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Characterization of bedform morphology generated under combined flows and currents using wavelet analysis

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ABSTRACT

The wavelet transform (WT) has been successfully implemented in many fields such as signal and image processing, communication theory, optics, numerical analysis, and fluid mechanics. However, the application of WT to describe bedform morphology in coastal areas, oceans, and rivers is rare. The present study demonstrates the capability of WT analysis to fully represent the space–frequency characteristics of signals describing bed topography generated in marine and river environments. In this study WT is used to examine the morphological characteristics of bedforms generated in two separate laboratory facilities: a wave tank and a meandering channel. In the wave tank a set of ripples superimposed upon large wave ripples were generated; while in the meandering channel, 2D and 3D migrating ripples and dunes were observed. The WT proved to be a useful tool in detecting the complex variability of the generated bedform structures. The size distribution of the bottom features such as ripples, large wave ripples and sandbars were first examined along a 2D bed profile. Later analysis studied the variability of features in the transverse direction by using the power Hovmöller. Experiments in the wave tank were conducted for a mobility number of $\psi = (10, 28)$, and a Reynolds wave number of $R_{ew} = (17{,}500, 83{,}500)$ which correspond to waves alone (WA) and to combined flow (CF) scenarios, respectively. Experiments in the meandering channel were conducted under a morphological regime that produced mainly migrating sandbars.

1. Introduction

Morphological bed features, such as ripples, large wave ripples (LWRs), sandwaves (SWs), and sandbars, are commonly found in continental shelves and rivers. The term sandwave commonly denotes large bedforms found on continental shelves formed under the action of tidal currents (Komarova and Newell, 2000; Komarova and Hulscher, 2000; Knaapen and Hulscher, 2002; Morelissen et al., 2003). Large wave ripples are much smaller than SWs and have been identified in both laboratory and field studies (Hanes et al., 2001; Grasmeijer and Kleinhans, 2004; Williams et al., 2005). Ripples have been found in the field in isolation (Masselink et al., 2007). However, bedforms are usually observed in amalgamated form, i.e. ripples superimposed upon SWs, LWRs, mega-ripples and sandbars (Hanes et al., 2001; Grasmeijer and Kleinhans, 2004; Gallagher, 2003; Best, 2005). For the remainder of this paper we will focus on amalgamated bedforms.

Very large mega-ripples have been observed in the continental shelf and in the near shore (Li and Amos, 1999; Gallagher, 2003). Ripples vary in size and shape depending on their relative position with respect to the sandwave they are superimposed upon (García and Maza, 1984; Williams et al., 2005; Cataño-Lopera and García, 2006b). Jan and Lin (1998) and Landry et al. (2007) conducted experiments to study the superimposition of ripples upon sandbars under oblique standing waves, and under totally and partially stationary waves, respectively. Landry et al. (2007) found that sorting of sediments also plays an important role in the sandbar formation. Landry et al. (2007) showed that bar crests (located beneath surface wave nodes) were composed of coarser sand while flat plateaus (located beneath surface wave antinodes) were characterized by finer sands. Similar findings based upon field observations of low-energy sandy beaches generated under long period waves were also reported by Doucette (2002). Observations of small scale ripples superimposed upon sand dunes were described by Venditti et al. (2005).

The study of ripples and larger bedforms are of both scientific and engineering interest, as recognized by Yu and Mei (2000a, b), Williams et al. (2005), Németh et al. (2002, 2006), Morelissen et al. (2003), and Knaapen and Hulscher (2002). The form resistance due to bedforms caused by local flow separation and recirculation can be significant and is dependent on their

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Nomenclature

a	wavelet scale
a_j	set of scales
a_m	amplitude of the orbital motion of the water particles at the bed
B_c	channel width of the meandering flume
C_δ	empirical constant
d_{50}	median sediment size
f_w	wave friction coefficient
g	acceleration due to gravity
h	mean water depth
h_{LWR}	sandwave height
h_r	ripple height
H_c	water depth in the meandering flume
H_w	wave height
j_1, j_2	lower and upper scales to be analyzed
J	index that determines the largest scale used in the wavelet transform
l_r	sandwave length
L_{LWR}	sandwave length
L_w	wavelength
n	localized space index
Q_w	flow discharge
R	reflection coefficient
R_{ew}	Reynolds wave number
s_o	smallest resolvable scale in the wavelet transform
S_{bed}	bed slope
t	time
T	water temperature
T_w	wave period
U	mean current velocity
U_m	maximum orbital velocity at bed level
U_r	Ursell number
U_w	wave velocity
U_{wc}	wave-current velocity
U_*	shear velocity
x	longitudinal spatial coordinate
x_n	discrete sequence
y	transversal spatial coordinate
z	vertical spatial coordinate
α	correlation coefficient associated to a red noise process
β	angle of interaction between the current and the waves
γ_s	specific gravity of sand
δj	scale interval
δx	space interval
ΔT	window duration in the WFT
η	dummy variable
θ	Shields shear stress
ϕ	internal angle of repose of sand
k	frequency index
k_b	equivalent roughness height
λ_p	porosity of sand
ν	water kinematic viscosity
σ^2	signal variance
φ	mother wavelet function
ψ	mobility number
ω_k	angular frequency defined in the wavelet analysis
ω_o	nondimensional frequency

dimensions, as well as, flow and sediment characteristics (Karim, 1999). Ripple size and geometry play an important role in bottom friction distribution, bottom boundary layer flow, wave attenuation, sediment transport, sediment stratification, and other phenomena in riverine and marine environments. For these reasons, many theoretical, laboratory and field investigations of bedforms generated by the interaction of oscillatory flows and movable beds have been conducted in the past several decades (Miller and Komar, 1980a, b; Grant and Madsen, 1982; Foti and Blondeaux, 1995; Li and Davies, 1996; Li and Amos, 1998; Karim, 1999; Blondeaux et al., 2000; O'Donoghue et al., 2006).

Sandwaves and sandbars may represent a hazard to pipelines (Morelissen et al., 2003). The directional shift of these bed features can have a significant impact on pipelines as well as navigational channels, cables, and windmill turbines. Depending on the scale of their dimensions and migration rates, bedforms have the potential to decrease navigable depths thus making frequent dredging activities necessary (Besio et al., 2008).

Prediction of bedform geometry is an essential component for estimating flow resistance and water levels during floods in rivers (Karim, 1999). The importance of bedform study is demonstrated, for example, by the case of a subterranean tunnel built in the Paraná River (Argentina) in 1968. The sand layer thickness above the tunnel was not adequate to stand high flows. Over time, large dunes migrated exposing the tunnel and threatening its structural stability (Amsler and García, 1997; García, 2008).

Most theoretical and numerical models developed thus far are in the early stages of development and their predictive capabilities are limited. For the case of sandwaves formed under tidal influence, several models have been proposed including those by Komarova and Newell (2000), Gerkema (2000), Komarova and Hulscher (2000), Németh et al. (2002, 2006), and Morelissen et al. (2003). For sandbars observed in coastal areas, models by Yu and Mei (2000a, b) and Hancock et al. (2007) have been proposed. Giri and Shimizu (2006) developed a numerical model dealing with the migration of sand dunes in rivers. Extensive reviews of recent model developments and experimental and theoretical advances in river dune study are found in Besio et al. (2008) and Best (2005), respectively. Most of these models are based upon the assumption that nonlinear effects are weak, which is often not the case in nature. It is also worth noting that currently all models developed for ocean-like or river-like flow conditions are not able to reproduce the coexistence of smaller scale ripples formed upon the larger scale features. Thus, further research on the interaction of multiple size bedforms and how this interaction defines the dominant bedform modes observed in both coastal and river systems is needed.

In cases of ocean-like flows, the typical dimensions of bedforms created in laboratory flumes are approximately 2 cm in height and 5–30 cm in length for ripples and tens of centimeters in height and several meters in length for LWR (García and Maza, 1984; Williams et al., 2005; Cataño-Lopera and García, 2006a, b). Typical sandwaves observed in the field are several meters high and hundreds of meters long (Morelissen et al., 2003; Komarova and Newell, 2000; Németh et al., 2002, 2006, 2007). Field investigations describing the hydrodynamics over sandwaves through velocity measurements in the coastal shelf can be found in Perillo and Ludwick (1984) and Li and Amos (1999). Using state of the art acoustic equipment, Goff et al. (1999) reported detailed bathymetry of offshore environments.

In the case of river-like flows, the typical dimensions of bedforms in laboratory experiments are tens of centimeters in