Coastal Engineering 127 (2017) 119–133

Contents lists available at ScienceDirect

Coastal Engineering

journal homepage: www.elsevier.com/locate/coastaleng

Cross-shore variability and vorticity dynamics during wave breaking on a fixed bar

L. Chiapponi [a], M. Cobos [b], M.A. Losada [b], S. Longo [a,*]

[a] *Dipartimento di Ingegneria e Architettura (DIA), Università di Parma, Parco Area delle Scienze, 181/A, 43124 Parma, Italy*

[b] *Instituto Interuniversitario de Investigación del Sistema Tierra, Universidad de Granada, Avda. del Mediterráneo s/n, 18006 Granada, Spain*

ARTICLE INFO

Keywords:
Breaking waves
Vorticity
Laboratory experiments

ABSTRACT

In the present experiments a volumetric particle-tracking system (V3V from TSI Inc.) allowed the measurement of the velocity fields generated by regular breaking waves past a fixed bar on a 1:10 rigid plane slope. The measurement volume extended from the wave crest to a portion of the domain below the wave trough, with two sets of monochromatic wave trains with different periods and heights. The aim of the present work is the quantification of the terms in the vorticity balance equation by including all the terms in a fully 3D approach. A possible new vorticity generation mechanism is revealed, that is amplified by the geometry of the laboratory flume and that awaits experimental validation in 3D wave tanks and in the field. The results are new and original and represent a data set for the comprehension of the effects of a submerged berm, for developing conceptual models of vorticity and for the calibration of numerical codes.

1. Introduction

Breaking waves in shallow water are the most prominent feature of the flow field in the nearshore and in the surf-zone and affect sediment transport and the bottom shape of sandy beaches either directly or indirectly through the generated currents. They generate ample vorticity often in presence of preexisting vorticity due to the past sequence of bores. The mechanism is strongly influenced by the geometry of the bottom, which is often characterized by single or multiple bars. Bars are an important feature of many natural beaches. The seminal paper by Roelvink and Stive (1989) lists numerous models invoked to explain the observed patterns of bars, and the contributions to their generation due to asymmetric oscillatory flow, long-wave flow generated by wave grouping, turbulent flow due to breaking, undertow due to momentum decay, mass and momentum transport (see Baldock et al., 2004; Baldock, 2006). Field observations of the bars indicate that they are related to reflecting free long waves, eventually in the presence of leaky waves or edge waves. The bars, in turn, modify the flow pattern and induce refraction, diffraction, reflection of the wave energy offshore, and affect the rip currents position. In this respect there are many differences of all the wave characteristics if a bar is present or absent, in the regime of sediment transport, of the currents, in all the main complex features that finally control the short and the long-term evolution of the beach. A detailed 3D experimental analysis of the effects of the bars with rip channels is reported in Haller et al. (2002). As a consequence, the knowledge of these modifications induced by the bars helps in planning the artificial berms and in analyzing their effects. The specific geometry of the present experiments, with a submerged bar mimicking a sand bar present in natural cross-shore sections of beaches, makes the analysis applicable. The detailed analysis of momentum balance and turbulence can be found in Clavero et al. (2016), in the present analysis we are mainly interested in vorticity structure and balance. Vorticity generation in dissipating and breaking waves is widespread in numerous geophysical phenomena, in the sea and in the atmosphere (see, e.g., Holton et al., 1995). Usually, a link can be detected and quantified between the energy decay or the momentum decay of waves and vorticity creation, which can be used for limiting the computation efforts in modeling large scale phenomena (Bühler, 2000).

Vorticity in the nearshore is generated at two different length scales, (i) at the scale of the crest length (large scale), and (ii) at the scale of the

* Corresponding author.
E-mail address: sandro.longo@unipr.it (S. Longo).

http://dx.doi.org/10.1016/j.coastaleng.2017.06.011
Received 30 July 2016; Received in revised form 31 March 2017; Accepted 2 June 2017

wave crest (small scale). The vorticity at the scale of the crest length is mainly represented by eddies with vertical axis and has important implications in the shape of the breaker and in the morphodynamics of the submerged beach. See Peregrine (1998) for the description of the surf zone currents and for several insights of the processes related to vorticity in the surf zone.

The vorticity at the scale of the wave crest (small scale) is more amenable to experimental analysis in the lab and again has a quite important role in wave breaking and post-breaking development. We first note that vorticity (it is true also at large scale) is not merely a different point of view of the flow field by analyzing the curl of the velocity, but offers new insights in complex flow fields where momentum, energy, chemicals, can be efficiently trapped in eddies or other coherent structures. In this respect, the oblique descending eddies and the multiple horizontal eddies (parallel to the wave crest) observed and documented by Nadaoka et al. (1989), increase the mass and momentum transport and favors a decrease in wave height. The video image analysis in the experiments by Zhang and Sunamura (1994) confirmed the role of the breaker-induced vortices in multiple bar formation.

The source of vorticity in breaking waves has been explained in different ways (see Longo et al., 2002 and references therein). The most obvious source is at the bottom, but we neglect it since it has a modest intensity and a marginal role during breaking and we will consider only other regions of generation of vorticity, mainly the region beneath the free surface. Longuet-Higgins (1992) explained the appearance of vorticity in the waves in terms of the combined effects of surface curvature and zero-shear stress boundary conditions at the interface, with a Stokes layer initially confining the generated vorticity, which in a subsequent stage escapes and fills the domain. Yeh (1991) considered the baroclinic torque in the presence of a density gradient to be the main driver of vorticity generation, with the viscous-shear torque of negligible relevance. The free surface fluid deceleration before breaking (with an increase of fluid pressure on the back of the wave, pushing the crest to spill or to plunge) is considered a major source of vorticity in spilling breakers by Dabiri and Gharib (1997), in contrast with previous studies attributing the vorticity generation to the sharp curvature of the interface, where a flow separation occurs (Lin and Rockwell, 1994).

The various phenomena occurring after vorticity generation in breaking waves have been numerically analysed in Watanabe et al. (2005). All the analyses agree that there is a continuous generation of vorticity at the front of the breaker that appears similar to a comet, with a core moving with the crest and the tail spreading out behind the crest (e.g., Lin and Liu, 1998). In most (if not all) cases, this vorticity is coupled with turbulence.

Early measurements of vorticity using planar Particle Image Velocimetry (PIV) were obtained by Petti et al. (1994), who made experiments with waves breaking on a submerged breakwater on 1:100 beach, and by Chang and Liu (1998), who gained information on the overall characteristics of the (two-dimensional) flow field of breaking waves in shallow water and confirmed the existence of oblique vortices. An extensive investigation on surf-zone breaking waves over a sloping beach with PIV is reported in Kimmoun and Branger (2007), including the longshore vorticity measurement. The mean vorticity dynamics under breaking waves has been numerically analysed, amongst numerous authors, by Lin and Liu (1998) in a two-dimensional framework, where vortex stretching is absent and only advection and diffusion redistribute the vorticity once it has been generated. A large eddy simulation of breaking waves in a 3D domain has been performed by Christensen and Deigaard (2001) for spilling, plunging and weak plunging waves. However, to the best of our knowledge, no experimental data on three-dimensional vorticity structure and dynamics have yet been presented and discussed, with the exception of the recent paper by Ting and Reimnitz (2015) who focused on coherent structures in a breaker on an inclined bottom (in different flow fields, vorticity analysis of experimental data obtained with a system identical to the V3V system of the present experiments has been documented in Calderon et al., 2012). A key element of the analysis is that vorticity dynamics is a 3D phenomenon which can be properly modeled or described only having the three components of velocity in space. Given the inherent three-dimensional structure of the breaking waves and the relevance of stretching processes, a step forward is necessary to fill this gap in knowledge. This step is allowed by the new measurement system represented by the three-dimensional particle tracking device adopted in the present experiments. The availability of instantaneous velocity measurements with a decent spatial resolution and data rate, allow the computation of virtually all the terms and variables (with the exception of pressure) in the equations of the most adopted models, hence allow some kinds of analyses never attempted in the past (or conducted with a series of approximations and simplifying hypotheses).

The aims of the present work are the analysis and balance of vorticity at the wave crest scale in the presence of a bar. The results are compared to vorticity measurements in similar conditions but without bar, in order to estimate the differences.

The experimental layout and the experiments and the data analysis are detailed in Clavero et al. (2016) and are briefly described in the present work in §2 and in §3. Section 4 describes the structure of the vorticity with quantification of the balance of vorticity. A possible new mechanism for vortex generation at the free surface is discussed in §5. The conclusions are reported in §6.

2. Experimental set-up and experiments

The experiments were conducted in the wave flume located in the Laboratorio de Dinámica de Fluidos Ambientales of the CEAMA (Centro Andaluz de Medio Ambiente) in Granada, with an artificial slope of 1:10 and with a berm of stones and plastic blocks, see Fig. 1. The flume is 23 m long and 65 cm wide. The still-water depth in front of the paddle was of 43 cm and an active absorption system (AWACS) was active during the experiments.

Velocity measurements were taken with a 3D Particle Tracking Velocimetry system (V3V from TSI Inc.) in a volume of measurements with a side length equal to ≈14 cm in the cross-shore and vertical directions and equal to ≈ 10 cm in the alongshore direction. It was centred at $X = 1138$ cm in the mid section of the flume, with a minimum distance of the measurements ≈25 cm from the side walls. In this condition the side walls effects can be safely assumed as negligible. The volume of measurement was illuminated by a laser and three cameras (2048 × 2048 pixels) generated three pairs of 12-bit images. The two images of each pair were captured with a time delay of 100 μs. The surface elevation during tests was measured in several sections (see Fig. 1*a*), including the section of the breaker, using Ultrasonic probes (UltraLab® USL 80D by General Acoustics, sensor model USS635, with an accuracy on the instantaneous water level measurements equal to ±0.5 mm). The acquisition of the V3V images was triggered by the water level measured in Section 4, at the internal toe of the bar: the firing of the laser was corresponding (with a delay) to the maximum of the water surface elevation. Due to the intrinsic random nature of the breaking waves and to the uncertain definition of "maximum", a fluctuation of less than 0.02 s was recorded for the 10 sequences of shots. The images were post-processed in order to detect the 'triplets' of particles (a triplet indicates the same particle observed by the three cameras) in two subsequent images. Then the calibration of the cameras allowed the computation of the spatial coordinates of the particles in time, and of the three components of the velocity of the particles, subject to further validation (see Ohm and Li, 2000 and Sharp et al., 2010 for details on the procedures and on the algorithms). In the best shots we had images containing ≈100 000 particles with more than