Vertical structure of the turbulence dissipation rate in the surf zone

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ABSTRACT

High-energy wave conditions induce major morphological changes of sandy beaches; however, the lack of knowledge on physical processes acting in the inner surf zone limits our ability to predict accurately such storm-induced changes. It may be explained by not considering effects of wave-breaking induced turbulence on sand suspension. We use field data collected at Truc Vert beach (France) during a 18-day period in the shallow-water surf zone under high-energy wave conditions to estimate the turbulence dissipation rates at three elevations between the sea bed and the wave trough level. The vertical structure of the dissipation rate and its correlation with breaking-wave intensity (wave height to depth ratio) are investigated. The large dissipation rates up to $10^{-2}$ m$^2$ s$^{-3}$ highlight the high-energy wave conditions of this study. The vertical structure of the turbulence dissipation rate of our data demonstrates surface-generated turbulence as a dominant source of turbulence. Nonetheless, turbulence generated in the bottom boundary layer is not negligible, especially for weakly-breaking wave conditions. As main trend, the dissipation rate increases with breaking-wave intensity; however, a saturation of the dissipation rate is observed for highly-breaking waves, which may be due to less vortex injection as waves modify from breakers into bores. Our results suggest that wave-breaking induced turbulence has to be considered in numerical models to predict accurately sediment transport in the surf zone.

ADDITIONAL INDEX WORDS: Field measurement, Storm event, Breaking wave

INTRODUCTION
High-energy wave conditions induce major morphological changes of sandy beaches; however, our ability to predict such storm-induced changes is still limited. This is primarily due to the lack of knowledge on physical processes acting in the inner surf zone ($< 3$ m water depth), especially concerning the effect of wave breaking on sediment suspension and transport. Breaking waves generate turbulence in the water column that stirs and suspends sediment (Butt et al., 2004). The generation of turbulence under breaking waves occurs in both the sea surface and bottom boundary layers (Thornton, 1979). At the sea surface, there is a downward injection of turbulence due to the breaking wave; if the water depth is sufficiently shallow, the breaker-generated turbulence may be large all the way to the bed (Scott et al., 2005; Hsu and Raubenheimer, 2006; Aagaard and Hughes, 2010). At the bottom, the boundary layer vorticity is diffused upward owing to the bottom shear stress. The height of the boundary layer above the bed is dependent on bottom roughness, strength of flow, and the time or distance over which the boundary layer has to grow.

Coastal-evolution models only consider the latter source of turbulence because the fate of surface-generated turbulence under natural waves is not well understood. In particular, it is not known how far breaking-induced turbulence can penetrate through the water column and stir sediment. If the breaking-induced vortices hit the bed, it could imply that sediment stirring beneath surf-zone bores is fundamentally different from that in deeper water. We believe that a better understanding of surf zone turbulence is a key to the improvement of our coastal-evolution models.

The oceanic and nearshore turbulence is often studied by the examination of the rate of turbulent kinetic energy dissipation $\varepsilon$, as it represents the energy released to the flow. In deep-water conditions, $\varepsilon$ is large in the wavy ocean boundary layer and decreases downward (Gerbi et al., 2009); this is the signature of surface-generated turbulence effects. For whitecapping breaking wave conditions in the nearshore (in 3.2 m water depth), Feddersen et al. (2007) observed $\varepsilon$ maxima near the sea surface and the bed. Hence, the water column is both affected by surface- and bed-generated turbulence. Due to the challenge to collect field dataset in the harsh surf zone conditions, only few studies analysed turbulence quantities under depth-limited breaking waves (e.g. George et al., 1994; Trowbridge and Elgar, 2001). Bryan et al. (2003) studied the cross-shore structure of $\varepsilon$ in the surf zone for moderate wave conditions (significant wave height $H_s \leq 0.62$ m). They observed that inside and near the breakpoint, $\varepsilon$ increases markedly in the onshore direction; the dependence of $\varepsilon$ on the offshore wave height was only weak. The vertical structure of $\varepsilon$ in the shallow-water surf zone was not considered.

Recently, Ruessink (in press) analysed the vertical structure of the Reynolds stresses from measurements collected in the surf zone during high-energy breaking wave conditions. Here, we use the same field dataset to (1) determine the vertical structure of the turbulence dissipation rate ($\varepsilon$) in the shallow-water surf zone beneath high-energy breaking waves; and to (2) investigate how this vertical structure is affected by breaking-wave intensity. We see this as the first step to determine the influence of surface-generated turbulence on surf zone sediment transport.
METHODS

Instruments

The measurements were conducted at Truc Vert Beach (Cap Ferret, France), part of the approximately 100 km long uninterrupted Aquitanian coast in the framework of the “ECORS-Truc Vert 2008” field experiment. An instrumented rig was positioned at the neap low-tide level to study the vertical structure of turbulence beneath breaking waves. Sensors used here include three single-point, sideways oriented, 5-MHz Sontek acoustic Doppler velocimeter ocean (ADVO) probes stacked in a 0.43 m-high vertical array to measure 3D flow velocities and to estimate turbulence, and an acoustic backscatter sensor (ABS) to estimate bed level. All three ADVOs were fitted with pressure, temperature, pitch and roll sensors, as well as a compass, and had their own logger that sampled each instrument at 10 Hz in one burst of 24 minutes and 20 seconds each half hour. The vertical distance between the sample volumes of the lower and middle ADVO (henceforth, ADVO1 and ADVO2) was 0.22 m, and between the middle and upper (ADVO3) sensor 0.21 m. The ABS, mounted about 0.45 m seaward of the ADVO array, comprised three transducers operating at 1.0, 2.0 and 4.0 MHz. For each transducer, the pulse repetition frequency was set to 80 Hz, and the backscattered signals with 5 mm vertical resolution were hardware averaged over 10 profiles to yield a 0.1-s temporal resolution. The ABS was sampled during the same 24 minutes and 20 seconds as the ADVOs. Each half hour the three ADVOs and the ABS were triggered externally to ensure synchronous measurements. In the design and the actual construction of the rig on the beach, special attention was paid to the positioning and orientation of all instruments to minimize disturbance of the flow field and of the bed by the instruments themselves, by the rig and by its power and logging canisters.

Initial Data Processing

The ADVO velocity series were quality-controlled based on guidelines in Elgar et al. (2005) and Mori et al. (2007). Beam velocities were transformed into the ADVO’s orthogonal coordinate system, which was subsequently rotated into cross-shore \(a\), alongshore \(v\), vertical \(w\) velocity, with positive \(a\) directed onshore, positive \(v\) to the north, and positive \(w\) upward. The total number of rejected data points increased with sensor height above the bed and with wave-energy conditions. At ADVO1 50% and 99% of the bursts had less than 0.75 and 8.9% bad data; at ADVO3, these numbers were about 2 and 29%. The applied interpolation to fill bad data gaps will bias low turbulence
fluctuations. Results in Feddersen (in press) indicate that the magnitude of this bias is likely to be minor for fractions of bad correlation points less than about 10−15%.

The elevation of the sea bed at the rig with respect to chart datum (≈ mean sea level, MSL) was estimated from the sea bed echo in the ABS data using a thresholding algorithm. The time-average of this transducer series over each measurement block of 24 minutes and 20 seconds represents the burst-averaged bed level with respect to chart datum and was used to determine the height above the bed for each ADVO during each burst. For each burst, the pressure series at ADVO1 was converted to sea surface elevation \( \eta \) using linear wave theory. The mean of \( \eta \) was added to the estimated height of ADVO1 above the bed to yield the water depth \( h \) at the rig for each burst. The pressure series at ADVO2 and ADVO3 yielded virtually identical \( h \). More detail on velocity series quality-control and sea bed detection are presented in Ruessink (in press).

Experimental Conditions

The rig was deployed from 7 March (yearday 67) until 30 March (yearday 90) 2008. Here we focus on an 18-day period from yearday 67 to 85 with high-energy wave conditions, during which all three ADVOs were operational. During this period, offshore significant spectral wave height (in 20-m water depth) ranged from 2 to 8 m with periods between 5 and 14 s, coinciding with spring tides (range ≈ 2-4 m).

Figure 1 provides a summary of the wave and water level conditions at the rig. The sea-swell (0.04-1 Hz) waves were mostly shore-normally incident. The significant spectral wave height \( H_s \), ranged from 0.5 to 2 m (Fig. 1a) with local water depth \( h \) between 1 and 3 m (Fig. 1b). The relative wave height \( H_s/h \), characterizing the breaking-wave intensity, varied between 0.31 and 0.77 (Fig. 1c). From video images of the study site collected concurrently with the rig measurements (Almar et al. 2010), Ruessink (in press) determined thresholds for \( H_s/h = 0.38 \) and 0.48, representing approximate boundaries between non-breaking, weakly breaking, and fully breaking conditions.

Dissipation Rate Estimation Method

The rate of turbulent kinetic energy dissipation \( \varepsilon \) was estimated by using the observed velocity (high) frequency spectrum together with the Lumley and Terray (1983) model for the effect of waves on the turbulent wave-number spectrum. Fitting this model spectrum to the observed spectra allowed for the estimation of the variance explained by turbulent velocity fluctuations. We used here the method presented by Feddersen et al. (2007), with the correction provided by Gerbi et al. (2009). The dissipation rate is computed in the turbulent inertial-subrange defined by \([1.5-3] \) Hz. Two quality-control methods, based upon the properties of the turbulent inertial-subrange, are used to reject bad \( \varepsilon \) data runs (Feddersen, in press). The first test checks that the \( u, v, w \) velocity spectra have a frequency dependence of \( f^{-5/3} \). The second test checks that the ratio \( R \) of horizontal and vertical velocity spectra is near one (0.5 \( \leq R \leq 2 \)). Following these methods, 74% of our data passed the tests, yielding 167 estimations of \( \varepsilon \) per ADVO, thus, 501 estimations of \( \varepsilon \) during the considering period (Fig. 1e). The \( \varepsilon \) time evolution highlights correlations with wave characteristics; these are discussed in the next section.
RESULTS AND DISCUSSION

Dissipation in the surf zone

Figure 2 presents the dissipation rates at ADVO 1-3 for each measurement burst, versus the relative water depth \( z/h \), where \( z \) is ADVO elevation above the bed. The dissipation rates, ranging from \( 10^{-2} \) to \( 10^{-4} \) m\(^2\) s\(^{-1}\), are quite strong compared to previous measurements in the surf zone (e.g., Bryan et al., 2003). It highlights the high-energy wave conditions of our study. The average dissipation structure (circles) is almost independent of \( z/h \) when considering all the data. This indicates that vertical turbulence mixing is strong.

Comparing Figures 1a and e, the dissipation rate is somewhat larger when the local significant wave height \( H_s \) increases, but no strong correlation is observed. Therefore, \( \varepsilon \) is compared to the relative wave height \( H_s/h \) (Fig. 3). As the main trend, the dissipation rate increases with \( H_s/h \), especially during fully breaking conditions \( (H_s/h \geq 0.48) \). Surprisingly, a saturation of the dissipation rate is observed for \( H_s/h \geq 0.58 \). This implies that the dissipation rate in the water column does not have a monotonic correlation with the breaking-wave intensity.

Vertical Structure of Dissipation

In our study, \( z \) changes with the bed elevation and \( h \) changes with the tide, thus, \( z/h \) variations describe both the vertical structure in the water column and the cross-shore structure for different water depths. To analyse the vertical structure of the dissipation rates individually, Figure 4 presents \( \varepsilon \) averaged at ADVO 1-3 versus the elevation \( z = h - z \), with \( z = h \) at the surface, for different water depths and breaking-wave intensities. The analysis of the vertical \( \varepsilon \) structure enables to quantify the relative importance of bed- and surface-generated turbulence in the water column. An increase in \( \varepsilon \) close to the sea surface characterizes an increasing importance of the surface-generated turbulence induced by the breaking waves, whereas an increase of \( \varepsilon \) close to the sea bed characterizes an increasing importance of the bed-generated turbulence induced by the bottom boundary layer.

For \( 3 \leq h < 3.5 \) (Fig. 4a), the vertical structure of \( \varepsilon \) changes with the relative wave height. For weakly-breaking conditions \((0.38 \leq H_s/h < 0.48)\), the influence of bed-generated turbulence is clearly visible as an increase in the dissipation rate close to the bed. When \( H_s/h \) increases to 0.58, as fully-breaking conditions, \( \varepsilon \) becomes larger and its vertical structure indicates an increasing importance of surface-generated over bed-generated turbulence. Note that highly-breaking conditions \((H_s/h \geq 0.58)\) did not occur at these depths.

For shallower water depths (Figs. 4b-d), the dissipation rates for the weakly-breaking conditions are still weaker and the water column is mainly affected by bed-generated turbulence. Again, the magnitude of \( \varepsilon \) and the effects of surface-generated turbulence increase with the wave-breaking intensity until 0.58.

Whereas weakly-breaking conditions were not observed in shallow water \((1 \leq h < 1.5 \text{ m}, \text{Fig. 4e})\), highly-breaking conditions \((H_s/h \geq 0.58)\) started to occur for \( h < 2.5 \) m (Figs. 4c-e). As observed in Figure 3, the dissipation rate saturates and is substantially weaker than for 0.53 \( \leq H_s/h < 0.58 \). The effect of bed-generated turbulence is also clearly observed for \( 1.5 \leq h < 2.5 \) m (Figs. 4c-e), suggesting that less turbulence is injected at the surface. According to laboratory experiments (Ting and Kirby, 1995; 1996), the nature of turbulence in the inner surf zone depends on a particular wave condition and it is not similar for different types of breakers. In particular, turbulent kinetic energy in the water column is much larger under plunging breakers rather than spilling breakers. Consequently, the observed highly-

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Figure 4. Average dissipation rate measured at ADVO 1-3 versus the elevation \( z = z - h \). For different water depths \( h \):
(a) \( 3 \leq h < 3.5 \) m, (b) \( 2.5 \leq h < 3 \) m, (c) \( 2 \leq h < 2.5 \) m,
(d) \( 1.5 \leq h < 2 \) m, (e) \( 1 \leq h < 1.5 \) m;
and different breaking-wave conditions \( H_s/h \):
(circles) \( 0.38 \leq H_s/h < 0.48 \), (star) \( 0.48 \leq H_s/h < 0.53 \),
(square) \( 0.53 \leq H_s/h < 0.58 \), and (triangle) \( 0.58 \leq H_s/h < 0.7 \).
Gray boxes represent sea bed locations. For each point, the horizontal and vertical bars are \( \pm 1/2 \) standard deviation.
breaking waves would correspond to bore propagation in shallow water, in which most of the dissipation occurs in the roller area above the trough level and vortex injection is probably less pronounced than during initial wave breaking.

For most of the observations, a larger $\varepsilon$ is observed at the upper measurement point, which indicates the breaking-wave turbulence generated at the surface as the main turbulence source.

**Cross-Shore Distribution of Dissipation Vertical Structure**

Analysing $\varepsilon$ for several water depths provides a representation of the cross-shore evolution. Considering that dissipation rates were not measured at the same time, it assumes a time average of the incoming wave conditions. The wave-breaking intensity and the dissipation rate mainly increase shoreward (Figs. 4a to e), which has also been observed by Bryan et al. (2003). Moreover, the $\varepsilon$ vertical structure is more affected by the surface-generated turbulence in the onshore direction. Scott et al. (2005) carried out large-scale laboratory experiments on a fixed bed to measure vertical structure of turbulent kinetic energy in the surf zone. More recently, in the same wave flume with sediments, Yoon and Cox (2010) analysed the cross-shore and vertical distributions of dissipation rates in the surf zone over evolving beach profiles. As inferred from our measurements in the field, $\varepsilon$ increases shoreward and the effects of surface-generated turbulence becomes stronger in shallow water. Such trends are more marked for the erosive wave conditions, corresponding to higher relative wave height $H_s/h$, as observed in our study.

To the best of our knowledge, it is the first time that cross-shore and vertical distributions of dissipation rates are presented for field measurements collected in the shallow-water surf zone during high-energy breaking wave conditions.

**CONCLUSIONS**

The vertical structure of the turbulence dissipation rate of our data demonstrates surface-generated turbulence as a dominant source of turbulence in the shallow-water surf zone. Nonetheless, the turbulence generated in the bottom boundary layer is not negligible, especially for the lower $H_s/h$ in our data. When $H_s/h$ increases to 0.58, the dissipation rate vertical structure indicates an increasing importance of surface-generated over bed-generated turbulence. The reduction in dissipation rate for very high $H_s/h$ (≥0.58) may be due to less vortex injection as waves modify from breakers into bars. The dissipation rates, thus, have to be correlated with breaker types and their cross-shore localizations in the surf zone have to be identified. This study suggests that wave-breaking induced turbulence has to be considered in numerical models to predict accurately sediment transport in the surf zone.

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**LITERATURE CITED**


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