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Theoretical and Observed Breaking Wave Height on a Barred Macrotidal Beach: Implications for the Estimation of Breaker Index on Beaches with Large Tidal Range

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ABSTRACT

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Although a large number of studies were dedicated to the observation and prediction of wave height at breaking, field investigations were essentially carried out in micro- to mesotidal environments. Here we report the results of a study conducted on a barred macrotidal beach of northern France during which video observations of wave breaking were carried out simultaneously with measurements of wave data using a series of hydrodynamic instruments deployed across the intertidal and the nearshore zones and an offshore wave buoy. Our results show that waves were breaking when the ratio of wave height to depth (H_b/h_b) was comprised between approximately 0.2 to 0.45, the lower value being slightly lower than what is commonly reported in the literature for macrotidal beaches. Comparison of measured and calculated wave height at breaking using a series of predictive equations revealed that the Rattanapitikon *et al*. (2003) formula gave the best results for our data set. Predicted breaker heights were nevertheless overestimated when using offshore wave measurements and better results were obtained with wave data recorded in 5 m water depth instead. This can be explained by the presence of offshore tidal sand banks that are responsible for significant wave refraction and wave energy dissipation. These results contribute to determine more precisely the range of appropriate breaker index values for barred macrotidal beaches and highlight that nearshore wave parameters should be used rather than offshore wave statistics for predicting breaking wave height and breaking depth where sand banks strongly alter wave characteristics.

ADDITIONAL INDEX WORDS: *Breaker height prediction, macrotidal beach, coastal hydrodynamics.*

INTRODUCTION

Wave metrics are essential parameters in a wide range of theoretical as well as applied studies dealing with the hydrodynamics and morphodynamics of the coastal zone. If deep-water wave statistics can commonly be obtained from offshore buoy measurements, wave characteristics in the nearshore zone are generally seldom available due to the paucity of *in situ* wave measurements in the shallow depths of the coastal zone. Nevertheless, breaking wave parameters such as significant breaker height (H_{sb}) or ratio of breaking wave height to breaker depth (H_b/h_b), also known as beaker index (γ_b), are required in most coastal sediment transport and morphodynamic models, but also for the design of coastal structures and other coastal engineering applications. This can explain why so much effort was dedicated for years for trying to predict breaking wave height and breaking depth. These investigations resulted in the development of a significant number of predictive equations based on laboratory experiments or on field measurements using deep-water and breaking wave observations (e.g., Le Mehaute and Koh, 1967; Komar and Gaughan, 1972; Kamphuis, 1991; Rattanapitikon and Shibayama, 2006). The reliability of these empirical or semi-empirical equations for accurately predicting breaking wave parameters is extremely variable (Camenen and Larson, 2007; Robertson *et al*., 2013) and seems to depend on several site-specific characteristics (beach and/or surf zone slope, grain-size, bedforms,…) and wave characteristics (regular or irregular waves, initial deep-water wave steepness,..), as well as wind and tidal currents that may also interact with breaking wave processes.

Most of the studies aimed at predicting breaking wave height and breaking depth were conducted under microtidal or stable, laboratory-controlled, water level conditions. Although the prediction of breaking parameters is a complex task when mean water level changes are limited, it is even more complex in macrotidal environments where large vertical tidal fluctuations induce significant horizontal translations of the different hydrodynamic zones (shoaling, breaker and surf zones) across the bar-trough topography of the nearshore and intertidal zones (Levoy *et al*., 2001). In comparison with micro- to mesotidal coastal settings, investigations aiming at determining the height and depth at which waves break on macrotidal beaches are extremely limited. The objective of this paper is to present the results of a study conducted on the macrotidal coast of Northern France during which wave height and water depth at breaking were measured. *In situ* measured wave breaker heights were compared with theoretical breaker heights calculated from several predictive equations using offshore and nearshore wave data.

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The field measurements were carried out on a low-gradient (tanβ = 0.019) barred beach located at Zuydcoote near the Belgium border, facing the North Sea (Fig. 1). The beach is composed of fine sand (mean grain-size: 0.2 mm) and comprises a series of 4 to 5 shore-parallel intertidal bars ranging from about 0.8 to 1.1 m high and 50 to 90 m wide (Fig. 1B). Mean tide at Zuydcoote is approximately 4.5 m, but the tidal range exceeds 5.5 m during spring tides. This high tidal range is responsible for relatively strong tidal currents that flow parallel to the shoreline in the coastal zone, the ebb being directed westward and the flood eastward. Current measurements conducted in previous studies show that the speeds of flood currents exceed those of the ebb, resulting in a flood-dominated asymmetry responsible for a net regional sediment transport to the east-northeast (Héquette *et al*., 2008).

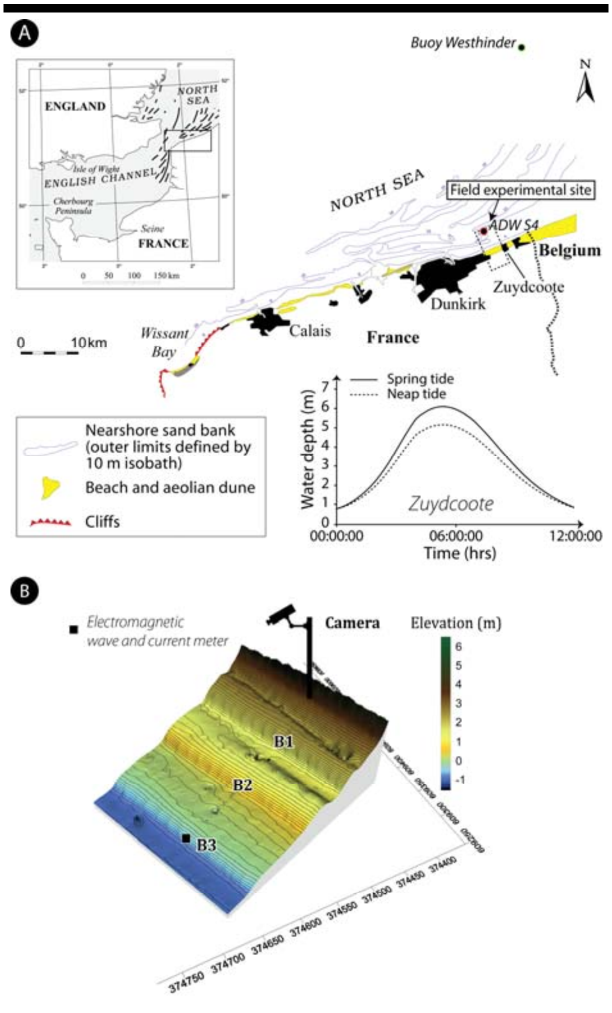

Figure 1. Location of (A) study area and (B) field experimental site.

The region is dominated by waves from southwest to west, originating from the English Channel, followed by waves from the northeast to north, generated in the North Sea. The presence of several sand banks on the shoreface and the inner shelf and the gentle beach slopes that characterize the coast of Northern France are responsible for strong wave energy dissipation, resulting in modal significant wave heights lower than 0.6 m in the intertidal zone (Héquette *et al*., 2009). Wave heights can nevertheless exceed 1.5 m on the foreshore during extreme events.

METHODS

Wave parameters were measured at different locations from the beach to the offshore zone from 2 to 9 June 2013. A Midas Valeport electromagnetic wave and current meter was deployed on the stoss side of an intertidal bar on the lower beach (bar B3, Fig. 1B) in order to record breaking waves at mid-tide or higher. An InterOcean ADW S4 wave and current meter was moored in the subtidal zone (Fig. 1A) in water depth of -5 m below Hydrographic Datum (*i.e*., approximately lowest astronomical tide level). Both instruments operated during 9 minutes intervals every 15 minutes at a frequency of 2 Hz. The duration of each burst of hydrodynamic measurements was chosen as a compromise between two opposite constraints. It had to be long enough to allow wave spectral analysis, but it also had to be short enough to respect stationary conditions as water depth is continuously changing over a tidal cycle on macrotidal beaches. Wave characteristics were obtained by spectral analysis, providing almost continuous records of significant wave height (Hs), wave period (T) and direction. Offshore wave data were also obtained from an offshore wave buoy (Westhinder) in 27 m water depth, approximately 36 km seaward of the Belgian coast (Fig. 1A), providing significant wave height and wave period every 30 minutes.

A video camera was installed in the backshore at an elevation of 10 m above the mean tide level and was programmed for recording a photograph of the beach and nearshore zone every 10 seconds. Series of 60 consecutive photographs were used for producing mean images of the coastal zone that were used for distinguishing the shoaling, breaking and surf zones during each burst of hydrodynamic measurements realized during day time (Fig. 2). This enabled to determine what wave processes (shoaling, breaking or surf) were occurring near each hydrographic instrument during each measurement period. These observations allowed the calculation of a breaker index (H_b/h_b) when waves were observed to break over an instrument, using the breaking wave height (H_{bm}) and water depth (h_{bm}) measured by the instrument.

The *in situ* measured breaking wave heights (H_{bm}) were compared with calculated breaker heights (H_{bc}) according to different predictive equations developed from laboratory experiments and field data for regular and irregular waves (Le Mehaute and Koh, 1967; Komar and Gaughan, 1972; Van Dorn, 1978; Kamphuis, 1991; Smith and Kraus, 1991; Rattanapitikon *et al*., 2003; Rattanapitikon and Shibayama, 2006; Goda, 2010) applicable for the environmental conditions observed at the experimental site, notably beach slope and offshore wave steepness. Because the deep-water wave data were measured at a distance of about 36 km offshore, the wave travel time between the offshore wave buoy and the surveyed beach was estimated based on wave celerity incrementally computed for decreasing water depths according to linear wave theory. These calculations resulted in a delay generally comprised between 1.0 to 1.5 hours between deep-water and nearshore/beach wave measurements.

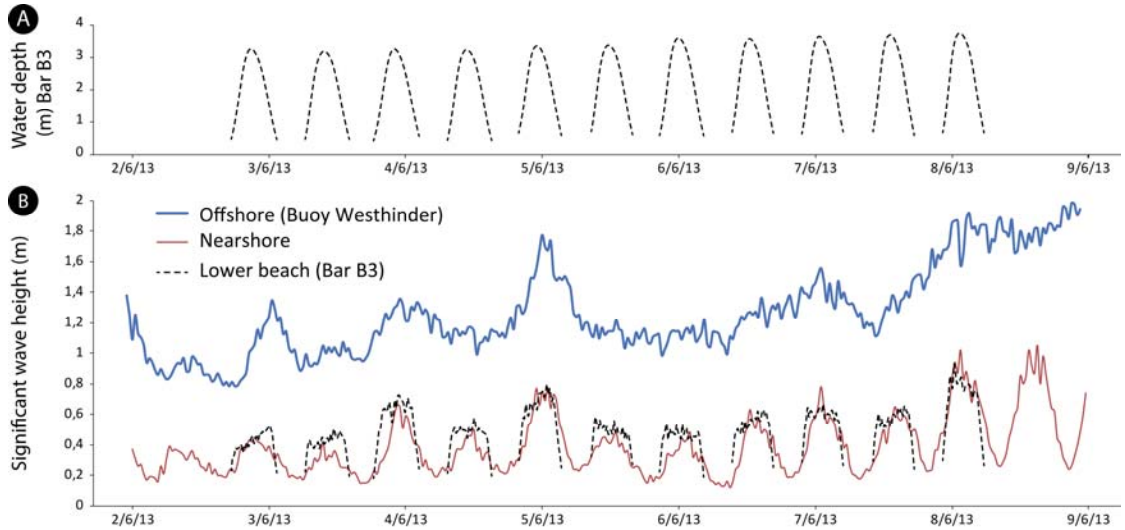

Figure 2. Time-series of (A) water depth on the lower beach and of (B) significant wave height recorded at different water depths from 2 to 9 June 2013 (see Fig. 1 for location of the instruments)

During each day of the field experiment, beach morphology was surveyed at low tide using a very high resolution Differential Global Positioning System (Leica TPS Syst1200) with vertical and horizontal accuracy of +/- 2.5 cm and +/- 1.5 cm respectively, allowing the determination of the beach slope seaward of the break point shortly before or after the breaking wave height measurements. The beach/nearshore slope was calculated for each wave breaking measurement down to the daily low-water line and was extended to a water depth of -5 m using available bathymetry data in order to consider a sufficiently long nearshore profile since it has been shown that the length of the effective seafloor slope over which waves undergo shoaling transformations and eventually breaking is of major importance for predicting breaking wave height (Robertson *et al*., 2015).

RESULTS

Deepwater significant wave height ranged from approximately 0.85 m to 2.0 m during the field experiment (Fig. 2B). Wave heights were considerably lower in the intertidal and nearshore zones, however, due to significant refraction and energy dissipation of the incident waves originating from the NNE to NE that propagated over the offshore sand banks and gently sloping inner shelf of the southern North Sea. Our measurements also show that significant wave height is strongly modulated by water depth in the coastal zone, the higher wave heights being always recorded at high tide while much lower wave heights were observed during the rising or falling tide (Fig. 2A & 2B), this dependence of wave height on water depth having been commonly observed in previous studies conducted on beach hydrodynamics in the region (Anthony *et al*., 2004; Héquette *et al*., 2009).

Wave height/depth ratio measured on the lower beach (H_{lb}/h_{lb}) were compared with nearshore wave steepness (H_n/L_n) calculated from wave data, where H_n is the nearshore significant wave height recorded in 5 m water depth and L_n is the computed nearshore wave length at the same depth according to linear wave theory (Fig. 3). Our results indicate that the highest H_{lb}/h_{lb} values, which correspond to breaking to surf zone conditions (as determined from video imagery), are associated with low H_n/L_n values, showing that low nearshore wave steepness allows waves to break in shallower water. In comparison, lower ratios of breaking wave height to water depth (H_{lb}/h_{lb}), corresponding to waves breaking in deeper water (for a given wave height), tend to be associated with higher wave steepness values although a relatively wide range of H_n/L_n values is observed, which can be explained by tidal water level changes that partly control wave steepness in the nearshore zone. A broad range of H_n/L_n values is also observed for shoaling conditions, but only with low H_{lb}/h_{lb} values (<0.22) as water depth is always large compared to wave height in the shoaling zone.

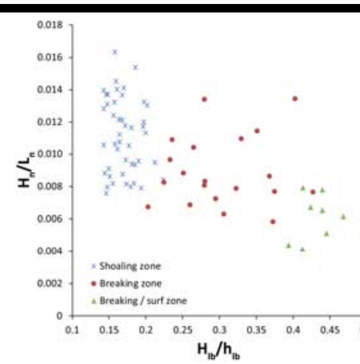

Figure 3. Relationship between nearshore wave steepness (H_n/L_n) measured in 5 m water depth and wave height to depth ratio (H_{lb}/h_{lb}) measured on bar B3 on the lower beach (see Fig. 1 for location). The distinction between shoaling, breaking and surf zones is based on visual determination from video images.

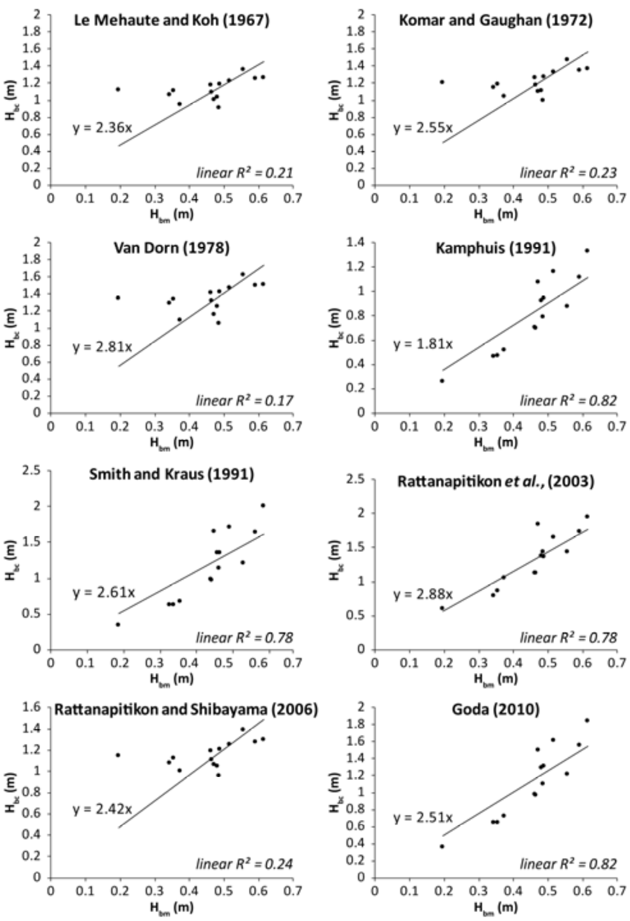

Figure 4. Comparison between measured (H_{bm}) and calculated breaking wave heights (H_{bc}) using various predictive equations.

Measured breaking wave heights were compared with theoretical breaker heights calculated from several predictive equations using deep-water wave characteristics (Komar and Gaughan, 1972; Van Dorn, 1978), notably wave steepness, and beach/surf zone slope (Le Mehaute and Koh, 1967; Kamphuis, 1991; Smith and Kraus, 1991; Rattanapitikon *et al*., 2003; Rattanapitikon and Shibayama, 2006; Goda, 2010). All equations overestimate breaking wave height, but the results given by the equations of Kamphuis (1991), Smith and Kraus (1991), Rattanapitikon *et al*. (2003) and Goda (2010) show a better fit between calculated and measured values as shown by linear regression coefficients ($R^2 \geq 0.78$) (Fig. 4).

It is noteworthy that these four equations, which gave more satisfactory results, are the only ones among the tested predictive formulas of breaker height that require some breaking parameter such as water depth at breaking or breaking wave length. These results suggest that predictive formulas of breaker heights using only offshore wave characteristics are not appropriate for estimating breaking wave height on the studied beach. In order to try to improve the results provided by these four equations, deep-water wave data were substituted by nearshore wave data measured in 5 m water depth. The use of nearshore wave data rather than offshore wave measurements lead to similar results with the Kamphuis (1991) and Goda (2010) equations (Tabl. 1). In the case of the Smith and Kraus (1991) equation, a slightly better linear relationship between measured and predicted wave heights is obtained, but the overestimation of wave height is increased further. Results are significantly improved, however, when nearshore wave data are used with the Rattanapitikon *et al*. (2003) formula, the overestimation of breaking wave height decreasing from a factor of about 2.9 to approximately 1.7 with a best fit linear regression coefficient increasing from 0.78 to 0.86 (Fig. 5).

Table 1. *Regression fit values for measured and calculated wave heights using different predictive equations.*

Equation	Offshore wave data		Nearshore wave data	
	y=ax	Linear R^2	*y=ax*	Linear R^2
Kamphuis (1991)	1.81	0.82	1.81	0.78
Smith and Kraus (1991)	2.61	0.78	2.93	0.75
Rattanapitikon *et al*. (2003)	2.88	0.78	1.72	0.86
Goda (2010)	2.51	0.82	2.62	0.78

The changes induced by the use of nearshore wave data in the equations of Kamphuis (1991), Smith and Kraus (1991) and Goda (2010) mainly result from the use of nearshore wavelength instead of deep-water wavelength. Because only moderate variations were observed between deep-water and nearshore wavelengths (calculated from the wave periods measured in 5 m water depth), only minor differences were obtained between breaker height values computed with offshore or with nearshore wave data. In contrast, the Rattanapitikon *et al*. (2003) equation also includes a wavelength at breaking, which is always considerably shorter than the deep-water wavelength, which explains the significant decrease in calculated breaker heights.

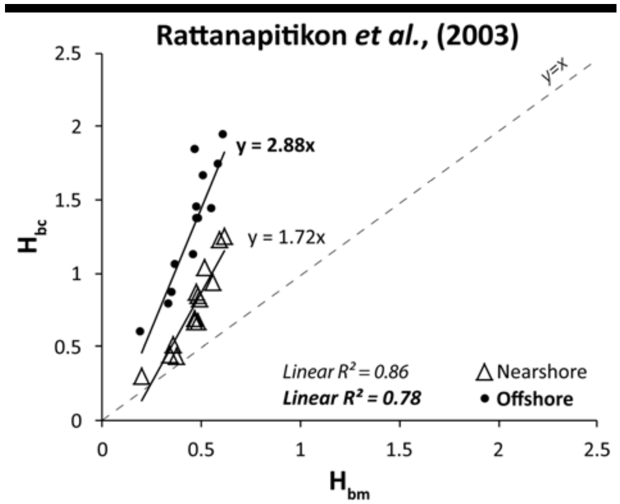

Figure 5. Comparison between measured (H_{bm}) and calculated breaking wave heights (H_{bc}) according to Rattanapitikon *et al*. (2003) predictive equation using offshore (27 m water depth) and nearshore (5 m water depth) wave data.

DISCUSSION

All the tested equations overestimate breaker heights. These differences between measured and predicted wave heights can probably be partly explained by strong wave energy dissipation during their propagation over the shallow sand banks on the gently sloping inner shelf and shoreface of the southern North Sea (Fig. 1), resulting in a significant reduction in wave height at the coast (Fig. 2). Nevertheless, better relationships between predicted and measured breaker heights were obtained with the equations of Kamphuis (1991), Smith and Kraus (1991), Rattanapitikon *et al*. (2003) and Goda (2010), which include some wave parameter at breaking. Our results also showed that the use of nearshore wave data instead of deep-water wave data can significantly improve breaker height prediction, notably when using the Rattanapitikon *et al*. (2003) equation in which a wavelength at breaking is considered, which can be explained by a change in wave period between the offshore and the nearshore zone. All these results suggest that breaker height can not be accurately estimated when using only deep-water wave data where waves propagate over a complex and dissipative shelf and coastal bathymetry responsible for a significant decrease in wave height.

The equations of Kamphuis (1991), Smith and Kraus (1991), Rattanapitikon *et al*. (2003) and Goda (2010), which gave better results than the other tested equations, all include the seafloor slope as an input parameter, suggesting that it represents an important factor for the prediction of breaking wave heights in the study area. These results are consistent with previous investigations that showed that the beach and nearshore slope represents an important parameter to consider for predicting breaking wave height (***e.g.***, Camenen and Larson, 2007; Robertson *et al*., 2015), which is presumably critical over highly dissipative, low-sloping, macrotidal beaches. Tidal currents may represent an additional factor influencing breaking wave processes in such environments.

Another factor that may explain some of the discrepancies between measured and predicted wave heights may also be due to the use of predictive equations that are based on regular wave tests which makes direct comparison difficult with irregular waves (Robertson *et al*., 2015). Some of the observed differences may also be related to the fact that calculated breaker heights correspond to a value at the breakpoint while our measurements of breaking wave height correspond to wave heights in the breaker zone, which can be slightly different.

CONCLUSIONS

Our results show that predictive equations based on deep-water wave characteristics overestimate breaking wave height on the studied beach. This can probably be explained by the presence of offshore sand banks and low-sloping inner shelf and shoreface that are responsible for significant wave refraction and wave energy dissipation. Our measurements also contribute to determine more precisely the range of appropriate breaker index values for barred macrotidal beaches and highlight that nearshore wave parameters should be used rather than offshore wave statistics for predicting breaking wave height and breaking depth where complex offshore and nearshore bathymetries strongly alter wave characteristics.

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LITERATURE CITED

Anthony, E.J., Levoy, F. and Montfort, O., 2004. Morphodynamics of intertidal bars on a megatidal beach, Merlimont, Northern France. *Marine Geology*, 208(1), 73-100.

Camenen, B. and Larson, M., 2007. Predictive formulas for breaking depth index and breaker type. *Journal of Coastal Research*, 23(4), 1028-1041.

Goda, Y., 2010. Reanalysis of regular and random breaking wave statistics. *Coastal Engineering Journal*, 52(1), 71-106.

Héquette, A., Hemdane, Y. and Anthony, E.J., 2008. Sediment transport under wave and current combined flows on a tide-dominated shoreface, northern coast of France. *Marine Geology*, 249(3-4), 226-242.

Héquette, A., Ruz, M.H., Maspataud, A. and Sipka, V., 2009. Effects of nearshore sand bank and associated channel on beach hydrodynamics : implications for beach and shoreline evolution. *Journal of Coastal Research*, SI 56, 59-63.

Kamphuis, J.W., 1991. Incipient wave breaking. *Coastal Engineering*, 15(3), 185-203.

Komar, P.D. and Gaughan, M.K., 1972. Airy wave theory and breaker height prediction. ***Proc.*** *13th* ***Conf.*** *Coastal Engineering*, Vancouver, Canada, pp. 405-418.

Le Mehaute, B. and Koh, R.C., 1967. On the breaking of waves arriving at an angle to the shore. *Journal of Hydraulic Research*, 5(1), 67-88.

Levoy, F., Monfort, O. and Larsonneur, C., 2001. Hydrodynamic variability on megatidal beaches, Normandy, France. *Continental Shelf Research*, 21(6-7), 563-586.

Rattanapitikon, W., Vivattanasirak, T and Shibayama, T., 2003. A proposal of new breaker height formula. *Coastal Engineering Journal*, 45(1), 29-48.

Rattanapitikon, W. and Shibayama, T., 2006. Breaking wave formulas for breaking depth and orbital to phase velocity ratio. *Coastal Engineering Journal*, 48(4), 395-416.

Robertson, B., Hall, K., Zytner, R. and Nistor, I., 2013. Breaking waves: Review of characteristic relationships. *Coastal Engineering Journal*, 55(1), 1-40.

Robertson, B., Hall, K., Nistor, K., Zytner, R. and Storlazzi, C., 2015. Remote sensing of irregular breaking wave parameters in field conditions. *Journal of Coastal Research*, 31(2), 348-363.

Smith, E.R. and Kraus, N.C., 1991. Laboratory study of wave breaking over bars and artificial reefs. *Journal of Waterway, Port, Coastal, and Ocean Engineering*, 117(4), 307-325.

Van Dorn, W.G., 1978. Breaking invariants in shoaling waves. *Journal of Geophysical Research*, 83(C6), 2981-2988.