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# Modeling depth-induced wave breaking over complex coastal bathymetries

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ABSTRACT

The correct representation of depth-induced wave breaking is important for understanding coastal morphology and for design and management in the coastal zone. Although numerous studies have demonstrated the applicability of a constant scaling of the Battjes and Janssen (1978) dissipation model for depth-induced breaking, recent studies have shown its inability to sufficiently reproduce wave dissipation over complex field cases. In the present study, we contrast the application of such a constant scaling to two alternative wave breaking parameterizations with a variable scaling based on either the wave nonlinearity (the $\varphi$ parameterization) or on both bottom slope and normalized wavelength supplemented with wave directionality (the $\beta - kd$ parameterization). We consider three field data sets characteristic of a simple beach-bar profile, a bay partially protected by a shoal and a complex intertidal region. We demonstrate that in these cases the $\beta - kd$ parameterization provides a better alternative to the use of a constant scaling or the $\varphi$ parameterization. To illustrate the operational consequences, we up-scale the conditions over the case of the intertidal region to correspond to design conditions for the Dutch coast (storm conditions with a 4000 year return period). Under these extreme conditions, for *locally* generated waves both the $\beta - kd$ and $\varphi$ parameterizations predict qualitatively similar increased significant wave heights but the $\beta - kd$ parameterization increased the waves twice as much as the $\varphi$ parameterization. Under other conditions, when *non-locally* generated waves (swell) dissipates over a gently sloping bottom, the $\beta - kd$ parameterization predicts lower significant wave heights compared to either the constant scaling or $\varphi$ parameterization.



## 1. Introduction

Depth-induced wave breaking is one of the most dominant hydrodynamic processes occurring in the coastal region. It not only controls the amount of wave energy impacting our coastlines and coastal defenses, but also plays a crucial role in driving many nearshore processes such as sediment transport, bottom morphology (Hoefel and Elgar, 2003) and turbulence (which has been shown to be important for the local ecology; Feddersen, 2012). Wave-breaking also induces radiation stresses which drive wave-induced set-up and currents (Longuet-Higgins and Stewart, 1964), both of which are of importance for coastal engineering design and management. However, despite the importance and relevance towards our knowledge of wave hydrodynamics, depth-induced wave breaking is still poorly understood partially due to its highly nonlinear nature and is therefore heavily parameterized in most wave models.

For the prediction of various wave parameters in finite water depth, phase-averaging stochastic spectral wave models based on an action (or energy) balance (e.g. Holthuijsen, 2007; Komen et al., 1984; WAMDI, 1988; WISE, 2007) are used on an operational basis. Under the assumption that the wave field can be modeled as a stationary Gaussian process, a number of statistical parameters such as significant wave height, defined as the average wave height of the highest one-third waves (Longuet-Higgins, 1952) can be estimated from the wave spectrum (see Appendix A). Although it can be argued that phase-resolving models of the Boussinesq-type (e.g. Lynett, 2006; Peregrine, 1967) or non-hydrostatic type (e.g. Zhou and Stansby, 1999; Zijlema et al., 2011) may be more applicable for resolving nonlinear processes such as wave breaking, in practice, such models are constrained for larger areas ($>1 \times 1$ km$^2$, say) by computational expense and inability to account for wave generation by wind.

Extensive research has therefore been carried out into the parameterization of dissipation due to depth-induced breaking for spectral wave models (e.g. Baldock et al., 1998; Battjes and Janssen, 1978; Thornton and Guza, 1983) and the scaling of these dissipation models (e.g. Apotsos et al., 2008; Battjes and Stive, 1985; Rattanapitikon and Shibayama, 2000; Ruessink et al., 2003, and many others). Despite fundamental shortcomings of using these source terms, which are at best quasi-linear, these dissipation models have been used with considerable success. In particular, the use of the Battjes and Janssen (1978)

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dissipation model in combination with a fixed calibration parameter $\gamma_{BJ} = 0.73$ (the ratio of maximum possible individual wave height to local depth) has been shown to be effective, particularly over sloping beach profiles (e.g. Salmon et al., 2015). It is therefore often the default parameterization for depth-induced wave breaking in spectral wave models, even in third-generation wave models in which many of the other processes affecting the waves are considerably better founded in theory and observations (e.g. WAMDI group, 1988).

However, although effective, this parameterization does not provide much physical insight towards our understanding of irregular wave breaking over varying bathymetry. Furthermore, it has been reported that even a calibrated constant $\gamma_{BJ}$ is unable to always give optimum results (Apotsos et al., 2008; van der Westhuysen, 2010). In particular, the commonly used value $\gamma_{BJ} = 0.73$ has been shown to consistently overestimate the dissipation of *locally* generated waves over horizontal bathymetries (e.g. Bottema and Beyer, 2002; de Waal, 2002; van Vledder et al., 2008) while underestimating the dissipation for *non-locally* generated waves (e.g. Katsardi, 2007; Nelson, 1997).

The focus of this study is to analyze the effect of bottom topography and local wave characteristics for the prediction of depth-induced wave breaking by considering two recent alternative parameterizations with variable scalings, proposed by van der Westhuysen (2009, 2010) and Salmon et al. (2015). These parameterizations are considered as they represent the most recent formulations which have been shown to provide improved model performance for the depth-induced breaking under *locally* generated wave conditions (e.g. Salmon et al., 2015). These improvements are expected to be important for representing complex coastal regions as well as for design conditions. Here, we analyze the differences between these alternatives compared to $\gamma_{BJ} = 0.73$ to predict the significant wave height and address the implications of their use for coastal applications. We consider three data sets representing coastal systems of increasing complexity, namely a fairly simple beach-bar profile (Petten); a bay partially protected by a shoal (Haringvliet) and a complex intertidal region with a number of characteristic coastal features such as tidal channels and extended shoals (Amelander Zeegat). Finally, we scale the boundary conditions for three cases over the Amelander Zeegat to represent a hypothetical 1:4000 year storm corresponding to Dutch design conditions for coastal defenses.

Here, we demonstrate that both alternatives perform better than $\gamma_{BJ} = 0.73$ for the prediction of significant wave height of locally-generated waves. Furthermore, in our up-scaled storm over the Amelander Zeegat, we show significant differences in using the two alternatives with higher waves predicted by both parameterizations over intertidal areas dominated by *locally* generated waves and lower waves by the parameterization of Salmon et al. (2015) for *non-locally* generated waves (swell) over gently sloping slopes.

This paper is organized as follows. In Section 2, we outline the field cases and methodology and in Section 3, we present the host wave model and introduce the three breaking parameterizations. The results of our comparison study are presented in Section 4 where we first show the performance of using $\gamma_{BJ} = 0.73$ and then compare and contrast this to the alternative parameterizations. We discuss the implications, particularly for design conditions, in Section 5 and finally present our conclusions in Section 6.

## 2. Field observations

To provide an objective comparison between the default and alternative parameterizations, they are applied to three separate field data sets. Each data set consists of a number of cases considered to be stationary. Together they cover a wide range of wave conditions including locally (wind-sea) and non-locally (swell) generated waves, over a variety of bathymetric profiles including a gently sloping beach, a near-horizontal shoal and an intertidal region.

### *2.1. Petten (1995 and 2002) observations*

The Petten site is located off the west coast of the Netherlands near the town of Petten (Fig. 1). The location represents a gently sloping beach profile with a large offshore shoal with a minimum depth of ~5.7 m and a smaller near-shore bar with a minimum depth of ~4.0 m. Wave conditions were measured along a transect normal to the beach with three to five instruments depending on when the observations were taken (shown in magenta (×) in Fig. 1A). Following a hindcast study to investigate the performance of the wave model SWAN (Booij et al., 1999; see Section 3.1) under instationary conditions (Groeneweg et al., 2003), a number of instances, typically four per storm, were chosen representing variations in the tide and development of the storm. Over the selected 21 cases, the offshore significant wave height varied between $3.0 < H_{m0} < 6.7$ *m* and the offshore mean wave period varied between $4.2 < T_{m01} < 9.9$ *s* as provided in Table 1. Computations were carried out in the frequency range between 0.03 Hz and 0.5 Hz with 31 discrete frequencies. Groeneweg et al. (2003) used similar settings in their hindcast but with an upper frequency limit of 0.8 Hz. We modified our frequency range to be consistent with the constraint for the DIA ($\Delta f = 0.1 f$; see Section 3.2). However, in a sensitivity analysis, this difference was found to be negligible.

For the 1995 storms, a fine inner computational grid over the region shown in Fig. 1A is nested within a coarser outer grid to calculate the spectral boundary conditions for the inner grid. The outer grid uses 2D spectra inferred from a directional Waverider buoy located approximately 5 km north–west (shown as an empty dot in Fig. 1D) of the directional Waverider buoy which provides the boundary conditions for the 2002 campaign (shown in red in Fig. 1A). The same inner grid is applied for the 2002 campaign with no need for nesting.

For the 1995 storms, wind speeds are estimated from three wind measurement locations in the vicinity of Petten (Texalhors, TXH; Noordwijk, MPN and K13; see Fig. 1D) to estimate the wind variation both along the coast and perpendicular to it. For the 2002 storms, digital wind fields were available and only two locations (TXH and IJmuiden Semafoor; YMS) were used to scale the computed wind speeds. Although this latter technique provides a wind field with more structure, the effect on the wave hindcasts cannot be verified. However, small differences in the computed $H_{m0}$ error between the 1995 and 2002 storm hindcasts (Groeneweg et al., 2003, their Table 4.4a) indicate that both storms are predicted with similar error and can be combined into a single data set. A two-dimensional circulation model (WAQUA) was used in an independent study to compute both the water level and depth-averaged current fields for all storms (Groeneweg et al., 2003). Bathymetric data was obtained from measurements made between 1996 and 1997 and supplemented with transect measurements taken in September to November 1994 and in February and November 2002.

### *2.2. Haringvliet (1982) observations*

The Haringvliet represents a 10 km × 10 km bay in the south–west of the Netherlands which is partially protected from the southern North Sea by a fairly flat shoal (the 'Hinderplaat') extending across half of its entrance. In the considered area, the water depth varies between 4 and 6 m with a depth over the Hinderplaat varying between 1.0 and 2.2 m (Fig. 1B). The up-slope of the shoal in the mean wave direction varies from 1:500 to horizontal (at the shoal crest).

Waves were measured at various locations around the shoal with six buoys and one wave gauge, excluding the deep water buoy used to provide the boundary conditions (shown with a red dot in Fig. 1B). Four cases during a storm on the 14th October 1982 representing conditions with a stationary wind field and relatively high waves were chosen as provided in Table 1 (Ris et al., 1999). During this period, the incident significant wave heights generated by an offshore north-westerly wind