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Ripple and sandbar dynamics under mid-reflecting conditions with a porous vertical breakwater

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ABSTRACT

This research is an experimental study of ripple and sandbar dynamics under regular and random waves in partially reflective conditions. As part of this study, a series of small-scale flume experiments were performed that reproduced the growth and migration of the bedforms, starting from a flat bed or rippled bed, with sediment transport in the bedload regime.

The results showed that the evolution and dynamics of sandbar geometry were slower processes than the evolution of ripples. Moreover, they were governed by the wave field, reflective conditions, and sediment characteristics. Sandbar generation was controlled by the intensity of reflection, whereas the location of the crests (or deposition and erosion areas) was constrained by the phase shift of the reflected waves. Significant differences were also found between sandbars under regular and random waves. Sandbars under regular waves showed flat or practically flat troughs. In contrast, sandbars under random waves were almost uniformly covered by ripples.

The experimental results showed that the concurrence of ripples and sandbars under partially reflected waves has a spatially modulating effect on ripple characteristics (i.e. growth, shape and migration celerity), which could not be consistently interpreted by using the classical formulas valid for ripples under progressive waves and/or without large-scale bedforms. This variability was more pronounced for regular waves than for random wave trains. Larger ripples develop in the nodes of the free surface envelope (more or less corresponding to the sandbars crests), whereas smaller ripples occurred in the antinodes (or sandbars troughs).

The statistics of ripples geometry and celerity were computed with a sample stratification, based on their position in reference to the sandbars. In addition, they were compared in two energetically equivalent tests with regular and random waves, respectively. Although ripples under random waves had a larger wavelength and height than ripples under regular waves, the celerity of migration was comparable. Our results showed that the sandbars modified the equilibrium geometry of ripples. Furthermore, because of roughness, streaming was induced by the highest and longest ripples in the sandbar crests.

The spatial modulation of the ripple celerity was found to be related to the local Lagrangian mass transport velocity, which was produced by the quasi-standing wave inside the bottom boundary layer at the grain-diameter scale.

1. Introduction

Surface waves and currents in shallow water interact with the bottom and induce bedforms of various shapes and characteristics. This occurs both in the laboratory as well as in natural settings. Knowledge of bottom processes in the presence or absence of these natural structures is fundamental for the quantification of sediment transport rate and for the computation of wave energy dissipation. Of these bedforms, ripples and sandbars occur in the nearshore region, which is roughly limited offshore by the bar where incoming waves generally break. Such bedforms can be classified as follows: (i) ripples of wavelength $\lambda \approx O(10^{-1})$ m (roughly the fluid particle semi-excursion near the bottom); (ii) dunes and antidunes of wavelength $\lambda \approx O(10^{0})$ m; (iii) bars of wavelength $\lambda \approx O(10)$ m; and (iv) sandbars of wavelength $\lambda \approx O(10^{2})$ m (the approximate wavelength of the free surface waves).

The fluid-particle interaction processes that generate these geomorphological structures have been widely studied, as reflected in the variety of the theoretical approaches, laboratory experiments, and field

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measurements. Early research on ripple marks under oscillatory flow was performed by Hunt [1], followed by Darwin [2] and Ayrton [3]. The pioneering work of Bagnold [4,5] focused on the processes governing ripple generation, based on experimental results obtained in an oscillating wave tank. He detected a critical velocity of the fluid near the bottom, at which the grains start to move. Under stationary conditions, when sediment is in motion but not lifted, a stable pattern of bedforms develops, with steepness (height to length ratio) <0.10. These are known as "rolling-grain ripples". Such ripples are stable for speeds up to twice the previously mentioned velocity. As steepness increases, a vortex develops, which moves the sediments up to the crest and eventually traps the smallest grains. This modifies the scenario and creates a new type of bedform called "vortex-ripples", which spread out quickly and eliminate the rolling-grain ripples (Sleath [6]).

The sediment motion threshold has been studied by various authors, such as Bagnold [4] and Komar and Miller [7] (see Losada and Desiré [8] for a comprehensive list). Komar and Miller [7] specified two thresholds: (i) a sediment motion threshold for a laminar boundary layer (applicable to very small grains with $d < 0.05$ cm); (ii) a sediment motion threshold for a turbulent boundary layer (applicable to larger grains). In both cases the threshold depends on the maximum fluid velocity and the orbital diameter near the bottom. Losada and Desiré [8] and Losada et al. [9] proposed a general equation for incipient sediment motion by including the Reynolds number and extending the analysis to turbulent regime.

Wiberg and Harris [10] related the orbital velocity amplitude and the mean sediment grain size to the ripple type. The ripples observed were thus classified in three types: (1) orbital ripples (wavelength proportional to near-bed wave orbital diameter, $2A$), with $2A/d_{50} < 2000$; (2) anorbital ripples (wavelength practically independent of the near-bed wave orbital diameter), for values $2A/d_{50} > 5000$; (3) sub-orbital (with the possibility of both orbital and anorbital scalings), with $2000 < 2A/d_{50} < 5000$.

Most theoretical studies on geomorphological evolution assume that a horizontal bed of non-cohesive fine sands perturbed by a monochromatic flow motion is in the generalized motion state, and sediment transport modifies the bed sediments according to the Exner equation. The first of these studies was performed by Kennedy [11], whose description of the evolution of bedform amplitude assumed a potential flow in shallow water. He characterized the bottom patterns on the basis of the Froude number as well as on the local shift between sediment transport and fluid velocity. Although this local shift is known to play a key role, most models of bed evolution do not include its effect. Near the bottom, a boundary layer (BBL) develops, limited by the interface with the sediments bed, where the no-slip condition is applied, and by the external region. The BBL has certain particularities stemming from the flux regime and bed roughness. Generally speaking, the irrotationality of the flow field is not applicable. This question was addressed by Vittori and Blondeaux [12], who developed a perturbation model based on the stream function as influenced by the wave-driven currents. Their research related the grain Froude number to the Reynolds BBL number and the nature of ripples. However, they dealt with weak non-linear effects, which in real contexts are relevant. Certain hypotheses of the model are usually not satisfied. These include the assertion that sediment grain size is much smaller than the thickness of the viscous boundary layer, and that ripple amplitude is smaller than viscous BBL thickness. This signifies that non-linear terms become progressively more important in the vorticity equation.

There is a large body of literature that focuses on the experimental analysis of bedforms because of the complexity of the analytical approach. Some of those studies found semi-empirical relations between bed features, sediment flux in various conditions, and the geometric shape of the bottom in stationary conditions. Laboratory flume experiments were performed in which the bottom was allowed to evolve until a stationary state was reached. The resulting equilibrium bedforms were then measured and analyzed.

Nielsen [13] analyzed data obtained in various experiments with regular and random waves (Manohar [14], Mogridge and Kamphuis [15], Dingler and Inman [16], Nielsen [17], Allen [18]). He formulated an equation for ripple wavelength and height in the laboratory, depending on the Shields parameter, with empirical coefficients. After analyzing the experimental data in Inman [19] and Dingler [20], he extended the analysis to field ripples and formulated a similar equation for predicting ripples in the field and under turbulent oscillatory boundary layers (Nielsen [21]).

Other studies analyzed bedform shape, forced by different wave types. For this purpose, the researchers measured the migration velocity, transition stages, and relict shape of the bedforms. Faraci and Foti [22] performed a comprehensive experimental analysis of the evolution of ripple characteristics under progressive regular and random waves on a horizontal bed. They observed a ripple migration velocity of up to ≈40 cm h^{-1}. Smith and Sleath [23] carried out a spectral analysis of the bottom profile with a view to studying the response time of the ripple-covered bed to a step change in the flux conditions (mainly a variation of the near-bottom amplitude of oscillation). Two growth mechanisms were observed for the new bed profile: in the first case, the new profile arose from a previously existing perturbation of the bed at the same wavenumber as that of the final bed; in the second case, the ripple wavelength gradually changed to adjust to the new conditions. In certain conditions both mechanisms were active. Doucette and O'Donoghue [24] performed laboratory experiments to analyze the influence of wave randomness on the temporal evolution of ripples.

Bed slope effects are considered quite relevant since ripples in a natural environment almost invariably occur on a sloping bed (Chang et al. [25]). The bed inclination affects the sediment transport rate and modifies the dynamics of the ripples (see, e.g., Damgaard et al. [26] and Messaros and Bruno [27]). For this reason, the experiments in our study include tests with a sloping bed, which shall be discussed in a forthcoming paper.

All these studies refer to bedforms outside of the breaking zone (so as to avoid the huge sediment transport effect associated with breakers), and where reflection is not important.

Field analyses and large-scale experiments are extremely rare (see Doucette and O'Donoghue [28] for a review). Nonetheless, Traykovski et al. [29] and Traykovski [30] obtained field measurements with a rotational sonar and used these data to analyze bed evolution in the spectral domain. Messaros and Bruno [27] carried out experiments in a large wave tank and found that ripple characteristics in presence of irregular waves in the laboratory are similar to ripples characteristics in the field. They also found a statistically insignificant difference between ripple steepness on a horizontal surface and on a sloped surface.

An important factor that must be included in the evaluation of experimental results is that the bed formation process and evolution under oscillatory flow is the long-term balance of offshore and onshore sediment transport. Although both terms can have relatively high values, the difference between them is usually quite small. This means that it takes a very long time to reach the equilibrium condition, or for ripples and other bedforms to be in balance with the forcing wave field. Furthermore, small variations in the forcing wave field can change the sign of the net sediment transport, and may eventually modify the sign of the velocity migration or the tendency of ripple height and wavelength to grow or to decay. The consequences of a very long time scale of bedform evolution and of the high sensitivity of the system are the following: (i) bedforms in the field cannot be in equilibrium with the forcing wave (plus currents) field since this varies notoriously; (ii) bed load transport rates in both the field and laboratory fluctuate even if hydraulic conditions are steady. This can be attributed to several factors, including the migration of bedforms (Turowski [31]). As a result, in regard to bedforms, steady state is more a conceptual description without any clear experimental evidence.

All of these experiments and models depict an accurate scenario of bedform characteristics in a set of real conditions. However, in the