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A bedload transport equation for the *Cerastoderma edule* cockle

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ABSTRACT

Hydrodynamics play an important role in the structure of many marine ecosystems of bivalves. After severe storm periods, large amounts of the *Cerastoderma edule* stocks were transported from the Lombos do Ulla shellfish bed (Spain). This paper presents the results of laboratory experiments carried out to analyze the bedload transport of this bivalve emulating the stormy shellfish bed conditions. Flow velocities were measured using particle image velocimetry and the double averaged methodology was applied to determine the main flow characteristics over different cockle patches. The flow structure exhibits properties of skimming and isolated flows depending on the density of bivalves. Bed shear stress was determined from the log-law and the cockles were geometrically characterized in order to derive specific bedload transport equations in a conventional deterministic sediment transport framework. The obtained formulas can be implemented in common numerical codes to further analyze mollusk stability, bedload transport and dispersal in their aquatic systems.

1. Introduction

In the last years ecological researchers and hydraulic engineers have focused their work on the emerging ecological research of aquatic systems, paying attention to the interaction between hydraulics and organisms (i.e. Butman, 1987; Friedrichs and Graf, 2009; Hoover and Ackerman, 2004; Nikora, 2010). Hydrodynamics play an important role in the structure of many marine ecosystems of bivalves. The dispersal of the organisms in both larvae and benthic life stages affects their distribution patterns and abundance.

The bivalves post-settlement dispersal can be influenced by behavioral and by physical processes. Some organisms are able to actively favor their dispersal during their first larval and juvenile stages by generating byssus threads that increase drag and cause their resuspension into the water column (Sidgursson et al., 1976). Bivalves may also be involuntarily or passively mobilized by currents or when the sediments they live in become eroded. In subtidal systems, tidal and wave induced currents are the main hydrodynamic forcing mechanisms. In these environments, saltation and roll bedload transport, are the main mode of dispersal for many marine benthic invertebrates, both in juvenile (Huxham and Richards, 2003) and post-juvenile stages (Hunt et al., 2007).

Several field and flume studies have been developed to analyze the bedload transport of soft sediment marine organisms. Field studies show evidences of sediment transport interaction with the mobilization of bottom dwelling marine organisms (Butman, 1987; Commito et al., 1995; Hunt et al., 2007; Valanko et al., 2010). At laboratory scale most of the works have been performed with larvae and juvenile organisms, and only a few have analyzed large (>15 mm) bivalve dispersal (e.g. Redjah et al., 2010; St-Onge and Miron, 2007).

In this study we have conducted a series of flume tests emulating stormy hydrodynamic conditions at the Lombos do Ulla shellfish bed (Spain). In the last years several mortality events of the *Cerastoderma edule* cockle have been recorded at the Ulla river mouth. Parada et al. (2007) link these events with short zero salinity periods recorded after some several flooding episodes. Furthermore, after March–April of 2003 and 2007 rainy periods, large amounts of mollusk stocks were swept from the shallow to the deeper area of shellfish bed.

Hence, the main objective of this article is to derive a specific cockle bedload transport formulation valid during the high flow events recorded at the Lombos do Ulla shellfish bed. Preliminary works on the onset of motion of isolated cockles of this estuary have been developed by the authors (Peña et al., 2008). Furthermore, in Anta (2010) we have analyzed the main factors influencing the erosion ratios of *C. edule* cockle patches with different size distributions, densities and cockle activities. The specific contribution of the present paper consists in the derivation of specific bedload transport equations for large cockles. In order to obtain these formulas, a conventional sediment transport framework has been applied to the series of flume experiments.

Abbreviations: PIV, particle image velocimetry; RMS, root mean square; DA, double average; CITEEC, Centre of Technological Innovation of Edification and Civil Engineering.

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2. Materials and methods

2.1. Study area

The Lombos do Ulla shellfish bed is placed in the Ulla River mouth (Galicia, Spain). It is a commercial shellfish bed of about 1135 ha, characterized by sandy bedforms covering almost the entire surface of the fishery. The dune area is the main productive zone of the Lombos do Ulla. The deeper area of the shellfish bed consists of a muddy formation, with depths ranging from 2 to 4 m below the mean sea level (Sánchez-Mata et al., 2006).

This shallow bed is mainly a subtidal environment with an average tidal amplitude of 3.6 m, in which tidal currents, short windy waves and fluvial regime dominate the hydrodynamics of the area. During the flooding events, flow discharge can rise from 30 m^3/s to 100–200 m^3/s. A more complete fishery description can be found for instance in Parada et al. (2006).

2.2. Bedload transport of marine bivalves

Different approaches can be taken to estimate the erosion and drag of marine bivalves. For instance, the knowledge gained from the analysis of partial or whole bodies exposed to a current may be used to determine the mollusks' onset of motion. Within this framework, the drag forces acting on the particles or individuals can be estimated using a quadratic velocity parametrization (Peña et al., 2008). This methodology has been widely used in the study of cohesive bed 'corrasion' or the increment of erosion due to the impact of articulated or disarticulated cockle shells (Amos et al., 1998; Ciutat et al., 2007; Quaresma et al., 2007).

In this paper, the cockle bedload transport is estimated by means of the stability and mobility parameters used in previous deterministic sediment transport works (i.e. Paintal, 1971). First, the well-known Shields stability parameter (θ) is defined as:

$$\theta = \tau_b/(\rho_s - \rho) g d_n \tag{1}$$

where τ_b is the bed shear stress, ρ_s and ρ are the particle and fluid density, g is the gravitational acceleration and d_n is the particle nominal diameter. According to this threshold stability concept, particles are eroded when θ exceeds a critical shear stress θ_{crit}. For uniform sediments in hydraulic rough flows θ_{crit} holds 0.056, although it presents a wide range of variation (Buffington and Montgomery, 1997).

This methodology has been previously applied to determine the threshold conditions of juvenile clams and marine worms — polychaete (Hunt, 2004; Olivier and Retière, 2006). Nevertheless, predicted values for threshold conditions did not match with experimental observations due to the empirical nature of the Shields diagram and the uncertainties in the definition and measurement of a characteristic diameter for non-spherical organisms' shape, such as bivalves or marine worms. This allows different interpretations of threshold parameters using different length scales (Paphitis et al., 2002). Furthermore, the entrainment processes can also be affected by the shape factor of the particle (Gögüs and Defne, 2005).

To determine cockle erosion, a transport function concept has been applied. Most of the bedload equations, such as Einstein–Brown or Meyer-Peter and Muller equation, define a functional relationship between the mobility or transport parameter Φ, and the Shields stability parameter θ (Graf and Altinakar, 1998):

$$\Phi = f(\theta). \tag{2}$$

In the previous equation θ quantifies the flow forces acting on the bed and Φ is used to evaluate the bed response. For practical purposes this relation can be expressed in the form of a power law (Cheng, 2002):

$$\Phi = a\theta^b \tag{3}$$

where a and b are empirical coefficients.

Lastly, the transport function has been defined using the bedload transport $q_s = (n d_n^3)/(Bt)$. The bedload transport q_s is proportional to the volume of the amount of particles (n) transported through a cross-section of width B per time t. The dimensionless bedload transport Φ is then defined as:

$$\Phi = q_s/\sqrt{\Delta g d_n^3} \tag{4}$$

where $\Delta = (\rho_s - \rho)/\rho$ is the relative submerged density of the particles.

2.3. Experimental facilities

The experiments were undertaken in a custom-made racetrack flume at the Centre of Technology Innovation of Edification and Civil Engineering—CITEEC at the University of A Coruña. The flow is conducted by the friction of 10 rotating disks (PVC, 66 cm diameter) connected to a variable-speed 134 W motor. The flume is 50 cm wide and was filled with filtered seawater (salinity = 35 ppt) to a depth of 15 cm at room temperature (18.3 ± 0.5 °C). The experimental section was placed in the straightway section of the racetrack, as shown in Fig. 1. In order to minimize bend-flow effects a series of parallel walls was installed along the semicircular sections.

In racetrack flumes centrifugal forces due to the curved channel may induce secondary currents which contribute to create cross-channel variations in flow velocities and shear stresses. Experimental works on racetrack flumes found lateral variations in the mean velocities and shear stresses of about 10% of the average cross-sectional values in 70–80% of the central part of the flume (Black and Cramp, 1995; Piedra-Cueva et al., 1997; Redjah et al., 2010). We have conducted a numerical simulation of the flume used in the experiments, finding

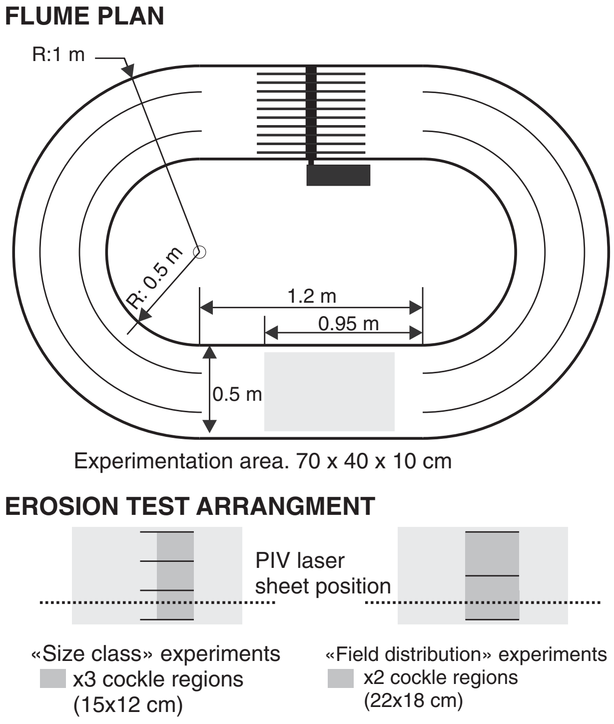

Fig. 1. Schematic plan of the racetrack flume.