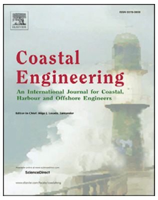
Coastal Engineering 138 (2018) 80–97

Contents lists available at ScienceDirect

Coastal Engineering

journal homepage: www.elsevier.com/locate/coastaleng



Pneumatic long-wave generation of tsunami-length waveforms and their runup

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ARTICLE INFO

Keywords:
Experiments
Pneumatic generation
Long wave
Tsunami
Runup

ABSTRACT

An experimental study is conducted using a pneumatic long-wave generator (also known as a Tsunami Generator). Scaled tsunami waveforms are produced with periods in the range of 5–230 s and wave amplitudes between 0.03 and 0.14 m in water depths of 0.7–1.0 m. Using Froude similitude in scaling, at scale 1:50, these laboratory waves are theoretically dynamically equivalent to prototype tsunami waveforms with periods between 1 and 27 min and positive wave amplitude between 1.5 and 7.0 m in water depths of 50 m. The purpose of these tests is to demonstrate that the pneumatic method can generate long waves in relatively short flumes and to investigate their runup. Standard wave parameters, (free-surface, wave celerity and velocity profiles) are used to characterise the waveforms. It is shown that for the purpose of runup and onshore ingression, minimal interference from the re-reflected waves is observed.

By generating tsunami waveforms with periods greater than ≈ 80 s (≈ 9.5 mins prototype scale) the available experimental data set is expanded and used to develop a new runup equation. Contrary to the shorter waves, shoaling of these longer waves is insignificant. For waveforms with periods greater ≈ 100 s the runup is best described by wave steepness not potential energy. When tested against available runup equations the results are mixed; most perform poorly for scaled tsunami length periods. A segmented regression analysis is performed on the data set and an empirical runup relationship is provided based on a new parameter termed the 'Relative Slope Length'.

The tests show the definition of offshore wave amplitude is non-trivial and may greatly affect the predicted relative runup of a given wave. It is noted that this appears to be a general issue for all types of tsunami simulation in the laboratory. Together these observations and proposed runup model provide a framework for future numerical studies of the topic.

1. Introduction

Tsunami waves are progressive gravity waves most commonly generated by under-sea mega-thrust fault motion. Their periods range between ≈ 90–7000 s (≈ 1.5 min to 2 h, see Brown, 2013) and they have sufficient potential energy to present a significant threat to coastal life and the built environment. The Indian Ocean tsunami in 2004 resulted in over two hundred and fifty thousand dead or missing, $9.9 billion in material damage losses and 1.7 million displaced persons (Telford et al., 2006). Catalogues of past tsunami events are available (NOAA, 2017a; NOAA, 2017b; Geist and Parsons, 2011) and demonstrate the destructive potential of tsunami waves. One of largest recent tsunami is the 2011 Japan event, commonly known as the 2011 Tohoku earthquake and tsunami. The human death toll, according to The National Police Agency of Japan (NPA, 2016) exceeds fifteen thousand. The economic impact measured over the succeeding year from the event is shown by Kajitani et al. (2013) to be over of 211 billion USD in direct damage.

One way of reducing human and economic losses from future tsunami events is through improved understanding of the inundation of tsunami on a coastline. Such improvements may lead to better engineering guidelines for coastal infrastructure that are at risk of large tsunami events. These are the main motivations of the presented research.

1.1. Characterisation of tsunami encroaching on land

One characterisation of the interaction of a tsunami with a

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https://doi.org/10.1016/j.coastaleng.2018.04.006
Received 25 August 2017; Received in revised form 26 March 2018; Accepted 5 April 2018

coastline is its runup. Runup is defined as the vertical height above static water level of the point of maximum inundation of the tsunami inland. It is a commonly used parameter to describe tsunami-like waveforms in the laboratory (for example Synolakis, 1987, Tadepalli and Synolakis, 1994, Briggs et al., 1995, Liu et al., 1995, Hughes, 2004a, Madsen and Schäffer, 2010, Charvet et al., 2013, Saelevik et al., 2013, Sriram et al., 2016 and Drähne et al., 2016), and in the assessment of tsunami interaction with a shoreline, particularly for risk analysis, planning and insurance (for example, Imamura, 2009 and ASCE/SEI, 2016).

More recently, tsuanmi inundation of the coastline and their over-land flow are also characterised by parameters such as flow velocity and depth. The ASCE/SEI (2016) 'Tsunami Loads and Effects' design standard outlines the energy grade line method to analyse the 2-dimensional tsunami flow inundation depth and velocity at a specified point onshore. Its use requires the maximum runup and inundation of a given wave and its offshore period and amplitude as inputs. Taubenböck et al. (2013) present the application of the specific energy head to assess the inundation of tsunami on a coastline incorporating the flow depth and velocities. These parametrisations are important when consideration of the tsunami over-land flow and velocities is desired. However, relating runup to offshore tsunami parameters remains important to improving mitigative engineering and planning of coastlines. This paper focuses on runup as the parameter that describes tsunami interaction with a coastline.

Early laboratory work on tsunami runup is based on solitary wave theory (for example, Synolakis, 1987, Briggs et al., 1995, Liu et al., 1995, Chang et al., 2009 and Saelevik et al., 2013). A solitary wave centred at X_1 and $t = 0$ has a free surface profile described by

$$\eta(X,0) = \frac{H}{d}\mathrm{sech}^2(K_s(X - X_1)) \tag{1}$$

where H is wave height, d is the water depth and $K_s = 1/d\sqrt{3H/4d}$. However, the work by Madsen et al. (2008) shows that the distance over which an arbitrary waveform develops into a solitary wave is generally greater than the typical geophysical scales of the prototype. They conclude that the solitary wave is an inappropriate model analouge for a tsunami wave at prototype.

First proposed by Tadepalli and Synolakis (1994), tsunami are also modelled using the N-wave assumption, (E.g., Madsen and Schäffer, 2010; Sriram et al., 2016). When extended in duration this provides a more realistic representation of prototype tsunami waveforms by accounting for the leading trough of the wave, as well as its period T. Madsen and Schäffer (2010) pose theoretical trough-led N-wave forms as

$$\eta(X,0) = \alpha\frac{H}{d}(X - X_2)\mathrm{sech}^2(K_s(X - X_1)) \tag{2}$$

where α is a constant, X_1 is the position the crest and X_2 is the horizontal position of the zero-crossing point in the wave profile. Madsen and Schäffer (2010) use Equation (2) to derive new runup equations.

In line with the development of knowledge of the waveform, over the last ten years there has been a drive to improve the generation techniques of tsunami waves in the laboratory. Both solitary and trough-led waveforms have been used to measure the performance of various novel tsunami simulation techniques. Goseberg et al. (2013) introduces a pump technique to generate tsunami in a closed-circuit flume. The technique uses a Proportional Integral Derivative (PID) controller to generate target waves and absorb reflections. Drähne et al. (2016) use this pump methodology to investigate 'long wave' runup on a beach. While no definition of 'long wave' is given, the waves tested include waves of tsunami length in period if a notional scale of 1:100 is used. In theory the period and wave amplitude limitations could be overcome by increasing the pump capacity and the reservoir volume. A disadvantage of the method relates to spurious short period waves that are observed superimposed on the target wave. Also termed as 'riding waves' these waves in some cases overtake the target long wave being generated and directly interfere with the maximum runup of the long wave (Drähne et al., 2016). Such spurious waves are reduced in Bremm et al. (2015) by (to the current authors' understanding), bypassing the active PID control of the wave signal in real-time and inputting the smoothed form of the target wave signal. It is not immediately clear how the smoothed signal is achieved, but it is presumed that the method is similar to the iterative calibration of the target wave signal which is described later in the present work.

Schimmels et al. (2016) explore the use of a piston-paddle wave maker, however, the experimental scale, depth and amplitude are limited due to the maximum stroke of the wave maker. They report that ' … the absolutely correct reproduction of the 'Mercator time series' with a piston type wave maker seems really to be unfeasible as the required stroke, although it only increases linearly with scale, becomes too large for very small water depth.' The 'Mercator' 2004 Indian Ocean Tsunami free-surface elevation time series is given in Appendix A, along with selected time series from the 2011 Great Eastern Japan Earthquake and Tsunami. The methodology is developed by Fernández et al. (2014) who use a Self-Correcting Method (SCM) to numerically optimize the control variable, before applying it to a paddle to generate tsunami-length waveforms at 1:100 scale. This methodology adapts the control signal iteratively in the frequency domain by adjusting wave phase and amplitude to achieve the target $\eta(X,t)$. The method incorporates the absorption of re-reflections within the corrected control variable (paddle motion), and removes spurious high frequency components. After two correction steps the resulting long waveform shows good agreement in overall target wave period, though there is still some deviation from the smoothness of the target waveform time-series. This is particularly observable for actual tsunami time-series. Additionally, the amplitudes generated in this facility are significantly limited by the maximum stroke meaning the correct scaling of a^+ and d requires an exceptionally large paddle stroke. Furthermore, the SCM requires that the target wave be described meaningfully in the frequency domain by a set of linear sine waves, which may not be the case for highly non-linear waves or solitary waves.

Between 2008 and 2015, collaboration between University College London and HR Wallingford, U.K. developed and improved the design of a Pneumatic Long-Wave Generator (PLWG). The first generation PLWG is described in Rossetto et al. (2011) who introduce the concept and apply it to flume with a propagation region of constant depth of 15.2 m. Waves are generated in an open-loop process between the control variable (the PLWG water head) and the output wave time-series. That is, the control variable time series is pre-calibrated for each wave. Sine waves up to 200 s in period are produced with the purpose of observing the response of the PLWG-flume system and the ability of the PLWG to reproduce simple periodic signals. Crest-led and trough-led waveforms are also produced with a maximum period of $\approx$ 18 s in order to check the repeatability of the PLWG and record wave runup for comparison with past experiments. The authors do not discuss wave absorption, and suggest future research with the PLWG method ought to include a longer constant-depth region in the flume (i.e., a longer flume) in order to increase the wavelength of the waves that can be generated.

Using the 1st generation PLWG and flume as described in Rossetto et al. (2011), Charvet et al. (2013) record the runup of crest-led 'elevated' and trough-led N-waves. Elevated waves are waves of translation characterised by a single positive elevation above the mean water level. They are nominally similar to a solitary wave but do not conform to its mathematical description, Equation (1), being generally much longer in length and therefore less steep than a solitary of equivalent amplitude. Charvet et al. (2013) compare elevated wave runup with solitary wave data of equivalent amplitude from Synolakis (1987) and find that elevated waves give a higher runup, suggesting