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ADVANCES IN PHYSICAL MODELLING OF NEARSHORE TSUNAMI WAVES AND THEIR IMPACT USING A UNIQUE TSUNAMI GENERATOR

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ABSTRACT

This paper presents the functioning principles and initial results of a new wave generator, designed and constructed to reproduce realistic tsunami waves at large scale in the laboratory. Initial stages of testing show the Tsunami Generator can recreate Solitary waves, N-waves, and the Mercator field record from the 2004 tsunami. Preliminary observations suggest "Mercator" type waves will runup higher and display greater shoreline velocities compared to their Solitary equivalent.

Introduction

The understanding of tsunami risk to coastal settlements presents many challenges to the engineering and geohazard science communities. Indeed, there are large uncertainties regarding near-shore processes of tsunami inundation prediction and patterns of tsunami loading on buildings. The current practice treats tsunami loading on buildings as equivalent to that of a flood with appropriate velocity and inundation height (FEMA 2008).

Generation and transformation of tsunami waves can be simulated by various numerical models (Grilli et al. 2007),(Titov & Synolakis 1998). The critical gaps in knowledge are in the propagation of tsunami waves in the nearshore region, across the shoreline, and inland. These flow processes cannot easily be simplified, and are indeed made more complex by interactions with beaches, sediment, coastal defences, and then around buildings. These processes can however be simulated in hydraulic models, but correct generation of the tsunami wave is essential, including in some instances the characteristic preceding draw-down wave. Many academic studies have been performed to physically model the generation and propagation of

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large waves. However, number of these studied relied on conventional paddle generators to simulate tsunami waves, and the wave forms created have been limited to idealised cnoidal and solitary waves (Goring 1978),(Synolakis 1987),(Jensen, Pedersen, & Wood 2003),(Tonkin et al. 2003) with relatively short wavelengths. Indeed, conventional paddle generators simply do not have the stroke to reproduce the desired wavelength at large scale of a tsunami, nor do they have the capacity to generate a preceding drawdown wave (i.e. N-wave, as described by (Tadepalli & Synolakis 1994).
These weaknesses have been addressed within the EPICENTRE research initiative through collaboration between UCL's EPICENTRE and a UK research coastal facility, HR Wallingford (HRW). Within this project, a unique tsunami generator was designed and constructed, and is capable of generating multiple waves, an initial draw-down and ensure realistic wavelengths.

Presentation of the new tsunami generator

The functioning of this device was inspired by the previous HRW tide generator, designed to add tide effects to the usual model waves generated. The tide generator was able to generate a typical prototype tide of 12.5h in 7.5min (Bazin 2008). The principle was to elevate a certain volume of water in a closed tank then release it in a controlled manner, using a fan linked to the tide box and a motor-controlled valve regulating the air pressure inside (Wilkie & Young 1952).
The period of a tsunami is smaller than that of a tide, and in our experiment the waves are generated in a flume rather than in a 3D environment. Therefore, the new machine had a different overall geometry and was designed for the water exchange between the tank and the propagation channel to be quicker.
The general description of the tsunami generator and its basic working principles are schematically presented in Figure 1.

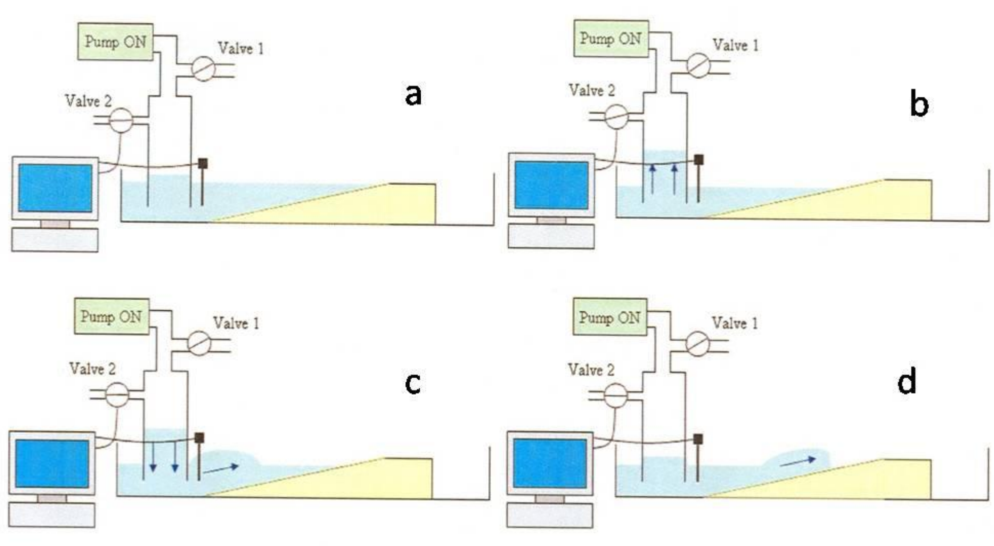

Figure 1: Generation of a leading depression wave. (a) Vacuum Pump is on, valve 1 slightly opened and valve 2 fully opened (b) Valve 2 closes, and the water level rises within the tank,

creating the first trough of the wave (c) Valve 2 is opened in a controlled manner and a wave peak will be created (d) eventually, Valve 2 will return to its original position and stop. The wave will then continue to propagate down the flume.

Operation of the conceptual design of the Tsunami Generator was checked using desk calculations to give confidence in its feasibility (Robinson 2008). The "typical tsunami" to be generated was chosen as the "Mercator" wave at scales between 1/100 to 1/50 in order to calculate tank size as well as pump and valve requirements. This wave is defined as the signal recorded by the echosounder of the Belgian yacht Mercator (Figure 2), which provided a reliable tsunami trace for this disaster. The ship was located a few kilometres off the coast of South Phuket. The sampling period of the instrument was 1 minute (the 2004 tsunami had a mean period of 40 minutes), and the boat was located in an open area and relatively close to the source. So the wave signal was less affected by the shoreline configuration and dispersion.

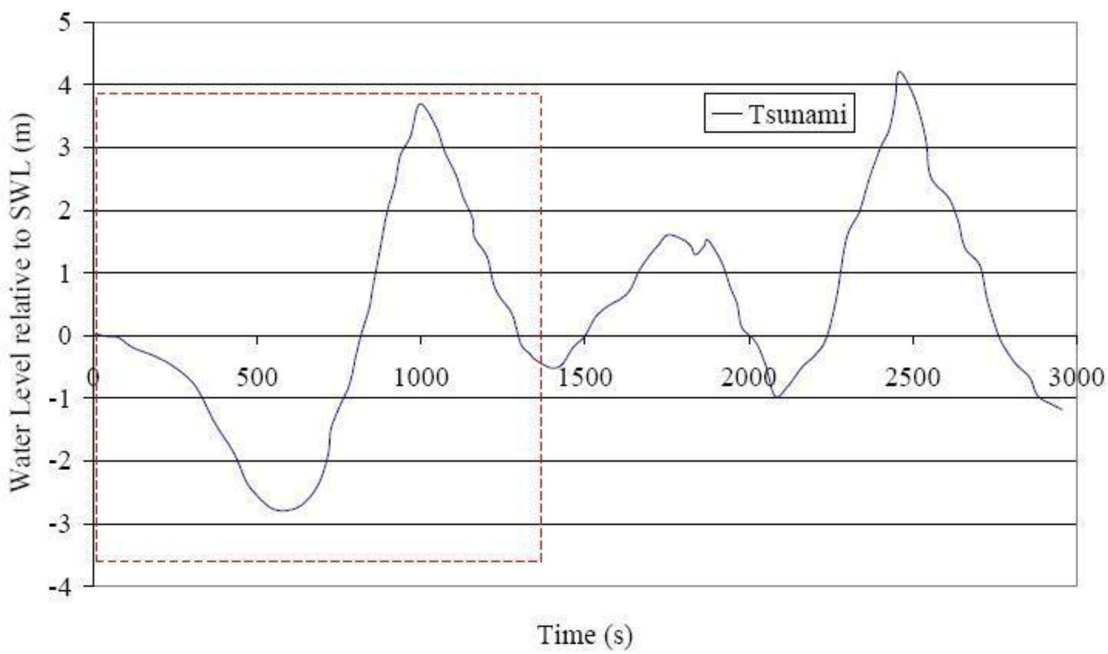

Figure 2: Mercator wave recorded during the 2004 tsunami. The red box represents the first trough and peak of the tsunami to be reproduced in the experiment. Indeed the last two waves are likely to be reflections from the coast travelling in the opposite direction (as mentionned by Synolakis through personal communication, in addition similar long wave reflection processes have been observed during our testing with the Tsunami Generator).

Validation and first stages of testing

Generation of Solitary and N-Waves

There are theoretical waveforms that are thought to represent the main characteristics of tsunami: solitary waves (Miles 1980) and N-Waves (Tadepalli & Synolakis 1994). Solitary wave especially have been extensively used in a number of theoretical and experimental studies (Goring 1978),(Synolakis 1987),(Briggs et al. 1995),(Jensen, Pedersen, & Wood 2003). But there is now some controversy regarding the use of solitary waves as realistic models for tsunami (Madsen, Fuhrman, & Schäffer 2008). In the case of N-waves, only theoretical studies could be carried out (Tadepalli & Synolakis 1996) as stable N-waves have not successfully been generated in the laboratory to date.
One aim of this work is to compare these idealised wave profiles with a wave displaying the main characteristics of the real phenomenon, for the time possible to generate in a large-scale laboratory setting.

It has been possible to recreate Solitary and N-waves of varying periods. However, when the wave period is greater than 6-8s, incoming wave profiles start to be affected by reflections travelling in opposite direction coming from the sloping bathymetry. Therefore, for initial wave design purposes and understanding only short waves were generated.

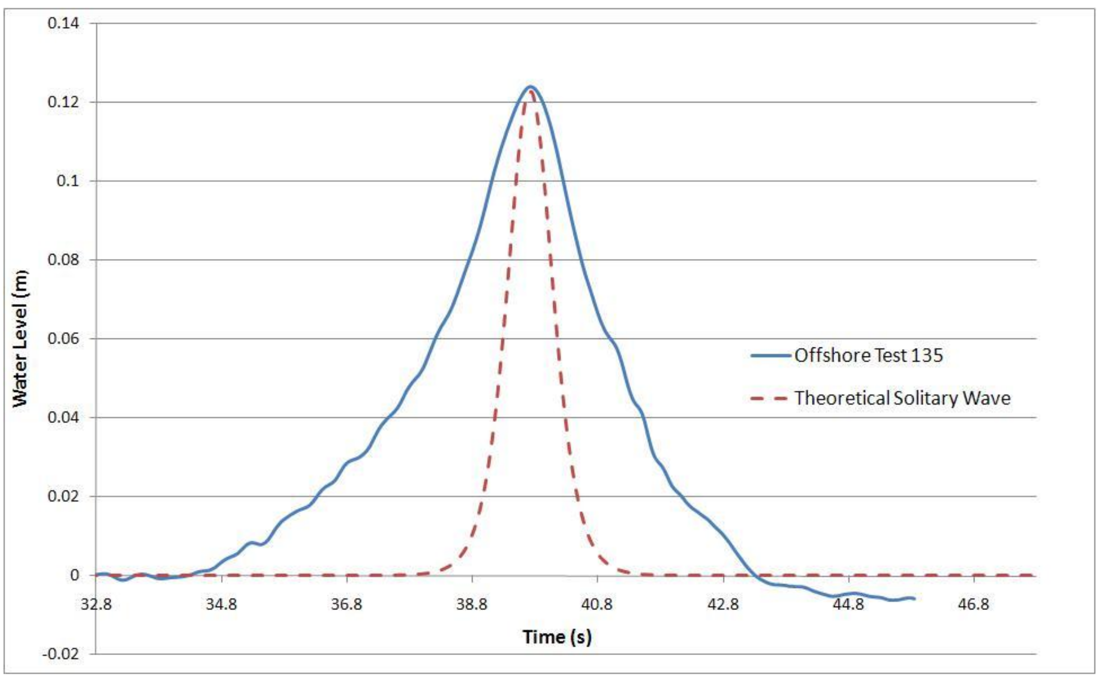

Figure 3: Comparison between a generated solitary wave (blue-solid) and the Boussinesq profile (red-dashed) according to (Miles 1980).

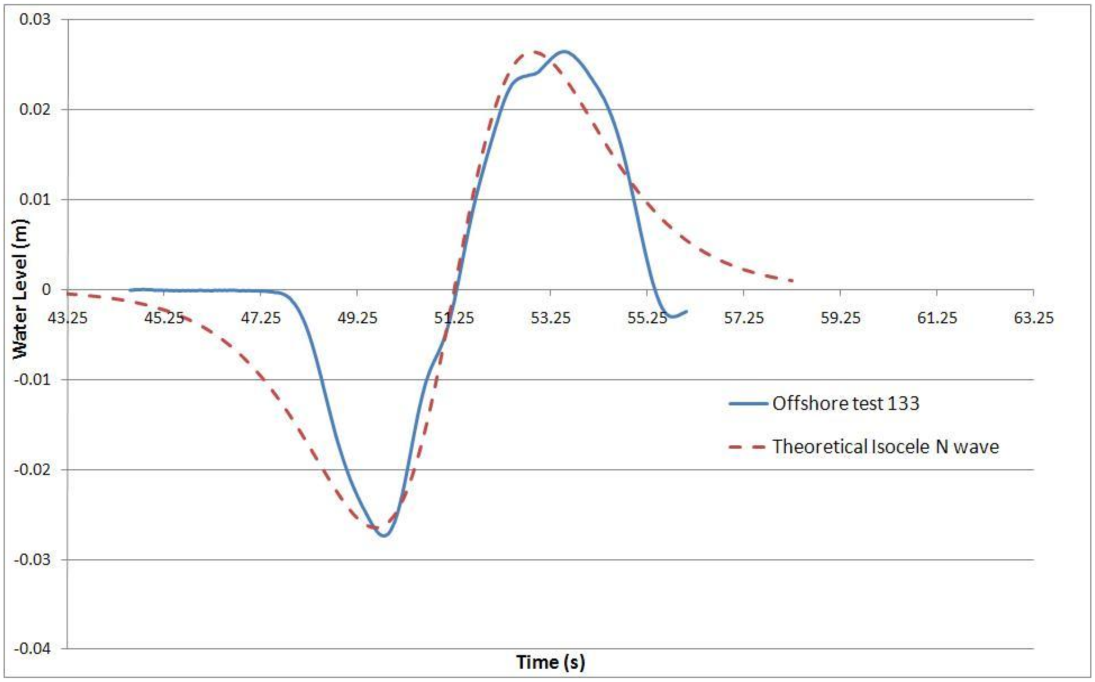

Figure 4: Comparison bewteen a generated N-Wave (blue-solid) and a theoretical N-Wave leading profile (red-dashed), according to (Tadepalli & Synolakis 1996).

Figure 4 and Figure 5 respectively compare the profile of a generated solitary wave with the theoretical Boussinesq solitary wave as presented in the review from (Miles 1980), and a generated N-wave with the corresponding leading profile of the theoretical N-Wave as described by (Tadepalli & Synolakis 1996).

Figure 6 shows these two types of waves are repeatable and propagate in a stable manner along the flume.

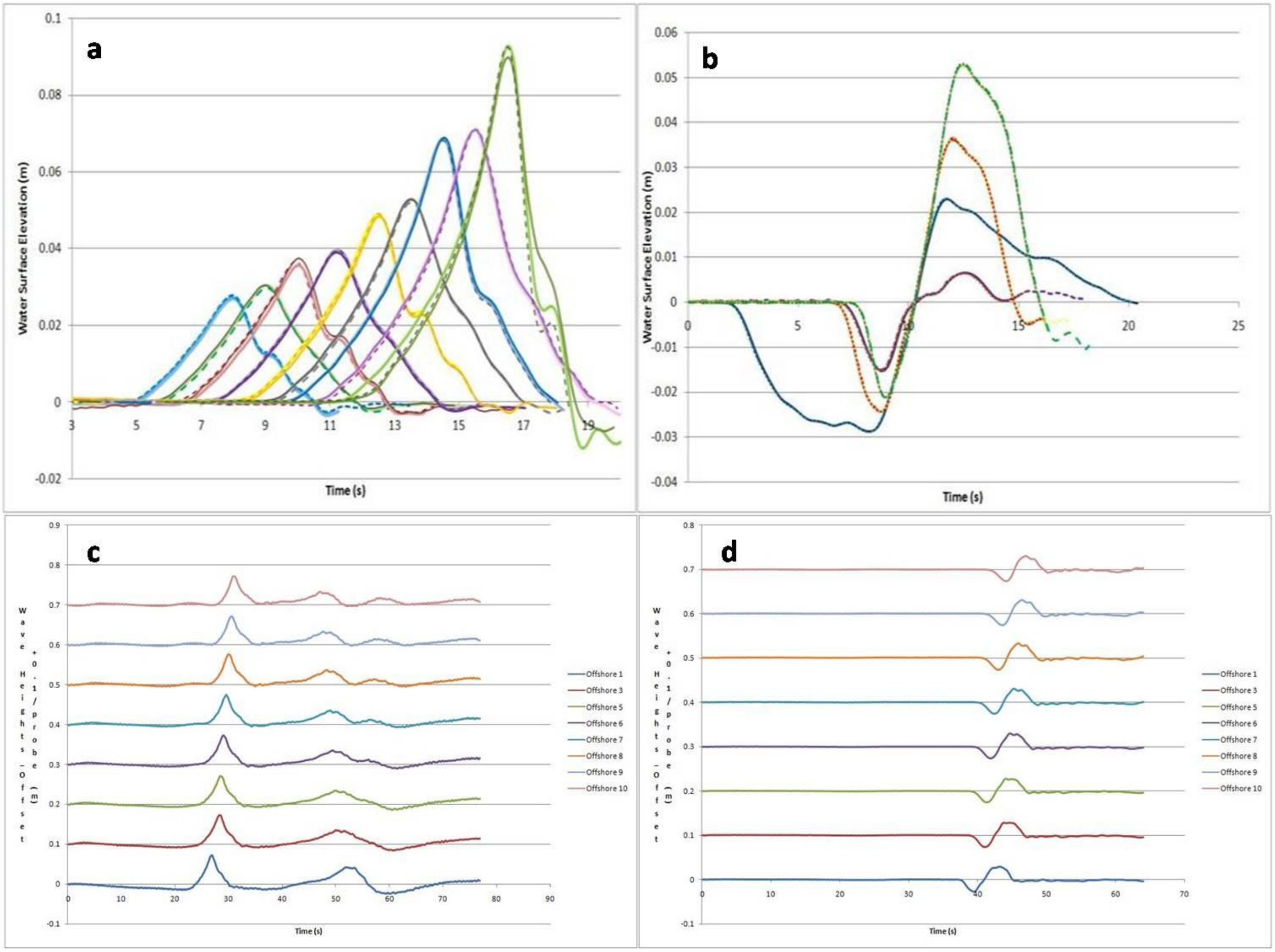

Figure 5: Repeatability of Solitary (a) and N-Waves (b) generated, each curve represents 3 to 5 repeats of the same test. Propagation of one typical solitary (c) and one typical N-Wave (d) in the constant depth region.

Runup tests have been carried out, and for a range of solitary waves ($0.04<a/h<0.18$), runup results are comparable match with Synolakis benchmark runup data (Synolakis 1987). This indicates the solitary waves generated with the new device are comparable to other typical hydraulic model waves (comparable nearshore hydrodynamic processes).

Generation of the "Mercator" wave

As the Mercator is a very long wave, its offshore profile is affected by reflections from the sloping beach. However, as the wave shoals up in the nearshore region, the model wave (scale 1/50) and prototype wave profiles prove to be comparable as shown in Figure 7. Because this wave, even at model scale, is very long compared to the length of the flume (Figure 8), it is acceptable to compare model and prototype profiles anywhere along the flume. The distance between the first and last probes recording the signal in the hydraulic model represent at most

6.28% of the total length of the model Mercator.

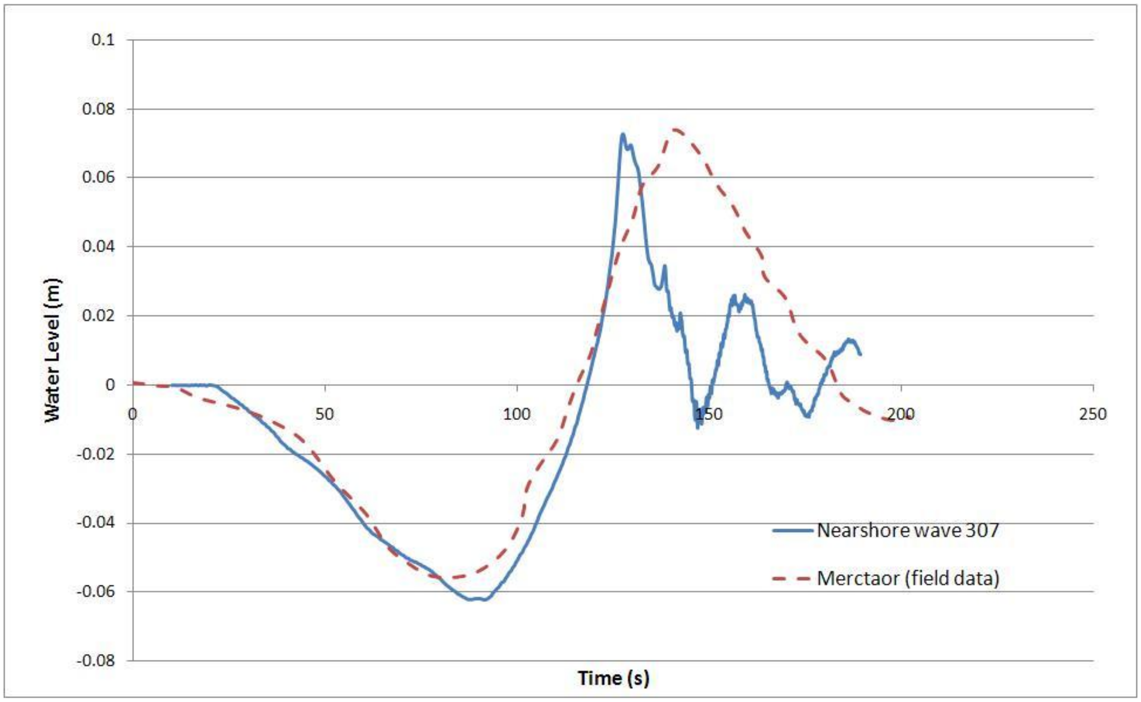

Figure 6: Comparison between the generated Mercator (nearshore probe, blue-solid) and the real Mercator record at a scale of 1/50 (red-dashed).

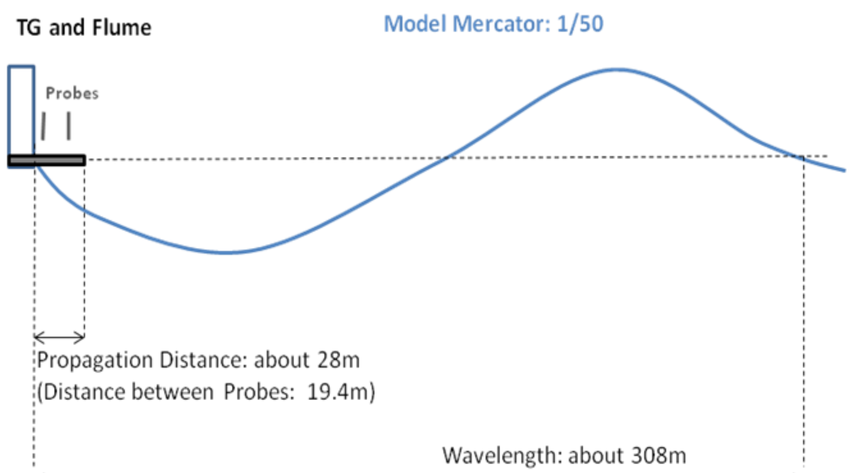

Figure 7: Schematic representation of the length of the model Mercator generated with respect to the flume length (not to scale)

After successful design of these different types of tsunami waves for a range of different parameters, wave impact on structures was investigated with a series of experiments and will be discussed in later publications.

Preliminary Observations for generated tsunami waves

New Runup Observations for N-Waves and Mercator waves

Runup was not only measured for solitary waves, but also for N-waves and Mercator-type waves.
N-waves runups were shown to follow the same trend as solitary waves (Synolakis 1987) for the range of a/h ratios tested (amplitude to depth ratio, a is the positive amplitude of the N-wave); see (Charvet et al. 2010), in preparation.

Mercator-type waves have been reproduced at different scales. Two different Mercator waves have been coupled with equivalent solitary waves (same normalized positive amplitudes) and runups have been measured.
Table 1 shows that for the first couple (409-360), the solitary wave runs-up 1.23 times higher than the Mercator wave for a similar amplitude, in the second case (382-392) the solitary wave runs-up 1.4 times higher than its Mercator equivalent.

Table 1: Normalized Runup of Mercator-type waves and their solitary equivalent (similar a/h)

Wave	a/h	R/h	Ratio a/h	Ratio R/h
409 (M)	0.094	0.25		
360 (SOL)	0.1	0.307	1.06383	1.228
382 (M)	0.075	0.19		
392 (SOL)	0.077	0.267	1.026667	1.405263

Velocities Observations for Solitary and Mercator waves

Velocities in the shoreline region were recorded for a sample of solitary waves and for Mercator-type waves. Indeed, several studies (field (Synolakis & Bernard 2006), numerical (Carrier, Wu, & Yeh 2003), and experimental (Synolakis & Bernard 2006),(Synolakis 1986)) pointed out in the past a remarkable feature of tsunami hitting the coast: the wave accelerates at the moving shoreline. Initial results show that for the largest solitary wave generated, velocity values recorded close to the shoreline were approximately 0.78m/s to 0.88m/s. For our experimental Mercator, these were approximately 0.65m/s to 0.8m/s. One interesting observation is that even though the overall velocity values for the Meractor wave were smaller, the velocity gradient for the Meractor wave was greater than the increase of velocity for an equivalent solitary wave (with respect to distance).

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Conclusions

A new tsunami generator aimed at generating long waves at realistic scales and taking into account the characteristic trough preceding tsunami waves has been successfully built. Validation tests show this new device can recreate different types of waves of varying periods (from 6-8s to 200s) in a repeatable and stable manner.
Present limitations lie in the tank and flume dimensions. A bigger tank would allow for larger water volumes to be displaced and a greater range of a/h ratio to be tested for all types of waves. A longer flume would allow waves longer than 8s to propagate without being affected by reflections in the offshore region. An improved valve control system could also remove the beach reflection and produce waves at a larger scale. It is envisioned this improvement, in combination with a longer flume, would remove beach reflections from the longest waves.

Some initial comparisons have been done for waves thought to be representative of tsunami (ie. Solitary and N-Waves) and a model wave from the 2004 tsunami ("Mercator"). From these initial observations it appears that short N-waves follow the same runup evolution with respect to a/h as solitary waves; and it also appears that solitary waves runup higher and travel faster in the nearshore region than Mercator-type waves. This suggests that approximating a tsunami approaching the coast as a solitary wave can lead to an overestimation of runup. Moreover, the maximum amplitude a may not be the main factor determining the runup of a tsunami. Further investigations are necessary to assess the relative influence of other wave parameters.

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