Coastal Engineering 113 (2016) 62–72

Contents lists available at ScienceDirect

Coastal Engineering

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

Observations of turbulence within the surf and swash zone of a field-scale sandy laboratory beach

J.A. Brinkkemper [a,*], T. Lanckriet [b], F. Grasso [c], J.A. Puleo [b], B.G. Ruessink [a]

[a] *Institute for Marine and Atmospheric Research, Department of Physical Geography, Faculty of Geosciences, Utrecht University, P.O. Box 80.115, 3508 TC Utrecht, Netherlands*
[b] *Center for Applied Coastal Research, Department of Civil and Environmental Engineering, University of Delaware, Newark, DE 19716, United States*
[c] *Ifremer — Dyneco/Physed, Centre de Bretagne, BP70, 29280 Plouzané, France*

ARTICLE INFO

Article history:
Received 10 October 2014
Received in revised form 9 May 2015
Accepted 20 July 2015
Available online 2 September 2015

Keywords:
Turbulence
Plunging breakers
Swash
Laboratory experiment

ABSTRACT

Current coastal-evolution models generally lack the ability to accurately predict bed level change in shallow (<~2 m) water, which is, at least partly, due to the preclusion of the effect of surface-induced turbulence on sand suspension and transport. As a first step to remedy this situation, we investigated the vertical structure of turbulence in the surf and swash zone using measurements collected under random shoaling and plunging waves on a steep (initially 1:15) field-scale sandy laboratory beach. Seaward of the swash zone, turbulence was measured with a vertical array of three Acoustic Doppler Velocimeters (ADVs), while in the swash zone two vertically spaced acoustic doppler velocimeter profilers (Vectrino profilers) were applied. The vertical turbulence structure evolves from bottom-dominated to approximately vertically uniform with an increase in the fraction of breaking waves to ~50%. In the swash zone, the turbulence is predominantly bottom-induced during the backwash and shows a homogeneous turbulence profile during uprush. We further find that the instantaneous turbulence kinetic energy is phase-coupled with the short-wave orbital motion under the plunging breakers, with higher levels shortly after the reversal from offshore to onshore motion (i.e. wavefront).

1. Introduction

Morphodynamic models can predict morphological change in the nearshore zone with reasonable accuracy, where the water depth exceeds ~2 m and the morphology is approximately alongshore uniform (e.g. Kuriyama, 2012; Plant et al., 2004; Ruessink, 2005; Ruessink et al., 2007; Ruggiero et al., 2009; Walstra et al., 2012). There is, however, still a mismatch between predictions and observations for the inner surf and swash zones (e.g. Masselink and Puleo, 2006; Ruessink, 2005; Ruessink and Kuriyama, 2008). These zones are the connection for sand exchange between deeper water and the beach and are thus of high importance for the design of beach-restoration and nourishment projects. Most morphodynamic models calculate sediment transport solely with near-bed wave orbital motions (e.g. Bailard, 1981; Ribberink, 1998), lacking the influence of surface-induced turbulence which also plays a role in sand entrainment in the surf and swash zone (Aagaard and Hughes, 2010; Nadaoka et al., 1988; Voulgaris and Collins, 2000; Yoon and Cox, 2012). To improve the transport formulations for shallow water, a better understanding of the mechanisms involved in the suspension and transport of sand in the surf and swash zone is needed (e.g. Van Rijn et al., 2013). This paper presents a recently collected field-scale laboratory dataset and focuses on the vertical structure of turbulence in the surf and swash zone as a first step towards more accurate sand transport predictions in these zones.

The difference between the shoaling and the surf zone in terms of sediment suspension by turbulence is the presence of surface-induced turbulence in the surf zone (Thornton, 1979). At the sea surface, turbulence is generated by breaking waves and bores in horizontal and oblique vortices (Nadaoka et al., 1989; Zhang and Sunamura, 1990), able to travel downward to the bed and suspend sediment intermittently (Aagaard and Hughes, 2010; Nadaoka et al., 1988; Voulgaris and Collins, 2000; Yoon and Cox, 2012). As these vortices also keep sediment in suspension, the timing of these vortices in the wave phase determines whether vortices, and thus sediment, are transported in the landward or seaward direction by the wave orbital motion. The structure and intermittency of the generated turbulence are highly dependent on the breaker type (Zhang and Sunamura, 1990). The turbulence in spilling breakers is confined to the upper part of the water column due to the relatively small size of the generated eddies (0.1–0.2*h*, where *h* is the water depth) (Ting and Kirby, 1996), but turbulence spreads downwards in obliquely descending eddies behind the wave crest (Nadaoka et al., 1989). The amount of turbulence is fairly homogeneous over a wave cycle beneath spilling breakers and thus turbulence is generally transported in the seaward direction due to the longer duration of the offshore wave motion (Ting and Kirby, 1994). Turbulence beneath plunging breakers is characterized by downburst vortices generated by the impact of the overturning wave crest.

---

* Corresponding author. Tel.: +31 302532982; fax: +31 302531145.
E-mail address: j.a.brinkkemper@uu.nl (J.A. Brinkkemper).

http://dx.doi.org/10.1016/j.coastaleng.2015.07.006
0378-3839/

This results in large mixing lengths and more homogeneous turbulence intensities in the vertical. The vortices were found around the breaking wave front and are thus correlated with onshore orbital motions, resulting in an onshore transport of turbulence beneath plunging breakers (e.g. Ting and Kirby, 1994, 1995). Recently, Aagaard and Hughes (2006) as well as Aagaard and Jensen (2013) found the largest sediment concentrations just after the onshore velocity maximum for plunging breakers in the field, suggesting the coupling between turbulence and suspension events and sediment transport by the wave orbital motion in the onshore direction. The sediment concentration beneath bores was much more homogeneous over time and no net wave-induced sediment transport was measured.

The change from near-bed orbital motion to surface-generated eddies as dominant sand stirring mechanism from the shoaling into the surf zone is also reflected in measured vertical profiles of wave-averaged turbulent kinetic energy (k). Numerous small-scale laboratory experiments have been conducted with a fixed bed and regular breaking waves using laser Doppler anemometry (LDA, see Mocke (2001) for an overview) and more recently with particle image velocimetry (PIV) (e.g. Govender et al., 2011; Kimmoun and Branger, 2007; Sou et al., 2010). These methods provide detailed turbulence measurements in the cross-shore and vertical directions, while the alongshore component is often approximated assuming that turbulence beneath breaking waves is similar to plane wake flow (Svendsen, 1987). The vertical structure of turbulence was found to depend strongly on the wave-breaking type. Conditions with plunging breakers result in a relatively uniform turbulence profile, while spilling breakers show a strong increase of turbulent kinetic energy close to the water surface. Typical values for the Froude-scaled turbulent kinetic energy ($\sqrt{k/gh}$, where g is the gravitational acceleration and h is the water depth) below the wave trough level are between 0.03 and 0.07 for spilling breakers, and between 0.05 and 0.1 below plunging breakers (Mocke, 2001).

While these small-scale laboratory studies have provided substantial knowledge on turbulence beneath regular breaking waves on a fixed bed, it is uncertain how these measurements compare to field scale and irregular waves over a mobile bed. Scott et al. (2005) measured turbulence beneath regular and irregular breaking waves above a fixed bed in a large-scale flume and found a similar vertical and cross-shore structure of turbulence for both wave conditions, but the magnitude of the turbulent kinetic energy was up to five times larger beneath regular waves. The vertical structure and intensity (Froude-scaled turbulence between 0.02 and 0.06 at the bar crest) of turbulent kinetic energy measured during the experiments with identical random wave conditions but with a movable bed were similar to experiments with a fixed bed (Yoon and Cox, 2010). In these large-scale laboratory experiments, turbulence characteristics were measured using several vertical arrays of Acoustic Doppler Velocimeters (ADVs), offering some insight into their cross-shore structure. In general the turbulent kinetic energy is maximum at the location where most wave energy is dissipated by breaking, consistent with the dominance of surface-generated turbulence. In the field, however, a vertical profile of turbulence is often measured at a single cross-shore location because of logistical constrains (e.g. Feddersen et al., 2007; Ruessink, 2010). The time-variation in offshore wave conditions and tidal water level then results in measurements at different locations with respect to the breaker zone, but instruments at one cross-shore location inherently do not provide any information on the cross-shore variability of the turbulent structure. Field experiments show a dependency of the vertical turbulence structure on H_s/h in the surf zone, where H_s is the significant wave height. Surface-induced turbulence becomes increasingly important with higher relative wave height and is dominant in the inner surf zone (e.g. Grasso et al., 2012; Lanckriet and Puleo, 2013), where the majority of the waves have transformed into bores and ripples are generally absent. Measurements in natural surf zones indicate that turbulence intensities increase towards the surface and towards the bed (Feddersen et al., 2007; Grasso et al., 2012), indicating that both surface-induced and bed-induced turbulence are important in the field. Grasso et al. (2012) hypothesized that the difference between field datasets in turbulence intensities in the lower part of the water column, and with laboratory measurements with a fixed bed, might be explained by differences in bed roughness (i.e. presence of ripples). On the whole, there is still substantial need for turbulence observations under natural conditions.

The turbulence in the swash zone can be advected from the surf zone as well as be generated locally. In comparison to the research conducted on the turbulence structure in the surf zone, the research on turbulence characteristics in the swash zone is still in its infancy, especially under natural conditions. As in the surf zone, turbulence can be generated at both the surface and the bottom by bores and bottom shear, respectively. During backwash, turbulence is dominantly generated by bottom shear (e.g. Cowen et al., 2003), but past studies are inconclusive on the shape of the dissipation profile and the dominant turbulence production mechanism during uprush. Petti and Longo (2001) observed k profiles increasing upward in measurements on a small-scale, smooth 1:10 beach slope, indicating that surface processes were dominant. On a small-scale, smooth 1:20 beach slope, Sou et al. (2010) observed that bed shear was dominant in the swash zone but surface processes were dominant in the inner surf zone. O'Donoghue et al. (2010) observed depth-uniform dissipation profiles on a large-scale (in terms of velocities and run-up length), smooth 1:10 slope and bottom-dominated profiles on a rough (grain diameter of 5–6 mm) 1:10 slope. Lanckriet and Puleo (2013), however, observed surface-dominated dissipation profiles in the inner surf and swash zone on a dissipative (slope 1:45) beach under field conditions.

Although the vertical structure of turbulence in idealized laboratory surf and swash zones is well researched, simultaneous measurements of turbulence in both zones at field scale are scarce but necessary to make progress in our understanding of sediment transport in shallow water. This lack of data and process understanding was one of the reasons to carry out the second large-scale Barrier Dynamics Experiment (BARDEXII). BARDEXII was designed to improve understanding of sediment transport processes in the surf, swash and overwash zone (see also Masselink et al. (2016–in this issue)) of a medium-coarse grained sandy barrier. This paper focuses on the measured vertical structure of turbulence and its variability from the shoaling into the swash zone. The structure of the paper is as follows. In Section 2, we describe the experimental setup, initial data processing and the methods used to extract turbulence from the measured velocities. In Section 3 we discuss the vertical profiles of turbulence and its intra-wave variability in the shoaling, surf and swash zones. These results are discussed and compared with earlier observations in Section 4. Conclusions are provided in Section 5.

2. Methods

2.1. BARDEXII

The BARDEXII experiment was carried out in the Delta Flume in Vollenhove, The Netherlands, from May to July 2012. A 4.5 m high, 5 m wide and 75 m long sandy (median grain diameter $d_{50} =$ 0.42 mm) barrier was constructed in the central region of the flume, enabling a lagoon to be situated at its landward side. Initially, the profile contained an 1:15 slope from $x = 49$ m to $x = 109$ m, where $x = 0$ is at the wavemaker (Fig. 1). Masselink et al. (2016–in this issue) describe the objectives and the experimental setup of the project. We now describe the conditions and instruments that are used here.

The experiment consisted of five test series (A–E) with a total of 19 distinct tests with different wave and water level conditions. Test series A focused on beach response to varying wave conditions and different lagoon levels; B on bar dynamics due to different water levels on the seaside of the barrier; C on beach response to varying wave conditions with a tide; D on identifying overtopping/overwash thresholds and E