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Surf-Swash Interactions on a Low-Tide Terraced Beach

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ABSTRACT


Through an integrated approach, this paper investigates the role of coupled surf-swash dynamics on outgoing waves using data collected at a low-tide terraced beach, Grand Popo, Benin (Gulf of Guinea, West Africa). Observed reflection is 8%. Analyses are conducted from deep water directional wave spectra measurements, daily beach surveys and remote video measurements. Our results show that the swash can be a non-negligible component of the nearshore energy balance (14% of total dissipation) and is closely tied to reflection. Reflection thus depends on waves at swash inception (offshore waves and surf zone saturation), and shoreface slope varying with tide and morphological evolution. An outgoing cut-off frequency (shortest reflected waves) can be linked to swash saturation with a strong dependence on shoreface slope. A phase-resolving Boussinesq model was validated and used to investigate the influence of terrace width, upper shoreface slope and tidal elevation over the terrace. This papers puts forward the role of the coupled system surf-swash and underlines potential key interactions between a rapid shoreface evolution and surf zone hydro-morphodynamics.

ADDITIONAL INDEX WORDS: Grand Popo, Benin (Gulf of Guinea), reflection, standing wave, incoming and outgoing waves.

INTRODUCTION

There is a potential for substantial wave reflection at the coast depending on hydrodynamic and morphological conditions. Understanding the mechanisms at the origin of such reflection and the nature of reflected waves is crucial for various aspects of coastal science including energy balance, standing and edge wave patterns and feedback with incoming waves, and resulting shoreface evolution. Pioneering studies based on laboratory experiments showed a link between reflection and the ratio of wave steepness to beach slope, hence vertical acceleration versus gravity, which can be summarized by the surf-similarity parameter (Battjes et al., 1974).

Field observations have shown that these predictions are poor for irregular waves and complex bathymetric profiles Elgar et al. (1994). More recent studies, although mainly focused on engineering structure design (Sutherland et al. (1998), among others), have underlined the key role played by swash zone dynamics in controlling the phase and energy of reflected waves. Reflection is linked to a parameter comparing swash "wavelength" with horizontal excursion originally developed by Hughes et al. (1995).

Significant research effort has been devoted to energy saturation in the nearshore, the surf zone saturation being linked to the height-to-depth ratio and describing the limit between non-breaking and breaking waves, and the remaining energy being transferred to larger frequencies and non-oscillatory dynamics (i.e. setup). Sallenger et al. (1985) observe that the height-to-depth ratio might increase with local slope and can be rather independent of deepwater wave steepness. It has been extensively observed that wind- and swell-waves (T<20 s) are generally saturated whereas longer infragravity waves (T>20 s) rarely saturate Ruessink et al. (1998) although recent observations have shown that saturation could extend to the infragravity band (Ruggiero et al., 2004; Senechal et al., 2011) and that infragravity wave can be dissipated through breaking (de Bakker et al., 2014). This high-frequency band saturation reflects surf-zone transformations but is also thought to result from non-linear swash zone processes such as swash-to-swash interaction Brocchini et al. (2008), bottom friction and infiltration. Supposedly crucial, the link between swash characteristics and reflection has not yet been clearly established, in particular the role of swash saturation for broadband spectra.

In this paper we revisit the link between surf and swash dynamics and reflection from field observations collected at a low tide terraced beach, Grand Popo beach, Benin, in the Gulf of Guinea (West Africa), where largest reflections on earth have been reported (Ardhuin and Roland, 2012). We show that reflection is mostly governed by surf zone saturation over the terrace, whereby the reflected spectrum essentially depends on swash slope.

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METHODS

An intensive field experiment was conducted during March 2014 at Grand Popo, Benin (Gulf of Guinea, West Africa), a sandy coast exposed to South Atlantic long swells (Almar et al., 2014). Grand Popo beach is an intermediate-reflective (Ω>2), micro-tidal, wave-dominated (annual mean, \(H_s = 1.4\) m, \(T_p = 9.4\) s, SW, \(RTR \sim 1\)), medium grain-sized \(D_{50} = 0.6\) mm, alongshore uniform, low-tide terraced beach (Figure 1). Incoming and reflected waves and tide were measured in 10-m depth. The terrace was instrumented with 2 lines which included pressure sensors, Acoustic Doppler Velocimeters, and two cross shore arrays of 20 video-poles (every m) for measuring at high frequency (25 Hz) wave transformation across surf and swash zones.

Figure 1. Study site, Grand Popo, Bénin. a) deployment setup on the terrace, b) image from video camera and c) bathymetric profil. Red circle shows ADCP location.

The 10-day experiment included daily differential GPS topographic surveys, deep water (11-m) directional wave measurements using an Acoustic Doppler Current Profiler (ADCP), and shore-based video swash monitoring.

Timeseries of runup were computed from 2-Hz cross-shore video spatio-temporal images collected during daylight hours, and extracted using a Radon Transform method (see Almar et al., 2014a). The 3-colourband timestacks are first converted into grayscale and the Radon Transform is applied to detect motion. This methods offers a reasonable proxy of instant runup motion, although the thin backwash layer can sometimes be missed.

In Results Section, swash zone energy \(E_{\text{swash}}\) is approximated from the commonly used formula (Guedes et al., 2013):

\[
E_{\text{swash}} = 4\theta S \tan \theta
\]

(1)

where \(S\) is runup timeseries derived from video and \(\theta\) local swash slope. The surf zone dissipation due to breaking \(D_{\text{breaking}}\) estimated from the roller characteristics following Haller et al., (2009):

\[
D_{\text{breaking}} = \rho g A \sin \theta \cos \theta / T
\]

(2)

where \(g\) is the gravitational constant, \(\theta\) a free parameter accounting for roller inclination (taken as \(\sim 6^\circ\) from literature), and \(T\) the roller period, and \(A = 0.11(L_r/cos\theta)^2\) with \(L_r\) the roller length estimated from cross-shore video spatio-temporal images.

Numerical computations are conducted using the phase resolving fully non-linear 4th-order finite volume Boussinesq model SERR1D (Cienfuegos et al., 2010). This model includes a parameterization for the wave-breaking energy dissipation. The model has been previously validated with laboratory data for very non-linear conditions on a gently sloping beach (Michallet et al., 2014). The model showed good performances in representing both short-wave dynamic and energy transfer to infragravity band.

RESULTS

Figure 2 shows timeseries of offshore hydrodynamic forcing (wave and tide), shoreface morphological and breaking over the terrace derived from video. Wave height has decreased over time, together with an increase of tidal range and a steepening of the upper beach. Breaking over the terrace was largely affected by tidal modulation. Reflection \(R\) reaches 8% on average, through varying substantially over time (from 3 to 12%, Figure 4). 

Influence of surf and swash processes on reflection

The relative contribution of surf and swash zones in the dissipation of wave energy is shown in Figure 3. \(D_{\text{breaking}}, E_{\text{swash}}\) and \(R\) vary with offshore wave, tide and morphological evolution. A multiple linear regression shows that \(D_{\text{breaking}}\) and \(E_{\text{swash}}\) dissipate 71 and 14 % of \(E_{\text{inc}}\) respectively, though varying substantially over time (from 3 to 12 %, Figure 4.a). \(E_{\text{swash}}\) can even be predominant at some specific moments, e.g. at high tide when breaking is weak over the terrace. In the meantime, \(E_{\text{swash}}\) contribution to \(R\) rises up to 62%. This is in line with what has
been observed elsewhere at dissipative beaches (i.e., intense breaking over the terrace), where the surf zone saturation may extend to the infragravity band (de Bakker et al., 2014; Senechal et al., 2011), resulting in a weak dependence of $R$ on the shoreface slope and swash dynamics. For such conditions, the swash could be scaled only through deep-water parameters (Guza et al., 1982), and the beach only introduces more scatter in the regression. The role of swash in modulating the reflected spectrum is investigated in the next section.

**Reflection cut-off frequency**

Swash energy spectra are computed from 20 min of video-derived timeseries. It is noteworthy that the saturation extends into the infragravity band ($T > 20$ s) at dissipative beaches whereas the swell-band might be unsaturated at reflective beaches such as Grand Popo. With the idea of linking swash saturation extent with reflection, and following the method described in Ruessink et al. (1998), the lowest saturated frequency is extracted from the spectra (Figure 5) as a swash cut-off period $f_{cswash}$ (Figure 4). The highest reflected frequency $f_{c_{offshore}}$ is also computed from offshore wave directional spectra. A reasonable fit ($r^2 = 0.42$, significant at the 95% level) is obtained between $f_{cswash}$ and $f_{c_{offshore}}$ with only a minor bias, $f_{c_{offshore}} = 0.89 f_{cswash}$. This link shows evidence of a feedback between swash dynamics and the whole nearshore domain, which includes incoming and outgoing wave interaction and resulting standing waves.

Contrary to that found for peak swash frequency or outgoing peak frequency ($f_p$), $f_{c_{offshore}}$ appears to be relatively independent of incoming waves. The correlation of $f_{c_{offshore}}$ is larger with $a(0.51)$ than with $f_{c_{offshore}}(0.32)$. This clearly indicates that $f_{c_{offshore}}$ essentially depends on $a$ and not the incoming waves.

**Model validation**

The skills of the Serr1D model in describing wave transformation over the terrace and reflection is tested here. The model is first compared to field observations over the full experiment duration. 20-min of surface elevation timeseries from ADCP are propagated over real bathymetry. Figure 4 shows that the model reproduces the frequency transfers that include secondary wave generation at high tide and infragravity at low tide. Reflection (computed using Radon Transform separation, see Almar et al., 2014) is reasonably reproduced, together with breaking intensity over the terrace, estimated from the breaking index $y = H_b/d$, $H_b$ and $d$ being breaker height and depth, respectively. Slope at waterline $a$ values (accounting for tide and wave-induced setup) are similar, despite that bathymetric profile was chosen constant in the model and cannot reproduce the observed flattening trend. This, together with $f_{cswash}$ and $f_{c_{offshore}}$ that show largest discrepancies, need to be further investigated. The model is used in the next Section to investigate the influence of terrace width, upper slope and tide on reflection.

**DISCUSSION**

Once validated, the model is used in Figure 6 to determine the modulation played by the terrace width, upper shoreface slope and tide on the interaction between outgoing and incoming waves in the surf zone. An increase of the terrace width moves the system toward a flatter beach and wider dissipative surf zone, which enhances wave frequency transfer to the infragravity band. Reflected energy increases with the upper shoreface slope, and the cut-off frequency shifts toward shorter periods. The control of outgoing component, through the enhancement/decrease of breaking, on incoming waves increases. As a result, incoming spectrum shifts toward the
outgoing one and, interestingly, the overall trapped energy increases which is a resonant condition.

Figure 5. Normalized hourly evolution of spectra over the experiment duration for field (left) observation and (right) model at (upper panels) 11-m depth (ADCP), terrace (pressure sensors) and runup (from video).

CONCLUSIONS

In this paper we investigate the link between swash and surf zone dynamics at the low-tide terraced Grand Popo beach, Benin. Our observations, combining video imagery of swash and surf zone as well as deep water wave spectra, underline the key role played by swash in the reflection (8 % observed) mechanism and feedback on incoming waves which leads to quasi-standing wave or even resonance. Swash contributes to 14 % of nearshore energy dissipation and its link with reflection increases from low to high tide (when breaking is limited). A good agreement was found between a cut-off frequency $F_c$ of reflected waves computed from deep water spectra and retrieved from swash saturation ($r^2=0.42$, $F_{c_{\text{offshore}}}=0.89F_{c_{\text{swash}}}$). Unlike reflection $R$, $F_c$ uniquely depends on shoreface slope $\alpha$.

A Boussinesq model was validated with these challenging reflective conditions and showed good skills at retrieving key parameters. The model was later used to investigate the influence of the terrace width, upper slope, and tide on reflected component and its interaction with incoming waves. The most striking influence is played by the upper shoreface slope which closely controls the outgoing waves, but also incoming waves through a positive feedback when frequencies coincide which enhances breaking rate at particular frequencies.

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