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SPH Modeling of Water-Related Natural Hazards

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Abstract

This paper collects some recent smoothed particle hydrodynamic (SPH) applications in the field of natural hazards connected to rapidly varied flows of both water and dense granular mixtures including sediment erosion and bed load transport. The paper gathers together and outlines the basic aspects of some relevant works dealing with flooding on complex topography, sediment scouring, fast landslide dynamics, and induced surge wave. Additionally, the preliminary results of a new study regarding the post-failure dynamics of rainfall-induced shallow landslide are presented. The paper also shows the latest advances in the use of high performance computing (HPC) techniques to accelerate computational fluid dynamic (CFD) codes through the efficient use of current computational resources. This aspect is extremely important when simulating complex three-dimensional problems that require a high computational cost and are generally involved in the modeling of water-related natural hazards of practical interest. The paper provides an overview of some widespread SPH free open source software (FOSS) codes applied to multiphase problems of theoretical and practical interest in the field of hydraulic engineering. The paper aims to provide insight into the SPH modeling of some relevant physical aspects involved in water-related natural hazards (e.g., sediment erosion and non-Newtonian rheology). The future perspectives of SPH in this application field are finally pointed out.

Keywords

SPH (Smoothed Particle Hydrodynamics); Water-related natural hazards; Sediment scouring; Dense granular flow; fast landslide; Surge wave; flooding on complex topography; HPC (High Performance Computing); FOSS (Free Open Source Software).

1. Introduction

Thanks to the availability of high-performance computers, in the last few years, computational fluid dynamics (CFD) has been widely applied to simulate natural hazards in the field of hydraulic engineering. Due to the fast and large deformations characterizing the problems in this research field, meshless techniques allow for some intrinsic limitations of traditional grid-based methods (e.g., mesh deformation and cracking; free-surface, and interface treatment) to be overcome. Among the meshless techniques, the smoothed particle hydrodynamics (SPH) method has proven to have advantages over other methods. Following a Lagrangian approach, each continuum is discretized through a discrete set of material particles that lack connective mesh and follow the deformation undergone by the material. The dynamics of material particles obeys Newton's laws of motion and the discretized form of the governing equations (i.e., momentum and mass balance) is obtained through particle approximation using an interpolant kernel function (i.e., a central function of the particles' relative distance). Based on the solution algorithm of the discretized governing equations, two different approaches can usually be defined: weakly compressible SPH (WCSPH), if the continuum is assumed to be slightly compressible (governing equations can be decoupled), and incompressible SPH (ISPH).

Another limitation that computational modeling suffers is the inherent uncertainties of some modeling parameters that influence (in some cases even significantly) the model response and lower the reliability of the results. Despite this intrinsic limitation, such deterministic models may be useful anyhow to support risk analysis and mitigation through the development of fast-running numerical models that can help to create probabilistic maps of risk variables. In this way, a multi-disciplinary decision support system for natural hazard risk reduction and management could be developed that allows for the exploration of several scenarios including potential risk-reduction options [26]. In this context, the aim of the paper was to provide an overview of some recent applications of the SPH method to the modeling of water-related natural hazards. The selected works illustrate some of the relevant problems of practical and theoretical interest in the field of hydraulic engineering that could be useful to provide an introduction to the SPH method as applied to the analysis and mitigation of water-related natural hazards.

Additionally, some widespread free and open-source software (FOSS) CFD codes for multiphase engineering applications are reviewed as well as their capabilities in modeling some of the problems described in this paper.

2. Two-Phase Coupled Dynamics

This section illustrates some engineering applications of the SPH method in the simulation of two-phase flows involved in hydraulic engineering problems of practical interest in the field of water-related natural hazards.

2.1. Scouring and Sediment Transport

An important aspect of the design and maintenance of the bottom-founded submerged structure is non-cohesive sediment scouring. Bottom sediment erosion around the structure is caused by a complex flow pattern induced by the presence of the structure that strongly modifies the upstream undisturbed flow field [33]. The scouring evolution over time must be properly analyzed and mitigated in order to avoid worsening of structural stability due to foundation exposure.

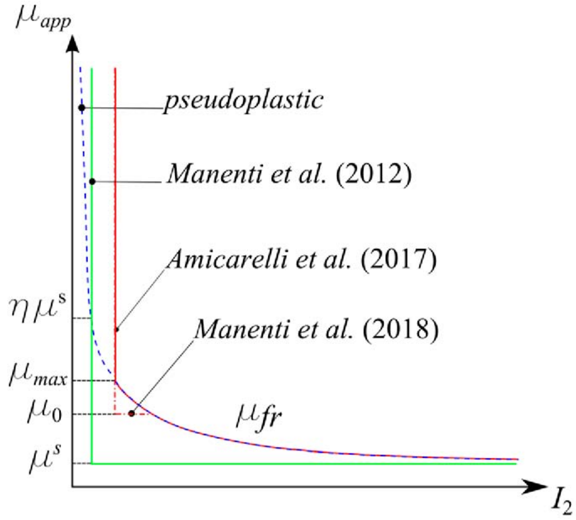

Figure 1. Rheological models for non-cohesive sediment erosion with bed load transport and for dense granular flows. I2: second invariant of the rate of deformation tensor; μapp: apparent viscosity

2.2. Fast Landslides and Dense Granular Flows Interacting with Water

Numerical modeling of dense granular flows and landslides is still a challenging topic, especially when considering the interaction between the sediment and the water that may be both an internal interaction, related to pore water in landslide-prone saturated soil, and an external interaction with stored water in a basin with unstable slopes.

In the peculiar case described above, the modeling approach based on the infinite landslide with constant depth and moving at a constant velocity on a constant slope may be less appropriate. Therefore, the solution of the governing equation in the three-dimensional form seems more appropriate than the depth-integrated model. The simulation shown in Figure 4 was carried out with the code SPHERA v.9.0.0 adopting the mixture model for dense granular flow discussed in [8]. Even if the code has a 3D formulation, a 2D approach may be conveniently adopted in this case because the landslide is relatively narrow and the flow may be assumed to be identical on the vertical planes along the flow direction.

3. Flooding in Complex Topography with the Transport of Sediments

This section provides synthetic discussions on the following topics: state-of-the-art of CFD mesh-based codes for flood propagation on complex topography with sediment transport; advantages of SPH modeling for flood propagation on complex topography; state-of-the-art of SPH codes for sediment transport; example of a SPH code for flood propagation on complex topography with sediment transport; and pre-processing and post-processing tools for floods on complex topographies (i.e., real topographic surfaces or their scale models). The most popular codes used to represent erosional floods (i.e., flood propagation over granular beds) rely on mesh-based numerical methods and the shallow water equations (SWE). These are briefly recalled in the following. The work in [78] presents a finite element code for bed-load transport. A major novelty is the 3D mathematical formulation. However, the code validations only refer to 1D configurations in 2D domains where analytical solutions are available. The work in [79] introduced a Godunov-type 1D SWE model for 2D erosional dam-break floods. The work in [80] presented a 2D SWE-FVM (finite volume method) model for 3D erosional dam-break floods, which uses Exner's equation for the bed top evolution, a 1D heuristic formula for the bed-load transport rate, and a 1D spatial reconstruction scheme based on Riemann solvers suitable for multi-phase flows. The work in [81] presented a 2D SWE model for 3D erosional dam-break floods; validations refer to 1D and 2D bed-load transport configurations, whereas a

3D demonstrative configuration (still represented with a 2D code) was reported on a quake-induced erosional dam-break flood (Tangjiashan Quake Lake). The work in [82] applied a 2D SWE-FVM code to simulate an erosional flood with bed-load transport in the Yellow River. The last two examples might represent typical applications of 2D SWE mesh-based models to 3D erosional floods on complex topography with 1D schemes for sediment transport.

The above mesh-based models share the following drawbacks: 2D modeling; no consistency with the KTGF; ad-hoc tuning procedure for the viscosity of the 2-phase mixture (water and granular material); and shallow-water approximation (e.g., hydrostatic pressure profiles, velocity is uniform along the vertical).

With respect to the above state-of-the-art mesh-based models, the meshless SPH numerical method introduces several advantages, which are synthesized in the following. SPH allows the detailed 3D fluid dynamics fields within the urban canopy (urban fabric) to be simulated including fluid-structure interactions, whilst the mesh-based 2D porous models do not provide a direct modeling of the flood-building interactions. The SPH method can simulate the 3D transport of solid structures and fluid interactions with other mobile and fixed structures and can also represent 3D bed-load transport and its impact on mobile and fixed solid structures. The SPH method provides a direct estimation of the position of the free surface and the fluid and phase interfaces due to its Lagrangian nature. The direct representation of Lagrangian derivatives is also responsible for the absence of the advective non-linear terms arising in the Eulerian formulation of the balance equations. No computational mesh generation is requested, thus saving person-months, software licenses, and computational resources. Nonetheless, several drawbacks have been reported. SPH is slightly more time consuming then mesh-based methods (fixed with the same spatial resolution and accuracy) and has a narrower, but peculiar range of application fields, whose number is nonetheless elevated and relevantly involve floods. Furthermore, a SPH code can usually cover a wide range of spatial resolutions at different accuracy levels, but maintain stable algorithms. This allows the same code to be used for both preliminary analyses at a coarse spatial resolution and accurate simulations (at fine spatial resolution).

Although several SPH studies are available for 2D and 3D applications for granular flows, only a few have been dedicated to floods with sediment transport (over a simplified topography). Among these studies, [7] introduced a 2D erosion criterion to represent the sediment removal from water bodies by means of discharge channels (i.e., flushing procedures). Regardless of the application, the SPH models for granular flows were mostly restricted to 2D codes, featured by either 2-phase models or ad-hoc tuning for mixture viscosity.

Recently, a numerical mixture model for dense granular flows was presented in [8] to simulate the sediment dynamics phenomena, which typically involve the failure of earth-filled dams and dykes, bed-load transport, and fast landslides over complex topography. This model is discussed in the following. This was integrated into the FOSS SPH code SPHERA (RSE SpA) [76]. This mixture model permits the simulation of the above phenomena by solving a system of balance equations, coherent with the theoretical state-of-the-art frame represented by the KTG [83], under the conditions of the "packing limit". The model is based on mixture parameters (velocity, density, viscosity, and pressure) and phase variables (e.g., mean effective stress, frictional viscosity, and liquid phase pressure). The viscous parameters (mixture viscosity, frictional viscosity, and liquid viscosity) do not need any calibration/tuning (Section 2.1) [8]. Filtration is partly and implicitly represented; despite the absence of an explicit filtration scheme, a Lagrangian sub-scheme for saturation conditions was based on the hypotheses of stratified flows and local 1D filtration flows parallel to the local seepage [8]. A separated treatment involves the mixture particles under the elastic–plastic strain regime: they are held fixed as their velocities are negligible for applications such as bed-load transport and fast landslides [8]. The mixture model allows a high number of fluids to be simultaneously represented in the same domain, provided that they are either liquids or granular materials (both fully saturated or dry).

The model above was validated through laboratory experiments [8] and applied to a 3D erosional dam-break flood on complex topography (Figure 6). This demonstrative test case showed the applicability of the SPH method in simulating a flood on complex topography with bed-load transport. The 3D erosional dam break was triggered by an instantaneous and almost complete failure of a gravity dam, whose structure was not simulated. The water flow impacts, thrusts, or erodes, and then transports a portion of the downstream mobile bed, which is composed of a bed of granular material. Its original sedimentation was related to the presence of a weir, whose structure was then removed before the dam building. The 3D fields of the velocity vector and pressure were computed and the 2D fields of the maximum (over time) water depth and specific flow rate (i.e., flow rate per width unit) were elaborated. These quantities, requested for risk analyses, were derived from the particle and the topography heights, and the magnitude of the depth-averaged velocity vectors. The time series of the water depth, the fluid volumes (cumulated in selected sub-domains), and the flow rate were assessed at specific monitoring sections. This demonstrative test, reported in [8] and available as tutorial no. 18 of SPHERA v.9.0.0 [76], shows the potential of the SPH method in simulating a full-scale 3D flood on complex topography with sediment transport. Although validations were reported in terms of comparisons with laboratory datasets [8], these only refer to simplified topographies. A full scale validation still has to be investigated due to the lack of available measures for complex topographies with sediment transport.

CFD codes for flood propagation on complex topography need a suitable numerical chain. A non-exhaustive list of pre-processing and post-processing free tools for floods on complex topography is discussed hereafter.

The dataset SRTM3 (USGS) represents the most accurate open data DEM ("digital elevation model", not to be confused with the "discrete element method" from Section 2.2) archive with a spatial resolution of 1" (spatial resolution length scale approximately equal to 31 m) and an almost global cover. The SRTM3 files are available in the ".tif" format. The numerical tool GDAL [84] can be used to convert the DEM ".tif" file format of SRTM3 in the alternative format ".dem". DEM2xyz [85] can read the DEM file (".dem" format), convert the geographic coordinates in Cartesian coordinates over a regular grid, and write the resulting DEM on an output file (".xyz" format), possibly coarsening the spatial resolution and reconstructing bathymetry where it is not available. Paraview (Kitware) [86] can read the ".xyz" output file of DEM2xyz and elaborate a 2D Delaunay grid starting from the DEM vertices. Paraview also allows cutting the numerical domain, drawing particular regions of interest (e.g., water bodies), engineering works (e.g., dams), and monitoring elements (e.g., points, lines, surfaces). The above information, derived from Paraview, can be provided to DEM2xyz, which can be executed again to add the new elements designed with Paraview.

4. High Performance Computing Solutions for Complex Hydraulic Engineering Problems

Numerical modeling is becoming more useful and practical thanks to the capability of the current computer hardware. Years ago, significant simplifications of the problem needed to be undertaken in order to make the numerical simulation feasible due to past hardware limitations. Nowadays, thanks to the continuous hardware improvement and the use of HPC techniques that allow for the advantages of the enormous calculation power of the current hardware to be taken, it is possible to now simulate complex problems with fewer simplifications, and problems that were impossible to be simulated due to their spatial and/or temporal scale can now be carried out. Therefore, several codes have been developed that use these HPC techniques to simulate complex hydraulic engineering problems of water-related natural hazards in reasonable execution times. Some examples are SPHERA for sediment transport [8] and landslides [9]; DualSPHysics to model the scouring of two-phase liquid-sediments flows [6,53]; and GPUSPH for simulating lava flows [74]. As explained in [89], due to the limitation of sequential computing and the high cost of increasing performance in sequential architectures, the era of sequential computing was replaced by the era of parallel computing. Currently, hardware performance is fundamentally increased by expanding the number of processing units, instead of increasing the power of a single processing unit. Therefore, it is mandatory to use parallel programming techniques to distribute the workload among the available processing units and synchronize their execution.

5. Conclusions and Future Perspectives

This paper collected some recent works showing the application of CFD techniques for modeling problems of practical and theoretical interest involving complex multiphase flows relevant for the analysis and mitigation of water-related natural hazards. The paper focused on meshless techniques for the numerical modeling of fast landslides, tsunami wave, flooding in complex geometry and sediment scouring; few relevant examples have also been mentioned concerning traditional grid-based methods applied to the analysis of environmental risks related to flooding in complex topography. The peculiar features of the examined works in terms of mathematical modeling and numerical implementation have been illustrated and outline the principal differences.

Conflicts of Interest: The authors declare no conflict of interest.

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References

[1] Wang, D.; Shao, S.; Li, S.; Shi, Y.; Arikawa, T.; Zhang, H. 3D ISPH erosion model for flow passing a vertical cylinder. J. Fluids Struct. 2018, 78, 374–399. [CrossRef]

[2] Wang, D.; Shaowu, L.; Arikawa, T.; Gen, H. ISPH Simulation of Scour Behind Seawall Due to Continuous Tsunami Overflow. Coast. Eng. J. 2016, 58, 1650014. [CrossRef]

[3] Wang, C.; Peng, C.; Meng, X. Smoothed Particle Hydrodynamics Simulation of Water-Soil Mixture Flows. J. Hydraul. Eng. 2016, 142, 04016032. [CrossRef]

[4] Guandalini, R.; Agate, G.; Manenti, S.; Sibilla, S.; Gallati, M. SPH Based Approach toward the Simulation of Non-cohesive Sediment Removal by an Innovative Technique Using a Controlled Sequence of Underwater Micro-explosions. Procedia IUTAM 2015, 18, 28–39. [CrossRef]