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Wave Transformation and Energy Dissipation in the Surf Zone: Comparison Between a Non-linear Model and Field Data.

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ABSTRACT

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A numerical model based on the one-dimensional Saint Venant equations was developed to simulate wave transformation in the surf zone. Data collected during a field experiment conducted on October 2001 on a sandy beach were employed to evaluate the applicability of this model to high energy surf zone conditions. The variations of wave shape and energy spectra across the inner surf and swash zones are well predicted by the numerical model. It predicts the rapid cross-shore variations of energy at both infragravity ($0.004 < f < 0.05$ Hz) and sea swell frequencies ($0.05 < f < 0.6$ Hz). Analysis of observed and predicted values of the significant height Hs in the surf zone, confirms the validity of the wave height decay parameterization proposed by RAUBENHEIMER *et al.* (1996) and SÉNÉCHAL *et al.* (2004).

ADDITIONAL INDEX WORDS: *Bore, shock wave, infragravity wave*

INTRODUCTION

As the waves propagate shoreward to gradually smaller depth, their height and their steepness increase, until they break. On gently sloping beaches two types of breakers may be distinguished: the violent and sudden plunging breaker and the spilling breaker in which vortical motions take place with a less violent appearance. In both cases, immediately after the initiation of breaking a rapid change in the wave shape occurs, in a region that has been termed the "transition region" (SVENDSEN *et al.* (1978)). Shoreward of this transition region the wave field changes more slowly and it reorganizes itself into quasi-periodic borelike waves. This region, which extends to the shoreline where the run-up starts (swash zone), has been termed the "inner surf zone" (ISZ) (SVENDSEN *et al.* (1978)).

In the present study, predictions of a one-dimensional numerical model (BONNETON and DUPUIS (2000) and VINCENT *et al.* (2001)) based on the nonlinear Saint Venant equations with shock dissipation and bottom friction are compared to observations in the ISZ and the swash zone on a gently sloping beach. Our analysis is confined to high energy wave conditions for which the surf zone has a significant ISZ.

The main objective of this paper is to assess the capability of this time dependent model to predict the cross-shore variations of wave shape and energy spectra at both infragravity ($0.004 < f < 0.05$ Hz) and sea swell frequencies ($0.05 < f < 0.6$ Hz).

The observations and numerical model are briefly discussed, and then model-data comparisons are presented, followed by a discussion of a wave height decay parameterization.

FIELD DATA

This study is based on data collected during a field experiment conducted on October 2001 (see SÉNÉCHAL *et al.* 2003) on a sandy beach (Truc Vert beach), situated on the southern part of the French Atlantic coastline, at approximately 10 km north of the Cap Ferret spit at the mouth of the Arcachon lagoon. The beach exhibits a ridge and runnel system in the intertidal domain. The high tidal range (3.9 m in this experiment) allows instruments to be deployed safely at low tide while measurements can be obtained at high tide. Sensors were deployed in the intertidal zone along three parallel cross-shore transects.

In this paper, we focus on pressure data collected the 18th October at high tide: $t[t_h\text{-}127$ min, t_h+203 min], where t_h=16:27 hours is the high tide time. Pressure measurements were acquired at six locations along one cross-shore transect (see figure 1), located outside the influence of the rip channel. Pressure were measured using four bottom-mounted piezoresistive pressure transmitters (P3, P4, P5 and P6), one Directional Wave Current Meter (P1) from InterOcean system and one Acoustic Doppler Velocimeter (P2) from Nortek. Figure 1 shows the cross-shore location of these sensors. Data were continuously acquired at a sample rate of 2 Hz for P1, 32 Hz for P2 and 8 Hz for P3, P4, P5 and P6.

The beach profile (see figure 1) displayed fairly mid slopes about 3 %. The offshore conditions measured in 56 m water depth (see figure 2) correspond to a high energy long incoming swell with a significant period Ts ranged between 11.7 s and 12.3 s and a significant wave height Hs between 2.2 m and 3 m. The wave field propagated normally to the beach with wave groups of varying amplitudes, which induced infragravity waves in the surf zone. Wave breaking showed a majority of plunging breakers (see figure 3). In this experiment the surf zone was large, with a maximum width of 500 m and consequently all the pressure sensors are located inside the ISZ or the swash zone.

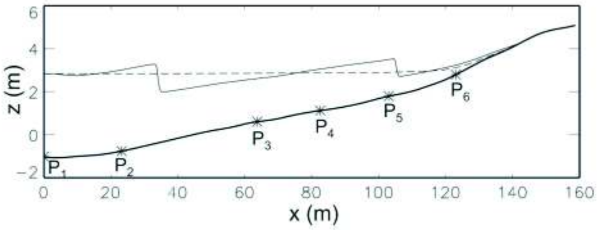

Figure 1. Bottom topography (thick line) measured along one transect at Truc Vert beach on October 18th 2001 and locations of pressure sensors (P1-P6). Numerical simulations at high tide ($t=t_h$): instantaneous water surface elevation (solid line), 10 min-averaged water surface elevation (dashed line).

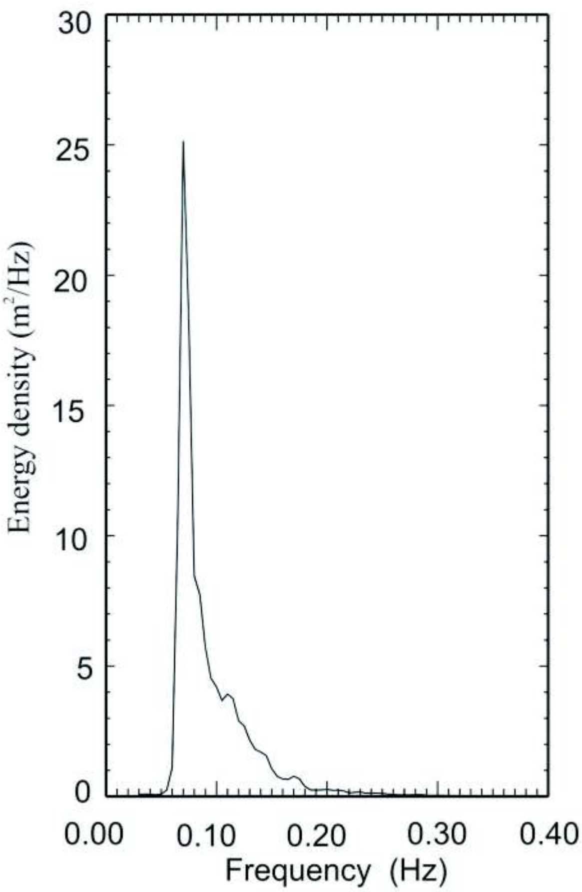

Figure 2. Offshore sea surface elevation energy density spectra measured in 56 m water depth on October 18th 2001 at high tide ($t=t_h$).

Consistent with the long wave approximation used in the Saint Venant equations, water depths were estimated assuming that the measured pressure field is hydrostatic (see also RAUBENHEIMER *et al.* (1996)). Beach profiles were determined at each low tide using a DGPS system. The slight variation of the heights of the bottom-mounted sensors above the sea floor was also measured to adjust water depth. Thus, the absolute water depth error is estimated to be smaller than 0.1 m.

TIME-DEPENDENT NUMERICAL MODEL

Our model is based on the one-dimensional Saint Venant equations with bottom friction:

$$\frac{\partial h}{\partial t} + \frac{\partial hu}{\partial x} = 0$$
$$\frac{\partial hu}{\partial t} + \frac{\partial}{\partial x}(hu^2 + 0.5gh^2) = -gh\frac{\partial Z}{\partial x} - 0.5f|u|u \qquad (1)$$

where x is the distance onshore from the model seaward boundary, u(x,t) is the depth-averaged cross-shore velocity, h(x,t) is the total water depth, Z(x) is the bed elevation, g is the gravitational acceleration and f is a constant friction coefficient.

Previous numerical studies by KOBAYASHI *et al.* (1989), RAUBENHEIMER *et al.* (1996) or BONNETON and DUPUIS (2000) have shown the ability of these non-linear shallow water equations to describe wave transformation in the ISZ and swash zone, even if they are inadequate for the prediction of initial breaking.

Recently, BONNETON (2001, 2004a) presented a theoretical analysis of the Saint Venant equations based on the hyperbolic theory for periodic shock waves. He showed that the "shock wave" concept is an appropriate tool to describe wave distortion and energy dissipation in the ISZ. This concept, which goes far beyond the classical hydraulic jump analogy, can be used both for finding analytical solutions and for developing appropriate numerical schemes in presence of wave front.

Numerical methods

To compute broken wave propagation it is necessary to implement a shock-capturing numerical method. HIBBERT and PEREGRINE (1979) and KOBAYASHI *et al.* (1989) chose the Lax-Wendroff scheme, which has been successfully applied for solving numerous hyperbolic systems. However, in presence of fronts, the dispersive properties of this scheme introduce spurious numerical oscillations. To reduce these high-frequency oscillations which tend to appear at the rear of a wave fronts, and PEREGRINE (1979) and KOBAYASHI *et al.* (1989) included an artificial dissipative term. An alternative to this approach is to use a TVD (total variation diminishing) scheme, which represents a rational method for the determination of dissipation terms. The Saint Venant equations are solved using an explicit MacCormack scheme with a TVD flux correction. The TVD MacCormack scheme so obtained retains second-order precision in space and time in regular zones and is oscillation-free across wave fronts.

At the seaward boundary (x = 0) we have implemented a method developed by COX *et al.* (1994), which determines the outgoing Riemann invariant by an implicit scheme. This method allows to specify the measured water depth h(x =0, t) without any reflection of outgoing waves at the boundary. For computations of wave runup in the swash zone it is necessary for the model to be able to simulate the land-sea interface realistically. To do this, the entire computational domain is considered active with an artificial thin water layer ($h=10^{-4}$ m) in dry meshes. At the shoreline a specific treatment is applied in the momentum equation to the discretization of the horizontal gradient of the surface elevation. It consists in omitting the landward spatial differences of this term.

Details of these numerical methods and validations are given in BONNETON and DUPUIS (2000) and VINCENT *et al.* (2001).

Numerical parameters

The fluid domain was discretised by 397 nodes using a grid spacing of $\Delta x = 0.4$ m. The stability of the TVD MacCormack scheme requires a stronger condition than the Courant-Friedrichs-Levy (CFL) condition. Thus, the model was run with a time step $\Delta t = 0.025$ s, which corresponds to a CFL number smaller than 0.5. The spatial and time steps corresponded approximately to $\Delta x = \lambda / 186$ and $\Delta t = Ts / 480$, where λ is the wavelength at the seaward boundary.

The seaward boundary condition of the model was given by time series of water depth (P1 sensor) and the duration of the run was 19800 s. The initial condition of no wave motion leads to a transient period of 200 s, which is eliminated from time series presented hereafter. On the basis of previous calibrations and

Figure 3. View of the surf zone at Truc Vert beach on October 18th 2001 at time $t = t_h$+90 min.

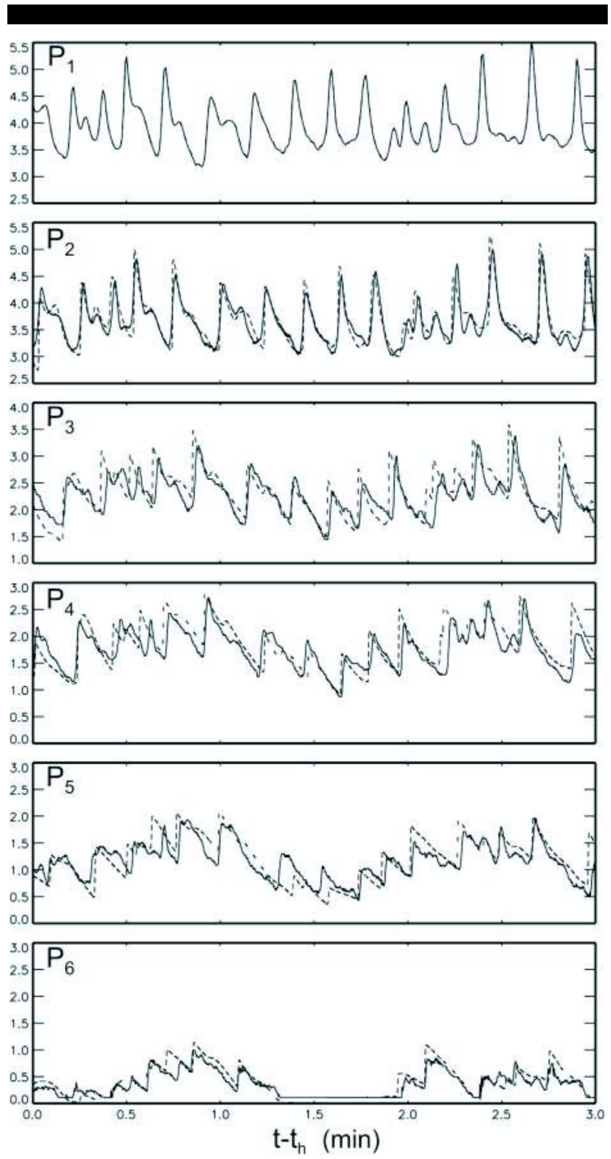

Figure 4. Comparison between observed (solid line) and predicted (dashed line) time series of water depth at sensors P1-6; $t=t_h$.

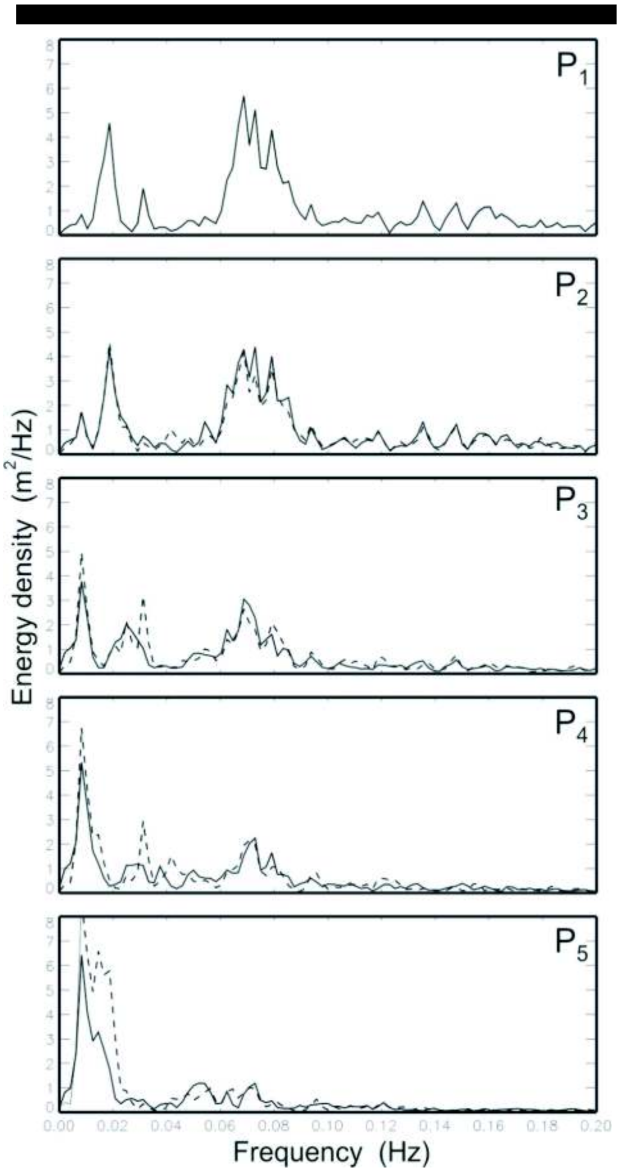

Figure 5. Comparison between observed (solid line) and predicted (dashed line) sea surface elevation density spectra at sensors P1-5; $t=t_h$.

model tests (e.g. KOBAYASHI *et al.* (1989) or RAUBENHEIMER *et al.* (1995)) we used a friction coefficient f=0.015. Comparison of model predictions using a smaller mesh size ($\Delta x = 0.2$ m) shows that predicted time series are not significantly affected by Δx.

MODEL-DATA COMPARISONS

Although simulations were carried out for the complete experimental run ($t \in [t_h$-127 min, t_h+203 min]), only parts of this run was selected for detailed discussion here. However, the general conclusions given are based on the results from the whole run.

Figure 1 shows the cross-shore beach topography and illustrates the computational domain with an example of instantaneous and mean waver surface elevations computed at high tide. This domain contains approximately two sea swell wavelengths. Sensors P1-5 were located inside the ISZ and P6 inside the swash zone.

Figure 4 shows typical time series of computed (dashed line) and measured (solid line) water depths through the IZS and the swash zone. The observed decrease of wave front height and relative increase of infragravity wave contribution shoreward are predicted. The run-up in the swash zone (sensor P6) is dominated by infragravity waves with a period of about 2 min and with relatively little energy at sea swell frequencies. The cross-shore variations in the shape of the broken waves are well predicted by the model, that is, the development of saw-tooth shape in the ISZ. Previous studies with Saint Venant-type model (e.g. KOBAYASHI *et al.* (1989)) or Boussinesq-type model (e.g. OZANNE *et al.* (2000) or BAYRAM *et al.* (2000)) showed the presence of spurious numerical oscillations at the rear of wave fronts. For instance, BAYRAM *et al.* (2000) noted that there is a tendency for Boussinesq-type model to generate too many small oscillations sometimes almost resulting in complete wave disintegration. Thanks to our shock-capturing TVD method we do not observe such a problem. Figure 4 also shows a good phase agreement between observed and predicted time series. This result confirms that the shock wave theory, applied to the Saint Venant equations, is relevant to predict bore celerity (see also BONNETON (2004b)), even for irregular sea swell waves in presence of infragravity waves. Between P1 sensor and P6 sensor (inside the swash zone) the observed setup (about 0.30 m) is well predicted by the model.

Figure 5 shows energy density spectra for the measured (solid line) and computed (dashed line) free surface elevation in the ISZ at sensors P1-5. Energy estimates were calculated by Fourier transforming overlapping (75%), Hanning-windowed

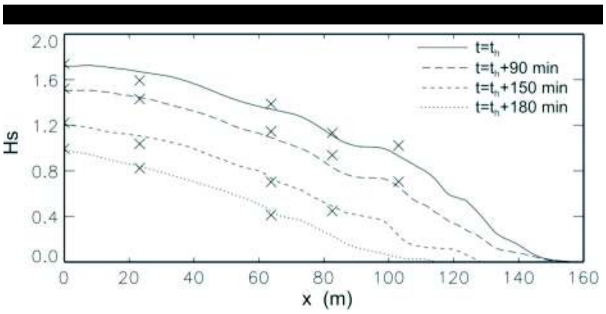

Figure 6. Observed (X) and predicted (line) significant wave height versus cross-shore distance.

and detrended 4-min data segments averaged over 20 min. At the seaward boundary (P1 sensor) we observe a wave field characterized by high sea swell energy and high infragravity wave energy. Non-linear interactions in shallow water lead to substantial cross spectral energy transfer on relative short distances. The model predicts the rapid cross-shore variation of energy at both infragravity ($0.004 < f < 0.05$ Hz) and sea swell frequencies ($0.05 < f < 0.2$ Hz). The comparison between observed and predicted spectra shows that the model simulates both the spectral shape and the energy levels rather accurately. However, in sensor P5 the energy in the infragravity band is overestimated by the model. This discrepancy could be due to long-shore effects which are not taken into account in the one-dimensional model. For instance, low-mode edge-wave energy at infragravity frequencies can be significant in the swash zone and could cause discrepancies between model predictions and observations.

DISCUSSION OF DEPTH-LIMITED PARAMETERIZATION

Field observations in the surf zone (e.g. THORNTON and GUZA (1982), RAUBENHEIMER *et al.* (1996) or SÉNÉCHAL *et al.* (2001, 2004)) suggest that at sea swell frequencies, significant waves heights Hs (defined as four times the sea surface elevation standard deviation) are limited by the local mean water depth h: $Hs = \gamma / \bar{h}$, with γ depending on the beach slope β and on the incident wave characteristics. In time-averaged models of surf zone hydrodynamics, wave energy dissipation is frequently parameterized in terms of γ. In this section, we assess the capacity of our time dependent numerical model to predict the cross-shore evolution of Hs and we discuss about a γ-parameterization initially proposed by RAUBENHEIMER *et al.* (1996).

The observed and predicted cross-shore variations of the sea-swell significant wave heights Hs are shown in figure 6 at different times of the falling tide ($t \in \{t_h, t_h+90, t_h+150, t_h+180$ min$\}$). All experimental and predicted data were processed similarly. Time series were divided into sections of 600 s each. Energy estimates were calculated by Fourier transforming over each section. The significant wave height is obtained by integrating the energy over the sea swell frequency band ($0.05 < f < 0.6$ Hz). The cross-shore decrease of Hs in the surf zone is well predicted by the numerical model (see figure 6). This result confirms that the shock wave concept is an appropriate tool to predict wave energy dissipation.

Previous studies by RAUBENHEIMER *et al.* (1996) and SÉNÉCHAL *et al.* (2001, 2004) have shown that γ is well correlated with $(k\,\bar{h})/\beta$, where k is a characteristic local number and ??is the beach slope estimated from the observed profiles as the difference in vertical elevation over a distance equal to the shallow water wavelength. During the experiment studied in this paper, the sea swell frequency peak fp remained constant across the surf zone. Thus, the local wavenumber k can be estimated by $k = (2\pi fp) / (g)^{1/2}$.

Moreover, β was approximately constant across the beach see figure 1). Thus the γ-parameterization, which

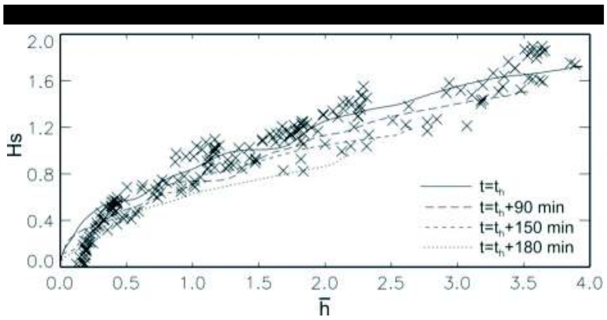

Figure 7. Observed (X) and predicted (line) significant wave height versus mean water depth. Experimental data correspond to the whole data set ($t \in [t_h$-127 min, t_h+203 min]).

corresponds to a relation between γ and $(k\,\bar{h})/\beta = (2\pi fp^{1/2}) / (\beta g^{1/2})$, is limited in this experiment to a relation between Hs and The observed and predicted Hs values versus $\bar{h}$ are shown in figure 7. We observe a good correlation between Hs and $\bar{h}$, in agreement with the γ-parameterization (see also SÉNÉCHAL *et al.* (2003)), even if computed values of Hs show a slight vertical shift in function of time. This trend seems to be related to the cross-shore variation of β that we neglect in the present analysis.

CONCLUSION

The experiment presented in this paper was conducted during high swell conditions that were ideal both for investigating random wave transformation in the surf zone and for evaluating the capability of time dependent surf zone models (Saint Venant-type model or Boussinesq-type model).

We have shown that the cross-shore variations in the shape of the broken waves are well predicted by our numerical model. This confirms that the shock wave concept, applied to the Saint Venant equations, is efficient for predicting broken wave propagation and energy dissipation. The model accurately predicts the rapid cross-shore variation of energy at both infragravity ($0.004 < f < 0.05$ Hz) and sea swell frequencies ($0.05 < f < 0.6$ Hz).

Finally, the analysis of observed and predicted values of the significant height Hs in the surf zone, confirms the validity of the wave height decay parameterization proposed by RAUBENHEIMER *et al.* (1996) and SÉNÉCHAL *et al.* (2004).

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