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Numerical Simulation of Coastal Wave Processes with the Use of Smoothed Particle Hydrodynamics (SPH) Method

Doctoral Thesis Abstract

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ABSTRACT

The subject of the present doctoral dissertation is the effect of near-shore wave breaking of weak plunging form, transverse to a coast with impermeable bottom and a constant mild slope (1/20), and the consequent creation of several wave-induced coastal processes within the surf zone. The relevant research focuses on the configuration, implementation, and calibration of a modern numerical simulation model, in the framework of the relatively recent computational method Smoothed Particle Hydrodynamics (SPH) of Gingold, Lucy and Monaghan.

The primary objective is to track and analyze thoroughly the phenomenon of regular nonlinear waves breaking in the coastal zone, and the ultimate goal is the detailed mapping of the kinematic characteristics of the turbulent hydrodynamic field generated in the created surf zone. The studied waves have specific characteristics regarding the form of breaking, i.e. they are weak plungers. This type of wave breaking has been studied only little in comparison with the rest types of breaking (i.e. spilling and strong plunging), mainly in appropriate experimental laboratory devices, but not with the use of proper computational modelling methods. To this end, the numerical simulation method SPH is implemented. It is relatively new to the subject of hydrodynamic modelling of bounded turbulent flows with a free surface. It is a numerical approach based on particle-type spatial discretization and uses the concept of integral smoothing operators throughout the whole computational domain, the flow in which is described by the full Navier-Stokes equations with Lagrange formulation. The usage of the specific numerical method in the present thesis implies, that another key objective is the implementation and certification of the ability of SPH method to reproduce in detail the violent phenomenon of plunging wave breaking, regarding all classical wave features in the surf zone, the relevant strong deformations of the free surface, and the consequent more complex turbulent flow properties. In this effort, another main objective is to check also the possibility, of the model used, to simulate the wave-induced processes, such as the mean free surface elevation within the surf zone, the cross-shore currents (mean flows) etc.

The main request was that the applied mathematical model had to be an academic (rather than a commercial) computational package using an “open source” code (SPHysics), which has been constructed to simulate free-surface flows, for unrestrained use by researchers in the sense of “free software”. Additional main objectives of the present thesis are the study of the dynamics and the kinematics of the wave-induced

turbulent flow within the surf zone, and the validation of the related model in relation to the reproduction of coastal wave breaking, coherent turbulent structures and intermittent events in the surf zone. In this direction, a turbulence “closure” model is used, for the sub-particle scale (SPS) Reynolds stresses, similarly to the concept of sub-grid scale (SGS) stresses, with a Smagorinsky-type approach, as is the common practice in Large Eddy Simulations (LES) methods. The essential requirement of this task was to avoid using any empirical criterion and/or a mechanistic approach, firstly for the initiation and cessation of wave breaking, such as the “surface roller” model, secondly for the abrupt deformation of the free surface, and finally for the reproduction of the turbulent flow within the surf zone.

To achieve these goals, it was necessary to reproduce in detail and achieve the numerical mapping of the specific characteristics of the wave-induced turbulent flow, such as the recurring vortical patterns, the coherent turbulent structures, the Fourier spectra of the turbulent velocity fluctuations, the mapping of the turbulent kinetic energy and the Reynolds stresses fields, by combining different heuristic methods. Therefore, it can be said that the combination of all the above tasks and their reproduction with the implementation of a particle-type Computational Fluid Dynamics (CFD) model that tends to a LES approach, is attempted for the first time. The overall aim is to fill this gap in the research so far, regarding the computational simulation methods for coastal wave breaking in general, and specifically in relation to SPH. A secondary, yet important, goal is the analysis and classification of intermittent turbulent processes in the surf zone, and the identification of the mechanisms that invoke and arise as a result of coastal breaking waves, especially of the weak plunging type.

In this context, the problem is set as clearly as possible, and the reader is introduced to the phenomenon of coastal wave breaking and wave-induced turbulence processes. Specifically, the coherent and intermittent nature of turbulence for breaking waves is determined, and the most important wave-induced processes in the coastal zone are introduced. Moreover, an extensive literature review on the subject of coastal wave breaking is presented. Specifically, the basic analytical theory together with the corresponding relations for the classical models approach of the phenomenon are given, and subsequently the major research efforts of the past decades, involving both laboratory experiments and computer simulations, are cited. Based on the above, the contribution of the present research work is composed, targeting the shortages of the prior research endeavours and providing recommendations for their coverage.

In regard to the computational simulation method SPH, its short background is given together with the basic idea behind it, the fundamental relations and the numerical interpolation operators in SPH formulation are introduced, the full Navier-Stokes equations in Lagrange-type particle discretization are deduced, the properties of the particle smoothing approach in SPH are listed, the specific treatments of the numerical method (boundary conditions, artificial compressibility, time integration algorithms, etc.) are discussed, the inherent erroneous behavior (e.g. exaggerated dissipative structures) of the SPH method are detected, and the corresponding technical corrections used are presented. Additionally, the turbulence models for SPH method are analyzed, with specific focus on the Lagrangian approach of the eddy viscosity concept (Boussinesq hypothesis), and especially the model of a LES-type turbulence closure (SPS-SPH), by modelling the SPS stresses with Smagorinsky-type approach. The specific numerical tool for applying the SPH method is presented in detail, namely the academic "open source" code SPHysics. All the implemented numerical integration techniques are listed, together with the hints of computational functionality and the specific boundary and initial conditions for the problem of nonlinear regular wave breaking within a numerical wave flume for free-surface flows.

For the targeted application of the SPH method, the specific computational field and numerical configuration are described, based on the experimental setup, the results of which are used for comparisons with the numerical results. The specific characteristics of the numerical wave-maker are given, and a heuristic sampling method is introduced, using convolution integral interpolation for the conversion of the dispersed (particle-discretized) Lagrange-type data to a respective Eulerian form, on constant gauges throughout the whole computational domain. This is combined with an appropriate ensemble-averaging method, for turbulent hydrodynamic features specifically fitted for transitional and turbulent flows with free surface, against the implementation of a simple phase-averaging operator used in common practice, which is considered to be inadequate for the separation of ordered rotational motions due to the wave, from the large-scale coherent turbulent structures and the small-scale residual turbulence. Thorough analysis of the turbulent scales of the wave-induced flow is presented, proper methods for the calculation of them are proposed, and based on these, the final calibration cases of the SPH model are defined.

The results of SPH simulations are compared with the available experimental data, which concern the mapping of the violent phenomenon of plunging wave breaking (impingement of the plunging jet on the forward wave trough), the quantification of wave heights distribution and the free-surface elevation, the depiction of the wave-induced kinematics at specific gauges through ensemble-averaging, the calculation of the depth-averaged velocities and their statistics, the derivation of the cross-shore wave-induced currents and normalized flux.

Additionally, the analysis attempts to capture the characteristics of the turbulent flow within the surf zone, only in 2D vertical cross-sections to compare them with the available experimental data. The intensities of the turbulent velocities are calculated, and based on them, several turbulent features are examined, such as the log-log Fourier spectra (probability density functions) of turbulent fluctuations of velocities, the coherent turbulent structures in space and time, the recurring vorticity patterns (both Lagrangian and Eulerian), the ensemble-averaged fields for the turbulent kinetic energy and Reynolds stresses, the intermittent behavior of turbulence within the surf zone, along with the statistics of the coherent and intense intermittent turbulent events. Finally a rudimentary analysis is attempted for the wave-induced processes of the swash zone, as derived from SPH simulations, yet without explicit experimental data for comparison. The conclusions refer to the performance of the SPH method concerning the wave-induced flow under plunging breakers, and in the very process of wave breaking on weakly plunging form, while prospects for future research are proposed.

In brief, the original and innovative aspects of the present thesis are:

- The detailed simulation of the highly non-linear process of coastal wave breaking in weakly plunging form, over a plane impermeable bottom of relatively mild slope.
- The proper pre-processing of simulations, based on specific experimental models and thorough analysis of the turbulent length scales of the flow, which leads to fine spatial resolution of the computational domain with a discretization step, which abuts the dimension that discriminates the integral turbulence length scale (energy containing range) from the Taylor micro-scales (inertial turbulent length scales), i.e. implementing ~$1.5 \cdot 10^6$ for a 2D SPH computational field.
- The proper use and appropriate calibration of a sub-particle scale (SPS) model of the Smagorinsky type, for turbulence closure in conjunction with the SPH method, similarly to Large Eddy Simulation (LES) approaches.
- The advanced method of post-processing the numerical results, based on the combination of different heuristic techniques for the sampling conversion of dispersed (particle discretized) Lagrange-type data to Eulerian ones, at specific gauges

throughout the whole computational domain. That is, the incorporation in the present analysis of a convolution-type integral interpolant along with an ensemble-averaging technique.

- The use of an ensemble-averaging technique for sampling along the typical wave period, which is a combination of a moving-average procedure (low-pass filter) for the removal of the high harmonics, together with a classic phase-average operator, for the separation of the ordered wave-induced rotational motions, from the large-scale turbulent coherent structures and the small-scale residual turbulence.
- The extensive comparative analysis between the model results and available experimental data, which sheds light on the robustness of the SPH method and suggests specific upgrades for future research on SPH models.
- The satisfactory accuracy of reproduction of wave-induced ensemble-averaged flows, both due to its propagation and breaking within the surf zone.
- The identification and accurate reproduction of wave-induced kinematics in the surf zone, as the wave-induced mean cross-shore flows, the mean free-surface elevation, and the wave run-up.
- The reproduction of the streaming phenomenon in the bottom boundary layer of the flow, underneath the undertow.
- The definition and identification of coherent turbulent structures (based on the vorticity, the turbulent kinetic energy, and the Reynolds stresses) within the surf zone, and the determination of their lifespan and their dimensions.
- The detection of coherent and intense intermittent events of turbulence in the surf zone, and the determination of their significance in shaping the wave-induced flow and the consequent sediment suspension and transport.
- The identification of specific flow patterns and mechanisms for the phenomenon of coastal wave breaking in weakly plunging form.