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An assessment of the roller approach for wave breaking in a hybrid finite-volume finite-difference Boussinesq-type model for the surf-zone

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ABSTRACT

This paper investigates the application of the roller approach for breaking waves in a 1D hybrid finite-volume finite-difference weakly-nonlinear Boussinesq-type model. The vorticity transport equation is employed to model the movement of vorticity through the fluid. This allows vertical profiles of horizontal velocity and undertow to be computed. Previous implementations of this method caused numerical dissipation that influenced the physical behaviour of the breaking process. The use of a hybrid scheme overcomes this issue as the need to filter flow variables in the surf-zone is removed. Greater numerical stability increases the flexibility of the calibration parameters, allowing finer control over the breaking process and a more detailed investigation of the underlying physics. The mechanism used to dissipate energy during breaking is derived from physical principles and the Boussinesq equations are retained throughout the breaking procedure, providing a realistic description of the hydrodynamics throughout the surf-zone. The dissipative performance of the proposed model is discussed and compared with other state-of-the-art approaches, proving the feasibility and value of using a rotational roller model with a finite-volume finite-difference scheme to model surf-zone hydrodynamics with a Boussinesq-type model. Tests involving waves breaking on a sloping beach are performed to validate against results from physical experiments, demonstrating the model to be capable of accurately resolving profiles of the free surface, velocity and undertow. The resulting new model overcomes many of the issues encountered by previous Boussinesq solvers based on the same approach and provides significant improvements in the accuracy of predictions of breaking wave processes. The proposed approach is very flexible and can be used in any hybrid finite-volume finite-difference weakly-nonlinear Boussinesq-type model.

1. Introduction

Flow dynamics in the surf-zone play an important role in coastal engineering and, due to the complex physics describing the processes occurring in this region, receive much interest from the research community. This area of study has been increasingly served by computational fluid dynamics, with a growing number of mathematical models developed to suit an algorithmic solution.

In recent years, there have been many advances in the use of Boussinesq-type equations (BTEs) [1]. These allow a reasonable level of computational efficiency to be obtained while replicating numerous physical phenomena. BTEs have provided an efficient means to model a large region of interest with a single approach [2,3].

The introduction of wave breaking in Boussinesq-type models (BTMs) was crucial for their application to nearshore simulations. The derivation of BTEs often involves the assumption of potential flow, which neglects dissipation due to breaking. Further treatment must therefore be considered to compensate for this inadequacy. Numerous procedures have been employed for this purpose, each possessing different advantages and limitations [4]. One widely used example is the eddy viscosity approach proposed by Zelt [5] and Kennedy et al. [6]. This method relies on the introduction of an additional term in the momentum equation, and was extended by Cienfuegos et al. [7] to also include a modification to the continuity equation. This approach is also used in more recent works such as that of Klonaris et al. [8].

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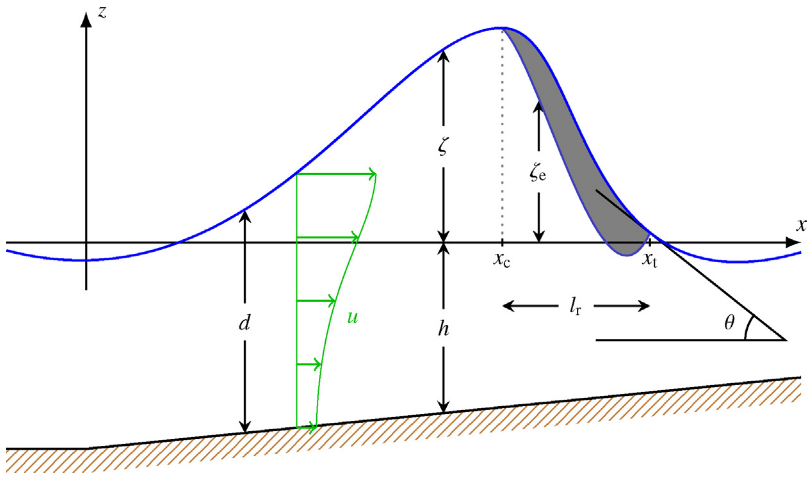

Fig. 1. Description of reference system, equation variables and roller geometry. A two phase flow is considered in the roller region (●), while the remainder of the flow is considered to be single phase.

The definition of a 'roller' region commonly forms the basis of schemes looking to artificially replicate breaking within a numerical system [9–11]. Several techniques have been explored using this method, each proposing a different way of representing the dissipation of energy due to rotational flow in this area.

The assumption of rotational flow is used by Veeramony and Svendsen [12], enabling the vorticity to be described in terms of a scalar stream-function. The resulting BTEs incorporate energy dissipation terms that are computed by solving the vorticity transport equations with the knowledge of an artificially injected vorticity. A benefit of this approach is the possibility of computing the undertow current, which allows sediment transport processes to be modelled. A simplified approach to include vorticity in the flow is proposed by Lynett [13]. More recent attempts to improve the description of rotation within the flow include that of Son and Lynett [14], where additional stress terms were introduced, and Panda et al. [15], where an alternative numerical solver was adopted. A polynomial expansion was used by Zhang et al. [16] to circumvent the irrotational assumption; this was tested on the surf-zone by Zhang et al. [17]. This study concluded that a more comprehensive turbulence model was required to accurately reproduce the physics in this region.

The approach of Veeramony and Svendsen [12] was developed using a framework of a finite-difference (FD) scheme to solve the BTEs, and encountered limitations in modelling breaking waves due to the onset of numerical instabilities. These required intensive numerical filtering and were further mitigated by the use of complex self adaptive grids [18,19]. The complexity of the numerical treatment in the aforementioned works limited the use of the approach of Veeramony and Svendsen [12] in the modelling community.

In the last decade, finite-volume (FV) schemes have become the standard in surf-zone modelling with BTMs, overcoming many instability issues present in FD schemes. FV schemes possess good shock capturing capabilities, which are well suited to modelling bore-like propagation and wave breaking. Employing a hybrid finite-volume finite-difference (FV–FD) scheme for BTMs allows the stability and flexibility of respective approaches to be exploited. An example of the use of this approach to model wave breaking is given by Tonelli and Petti [20]. Based on the consideration that dispersive terms become progressively less important than nonlinear terms as the wave approaches breaking, a switch from BTEs to nonlinear shallow water equations (NSWEs) was performed at the computed breaking point. NSWEs intrinsically possess the ability to represent dissipation across a bore, making the simulation of breaking straightforward. This approach became popular and was used in other models such as that of Shi et al. [21]. Similar techniques have been adopted elsewhere with different criteria selected to determine initiation of breaking, such as the local free surface gradient used by Orszaghova et al. [22] and Tissier et al. [23], the local momentum gradient used by Roeber and Cheung [24], and the rate of change of free surface elevation used by McCabe et al. [25] and Smit et al. [26]. While straightforward, this method possesses two main drawbacks. Firstly, the free surface and the velocity field are not well described, and secondly, the bore formation prevents accurate modelling of wave reforming and breaking reinitiation. Instead, by replicating the energy dissipation introduced by wave breaking by using additional terms, a more physical representation can be developed. The assumption of irrotationality present in most BTMs requires that these terms represent dissipation due to the rotational flow dynamics of a breaking wave. It is anticipated that this more physical approach provides potential for assigning calibration parameters according to tangible quantities. In turn, this gives greater scope for tuning numerical models to a range of cases.

In the present study, the roller approach is also used in a FV–FD system with the intent of combining the robustness of the hybrid scheme with the description of the vorticity. The aim of this work is to assess the efficiency of the energy dissipation compared to other existing approaches. To this end, the vorticity formulation of the breaking terms is analysed together with two other formulations, namely the eddy viscosity approach of Cienfuegos et al. [7] and the intrinsic dissipation of the NSWEs employed by Tonelli and Petti [20]. This analysis also provides an opportunity to distinguish the physically based contribution of wave energy dissipation from the numerical one. The FV schemes discussed here rely on total variation diminishing (TVD) methods, which limit either fluxes or surface gradients and therefore act in a similar way to filters. To the best of the authors' knowledge, their role in surf-zone modelling has never been investigated in depth.

This paper is organised as follows: Section 2 outlines the equations used by the model and provides details of the roller approach and breaking formulation. The numerical scheme used to solve this system of equations is then presented in Section 3. The performance of the approach is assessed in Section 4 by comparing model predictions with alternative approaches and data from physical experiments, and analysing the dissipation provided by each breaking method. The modelling of the velocity and vorticity is presented in Section 4.3.1, and discussed in Section 5. Finally, the feasibility and relevance of the proposed approach is considered in Section 6.