined effect of multiple waves can be devastating. A further misnomer is that they are always preceded by a negative wave or trough. In reality, most subduction driven tsunami generate a trough on the over-riding side of the slip, but not on the other side. Generation and propagation of Tsunami have been simulated by various numerical models, from source to nearshore (e.g. Richardson, 2006, or Titov & Synolakis, 1998). The critical gaps in knowledge are in the propagation of Tsunami in the nearshore region, across the shoreline and any coastal structures, and then inland. These flow processes can be simplified for numerical models, but the limitations that flow from those simplifications are not yet well established as there are complex interactions with beaches, sediment, coastal defences, and then around buildings. These processes can however be simulated in physical models, but correct generation of the Tsunami waves is essential, including in some instances the characteristic draw-down of the preceding trough. Many academic studies have been performed to physically model the generation and propagation of large waves, but they have mainly concentrated on idealised cnoidal and solitary waves (Goring, 1987; Synolakis, 1987), or have attempted to model landslide generated Tsunami by dropping or sliding a large object into the water (Wiegel, 1960), and Thusayanthan & Madabhushi (2008). These simplified approaches introduce significant uncertainty into the wave generation, and fail to respect either the inherent wave lengths, the multiple waves, or the preceding trough. Other researchers have used conventional piston or sliding wedge wavemakers which could theoretically make multiple waves, but must still abbreviate the wavelength. The inland flows so produced are therefore likely to be substantially lower than in reality.

3. THE NEW TSUNAMI GENERATOR

Physical modelling of wave - structure processes is commonly used in coastal structure analysis / design to predict armour movement, component forces, wave overtopping, and related responses where the complexity of the fluid flow processes are too great to model numerically. The major problem with physical modelling of Tsunami waves is the generation of the full length of the wave. Conventional flap or piston paddle generators simply do not have the stroke to reproduce the entire wavelength, which can be of orders 1 - 10km at prototype scale. This project aims to design and construct the first Tsunami Generator that will be capable of generating a complete Tsunami within a physical model. It adapts the principles of HRW’s pneumatic tide generators with the intention to run tests at scales between 1:75 and 1:150. Generation of the full wavelength is important to be certain of fully capturing the forces that can act on coastal structures, buildings and vegetation as the Tsunami propagates onshore. These forces can be divided into three stages: momentum-driven forces imparted by the wave front; drag forces (mostly) from onshore flows that follow the wave front; and (drag) forces exerted as the wave retreats seaward. This last force, and of subsequent waves, can be aggravated by debris in the flow, note particularly the discussion in FEMA (2008).

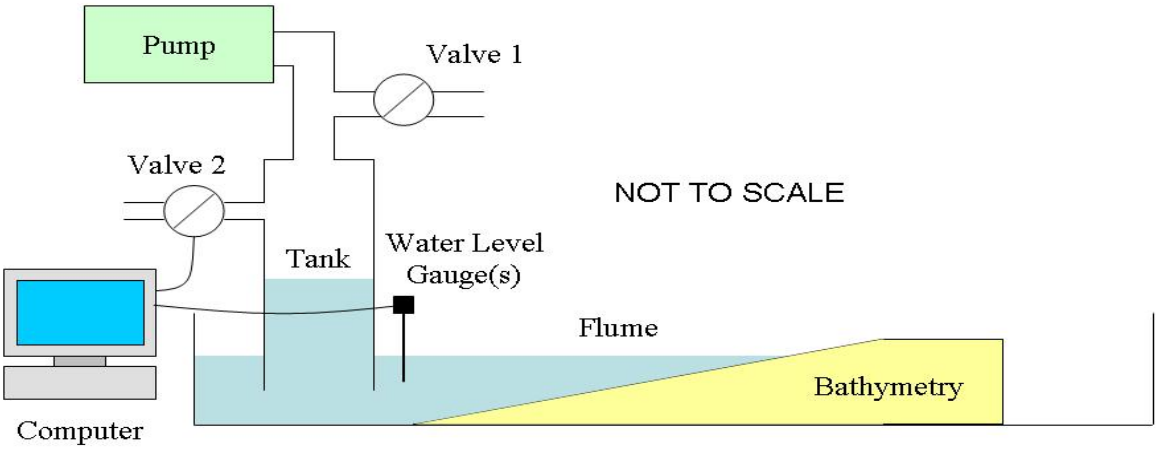


Figure 1: Conceptual design of the Tsunami Generator

The HRW Tsunami Generator is designed along the principles of the Pneumatic Tide Generator previously built and used by HR Wallingford (Wilkie & Young, 1952). Such tide generators are particularly useful in moving large amounts of water in and out of a model in a controlled manner using relatively small control elements. This ability makes this type of tide generator ideally suited to the generation of Tsunami because they are capable of creating the unusually long wavelengths that characterise these waves, and can generate both crest and trough components. At the time of writing this paper (July 2008), the Tsunami Generator has been constructed and is under initial trials. When in use, the Tsunami Generator will be installed at the end of one of the 45m long 2-dimensional wave flumes within the Froude Model Hall at HR Wallingford, placed just in front of the conventional piston paddle. First generation / propagation tests will be conducted with an approach slope of approximately 1:20. When not in use the Tsunami Generator can be lifted out of the flume and stored, allowing the Wave Flume to be used for its main purpose. The concept design is shown in Figure 1, and schematic drawings of the Tsunami Generator in a wave flume in Figure 2.

It is intended that the Tsunami Generator will be capable of generating Tsunami at a scale factor between 1:75 and 1:150, using undistorted Froude scaling. The time period of a Tsunami is rather shorter than of a tide. The main alteration to the tide generator will therefore be to change the control system to operate at increased speed.

As for most such physical modeling the bathymetry in the test flume will be formed by cement mortar overlying compacted fill. The bathymetry profile that will be used during the testing has not been finally chosen, but the provisional assumption is that tests will be run on two different bathymetries. For the initial tests, a (relatively) constant slope of approximately 1:20 will be used to test run-up characteristics for a range of wave forms. Once the performance of the Tsunami Generator has been validated on this simplified bathymetry, it will be moved to the second wave flume with an upper beach slope of approximately 1:100 slope, with a steeper approach slope, say 1:20, to fit into the main body of the flume. This configuration will allow for onshore topography to be included, perhaps including an onshore tank to collect inundating water.

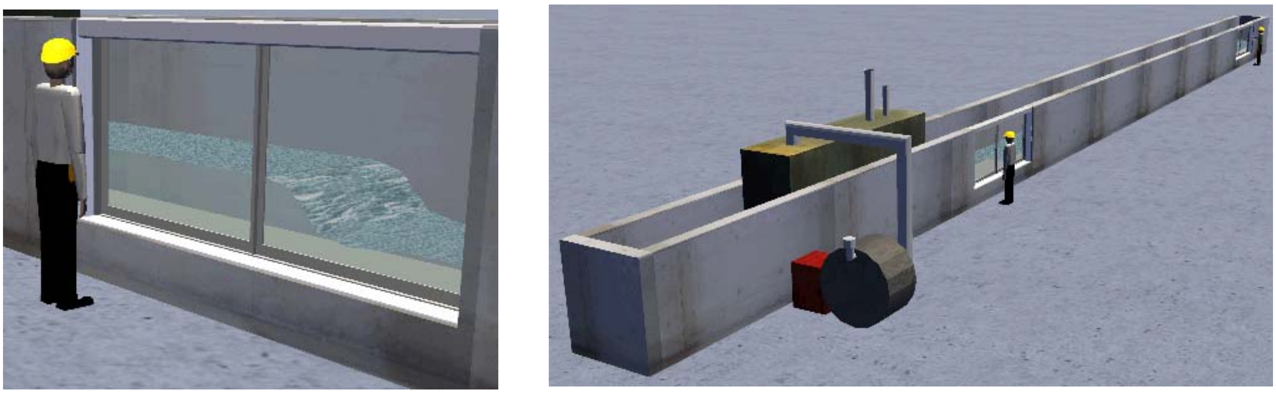


Figure 2: Schematic of the Tsunami Generator in one of the wave flumes at Wallingford

4. PREPARATORY ANALYSIS

4.1. Desk Calculations

Operation of the Tsunami Generator has been analysed using desk calculations to give confidence in its feasibility, and guide the control system design. The desk calculations were carried out in two phases.

Phase 1 estimated the speed of response of the system and explored potential oscillations (overshoot) in the tank water level once the required tsunami had been generated. These suggested how potential oscillations might be minimized. Once the major part of a required tsunami wave crest has been generated, the water within the test flume will need to fall through the equilibrium position under control to a wave trough (i.e. avoiding any further unwanted wave generation). As the control mechanism is air, and therefore rather elastic, it is likely that the falling water column will oscillate in the control tank. Estimating any overshoot will help establish how accurately the trough and tail end of tsunami waves can be modeled. The two drivers for oscillations in the water level are the surface level velocity in the tank at the end of wave generation and the time lag between valve movement and tank water level response. The drivers for these oscillations depend on kinetic and potential energies within the water column. Once equations to model these oscillations were defined, the key parameters were varied to calculate their respective influences on the overshoot magnitude, and period. The calculation was set up, and time lag and water level velocity were then varied independently and their respective effect on the overshoot and required stopping offset were output.

The tsunami generator must be able to draw up (and release) water from the test flume under the control of the vacuum pump and one or two air valves (see Figure 1). The pump must have a suitable performance envelope and the valve control system must be capable of moving the valves at sufficient speed and accuracy. Phase 2 of the calculations therefore involved estimating the performance that will be required from the pump and valve control system. To do so required assumptions on the tsunami waves to be generated. In designing the system, it was assumed that idealised solitary or N-waves would probably be required, but that the test schedule should also expect to reproduce example time series such as that recorded during the Indian Ocean tsunami off Thailand by the Belgian yacht “Mercator”, see Figure 3. The Phase 2 calculations were therefore run for this time series at scales between 1:75 and 1:150.

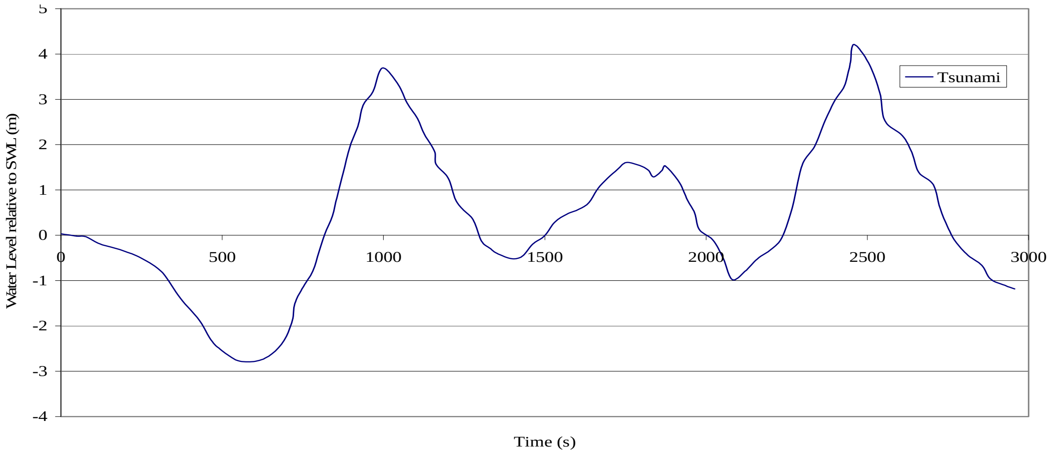


Figure 3: Time series of water surface elevation taken on the yacht “Mercator”.

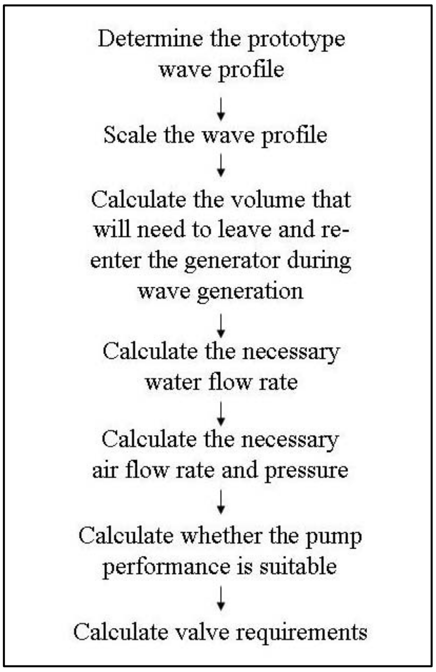


Figure 4: Methodology of Wilkie and Young (1952)

Figure 5: End view into Tsunami Generator tank before installation into the test facility

For the design of the Tsunami Generator tank and control system, an empirical model was created to estimate flow rates, pressures and valve speeds in the tsunami generator based on methodologies described by Wilkie & Young (1952). This procedure gave the required performance envelope for the pump and control system, and relates the required water head and flow rate to generate typically scaled tsunami (see figure 4).

4.2 Shallow Water Wave Modeling

The tsunami generator will propagate a given tsunami shape along the flume. At the scales considered, the approach slope in the test flume will represent the last 2 to 5km of the prototype nearshore area. In most practical cases however, tsunami waves are generated at much greater distances from the coast. So the first stages of wave propagation need to be analysed using numerical models. In this project this is being carried out using ANEMONE (Brocchini & Dodd, 2008) and/or OXBOW (Borthwick et al, 2006), or TELEMAC. Example cases (including the Synolakis solitary wave case) have been modelled using one or more of these tools, to give example time series at the wavemaker boundary, and example wave run-up / inundation velocities for input into the design of instrumentation.

4.3 CFD Modeling

Having completed the initial empirical analysis and wave modeling discussed above, a more advanced CFD model was run to study detailed flows within the Tsunami Generator tank and the test flume. As water is sucked in and out of the tank, it is probable that local sloshing may be generated. Baffles have been placed within the tank to dampen this oscillation, but might reduce the peak flow rates. The CFD model includes water in the tank and in the test flume, and it uses the valve and pump pressure responses to predict water level changes in the tank as the tsunami is generated. The results of the CFD modelling were analysed to check the main flow characteristics, determine the degree of seiching and consequently confirm the effectiveness of the baffles.

5. FINAL DESIGN

The preparatory analysis discussed above was then used to refine the final design of the tank and control system. The tank is being made from flanged and coated steel panels that were bolted together in sections. This allows modular construction, easy removal and storage. Bracing of the panels is required to avoid breakage or distortion of the tank during operation due to the pressure differences that build up between the inside and outside of the tank. The Tsunami generator tank is shown in Figure 5 during installation into the wave flume.

6. DESIGN OF EXPERIMENTS

6.1 Initial trials

The initial experiments that to be performed with the Tsunami Generator will be designed to validate the Tsunami Generator performance against available test cases, probably including solitary wave run-up (Synolakis, 1987) and “N” waves (Tadepalli & Synolakis, 1996). These may require a simplified approach slope, perhaps the 1:20 slope used for previous theoretical work.

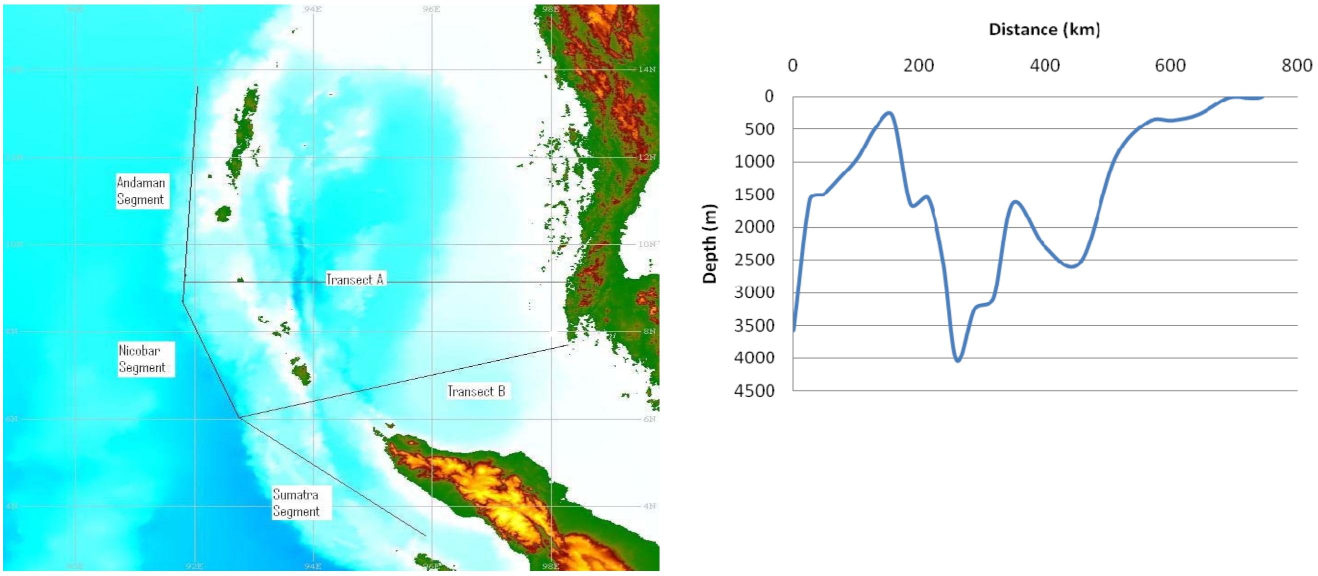
6.2 Use of measured time series

Once validation is complete, a test case from the 2004 Indian Ocean Tsunami will be run. The main data to be used will be the “Mercator” time series (Figure 3). The “Mercator” was anchored a few kilometres off the coast of Thailand at the time of the Indian Ocean Tsunami. It recorded the variations in water depth as the tsunami passed beneath it with an echosounder (1’ sampling interval). When inverted, this signal gives the surface elevation of the water on which Mercator was floating. The signal is relatively free from near-coastal effects and is therefore considerably more useful than records from traditional tide gauges, all of which “drowned-out”. This time sequence will probably be the main prototype event tested, although other wave profiles may be inferred from offshore data if they can be analysed and propagated (as described in section 4.2) to provide further input for the generator.

The initial test location adopted in the outline design of the experiments has therefore been the west coast of

Thailand, This is relatively close to the seismic source, so typical propagation effects affecting a tsunami generated a long distance away (effects of dispersion, Coriolis, earth curvature etc.,) are minimal. Moreover, at this point, the shoreline is approximately "parallel" to the source, so that it faces one of the most energetic propagation paths of the tsunami and allows realistic simplifications to be made as regards the most probable wave directions. Two transects have been drawn and are shown in Figure 6a (with the seismic source outline-west). The bathymetry has been determined from the 1' grid GEBCO bathymetric data. Transect A (Figures 6b) links the source to Ban Thung Dap (in Northern Thailand), where the largest wave height (about 20m) was recorded. Transect B links the source to the Mercator location. At a global scale, the probable wave propagation direction to reach Kamala and Patong is very similar to the wave propagation direction to the Mercator, so the same bathymetric profile can be inferred. So, equivalent Mercator locations proposed around Phuket have been deduced by observing that the most probable wave path from the source to the Mercator is Transect B. This transect is approximately perpendicular to the Nicobar Segment. So if the distance separating the Sumatra junction from the Mercator is 630km, any wave created on the Nicobar segment and propagating towards the shore with a direction parallel to transect B will have started as a time series similar to the Mercator 630km away from the source. In other words, any line perpendicular to transect B passing through the original Mercator location should host a similar wave profile.

Refining the proposed experiment design will require the numerical propagation of a typical tsunami from the source, (or the Mercator time series), to a distance 2 - 5km offshore. In this way we can obtain an input time series that will be physically propagated in the wave flume to simulate the effects observed on areas of the Thai coast. Very shallow nearshore bathymetries will be considered, as they are more representative of Thailand. Experimental data on building loads / damage will then be compared to observations (e.g. from Rossetto et al. 2007).



(a) (b)

Figure 6: (a) Wave directions, transects; (b) Transect A, source to Ban Thung Dap.

6.3 Loads on buildings

Tsunami wave impacts on structures will also be assessed in the physical experiments. This involved scaled models of typical buildings being placed within the flume and impact pressures and/or whole body forces being measured. At the initial stages of experiment design, it is proposed that newly designed "tsunami-proof" buildings and reinforced concrete moment-resisting frames with and without infill walls will be tested. Through these experiments, we aim to quantifying tsunami wave effects on structures in relation to a typical tsunami parameter, perhaps also assessing the validity of existing design guidance (e.g. FEMA 55) or compare with results from Thusayanthan & Madabhushi, 2008). Flow / wave driven pressures will be recorded rapidly to ensure that pressure impulses can be calculated correctly, as even though peak pressures are likely to be distorted by scale effects, the total impulse will be correctly modeled through Froude scaling.

7. FUTURE PLANS

Construction and initial testing of the Tsunami Generator is intended to be completed in Summer 2008. Once proving trials are complete, then the EPICentre team will be using the facility to perform their experimental studies until November 2008. It is intended that this facility will then become available for international teams to use, probably in autumn 2009. The authors should be contacted for further information.

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