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Run-up flow of a collapsing bore over a beach

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ABSTRACT

The collapse of a 2D bore propagating shoreward on a sloping beach and the subsequent run-up from the shoreline and run-down are simulated using a Reynolds Averaged Navier–Stokes (RANS) model based on a Volume of Fluid (VOF) method. The results are compared with experimental results. The bore collapse phenomenon is first studied and the transition between bore collapse and run-up is characterized. Numerical results indicate that the bore collapse phenomenon is not completed at the shoreline. The transition is further upslope and the energy at the transition includes a significant part of potential energy unlike that predicted by the classical theory of Whitham. The swash flow is investigated, showing the dissymmetry between run-up and run-down. Taking into account the modeling of turbulence slightly reduces the run-up height and allows recovering the value experimentally recorded. The bottom shear stress variations were computed from the results of numerical simulations. The maximum bottom shear stress is at any time found in the vicinity of the bore head. It is maximum at the transition between bore collapse and run-up flow and decreases while the run-up flow climbs on the beach.

1. Introduction

The surf and swash zones of coastal waters are the subject of numerous investigations because most sea/terrestrial interactions occur in these areas. Coastal morphodynamics changes result from hydrodynamics of waves and currents which transport sediment within the surf and swash zones. Wave breaking in the surf zone is especially important as a mechanism enhancing sediment suspension. The swash zone, which is the area on beaches alternatively discovered and covered by waves breaking at the shore, has been the subject of many studies. Masselink and Puleo [1] report in a recent review: "it is now established that transport rates in the swash zone are much higher than in the surf zone". When a beach is submitted to high tidal range variations, the sediment transport in the swash zone can contribute over a tidal period to beach changes extending over a large distance in the cross shore direction.

The present paper deals with the numerical simulation of the swash flow produced by a bore collapsing on the beach. The model solves the 2D Reynolds Averaged Navier–Stokes equations (RANS) using a Volume Of Fluid (VOF) approach to obtain the flows in water and air. The bore is produced by a dam-break condition and the 2D bore propagates on a sloping beach in a direction perpendicular to the coastline. The simulations were performed to reproduce the laboratory configuration of Yeh et al. [2]. The bore experiment is a simple initial condition to implement in numerical models and it shares common features with breaking waves propagating perpendicular to the shoreline [3]; like in the latter case a bore collapse is observed and a swash flow is also produced at the shoreline. The bore propagation on a sloping beach has been studied theoretically and experimentally by many authors for a long time. The early theories determined from the initial dam break condition the properties of the bore propagating over a water layer of constant depth (see [4]). Whitham [5] published a pioneering theory which describes the collapse of the bore at the shoreline. It is based on the depth-averaged shallow water equations and the bore is schematized as a water level discontinuity obeying the dynamic relation of a hydraulic jump. Fluid particles at the shoreline gain a finite non zero kinetic energy when the bore collapses at the shoreline. This initiates a run-up and run-down flow on the sloping beach which was subsequently described theoretically by Ho and Meyer [6] and Shen and Meyer [7,8], predicting the height and length of run-up from the conversion of kinetic energy into potential energy. To date, the aforementioned works remain the reference theories serving for the interpretation of laboratory and numerical simulation results. To our knowledge, Svendsen and Madsen [9] were the first to simulate numerically the evolution of a bore on a sloping beach using a RANS modeling with a k–ε turbulence closure. They investigated the evolution of turbulence properties but the bore collapse and the swash

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flow were not studied. Recently Zhang and Liu [10] published the results of numerical simulations which are in many points directly comparable to the results presented in the present paper. The case study considered by Zhang and Liu is also the laboratory experiment of Yeh et al. [2]. The COBRAS model used by Zhang and Liu is a 2D RANS solver with a k–ε turbulence closure using a VOF method which is comparable to the THETIS model used for the present study. The differences rely on the method of determination of the air–water interface, on the specific turbulence closure used, and on the fact that COBRAS does not solve the air motion. The two models were developed for similar applications (free surface flows, breaking waves, interactions of flows with porous media etc.). The capacity of COBRAS to simulate breaking waves in the surf zone and swash flows was demonstrated by Lin and Liu [11] and Lin et al. [12], among numerous publications of this group presenting results obtained with COBRAS. On their side Lubin et al. [13] demonstrated the capacity of THETIS to carry out 3D large eddy simulations of plunging breaking waves describing the air entrainment produced.

A comparison of results from our simulations with those obtained by Zhang and Liu [10] is included in the present paper and we propose a conclusion about the properties of RANS and VOF modeling for the simulation of swash flows. Additional flow features, which were not analyzed in detail by Zhang and Liu, are investigated in the present paper. We first discuss the bore collapse phenomenon. According to Whitham's theory, the phenomenon occurs at the shoreline. However, the laboratory experiment of Yeh et al. [2] and numerical simulation show significant discrepancies with this theory which we analyze in more detail. Second, the bottom shear stresses applied along the bed were computed from the results of our simulations. Unfortunately, Yeh et al. [2] provide no data on bottom shear stress values in the laboratory. In consideration of its role in sediment transport, the results on bottom shear stresses are presented and discussed in relationship with the modeling of turbulence.

It is really questionable whether the Yeh et al. [2] experiment is today the best experimental test case for comparison with numerical results. More complete sets of data have been made recently available, as for example by O'Donoghue et al. [14]. This does not diminish the importance of the Yeh et al. experiment, which has been very useful for comparisons between numerous studies, as we again do.

This paper reports on the results of a doctoral thesis and complementary information is given by Mauriet [15]. The following is divided into 7 sections. A summary of analytical theories is first given in Section 2 in order to prepare the discussion of the phenomenon of bore collapse at the shoreline. Sections 3 and 4 then contain the description of the test case and of the numerical models, respectively. The implementation of numerical simulations and the procedure of analysis of results are then described in Section 5. Section 6 analyzes the results of numerical simulations with a focus on the phenomenon of bore collapse in order to describe the transition to swash flow. The results concerning the bed shear stress evolution during run-up and run-down are finally presented in Section 7 before a general discussion in Section 8.

2. Analytical theories

The hydrodynamics of turbulent bores has been investigated for a long time. The conditions of a dam-break problem are depicted in Fig. 1, with h_1 the water depth in the reservoir and h_0 the water depth in the downstream side of the flume. When the gate separating the two compartments is removed, the water in the reservoir is released forming a bore propagating with velocity U_0 over the lower layer. Introducing the Froude number, the water depth h_m below the bore head and the propagation speed U_0 are related by the usual hydraulic jump formula

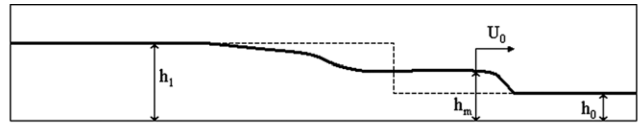

Fig. 1. Propagation of a bore generated by a dam-break: definitions. The dashed line is the initial water level surface. The solid line schematizes the air/water interface some time later, with U_0 the celerity of the bore head.

Table 1
Dam-break conditions (h_1, h_0) considered in this study and corresponding theoretical (Eqs. (1) and (2)) bore properties (h_m, F_0) for a bore propagating over a layer of constant depth h_0. U_* is the speed of the bore at the shoreline predicted by Whitham [5].

h_0 (cm)	h_1 (cm)	h_m (cm)	F_0	U_* (m/s)
9.75	19.9	14.3	1.35	2.19
9.75	22.5	15.4	1.43	2.42
9.75	26.0	16.8	1.53	2.70

$$F_0^2 = \frac{U_0^2}{gh_0} = \frac{1}{2}\frac{h_m}{h_0}\left(\frac{h_m}{h_0}+1\right). \tag{1}$$

The water depth h_m at the bore head is determined from the initial condition using the dam-break solution as given by Stoker [4, Section 10.8]

$$\sqrt{h_1} = \sqrt{h_m} + (h_m - h_0)\sqrt{\frac{h_m + h_0}{8h_m h_0}}. \tag{2}$$

The bore propagation is modified when the depth h_0 in front of the bore is no longer uniform but decreases linearly as happens on a sloping beach. The pioneering analytical study by Whitham [5], based on the shallow water equations and schematizing the bore as a water level jump, concluded that the bore collapses at the shoreline. More precisely, the theory shows that $h_m \to 0$ when $h_0 \to 0$ at the shore line, while the propagation speed of the bore and the velocity of fluid particles below the bore head tends to a finite value U_*. The theoretical values of the Froude number F_0, the water depth below the head h_m for a bore propagating over a layer of constant depth h_0, and the propagation speed U_* of the bore at the shoreline are given in Table 1 for the different dam-break conditions (h_1, h_0) considered in this paper.

When the bore collapses, the kinetic energy of fluid particles is not zero at the shoreline and this initiates the swash flow which runs up and down on the sloping beach. Shen and Meyer [8] determined theoretically that the maximum height of run-up H_{runup} from the shoreline level is simply given by the conversion of the initial kinetic energy $\rho U_*^2/2$ into potential energy, i.e.

$$H_{\text{runup}} = \frac{U_*^2}{2g}, \tag{3}$$

with g the acceleration of gravity. For a beach with slope β from the horizontal, the run-up length in the horizontal direction is $X_{\text{runup}} = U_*^2/(2g.tg\beta)$. This length scale is used for presenting in dimensionless form the variations in the horizontal direction.

The theories summarized above serve for analyzing results on bores propagating over a sloping bottom, although the laboratory experiments of Yeh et al. [2] provided the clear indication of a disagreement. Fig. 5 of their paper shows that the water level at the bore head remains almost constant in the vicinity of the shore line, having an altitude above the quiescent water level which is of the order of magnitude of the initial water depth h_0. This is not a minor difference and this motivated the focus made in the present paper on the analysis of the bore collapse phenomenon at the shoreline and the distinction between collapse and swash flow.