COHERENT VORTICAL STRUCTURES IN PLUNGING BREAKERS

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KEY POINTS

- *Wave breaking generates large scale Coherent vortical Structures (CS).*
- *CS strongly control sediment motion and diffusion of tracers, thus deserving a thorough study.*
- *CS induced by a regular plunging wave are analyzed.*
- *Preliminary results provide information on CS location and turbulent length scales.*

1 PROBLEM STATEMENT

Intense turbulent and vortical flows associated with breaking waves make the surf and swash zone of special significance for nearshore dynamics and costal sediment transport. Even if investigated since long, they are still far from being completely understood. Recent laboratory, field and numerical studies showed that the turbulent flow induced by breaking waves is characterized by the formation of some significant vorticity and turbulence that re-organizes in the shape of large-scale or coherent structures (CS) (*Kimmoun & Branger,* 2007; *Ting,* 2008; *Zhou et al.,*2014; *Farahani & Dalrymple,* 2014; *Lubin & Glockner*, 2015; *Lim et al.*, 2015).

Coherent structures (CS) are recognized as organized vortical motions that significantly contribute to fluid entrainment, mass transport, momentum and heat mixing and advection (*Camussi*, 2002; *Huang et al*., 2010, *Haller et al.*, 2016). Therefore, predicting nearshore morphodynamics and tracer diffusion requires thorough knowledge of their formation and spreading throughout the water column, as well as their interactions with bottom sediments (*Ting*, 2008). The identification of CS, based on vorticity or other turbulent features, is difficult along with the description of intermittent events of turbulent nature. Thus, several methods have been developed to identify these structures in a wide variety of turbulent shear flows (*Bonnet & Glauser*, 1993).

Previous studies of mechanism controlling the formation and evolution of CS under breaking waves have mainly focused on spilling waves in analogy with bores and jumps, where they were first documented (*Longo*, 2009; *Huang et al.*, 2010). Only few experimental studies examined this behavior under plunging waves (*Lim et al.*, 2015; *Na et al.*, 2016), where stronger turbulence was observed due to the presence of the overturning jet and the splash-up cycle. Depending on the type of breaker, different types of large-scale coherent vortices can be found in breaking waves (*Lubin & Glockner*, 2015). Under a turbulent bore propagating as a spilling wave, *Nadaoka et al*. (1989) first observed large dominant horizontal eddies present in the bore front, while behind the wave crest the flow structure changes rapidly into obliquely downward stretched (i.e descending) eddies, responsible for mass flux, and enhancing momentum transport (*Huang et al.*, 2010). In a laboratory study of spilling regular waves, *Kubo & Sunamura* (2001) observed along with obliquely descending vortices a new type of large-scale turbulence, which they called downburst. It is an aerated water mass descending without a great deal of rotation (*Ting*, 2008), diverging at the bed and producing more sediment movement than the obliquely descending vortices.

Using large eddy simulation, *Christensen & Deigaard* (2001) and *Watanabe et al.* (2005) have both predicted the formation of counter-rotating vortices extending obliquely downward in plunging and weakly plunging regular waves. *Ting* (2008) observed in a solitary breaking wave a downburst of turbulence descends and diverges at the bed creating two counter-rotating vortices. More recently, *Lubin & Glockner* (2015) numerically simulated plunging breaking waves and their results confirmed what shown in rare documentary footage where breaking waves were recorded from underwater. In fact, *Lubin & Glockner* (2015) computed 3D vortical tubes, like vortex filaments elongated in the main flow direction, occurring under the plunging breaker, connecting the splash-up and the main tube of air.

Taking the above into consideration, it is evident that further experimental investigation on coherent structures is still needed, especially those induced by a plunging breaker. The present study, carried out in the framework of a GII placement traineeship (http://www.gii-idraulica.net), provides a preliminary analysis of CS and of estimates of the turbulent length scales distribution in a laboratory surf-zone due to plunging breakers.

2 MATERIALS AND METHODS

Several techniques can be used to extract eddies in a flow field (*Camussi*, 2002; *Longo*, 2009), including: (i) direct analysis of the vorticity field as computed from velocity map; (ii) Galilean decomposition, that is a translation of the velocity field by an amount equal to the advection velocity of the coherent structure under identification; (iii) analysis of the velocity gradient tensor which has one imaginary eigenvalue whose distribution is associated with regions of local swirling motion; (iv) LES filtering, based on low pass filtering of velocity data to remove small scale contributions; (v) wavelet transform algorithms of the velocity vector field. In the present study, we focus on the analysis of the vorticity field, even if we note that, as stated by *Adrian et al.* (2000), the study of vorticity maps alone is not sufficient to identify vortices, since they are masked by background shear. Turbulence structures essentially evolve from interactions between vorticity and strain rate, which was consequently examined in this work as well.

The present experiment was carried out on plunging breakers produced in the wave flume of the Coastal Engineering Laboratory (LIC) of the Department of Civil, Environmental, Land, Building Engineering and Chemistry (DICATECh) of the Polytechnic University of Bari (Italy). The flume was 40 m long, 2.42 m wide and 1.20 m deep, provided with metallic sidewalls and concrete bottom (Fig.1). A fixed and uniform slope 1:10 was created in the channel, starting 27.38 m from the paddles. The slope was 12.62 m long.

The examined regular wave had height and period respectively equal to H=10 cm and T=2 s, and the still water level in the channel was 0.8 m above the horizontal bed. The computed Irribarren number, ξ_0=0.71, proved that the wave was a plunger. The Ursell parameter, indicator of the wave non-linear behavior, ranged between 5 and 193 from the wave paddles up to breaking. Breaking occurred at a depth of about 11 cm.

The measurements were carried out in some selected channel sections just seaward of the breaking zone, to limit the air entrainment that negatively affected the instrument measurements. The reference system for the position of these sections had origin at section "sect. 0", where the local depth was d=14 cm, and was positive towards the shore. Ten sections were measured inshore of "sect. 0" and longitudinally spaced with increments of 1cm. The longitudinal u and vertical w velocities, respectively measured along the longitudinal x axis and the vertical z axis, were assessed by means of a submersible 2D back-scatter, four-beam Laser Doppler Anemometer (LDA) along most of the water column. Due to technical limitations, in the bottom layer, for a thickness of about 3 cm, a 3D Acoustic Doppler Velocimeter (ADV) was used (that allowed also measurement of the transversal velocity v, not analyzed in this study). At the same time, an ultrasound probe aligned with the velocity probes, was used to measure the surface elevation. In each section, velocities were vertically assessed at points spaced of 0.5cm, except that near the surface, where they were spaced of 1cm.

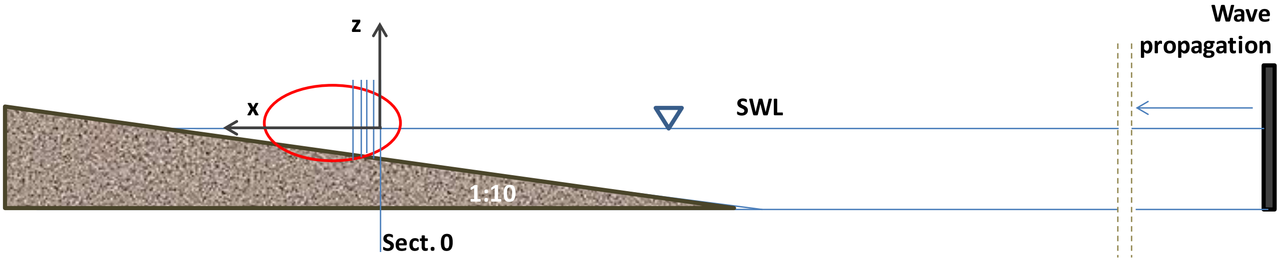

Figure 1. Sketch of the wave flume. The investigated region is in the red circle.

3 RESULTS AND CONCLUSIONS

Using the most common notation for periodic signal processing, the instantaneous signal can be regarded as the sum of a time-average, a phase-average and a turbulent fluctuation. Figures 2 and report time averages of some variables of interest. In particular, Fig 2a, giving the vertical profile of the mean streamwise velocity, illustrates the presence of the undertow *U* at each section (negative *U* values mean offshore directed). The typical triangular shape of the profile starting from the bottom shows that the maximum *U* velocity (in absolute value) is in the upper half of the water column, where the wave trough travels. An inversion of *U* occurs near the surface in the region between the still water level (SWL) and the wave trough.

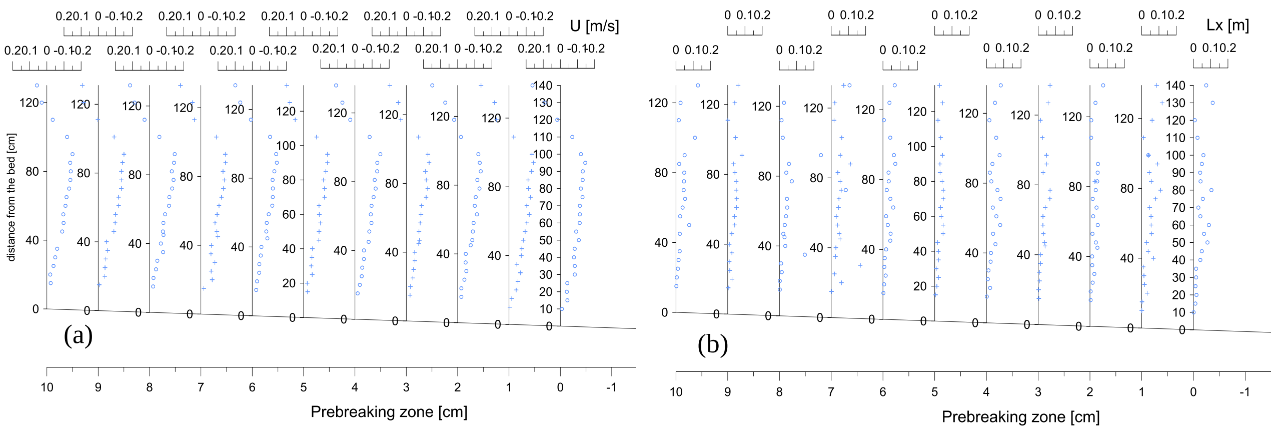

Figure 2. Vertical profiles, along the channel, of time-averaged (a) horizontal velocity, (b) turbulent macro length scales.

The time-averaged Reynolds shear stresses, both wave and turbulent, were also estimated but are not reported here, for brevity. They are found to be larger in the most superficial region where the passing of the wave trough takes place, and their values reduce approaching the shore. Further, confirming previous results (*De Serio & Mossa*, 2006, 2013), they are larger in size than the time-averaged turbulent Reynolds shear stresses. Turbulence, interpreted according to the classical cascade mechanism, was also investigated referring to its micro and macro scales. Turbulent length scales are order of magnitude O(10^{-2}m), with values close to 0.1*h*-0.2*h*, (being *h* the local depth), i.e. comparable to the turbulent mixing lengths in the surf zone reported by other researchers (*Hwang et al.*, 2015). Macroscale lengths were computed by multiplying the integral time scale by the local time-averaged velocity. The integral time scale was estimated by the autocorrelation function of the turbulent velocity fluctuations. Macroscales horizontal lengths *Lx* are plotted, as an example, in Figure 2b). Their greatest values have order of magnitude O(10^{-1}m), thus comparable with the local water depth, and suggest the presence of large eddies, with axis parallel to the wave front, in the most superficial region above the wave trough.

The map of vorticity (Fig. 3a) confirms the presence of eddies in the same region, with positive vorticity near the surface, attributable to the wave crest approaching breaking. On the contrary, bottom shear as well as broken waves turbulence induces negative vorticity in the lower half of the flume. The cyclic pattern in Figure 3a is only due to the interpolation spacing used for plotting (equal to the spacing used in the computation of the vorticity ω). The detection of coherent structures was made by using the Okubo Weiss parameter *OW* (*Chang & Oey*, 2013) which evaluates the relative dominance of vorticity and strain:

$$OW = s_n^2 + s_s^2 - \omega^2 \quad (1)$$

where $\omega = \partial w/\partial x - \partial u/\partial z$ is the vorticity, while $s_n = \partial u/\partial x - \partial w/\partial z$ and $s_s = \partial w/\partial x + \partial u/\partial z$ respectively are the normal and shear components of strain. Eddy cores (elliptic regions) are identified by negative values of *OW* while shearing (hyperbolic regions) is mapped by positive values of *OW*. The map of *OW*, shown in Figure 3b), highlights the presence of coherent eddies whose shape is vertically elongated and seem to obliquely approach the bottom, propagating offshore, thus confirming that in time-averaged terms also in the plunging breaker descending eddies can be observed.

Research is still ongoing, focusing on the analysis of possible bursts, sweeps and ejections, by using other processing techniques.

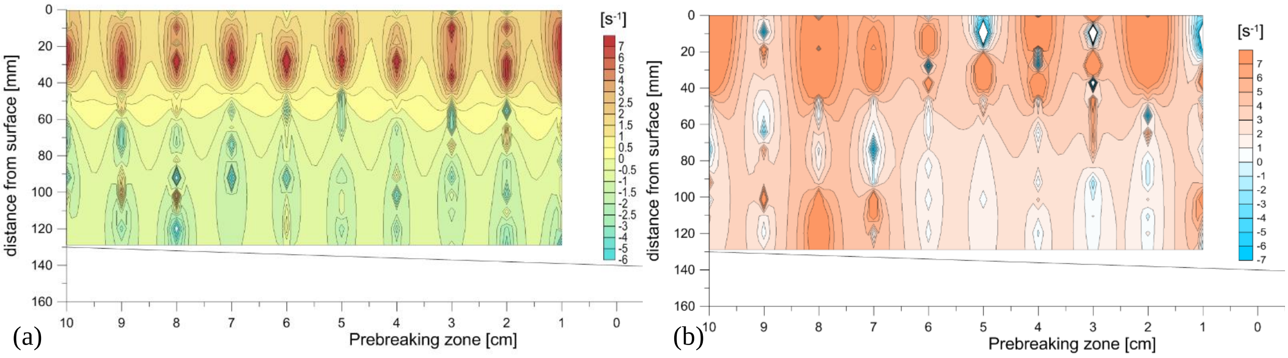

Figure 3. Vertical maps, along the channel, of time-averaged (a) vorticity (b) Okubo Weiss parameter.

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