Coastal Engineering 111 (2016) 39–49

Contents lists available at ScienceDirect

Coastal Engineering

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

On the distribution of wave height in shallow water

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ARTICLE INFO

Article history:
Received 7 September 2015
Received in revised form 15 December 2015
Accepted 30 January 2016
Available online 23 February 2016

Keywords:
Wave height
Shallow water
Weibull
Generalised Pareto
Miche

ABSTRACT

The statistical distribution of the height of sea waves in deep water has been modelled using the Rayleigh (Longuet-Higgins, 1952) and Weibull distributions (Forristall, 1978). Depth-induced wave breaking leading to restriction on the ratio of wave height to water depth requires new parameterisations of these or other distributional forms for shallow water. Glukhovskiy (1966) proposed a Weibull parameterisation accommodating depth-limited breaking, modified by van Vledder (1991). Battjes and Groenendijk (2000) suggested a two-part Weibull–Weibull distribution. Here we propose a two-part Weibull-generalised Pareto model for wave height in shallow water, parameterised empirically in terms of sea state parameters (significant wave height, H_S, local wave-number, k_L, and water depth, d), using data from both laboratory and field measurements from 4 offshore locations. We are particularly concerned that the model can be applied usefully in a straightforward manner; given three pre-specified universal parameters, the model further requires values for sea state significant wave height and wave number, and water depth so that it can be applied. The model has continuous probability density, smooth cumulative distribution function, incorporates the Miche upper limit for wave heights (Miche, 1944) and adopts H_S as the transition wave height from Weibull body to generalised Pareto tail forms. Accordingly, the model is effectively a new form for the breaking wave height distribution. The estimated model provides good predictive performance on laboratory and field data.
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1. Introduction

There is considerable interest in understanding the characteristics of ocean waves in shallow water. Specifically, from an engineering perspective, a design wave height in shallow water is required in order to determine wave loading on coastal structures, wave run-up and wave overtopping. As discussed by Katsardi and Swan (2011b) in their introduction to modelling of non-breaking unidirectional waves in intermediate and shallow water, the physics of evolving wave fields in shallow water is critically dependent upon water depth. Distributions of wave height in shallow water must therefore be expressed as functions of water depth or related parameters. As summarised in Section 3 below, considerable effort has been devoted to the development and refinement of parametric forms for the statistical distribution of wave height in shallow water based on field and laboratory measurements.

There is a long history of modelling the distribution of wave height in coastal regions; Guedes Soares (2003) provides an introduction. The LoWiSh Joint Industry Project addresses uncertainties in the specification of the maximum wave height occurring on a continental shelf. One of the objectives of LoWiSh is to review existing distributional forms for wave height in intermediate and shallow water. In the first phase of the project, the distribution of individual wave height from laboratory measurements (Katsardi and Swan, 2011a) was found to be well described by a Weibull form, with parameters expressed in terms of Ursell number. However, the same parameterisation did not hold for the field measurements. The two-part Weibull–Weibull distribution (of Battjes and Groenendijk, 2000) was found to explain the distribution of laboratory wave height well, capturing the discontinuity in slope of the cumulative distribution of wave height in very shallow water. The limiting characteristics of the largest waves in both intermediate and shallow waters were found to be critically dependent upon the effective water depth, $k_L d$, where k_L is a local wave-number based upon a locally measured wave period, and d is water depth. In the recent literature, Mai et al. (2011) report that a modified form of the two-part Weibull–Weibull distribution is appropriate to characterise the distribution of wave height from radar level gauge measurements at three locations in the German North Sea. Katsardi et al. (2013) observe that effective water depth and significant wave height influence the distribution of wave height in shallow water from laboratory measurements, but

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http://dx.doi.org/10.1016/j.coastaleng.2016.01.015
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that different wave spectral bandwidths and moderate bed slopes (less than 1 : 100) do not. They also observe that the Weibull–Weibull distribution over-predicts largest wave heights.

The objective of the current work is to extend the analysis conducted during the first phase of LoWiSh to establish a universal model for wave height in shallow water, appropriate for all available laboratory, field and numerical model data; and to compare the performance of the new model with competitor models from the literature. The contents of this article are arranged as follows. Laboratory and field data used for model estimation and validation are described in Section 2. Section 3 summarises existing models for the distributions of wave height, and motivates the requirements for the development of the new model, which is explained in detail in Section 4. Section 5 estimates the Weibull-generalised Pareto model for the laboratory and field data, and compares model performance against alternative model forms for the distributions of wave height. Conclusions and recommendations are made in Section 6.

2. Data

Five data sources were used to estimate the Weibull-generalised Pareto (henceforth WGP) model; four correspond to measured data from offshore locations, and the fifth to measured data from a wave tank at Imperial College London. The offshore locations are (a) Ameland Westgat (AWG), at 8 m water depth on the Dutch coast for December 2007; (b) Petten, at 8 m and 20 m water depth on the Dutch coast for different measurement campaigns over the period 2001–2008; (c) the Field Research Facility (FRF) at 9 m water depth on the coast of North Carolina for different measurement campaigns over the period 2003–2007, and (d) North Cormorant (NC), at 160 m water depth in the northern North Sea for the period November 2006 to February 2007.

Wave data at AWG were measured with a Saab Rex WaveRadar sensor. The Saab WaveRadar has been shown to give reliable measurements of the sea surface elevation over the frequency band (0.06, 0.60) Hz by Ewans et al. (2014). The unit on the AWG platform was mounted at 26.5 m above the sea surface, clear from immediate obstructions and in particular without obstruction for waves from between north and north-west, the direction of largest storm waves. The sensor recorded the sea surface elevation continuously at 2 Hz. Waves approaching from the seaward direction of north–north-west traverse small bottom slopes, reaching a maximum slope of 1 : 400 near to the platform. The wave data at the North Cormorant platform were also recorded with a Saab Rex WaveRadar sampling continuously at 2 Hz. The sensor was located on the south-east corner of the platform at an elevation of 28.7 m above mean sea level. Although North Cormorant in no way represents a shallow water location, we include it in the present study to ascertain whether a distribution for wave height can be specified which is applicable generally, not only in shallow water.

Wave data at the AWG and North Cormorant platforms were processed according to the following steps: (a) Air-gap was inverted to estimate surface elevation above a nominal datum, (b) mean water level was calculated for consecutive 10 minute segments, (c) a 2 Hz spline was fitted through each of these 10-minute values to represent a continuously varying mean water level, (d) the continuously varying mean water level time series was subtracted from the surface elevation above the nominal datum time series, and (e) individual waves were identified on zero-crossing basis.

The Petten wave data were recorded with a Directional Waverider buoy located in a nominal water depth of 20 m (the MP1 site), nearly 8 km from the shore, and an Etrometa wave staff located in a nominal water depth of 8 m (the MP3 site). MP3 is behind a bar (approximately 1.9 km seaward) and on the forward face of a second bar. These bars are likely to have introduced local breaking and shoaling, resulting in effects in the MP3 data that are not observed in the deeper water sites at Petten nor the other field locations not affected by bars. The average beach slope between MP1 and MP3 is approximately 1 : 600. The slope is less than 1 : 600 seaward of MP1. The Directional Waverider buoy data at MP1 were recorded at 1.28 Hz, while the wave staff data at MP3 were recorded at 2.56 Hz. Still water level measurements were made at MP3 with a digital level meter. Further details of the measurements can be found in Hordijk (2003,2004).

The Field Research Facility measurements were made with a pressure transducer in 8.5 m water depth. The measurements from the pressure sensor were made at 2 Hz and were converted to surface elevations, using linear wave theory, with a spectral density cap corresponding to an f^{-4} decay rate for frequencies f above 0.25 Hz, to avoid amplification of noise at high frequencies. The beach slope at the pressure transducer location is 1 : 150. Seaward of the location the bottom slope is around 1 : 300. Further details of the measurements can be found in Birkemeier et al. (1997).

For each of the field locations, original 20-minute sea state samples were combined into rolling three-hour sea states for consideration here. A small number of the resulting 3-hour sea states were omitted due to missing data or obviously unrealistic values. The resulting number of sea states for analysis per location was 414 (at AWG), 3646 (at NC), 4383 (at FRF) and 676 (at Petten). In addition, we found it useful to consider the Petten samples at 8 m and 20 m separately, henceforth denoted P8 and P20 respectively for brevity.

The experimental tank data were obtained in a specially commissioned wave flume at Imperial College London adopting a 1:100 laboratory length scale and 1:10 laboratory time scale. At laboratory scale, the flume is 60 m long and 0.3 m wide. The waves were generated by an absorbing flap-type wave maker located in deep water (0.7 m at model scale). The waves then propagated up a 1 : 15 slope to a water depth of 0.5 m for three different beach slopes: constant water depth of 0.3 m (flat-bed), 1 : 100 and 1 : 250 gradient. For each test case, 8 separate runs with different random phasing were undertaken. Each run consists of 256 s of complete data, giving a total record length of 2048 s , for each test case. The sampling rate was 128 Hz. Wave trains corresponding to JONSWAP and log-normal spectral shapes with different spectral parameters were measured at up to 8 gauge locations. A total of 175 cases corresponding to different combinations of wave spectrum, bed slope and gauge were recorded (together henceforth referred to as Tank data). The full details of the laboratory set-up, instrumentation, and experimental measurements undertaken at Imperial College London are given by Katsardi et al. (2013). At full scale, each of the 175 cases corresponds to observation of a three-hour sea state.

For each data source and sea state, values of sea state significant wave height (H_S, derived from the zeroth order moment of the wave spectrum) and water depth d were available, together with values of individual wave heights and corresponding individual wave numbers (k_L, determined from individual zero-crossing wave periods using the linear dispersion relationship). We use the median of individual wave numbers as sea state wave number. Further information regarding the data sources and cases used in this work is available on request from the authors.

3. Distributions for wave height

A number of distributional forms have been proposed for wave height. In this section, we begin (in Section 3.1) by summarising some of the more popular distributional forms. With this background, we motivate a new model (in Section 3.2).

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