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Surface-induced turbulence and resulting sand suspension beneath plunging waves

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Motivation

Breaking waves and bores inject large amounts of turbulence into the water column as vortices, which can travel downward and entrain sand from the bed. Coastal evolution models rarely include the effect of this surface-induced turbulence on sand suspension and subsequent transport to predict surf-zone morphodynamics. This research combines laboratory and field datasets of turbulence and sand concentration to increase our understanding of sand transport in the surf-zone.

Here, field-scale laboratory measurements beneath irregular plunging breakers are analysed, collected during the BARDEXII experiments. The objective is to investigate whether turbulence and sand concentrations are phase-coupled to the wave orbital motions. A phase coupling of suspension with wave orbital motions would imply cross-shore sand transport by these motions in the surf zone.

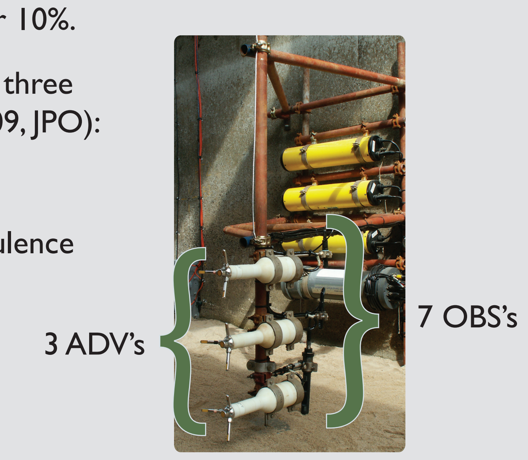
Methods

- Field-scale laboratory measurments; BARDEXII; Deltaflume
- Irregular waves
- Plunging breakers
- Significant wave height, H_s = 0.5 - 0.9 m
- Wave period, T = 8 - 12 s
- Sand size, d_{50} = 0.42 mm
- Water depth, h = 2 - 3 m

At a single cross-shore location, turbulence and suspension measurements were conducted with a rig comprising vertical arrays of 3 ADV's (10 Hz) and 7 OBS's (4 Hz). Due to the different wave conditions and water levels during the test cases, the percentage of broken waves passing the rig varied between 0 and 50%. For the following analyses, only the cases with a relative wave height H_s/h > 0.675 were selected, which correspond with a percentage of broken waves over 10%.

Measured velocity is separated in three components using Gerbi et al. (2009, JPO):

$$u = \underbrace{\bar{u}}_{\text{mean}} + \underbrace{\hat{u}}_{\text{wave}} + \underbrace{u'}_{\text{turbulence}}$$



- Instantaneous turbulent kinetic energy, $k' = 0.5(u'^2+v'^2+w'^2)$
- u is also seperated on wave frequency in u_{hf} and u_{ig}, with
  u_{hf} $0.05 < f < 1$ Hz
  u_{ig} $0.005 < f < 0.05$ Hz
- The timeseries of u_{hf} and u_{ig} were transformed to timeseries of wave phase (φ) with the Hilbert transform and expressed from 0 to 1, with at 0.25 the peak in negative u and at 0.75 the peak in positive u.
- Both turbulence and sediment concentration were phase-averaged for u_{hf} and u_{ig} using a bin width of 0.05, in order to study phase-coupling.
- The cross spectral density between u at the middle ADV and c at seven heights above the bed was calculated with a block size of 256s with 50% overlap.

Results

Turbulence

- High degree of vertical mixing, with high turbulent kinetic energy present under the wave face (Figure 1b)
- Large $\sqrt{\langle k\rangle/(gh)}$ *, in which* $\langle\ \rangle$ *denote a time average and g is the gravitation acceleration,* beneath the wave front higher in the water column suggests surface-generated turbulence (Figure 1b)
- Even stronger phase-coupling of turbulence with the cross-shore orbital infragravity motion, with most turbulence while the infragravity motion is in the offshore direction (Figure 1e). It was found that 2/3 of the broken short waves were propagating over the instrument rig while u_{ig} was in the offshore direction.
- The vertical flux of turbulence ($k'w'$) also shows a phase-coupling with u_{hf}, with an average upward flux following an average downward flux around the breaking wave front (Figure 1c). The downward flux of turbulence represents the injection of turbulence by the plunging jet of the breaking waves, the subsequent upward flux might be explained by the upward advection of air bubbles injected earlier in the wave phase.

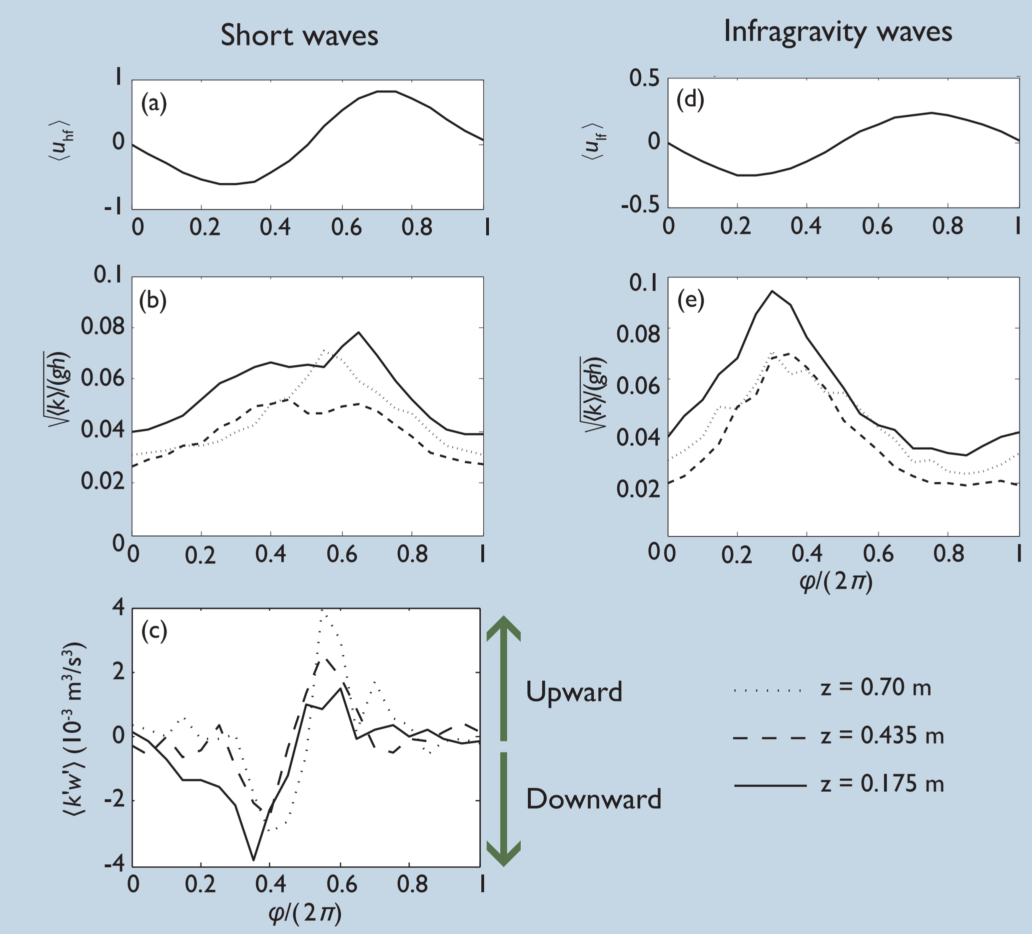


Figure 1. Phase-coupling of Froude-scaled turbulence, $\sqrt{\langle k\rangle/(gh)}$, with u_{hf} (b) and u_{ig} (e). And the phase-coupling of the vertical turbulence flux (k'w'), in which w' is the vertical turbulence, with u_{hf} (c). The top plots (a and d) show the mean wave signal for all waves used in the analyses.

Suspension

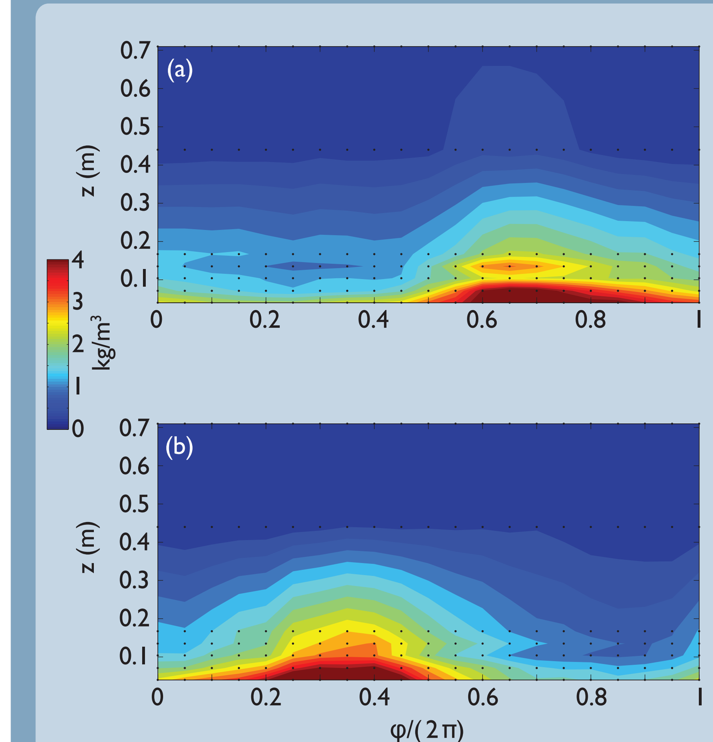


Figure 2. Phase-averaged sediment concentration at seven heights above the bed over all cases with H/h>0.675, for u_{hf} (a) and u_{ig} (b). The phase-averaging was conducted for each OBS using the velocity data from the middle ADV.

- The sediment concentration is phase-coupled with u_{hf} throughout the water column, with highest concentrations while u_{hf} is in the onshore direction (Figure 2a).
- The increase in sediment concentration in the wave phase coincides with the upward flux of turbulence (Figure 1c).
- The sediment concentration is strongly coupled with the infragravity motion (Figure 2b), highest values are found while u_{ig} is in the offshore direction.
- Cross power spectral density (CPSD) analyses show, consistent with the phase-coupling results, positive correlation for c with u for f>0.05Hz and negative for f<0.05Hz (Figure 3a).
- A large spread exists around the mean cross-spectra (Figure 3b), probably explained by the presence of ripples.

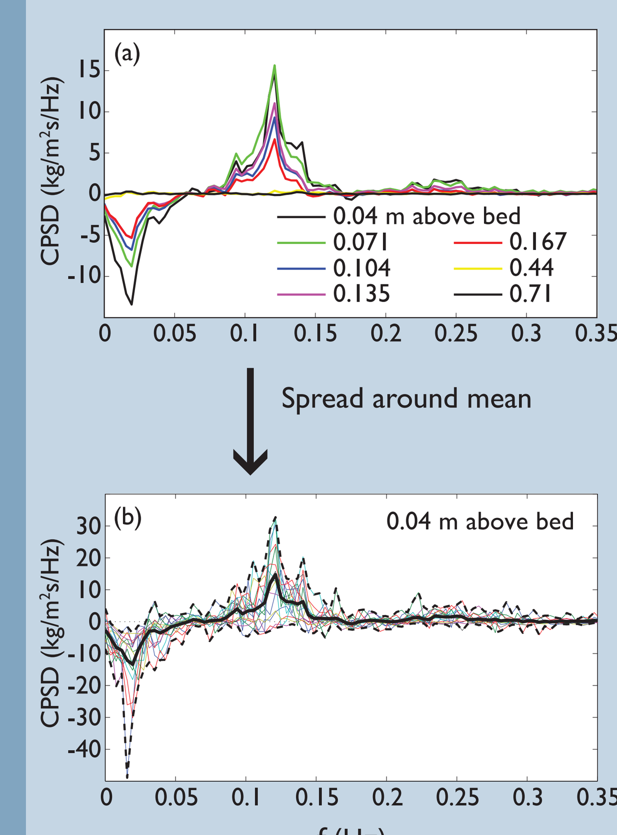


Figure 3. Mean cross-spectra for u (measured at z=0.435m) with sediment concentration at 7 heights above the bed over all cases with H/h>0.675 (a) and the cross-spectra for u with the sediment concentration closest to the bed for all cases with H/h>0.675 (b), the thick line in the second plot shows the mean, the dashed line the minimum and maximum value.

Next

The same instrument configuration was deployed at several natural beaches and measurements were collected under a wide range of conditions.

With this dataset the study will be extended to include sand transport;
- beneath spilling breakers
- in the inner surf-zone.

The ultimate aim will be to develop a parameterization that quantifies the effect of surface-induced turbulence on sand transport beneath broken waves and can be embedded in operational models.

Conclusions

- Both turbulence and sand concentration are phase-coupled to the high-frequency waves, with highest values when the short wave orbital motion is in the onshore direction.
- The increase in sediment concentration in the short wave phase coincides with an upward flux of turbulence.
- The phase-coupling of turbulence and sand suspension with cross-shore infragravity motion is stronger, with highest values while the infragravity motion is in the offshore direction. This is explained by an infragravity modulation of short-wave breaking.
- From these results we expect transport of sand in the onshore direction by short waves and in the offshore direction by infragravity waves in a surf-zone with plunging breakers.
- Further analyses with field datasets aim to develop a widely applicable parameterization of sand transport beneath broken waves.

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