EXPERIMENTAL WAVE BREAKING VELOCITY CHARACTERIZATION FOR MONOCHROMATIC, BICHROMATIC AND IRREGULAR WAVES

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Abstract

The present work focuses on the comparison between different types of data analysis (time analysis; Fourier transform spectral analysis; wavelet transform spectral analysis; and hodograph representation) applied to Acoustic Doppler Velocimetry (ADV) records of wave orbital velocities. Different wave conditions (monochromatic, bichromatic and irregular) have been tested, for the general purpose of experimentally investigating wave shoaling and breaking over a gentle slope. The analysis of the velocity data, through these methodologies, illustrates other relevant phenomena occurring in the wave propagation, which cannot be depicted by the usual wave gauges. Each of these techniques has advantages and drawbacks, and so they should be complementary.

Keywords: Acoustic Doppler Velocimetry; Wave Breaking; Regular Waves; Bichromatic Waves; Irregular Waves.

1. Introduction

The knowledge of wave transformation and wave breaking characteristics near the coastline is essential for nearshore hydrodynamics studies (*e.g.*, coastal sediment dynamics), for the design of coastal and port structures, and for estimating forces on pipelines crossing the surf zone. Physical models and laboratory experiments are an important part of the research methodology for acquiring a better knowledge and characterization of these phenomena. Also, the validation of the numerical models depends greatly on accurate and reliable experimental data.

Following this reasoning, a wide range of wave flume tests was performed at the National Laboratory for Civil Engineering (LNEC) to study wave transformation and wave breaking considering different incident conditions.

Okamoto *et al*., 2010, Endres *et al*., 2011, Neves *et al*., 2011, 2012b, and Conde *et al*., 2012, performed a set of experimental tests for incident regular wave conditions with and without wave breaking, considering different bottom slopes. Conde *et al*., 2013a, 2013b, 2013c, followed the methodology of these previous works, considering incident bichromatic and irregular waves.

In a previous paper Conde *et al*., 2014, compared three methods of data analysis (time analysis; Fourier transform spectral analysis; and wavelet transform spectral analysis), applying them to different types of waves (monochromatic, bichromatic and irregular). The data and results from these methods of analysis include: free surface elevation along the flume and the corresponding amplitude spectra; significant wave height, H_s, and significant wave period, T_s, along the flume. From the time domain analysis it was possible to observe the evolution of H_s along the flume, *i.e.*: the increase of H_s as the waves propagate along the flume due to wave shoaling, until the beginning of wave breaking; then, a remarkable decrease of H_s occurs within the breaker region; and after the end of the wave breaking the H_s values remain almost constant. The Fourier analysis allowed the characterization of the nonlinear phenomena and the harmonic generation due to shoaling and wave breaking. Similar conclusions could be obtained both with the Fourier analysis and with the wavelet technique. But, with the wavelet technique, more important information related to the energy distribution associated with each frequency over the course of the experiment was obtained. The monochromatic and bichromatic waves, due to its regular nature, present the transfer of energy between frequencies with a periodicity even after wave breaking. On the other hand, the irregular waves did not present a clear pattern of repeatability over the course of the experiment. As a final conclusion one may state that each of these techniques has its own advantages and drawbacks. None of them may be considered as a substitute of the other, instead each should be used as a complement to the others.

Velocity measurements may provide additional information about the physical properties of the wave flow, such as particle acceleration and reflection coefficient, which may be relevant to coastal engineering studies, although such additional information very often is disregarded in small scale models. One possible explanation is that the free surface elevation is easily recorded, and most engineering traditional practice is based on wave height; another reason is the amount of turbulent fluctuation which is recorded on velocity measurements; a third reason might be lack of well established procedures for converting particle velocities into engineering design information. Acoustic Doppler Velocimetry (ADV) probes used in the laboratory require careful positioning and the data should be carefully analyzed in order to account for slight deviations in vertical or horizontal orientation of the instrument. Also, ADV time series present, under some conditions (*e.g.*, improper seeding, static objects reflections, receivers out of the water, *etc.*), values that may not represent water suspended particles velocity, so a digital filter should be applied to reduce these occurrences.

Neves *et al.* (2012a) presented possible analytical methods to improve the quality of data interpretation of ADV records and corrections which should be applied to the data. This methodology is applied in the present paper to the same wave conditions presented by Conde *et al.* (2014), and thus may be seen as a continuation of that previous paper but, in this case, analyzing the velocity data components from ADV measurements.

This paper starts with a short description of the experimental layout, the incident wave conditions and the experimental procedures. Then, results from spectral analysis (Fourier and wavelet) and hodograph representation of the velocity components in some locations along the flume, obtained for three different types of waves (regular, bichromatic and irregular), are presented and discussed.

2. Experiments

The experimental tests were performed in the wave flume presented in Figure 1 and Figure 2. This flume, build in the 1950s, has a reduction of width and depth in order to increase regular wave heights and to improve the hydraulic behavior, by preventing unwanted transversal waves. The impermeable bottom is composed by a 10m long 1:22 slope ramp, followed by a 10m horizontal stretch, then by a 1:20 slope, ending at a 1:2 slope gravel beach which extends above water level. Horsehair sheets were installed over the 1:20 slope to reduce wave reflection. Nowadays, the flume is equipped with a piston-type irregular wave-maker system controlled by an A/D converter and a personal computer. This wave-maker can generate regular or irregular waves, and is equipped with a reflected wave dynamic absorption system (Capitão and Conde, 2013).

Figure 1. Wave Flume: side view (left), wave maker (middle), view from above (right).

The experiments considered for the present paper were:

1. Regular waves with 1.5s wave period (T) and 0.14m wave height (H);
2. Bichromatic waves considering a combination of two wave periods, 1.1s and 1.5s, with 0.08m wave height each;
3. Irregular waves (JONSWAP spectrum) with T_p=1.5s and H_s= 0.14m.

The water depth in the horizontal stretch (Figure 2) was d=0.1m, in order to have wave breaking conditions. Details about the wave generation procedure may be found in Conde *et al.*, 2012, 2013a and 2013c. The dynamic absorption for reflected waves was not activated, so that the waves would always be generated in the same manner for all the experimental tests, preventing automatic corrections by the wave maker that might be different from test to test.

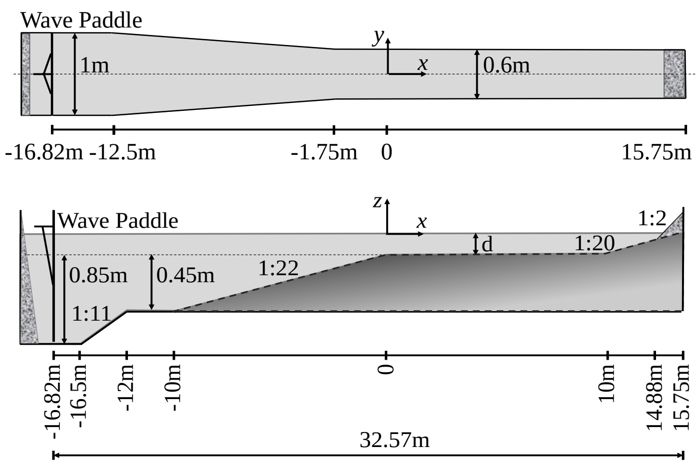

Figure 2. Wave flume's plan and longitudinal-section views.

The reflection coefficient was thus evaluated by the Mansard and Funke (1980) method, considering regular and irregular waves, for a water depth d=0.3m corresponding to nonbreaking wave condition (Capitão and Conde, 2013). For regular waves with T=1.5s and H=0.06m, 0.08m or 0.1m the reflection coefficient is r0~0.15. For this water depth (d=0.3m) the regular waves only break at the end of the flume over the porous blankets. The reflection coefficient increases with the wave period from 0.05, for T=1.1s, to 0.3, for T=2.5s, considering H=0.1m. Waves with H=0.12m and higher, for d=0.3m, break before the beginning of the horizontal zone. For d=0.1m, all tested waves (regular and irregular) break before this zone. The remaining wave energy will then dissipate in the blankets over a 1:20 slope.

Free surface elevations were measured using an eight gauge movable structure, 1.8m long (Figure 3 – left), with gauges positioned 0.2m apart. This structure was placed at different locations along the flume, and measurements were taken from x=-10m up to x=10m. A reference wave gauge was installed near the wave-maker at x=-10.8m, in order to verify the input wave height (Figure 3 – middle). The three orthogonal velocity components were measured by an ADV probe. Together with the ADV probe, a resistive gauge was placed in the same cross section for simultaneous measurements of the free surface elevation (Figure 3 – right). The ADV probe was located in the middle of the flume and at mid-depth of the water column, and measurements were obtained between x=-10m and x=7m, with a 1m interval. Vertical profiles of longitudinal velocity component were obtained at selected sections along the flume. The sampling frequency of all measurements was 25Hz and each run (incident wave) had a useful duration of 240s for regular and bichromatic and 190s for irregular waves.

Figure 3. Eight wave gauge mobile structure (left), wave gauge near the wave maker (middle) and ADV probe with wave gauge (right).

3. Results

For the incident wave conditions considered, different types of data analysis were made:

a) Time domain and spectral analysis of the free surface elevations along the flume, presented in Conde *et al*., 2014;
b) Time domain and spectral analysis of the particle velocity measurements along the flume at mid-depth of the water column. Moreover, these results allow the calculation of the particle velocities main characteristics and the two-dimensional distributions of velocity components in the xy, xz and yz planes;
c) Time domain and spectral analysis of velocity vertical profiles taken at several sections along the flume, to present in a future paper.

3.1 Spectra

Figure 4 presents the energy spectra at x=-10, -5, 2 and 3m. These energy spectra were obtained by a Fast Fourier Transform (FFT) using the software SAM (Capitão, 2002).

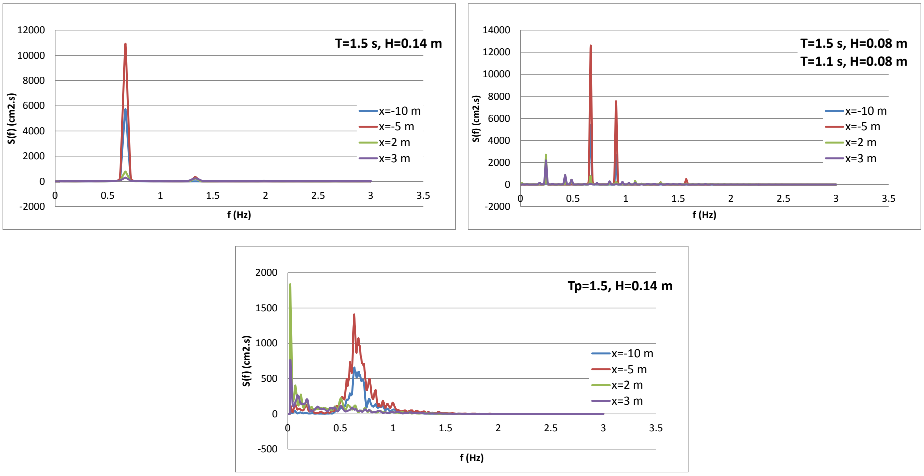

Figure 4. Energy spectra at different sections along the flume for regular (left up), bichhomatic (right up) and irregular waves (down).

Wavelet analysis has become a common tool for the analysis of transient effects within a time series (Liu, 2000). By decomposing a time series into time–frequency space, one is able to determine both the dominant modes of variability and how those modes vary in time. Figure 5 presents the Morlet wavelet power spectrum along the flume, at sections x=-5 and 2m.

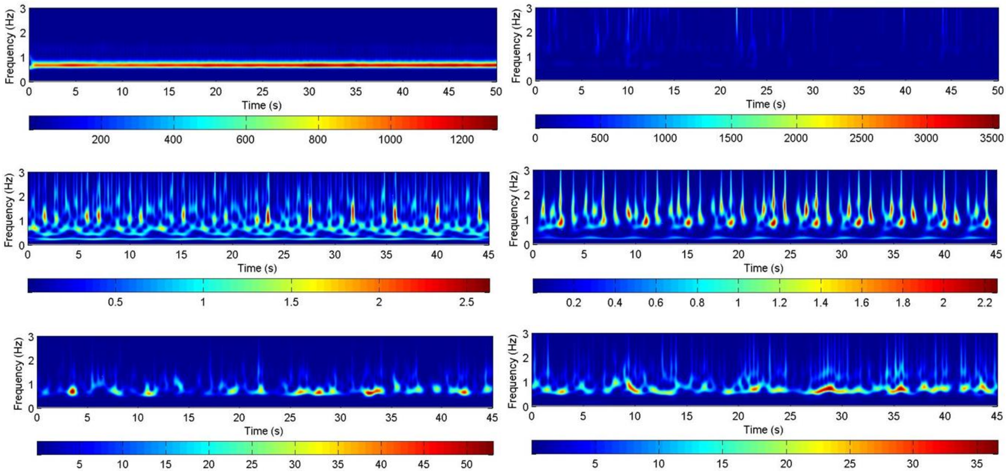

Figure 5. Wavelet analysis for regular (top), bichromatic (middle) and irregular (bottom) waves at different sections along the flume: x=-5m (left) and x=2 m (right).

3.2 Velocity components' two-dimensional distributions

The analysis of the Hodograph representation of the velocity components in the xy, xz and yz planes is performed in Figure 6 and Figure 7. Figure 6 presents the recorded data cloud distribution at x=-5m (middle of the water column) for the regular, bichromatic wave and irregular waves, while Figure 7 presents the same for x=2m.

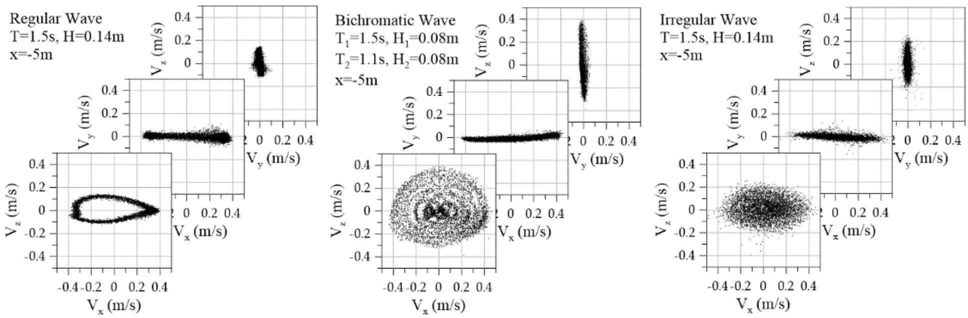

Figure 6. Hodograph of the velocity components: recorded data cloud for regular (left), bichromatic (center) and irregular wave (right), for x=-5m, without filter.

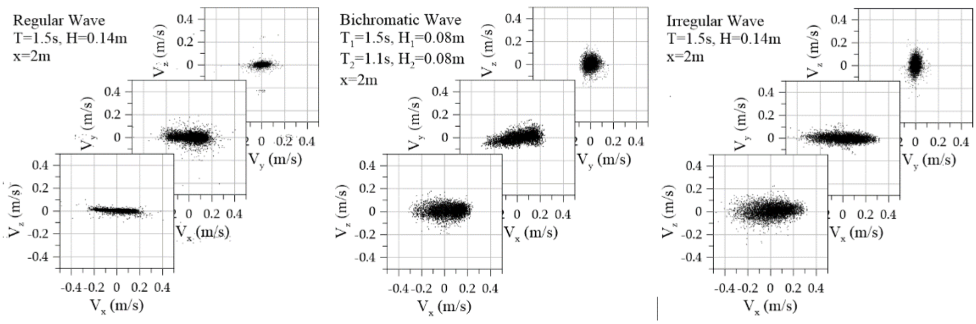

Figure 7. Hodograph of the velocity components: recorded data cloud for regular (left), bichromatic (center) and irregular wave (right), for x=2 m, without filter.

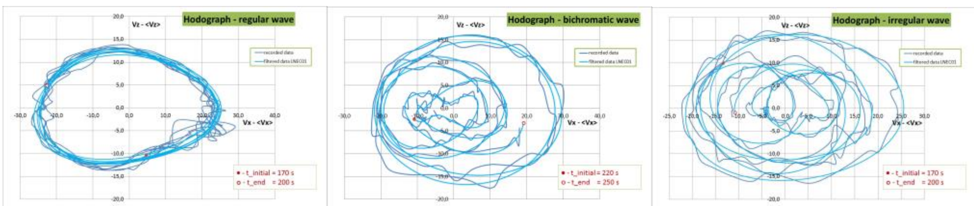

Figure 8. Hodograph of the velocity components (xz): recorded data (dark blue) and filtered data (light blue). Regular (left), bichromatic (center) and irregular (right) waves at x=-10m.

In order to remove the noise from the particle velocity data, a low-pass filter was used, which removes frequencies above three times the basic frequency or the peak frequency of the record, depending on the case. This filter, based on Thompson (1983), is applied to the time series, but is designed upon a pre-defined frequency response function (FRF), which is chosen by the user. The Fourier coefficients of the best fit curve to the idealized FRF correspond to the weights which will be used on the moving average to be applied to the time series. A 241 weight filter was used in all tests. Figure 8 shows a 30s plot of the vertical versus horizontal component of the velocity after the application of Thompson filter to the data.

4. Discussion

Measurements of oscillatory particle velocities are quite recent in coastal hydraulics laboratory, but have become more usual as a result of the development of lower cost acoustic Doppler instruments (Kraus *et al*., 1994). Compared to resistance or capacitance wave gauges, ADV instruments have in general greater sensitivity and resolution, among other advantages regarding electronic effects. However, most of coastal hydraulics investigation methodologies and coastal engineering design are based on surface elevation characteristics (*i.e*. significant wave height, zero crossing methods, spectral representation, *etc*.). Yet, within a wave flume, what really matters as far as wave induced forces and sediment transport is the hydrodynamic behavior of the oscillatory flow.

Results from conventional methods applied to wave particle velocities (time domain, Fourier and wavelet spectral analysis) have been presented in the previous section.

From the figures one can observe that:

- Spectra (Figure 4): There is an increase of the spectrum as the waves propagate along the flume, as a combined effect of the narrowing width and shoaling. As a matter of fact, for a depth of 0.10m at the horizontal portion of the flume, there is a 1:10 reduction in cross section area. There is also a clear energy transfer from the main frequency at x=-10m, both to higher and lower frequencies, as the wave propagates. For the bichromatic wave, periods equal to 1.5s and 1.1s, (frequencies equal to 0.667Hz and 0.909Hz, respectively), there is a clear peak at the frequency which is the difference between the two basic frequencies (0.242Hz), which corresponds to a period of 4.125s. This spectral peak is far more significant than the higher harmonics of the two basic frequencies. At the frequency 0.675Hz, which is the sum of both frequencies, there is also a small peak, an effect that was not so evident in the free surface elevation data. Between x=2m and x=3m, already in the horizontal portion, the wave energy reduction is due to breaking. In relation to irregular waves, there is also an increase of harmonics as the waves propagates along the flume (shoaling), due to the increase of nonlinear wave characteristics. There is a clear energy transfer from the main frequency at x=-10m to higher and lower frequencies, as the wave propagates. At x=2m, the wave energy reduction is due to wave breaking, although such decrease is more clear at x=3m.
- Wavelets (Figure 5): With the wavelet technique, the conclusions are similar to those based on the Fourier analysis. It is clear that there is an increase of wave energy as the wave propagates along the flume and there is a clear transference of the wave energy from the main frequency to the others harmonics. However, it is possible to identify, in the bichromatic case, an oscillating behavior with periodicity about 4s, compatible to the difference between the two basic frequencies. In the case of irregular waves, the energy distribution shows an alternating behavior between the deep (x=-5m) and the shallow sections (x=2m). This evolution of energy distribution cannot be identified by the Fourier analysis and is a quite useful pattern when interpreting results from a physical model.
- Hodographs (Figure 6, Figure 7 and Figure 8): A dispersion of points is visible in a distorted filled elliptical shape in the xz plane. A dispersion of points around zero is also visible in the xy and yz planes, this is a consequence of the Vy fluctuation around zero that is noticeable in Figure 6. A distorted elliptical shape is visible in the xz plane with a dispersion of points around its' average line. A dispersion of points around zero is also visible in the xy and yz planes, this is a consequence of the Vy fluctuation around zero. The elliptical shape is a consequence of the transitional water depth; in deep water it would have circular shape. Hodographs in the xz plane show that monochromatic waves

present clouds of points with a distorted elliptical shape, while bichromatic waves present a spiraling behavior and irregular waves present filled disc shapes.

- Time history of orbital velocities: There is an increase in the values of horizontal crest and trough horizontal velocities (V_{max} and V_{min}) due to shoaling, up to the beginning of wave breaking, a significant decrease during wave breaking and, after the end of breaking, these values remain nearly constant. There is almost a symmetry of maximum and minimum values in deeper water sections, whereas, for shallower depths, the crest and trough velocities become asymmetric (Conde *et al.*, 2012, 2013b, 2013c), consistent with Figure 7. The analysis of the Vx and Vz spectra shows an attenuation of around 30% for the fundamental frequencies. The Vy values (cross flume direction), that theoretically should be zero, may be a result of transverse waves due to the wave generation process. The amplitude values of Vy are around 5% of the Vx values.

A more detailed analysis shows some interesting aspects when using velocity records instead of free surface elevation data.

In fact, it is evident from the velocity records that there are many other relevant phenomena occurring inside the wave flume, which cannot be depicted by the usual wave gauges. However, special attention must be given to the instrument positioning, mainly because laboratory size ADVs do not have any precise inclination gauges (contrary to field equipment). A gauge may very easily be mis-aligned. Yet, an ADV has three degrees of freedom to be rotated, and such misalignments may contribute to the recorded velocities (Neves *et al*. 2012a).

First of all, ADV measurements allow identifying the presence of transversal velocities in the wave flume, usually associated with undesired resonance within the flume or cross wave instabilities. Therefore, one should always take into account the analysis of the three velocity components, a procedure which differs from the usual wave gauge analysis.

Second, the presence of reflected waves in wave flume experiments is almost unavoidable. Even if automatic control mechanisms are available on the wave generator, there are specific studies where reflection exists in a restricted portion of the flume, for instance on the lee side of structures. Partial standing waves have the curious property, as shown in NEYRPIC (1954), of having tilted particle trajectories and velocity hodographs as well (Neves *et al.*, 2012a). Indeed, the hodographs obtained from regular wave experiments, shown on previous section, were clearly tilted. This could be partially due to a misalignment of the ADV probe, but could be an indication of partial standing waves, especially because the dynamic absorption system of the wave generator had not been activated.

Third, the tests with the bichromatic waves showed hodographs of vertical and horizontal velocities with a quite interesting spiraling pattern, with long period oscillations between inward and outward movement. Although such long period oscillations can be identified in the Fourier spectral representation of free surface elevation and horizontal velocity component, it is certainly much more illustrative to view the Vz vs. Vx hodograph in order to understand hydrodynamic effects such as resonance of floating structures or wave induced fatigue in submerged pipes.

Due to the finer sensitivity of ADVs compared to usual wave gauges, it is evident the high dispersion of points around zero in the xy and yz planes, as well as dispersion around a distorted elliptical shape in the xz plane (Figure 6, Figure 7 or Figure 8). Filtering the data allow identifying mean patterns, since high frequency effects due to turbulence, higher harmonics or wave-wave interactions are all eliminated. Therefore, one can better identify long term effects on sediment dynamics or fundamental forces on structures. On the other hand, filtering also allows identifying small misalignments of the ADV probe.

It becomes evident how much richer the information about the wave conditions become, when one observes the particle patterns instead of the free surface. For regular waves, there is a clear elliptical pattern, for the bichromatic wave there is a spiraling behavior, either inward or outward from an elliptical shape, and for the irregular waves there is a filled ellipsis pattern, in all cases associated with the intermediate depth condition. It is worth noting what happened with T=1.5s, where an undulated shape is shown in Figure 7, which is a consequence of transverse instabilities generated at the wave maker.

5. Conclusions

In this paper, recent experimental studies on a wave flume at the National Laboratory for Civil Engineering (LNEC), Lisbon, Portugal, were presented. This is a contribution to the study of wave propagation hydrodynamics in varying slopping beaches in order to investigate in detail all the process related to the wave propagation and breaking in complex bathymetries.

The bathymetry comprised two regions with different gentle slopes. The tested conditions corresponded to regular, bichromatic and irregular waves.

The use of ADV measurements and the description of the waves by means of the flow velocity showed several advantages, compared to the data measured by usual wave gauges. The techniques used showed that each of them have its own advantages and disadvantages, and should be used as complementary tools for a better analysis of wave flow.

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