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Measurement of the Scale Effect on Breaking Waves

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ABSTRACT

Laser scanning technology, LiDAR, has been used to measure free-surface water profiles in the laboratory and in the field and the effect of scale has been investigated in the application of wave breaking theory. As a result of the calculation of wave parameters, such as breaker index and crest elevation, the difference between flume generated waves and waves in the surf zone were observed. The results show that while in most cases the field and laboratory derived breaking waves behave similarly, under some conditions in the flume waves can break outside the theoretical breaker criteria and whether this is a result of the scale effect is investigated.

KEY WORDS: LiDAR, free-surface profiles, breaking waves

INTRODUCTION

The technology described in this paper allows for the measurement of surf-zone profiles at high scan rates both in the laboratory and in-situ. The comparison of measurements between both study domains allows us to comment on the nature of the wave shoaling process as wave heights increases towards the breaking point. Although the processes are relatively easy to measure in a controlled laboratory experiment, measurements in the field may require elaborate or large scale instrumentation arrays. In this study the measurement of free-surface elevation uses the same LiDAR for the experiments in both scales. The results of these experiments aims to show the differences between processes that occur during wave breaking at differing scales. In the laboratory, scales can be compared with no significant observable influences on wave height or shape (Stive, 1985). However, according to Stagonas et al. (2011), the effect of scale on the influence on surface tension in the laboratory can be significant to the dissipation rate of waves when compared to the surf zone. These contrasting views present a grey area where some aspects of breaking waves may be influenced by the scale effect and some are not. Air entrainment is also a factor that can influence fluid behaviours at small scales as shown in Blenkinsopp and Chaplin (2007). Although wave shoaling should not be affected by this phenomenon, dissipation can be influenced. In this study wave dissipation is not considered and it is not expected to influence pre-breaking measurements. Some support for the scale effect on small amplitude waves is given in Couriel et al. (1998), where it was found that wave crest geometry can be influenced by surface tension for waves smaller than 0.05m. This could affect breaking wave height by prolonging or accelerating the incipient of breaking. It is well known that the theoretical breaking index for a gravity wave depends on a number of factors, such as the relationship between wave height and depth, as well as the sea bed slope for waves propagating over irregular bathymetry. Work performed by Weggel (1972) and Komar and Gaughan (1973) has determined a number of relationships for calculating the breaker height index and under what conditions breaking could be expected. For this study there is a possibility that the addition of seeding material to the flume (for effective use of the LiDAR instrumentation) may alter the surface tension or other properties of the water. The effect of certain seeding materials to change the surface tension has been used in studies, such as by Techet and McDonald (2005), and there is evidence of scale affecting many aspects of waves in the surf-zone. This is especially observable post-breaking where surface tension effects on air entrainment and roller propagation and splash can occur, and so the influence of scale cannot always be disregarded.

This paper aims to outline the use of LiDAR technology to measure free-surface water profiles of breaking waves in the flume and in the field. Due to the nature of the data measured using this technology a processing algorithm was constructed that tracks individual waves and determines when a breaking wave is detected. Wave-by-wave modelling has been performed extensively (Dally 1992) and wave-by-wave analysis has been performed (Postacchini and Brocchini, 2014), however, to the authors understanding, not for successive wave profiles. The method used in this paper allows for the processing of a large number of waves covering a variety of wave types. In the described experiments the scale effect between small and large scale waves is investigated using the breaker index relationships. Because the comparison includes laboratory and field data, the nature of the experiment inherently adds further variables into the study. It is important to consider whether the scale effect is significant or whether the ‘clean’ nature of flume waves is significant in explaining differences between breaking waves at either scale. This paper serves as a preliminary stage in producing a comprehensive methodology for using LiDAR sourced data for scale comparisons, and will be applied for model validation (Zhang and Chan, 2003).

EXPERIMENTAL SET-UP

Data from both laboratory and field measurements is required for an analysis of scale effects on wave breaking. For both types of experiments conducted in this study (laboratory and field) a high scan rate LiDAR was used to obtain non-uniform spatial profiles of the free-surface over time. The LiDAR used was a SICK LMS511-20100 PRO operating between 25-50Hz, and has been shown to provide suitable data for analysis of wave processes (eg. Harry et al., 2012). Analysis of the data also requires extensive processing and, for this study, a method for determining the breaking point from consecutive surface profiles measured in the flume was constructed.

Laboratory set-up

Various wave periods and wave heights were run within the wave flume at Griffith University, QLD, Australia. A regular wave signal was used to drive the wave generator. The results were validated against pressure transducers and a high-speed video camera system by comparing measured water elevations over a number of wave conditions (accuracy ±4mm). The LiDAR was positioned above the centre-line of the wave flume providing line of sight along the water surface. Seeding of the water was required for the LiDAR to operate successfully. Micro glass spheres ware placed onto the water surface and provided a reflective substance for the LiDAR. Experiments were run with a combination of initial wave heights of 0.075m, 0.1m, 0.125m and 0.15m and wave periods of 1s, 2s and 4s. In addition, all combinations were run over three water depths of 0.16m, 0.17m and 0.18m at the wave paddle. A fixed irregular bathymetry was used and was approximately a 1:10 scale representation of a typical beach profile in South-East Queensland, Australia. Both the bathymetry in the flume and the bathymetry in the field study have a submerged bar in the surf-zone.

Field set-up

Field measurements were taken from the Tweed River Entrance Sand Bypassing Project jetty in northern NSW, Australia. The LiDAR was mounted off the jetty deck at a height of approximately 8.75m above the Australian Height Datum (AHD). Calibration was performed against a pressure transducer, as well as with elevations from tidal analysis to confirm the water surface elevation. The LiDAR provided free-surface profiles along a cross-shore width of 60 m at approximately 1m from the jetty. It was unnecessary to provide seeding in the field as the surf conditions of the day presented a relatively foamy surface that was ideal for LiDAR. Bathymetry in the study domain was measured at 5 m intervals. The deep water wave conditions over the study period consisted of 1-1.6m significant wave heights with an average period of 5.75s.

Wave-by-wave analysis

There is a large amount of detail in free-surface profiles obtained by LiDAR and this allows the observation of hydrodynamic processes. In observing LiDAR-measured successive free-surface profiles it is evident that a number of water wave characteristics (such as wave speed, steepness and breaking height) are readily observable, much like the observations of a cross-sectional video. Quantifying these characteristics autonomously can be difficult due to the dynamic nature of the free-surface in the surf zone. The method described below allows for wave tracking near the breaker zone, and subsequently the ability to determine wave parameters at the breaking point. The method was used to track an individual wave face by identifying the steepness of the local free-surface profile. Changes to the angle of wave steepness due to shoaling were measured over a number of wave profiles. The wave crest corresponding to an identified wave face is tracked through the transformation of that individual wave from initial detection through to breaking.

An assumption was made in that a drop in the wave crest elevation for the tracked wave marks the incipient of wave breaking and at this point the breaking parameters were determined. This includes the maximum wave crest height, wave trough level and breaker depth. **Error! Reference source not found.** illustrates the wave parameters obtained by an algorithm. The algorithm can be described in two parts; wave tracking and breaker determination. The general method is described below:

Step 1. Wave tracking (for all surface profiles)
- Create a localised linear fit at intervals along the surface profile
- Identify the steepest location at each time step
- Determine the crest elevation and its location

Step 2. Breaker determination (for all identified wave crests)
- Check whether the current crest is from the same wave as the previously identified crest
- Check whether the current crest elevation is below a threshold set from the previous maximum crest
- If this is true, the break point is identified, wave parameters are determined and the next wave is analysed

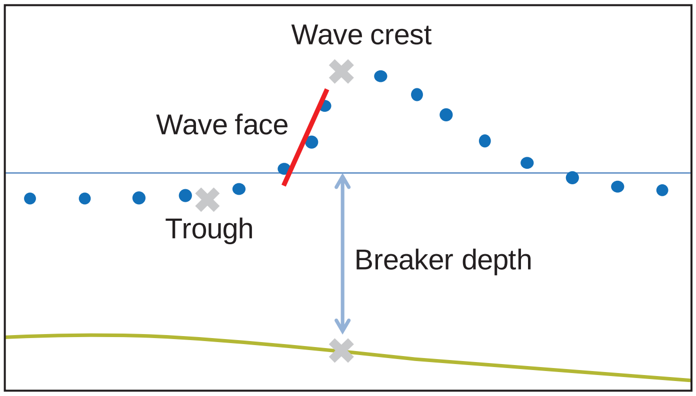

Figure 1 Generalised breaking wave parameters obtained by the wave-by-wave algorithm.

The wave tracking component of the algorithm was used to analyse each wave profile, which in the case of the flume experiments were at 35Hz. The large number of wave profiles allows the capture of a breaking wave no matter where it occurs in the study domain. The data collected from the algorithm includes (for a breaking wave): time, wave crest, wave trough, location and depth. As designed in the algorithm the wave trough was generally taken as the lowest point ahead of the breaking wave, however if this was more than a certain distance away an arbitrary point is chosen. The reason why this was a necessary part of the algorithm was a result of localised surface fluctuations which make it difficult to determine the trough. Figure 1 shows the wave parameters determined at the breaking point, including an arbitrary trough. The method was reliable for the LiDAR measurements of regular waves in the laboratory (in the current study). For this study the algorithm was not used for field data and a manual method was used instead. Nevertheless, free-surface profiles from the field could be analysed this way subject to certain limitations. For example, in the surf zone there is a higher chance of splashing due to breaking waves (this can interfere with the profile interpolation). Also the spectrum of wave periods can make it difficult to discretise waves of various frequencies.

RESULTS

Breaking wave parameters

The breaking wave parameters in the flume were determined using the wave-by-wave algorithm as described above. In the field a total of 20 breaking waves were analysed (manually) covering a range of wave periods, wave heights and breaker depths. Although the average wave period in the field was 5.75s, waves breaking in the study domain used for determining breaking parameters were generally closer to 10s.

It can be observed in Figure 2 that the majority of waves measured in the field had broken as intermediate depth waves. For the following figures and equations H is the wave height, H_b is the breaking wave height, g is the gravitational constant, T is the wave period, d is the depth, d_b is the breaker depth and γ_b is the breaker index. The breaker index (Eq.1) for all field data points is generally in the range of 0.3-0.5.

$$\gamma_b = H_b / d_b \qquad (1)$$

These values are reasonable and certainly within the theoretical bound of γ_b=0.78 (for horizontal sea bed). The majority of all flume data is outside this limit. However, the bathymetry is irregular with a non–zero slope and therefore the limit is higher than this given value. There are two distinct clusters of data points and it appears that the separation is related to the wave period relationship with both the breaker height and breaker depth. Although the flume runs are grouped into three wave periods, the wave parameters used result in breaking as either a shallow water wave or intermediate depth wave. Therefore, it is the wave steepness at the break point that is the reason for the clusters. Also of note is that approximately 10% of the waves pass beyond these points. As the data excludes ramp-up and ramp-down of the wave paddle, there are peculiar cases where the conditions for a single run remain constant and there is a measured variation in the location of the break point.

In flume experiments the reflection from run-up on the bathymetry can be a significant source of return surface fluctuations which may introduce variability in the regular wave signal. This is an important factor at small scales where the dissipation of wave run-up can be difficult to achieve without specific bathymetry porosity at the shoreline. In addition, due to the small scale of many flume experiments the two-dimensionality of the wave across the tank width is important to control. Nevertheless, for this study each wave was relatively 'clean' with the dominant influence on regular wave variability coming from some run-up reflection.

Initial observations of Figure 3 indicate that the wave heights encountered in the field and those generated in the laboratory were not relatively large enough to test the limits of the theoretical breaker wave heights in Weggel (1972), especially in regards to their corresponding periods. It can be observed that the waves in the field are all well within the vertical bounds for any given bed slope (maximum slope in the field was tanβ=0.075). In contrast, the measurements for waves in the flume vary considerably and are in at least two distinct bands related to the wave steepness. Overall, the wave steepness is relatively low (H/gT^2<0.004) and from the figure the bands could be inferred as a distinction between runs of various initial wave heights. However, it was determined after further analysis that the pattern of at least two distinct bands is common for all initial wave heights and all wave periods. Therefore, the grouping is present within each run, not just between the runs themselves. This variability in wave steepness within a single run can be influenced by excessive reflection that may have changed the local water depth. Otherwise there may be some other phenomena that affect the shoaling of successive regular waves that is still not understood – thus requiring further investigations to be carried out.

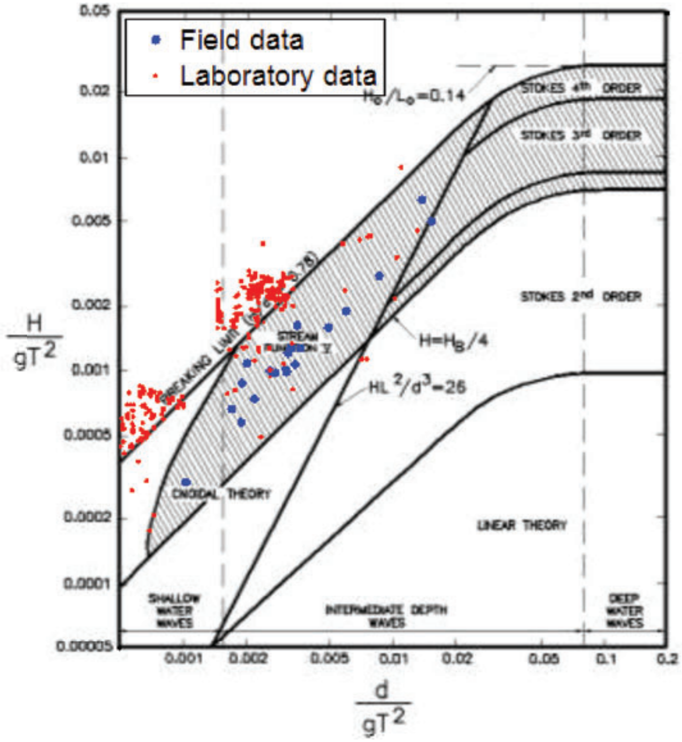

Figure 2 Breaker height and breaker depth relationship for both the flume data and the field data. The data is overlain a figure presented in Le Mehaut (1976)

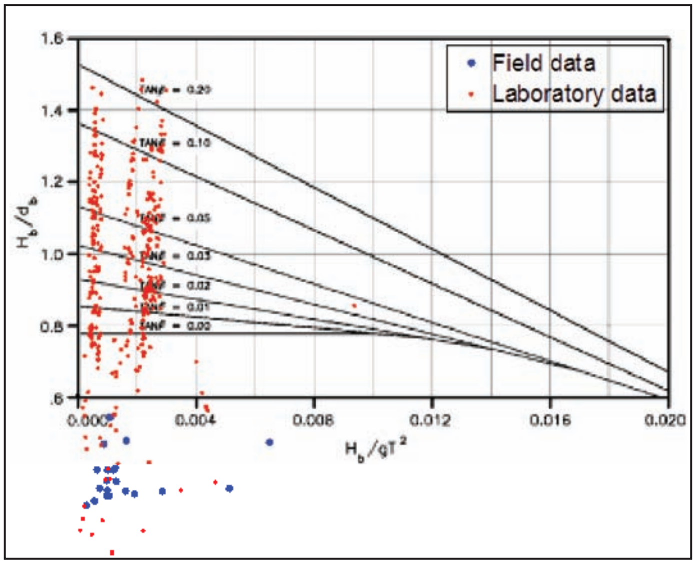

Figure 3 Breaker depth index data overlain a figure presented in Weggel 1972. Note that all field data is well within the expected bounds, even for a horizontal sea bed. The laboratory data varies considerably and exceeds the expected value for the slope used in the

flume

It is unusual that in the flume, for the given bathymetry with a maximum slope of tanβ=0.08, a number of breaker index values are outside of the theoretical bound. A small number (<10 waves) also exceed the maximum theoretical value of γ_b=0.156 for a low steepness wave. This suggests that some waves are holding their shape for longer than expected prior to breaking. The smaller scale flume waves were subject to seeding to aid in the LiDAR performance and this could be affecting the surface tension properties of the propagating wave. The average breaking wave height is 0.0875m with just under 10% of wave heights being less than the 0.05m height that is influenced by surface tension (Couriel et al., 1998). Therefore, a small number of the propagating waves may have had a suppressed breaking wave crest due to surface tension. This percentage could be higher if the seeding material also has an influence and it is recommended that a detailed analysis is undertaken on the effect of seeding material on water properties.

Breaking wave surface profiles

The breaking wave parameters were used to construct various water surface profiles. These profiles are the recorded surface elevations at the incipient of breaking. From LiDAR measurements it is possible to retrieve the entire profile within the study domain, provided there is no ‘shadow effect’ or loss of optical reflectivity of the water surface. In Figure 5 a total of six flume profiles and six field profiles are presented comparing the wave shape within each study domain. The data is normalised to the wavelength and to the breaker crest elevation (where 0 is the sea bed). It can be observed from the random selection of wave profiles that the wave steepness is visibly higher in the flume.

A representation of the breaker index can also be observed in that the troughs of the flume profiles almost 50% of the distance from the wave crest to the sea bed due indicating a high breaker index compared to the field data. It is evident that the surface elevation over a wavelength in the flume is corresponds to the breaker crest, whereas in the field there is more variation. Especially shoreward of the wave face, the surface elevation is within a relatively wide range. There is also more variation in wave steepness. This could in part be due to waves of other frequencies changing the local surface elevation. In general, the laboratory data suggests breaking waves are more predictable in the flume.

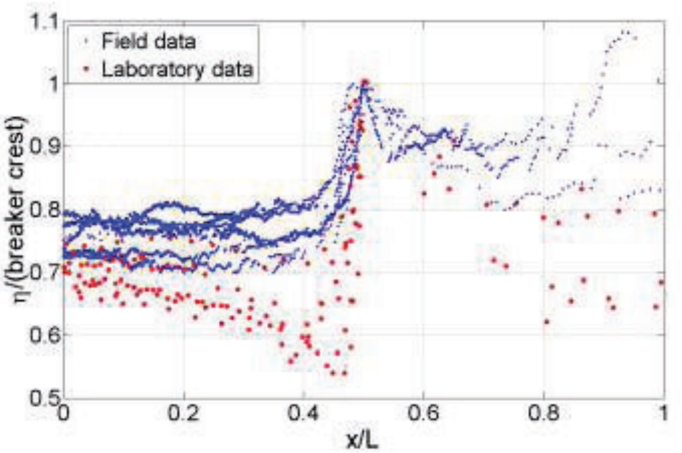

Figure 5 Normalised breaking wave surface profiles (12 in total)

A comparison between two individual wave profiles is provided in Figure 5. The field data (both surface profile and bathymetry) is plotted to the Australian Height Datum (mAHD) in elevation and to the LiDAR origin in the cross-shore distance. The laboratory data has been scaled to the field from the 1:10 prototype scale. Both the flume and field breaking surface profiles were chosen due to similar wave heights and wave shape. The breaking depth in the field is 1m (60%) deeper than the flume. Considering that the wave period in the field is twice as long as the flume, and that the steepness of each breaking wave is the same, it can be concluded that the flume wave can hold its form into much shallower waters until the breaking point is reached.

Analysis of the wave profiles suggests that waves in the flume are more predictable, but at small scales the breaking point may exhibit some variability and this supports the breaker index analysis in the previous section. The waves generated in the flume need to be under strict experimental control to remove any unwanted variability in breaking behaviour that can occur due to reflections as well as surface tension effects for very small scale gravity waves.

Future Studies

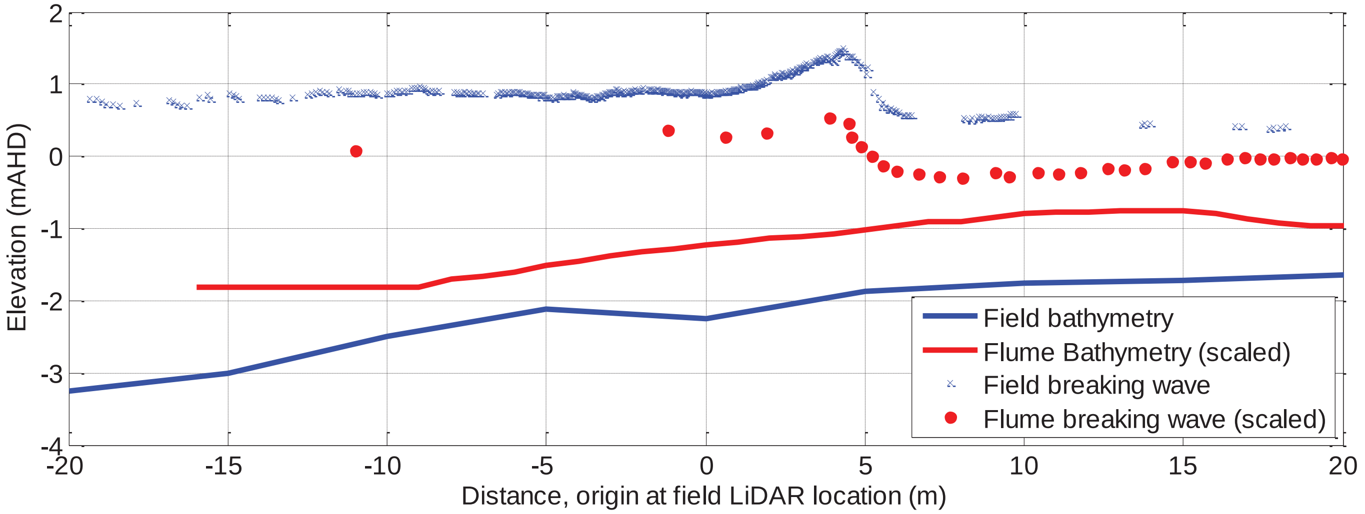

Figure 4 Surface profile data from a breaking wave in the field and a scaled wave in the flume

A number of further studies can be undertaken based on the findings of this paper. The most important improvement that can be made is to the wave-by-wave analysis to include multiple wave tracking for irregular wave signals. The LiDAR instrumentation can provide a large amount of data for a relatively simple set-up and time series analysis can be easily performed on the data, however the ability to capture successive surface profiles is the instruments real strength. Therefore it requires a robust data processing and analysis procedure similar to the algorithm in this paper, with further development so that any surf-zone conditions can be analysed.

In regards to the scale effect on breaking waves, this paper presents a number of questions based on the surface profile analysis.. Primarily, the influence of scale on the consistency of the breaking point can be determined with a larger array of input parameters, hence more runs, as well as removing set-up variability such as unrealistic run-up reflection. Scale effects will certainly have an influence on post breaking flow, including splash, and this can be investigated using LiDAR. From the field data measured for this paper the splash created by breaking waves can be detected and therefore it would be possible to draw comparisons with the flume where surface tension will certainly be an influence.

CONCLUSIONS

The LIDAR technique measures waves at various scales with similar accuracy. A wave-by-wave algorithm was constructed to analyse the individual surface elevation profiles. The algorithm was shown to perform well for regular wave conditions to automatically determine wave breaking parameters. Breaking waves in the flume and the field were compared and it was shown that under most conditions tested the scale effect is minimal, however there are a number of cases from the large data set that are influenced by phenomena not encountered in the field. A combination of surface tension, influence from particle seeding and experimental set-up variability can cause discrepancy in the flume results. Further investigation is required to develop the methods used in this study and to confirm the findings.

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