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3D SPH numerical simulation of the wave generated by the Vajont rockslide

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ABSTRACT

A 3D numerical modeling of the wave generated by the Vajont slide, one of the most destructive ever occurred, is presented in this paper. A meshless Lagrangian Smoothed Particle Hydrodynamics (SPH) technique was adopted to simulate the highly fragmented violent flow generated by the falling slide in the artificial reservoir. The speed-up achievable via General Purpose Graphic Processing Units (GP-GPU) allowed to adopt the adequate resolution to describe the phenomenon. The comparison with the data available in literature showed that the results of the numerical simulation reproduce satisfactorily the maximum run-up, also the water surface elevation in the residual lake after the event.

Moreover, the 3D velocity field of the flow during the event and the discharge hydrograph which overtopped the dam, were obtained.

1. Introduction

Landslides falling into water bodies often generate violent 3D free-surface flows which can cause large scale devastation. Their accurate simulation is still an open problem due to the interaction between the slide and the water and to the subsequent propagation of waves with a highly fragmented free surface. Despite their complexity, these phenomena have so far been simulated mainly via numerical models based on two dimensional Shallow Water Equations [44,3], which assume the pressure as hydrostatic and neglect the vertical velocity component. Gisler [18] used a Eulerian adaptive-grid code which discretizes the Euler equations to simulate the interaction between the wave and the slide and describes the wave generation mechanism. He then used the results of this model as an input for a shallow water code which describes the wave propagation only. This approach is suitable for simulating tsunamis in open sea, where the generation and the propagation of the wave are clearly distinct, but cannot be applied to phenomena where both the movement of the slide and the wave propagation occur at similar time scales and continuously interact. On the other hand, three-dimensional Eulerian models, already widespread in other Computational Fluid Dynamic (CFD) fields, are difficult to apply in these cases due to the presence of a highly fragmented free surface and due to the computational effort necessary to describe the water body adequately.

Recently there have been some attempts to numerically reproduce free-surface waves generated by landslides by integrating the Navier–Stokes equations using the "Smoothed Particle Hydrodynamics" (SPH) numerical technique. Ataie-Ashtiani and Shobeyri [1] simulated a rigid wedge sliding into water and a Scott Russell wave generator by means of an Incompressible SPH scheme, whereas Capone et al. [5] used a weakly compressible SPH code, analyzing the best rheological model which should be used to simulate the slide movement. In both papers simple laboratory test cases where simulated by means of a vertical 2D numerical scheme, and no 3D real cases were reproduced.

The "Smoothed Particle Hydrodynamics" (SPH) is a Lagrangian meshless method originally introduced in astrophysics [17] and subsequently extended to Computational Fluid Dynamics [27]. It has been applied to Navier–Stokes [27,37,20] and Shallow Water Equations [39,40,42,38,41]. One of the main advantages of the SPH method is that it does not require an explicit treatment of interfaces (landslide–water, water–air, etc.). This characteristic allows the simulation of phenomena such as breaking waves [10], dam-breaks [8], interactions between waves and coastal structures [19,21], and dam overtopping [24], which were considered too complicated to be simulated with classic Eulerian schemes. The main drawback of the SPH technique is the high computational cost which until recently prevented its application to practical engineering problems with complex geometries. In the past few years some authors [9,22,13,14] have developed parallel algorithms which overcome this limitation by means of the Compute

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Unified Device Architecture (CUDA) available for nVidia devices. In this way a speed-up of approximately 50–100 with respect of CPU runtime of non-parallel codes was obtained.

The open-source 3D SPH model DualSPHsysics (www.dual.sphysics.org) was used in this work to simulate the wave generated by the Vajont rockslide. To the authors' knowledge, this is the first literature contribution which applies a fully 3D model to the slide movement and to the wave simulation.

2. Literature review of the vajont rockslide

At 22:39 of October 9th 1963 a catastrophic rockslide slipped from the northern slope of Mount Toc, on the border between Friuli Venezia-Giulia and Veneto (Northern Italy), fell into the artificial reservoir of the Vajont dam. The slide generated one of the most destructive waves ever documented in literature. The wave overtopped the dam, which remained almost intact, and through the downstream narrow gorge reached the Piave valley and the village of Longarone, causing the death of about 2,000 people.

In the past 50 years the Vajont slide has been investigated in depth from a geological point of view [31,29,30,33,16]. Several authors investigated its kinematics and dynamics [23,34,15], and most agree that the rockslide can be schematized as a rigid body [28,32,12,35]. Erismann and Abele [15] observed that the surface of the slide preserved an "exceptionally coherent" state after the event, and that the slide body crossed the slopes of the Vajont gorge from the left to the right without falling to its bottom. There is also general agreement [32,6,11] on the total volume of the slide, which was estimated in about $2.70–3.00 \cdot 10^8$ m^3.

On the other hand, few studies have been devoted to the simulation of the wave generated by the rockslide. The older ones are mainly based on the empirical reconstruction of the wave, through the data collected by eye witnesses and by marks observed on the ground after the disaster [32,36,33,12]. More recently Bosa and Petti [3] have simulated this phenomenon by means of a 2D Shallow Water model. The slide was schematized as a moving vertical wall which acted as a "piston" in moving the water of the Vajont lake. After the halt of the slide the wall was removed from the model and the "previous" terrain elevation was substituted with the "subsequent" configuration of the valley. In this phenomenon, however, the ratio between the water and the rockslide masses is about 1/20 and the velocity of the rockslide is in the range of 20 m/s. It can thus be inferred that the water was "swept away" by the rockslide rather than "moved" [15]. The SWE assumptions are therefore not completely fulfilled. To overcome these limitations, a fully 3D numerical model is herein adopted.

3. 3D SPH numerical scheme

Through the SPH technique, the continuum is represented as a set of discrete particles, characterized by their own physical properties (such as mass, density, pressure). The main feature of the SPH technique is to approximate a generic scalar function $A(\mathbf{r})$ at any point $\mathbf{r}$, as follows:

$$A(\mathbf{r}) \cong \int_{\Omega} A(\mathbf{r}')W(\mathbf{r}-\mathbf{r}',h)d\mathbf{r}' \quad (1)$$

where h is the so-called "smoothing length", $W(\mathbf{r}-\mathbf{r}',h)$ is the weighting function or kernel and Ω is the domain. In discrete form this notation becomes:

$$\langle A(\mathbf{r})\rangle = \sum_b \frac{m_b}{\rho_b} A_b W_{ab} \quad (2)$$

where the summation is extended to all the particles within the domain of influence of particle a ($2h$ for the kernel function herein adopted), and m_b and ρ_b are respectively the mass and the density of particle b.

The gradient of the generic scalar function $A'(\mathbf{r})$ can be approximated by means of an SPH interpolation, as:

$$A'(\mathbf{r}) \cong \int_{\Omega} A(\mathbf{r})W'(\mathbf{r}-\mathbf{r}',h)d\mathbf{r}' \quad (3)$$

which can be written in discrete form as:

$$\langle A'(\mathbf{r})\rangle \cong \sum_b \frac{m_b}{\rho_b} A_b W'_{ab}. \quad (4)$$

In this work the quintic Wendland kernel [43] is adopted:

$$W(\mathbf{r}-\mathbf{r}',h) = \alpha_D\left(1-\frac{q}{2}\right)^4(2q+1); \quad 0 \leqslant q \leqslant 2 \quad (5)$$

where $q = ||\mathbf{r} - \mathbf{r}'||/h$ and α_D is $21/(16\pi h^3)$.

The movement of the particles is defined by integrating in time the Navier–Stokes equations written for a weakly compressible fluid. In Lagrangian formalism the mass continuity equation can be written as:

$$\frac{D\rho}{Dt} = -\rho\nabla\mathbf{v} \quad (6)$$

where $\mathbf{v}$ is the velocity vector and ρ is the density. Discretizing the $\nabla\mathbf{v}$ by means of the SPH interpolation Eq. (6) becomes:

$$\frac{D\rho_a}{Dt} = \sum_b m_b(\mathbf{v}_a - \mathbf{v}_b)\nabla_a W_{ab} \quad (7)$$

where $\nabla_a W_{ab}$ is the gradient of the kernel function. The summation of Eq. (7) is over all the particles within the region of compact support of the kernel function.

The momentum conservation equation in a continuum field is:

$$\frac{D\mathbf{v}}{Dt} = -\frac{1}{\rho}\nabla p + \mathbf{g} + \Theta \quad (8)$$

where p is the pressure. $\mathbf{g}$ is the gravity acceleration and Θ is the dissipative term.

In SPH notation, Eq. (8) can be written as:

$$\frac{D\mathbf{v}_a}{Dt} = -\sum_b m_b\left(\frac{p_b}{\rho_b^2} + \frac{p_a}{\rho_a^2} + \pi_{ab}\right)\nabla_a W_{ab} + \mathbf{g} \quad (9)$$

in which p_a and ρ_a are respectively the pressure and density for particle a (the same applies to particle b), and π_{ab} is the artificial viscosity [27] defined as follows:

$$\pi_{ab} = \begin{cases} \frac{-\alpha_v \bar{c}_{ab}\mu_{ab}}{\bar{\rho}_{ab}} & \mathbf{v}_{ab}\mathbf{r}_{ab} < 0 \\ 0 & \mathbf{v}_{ab}\mathbf{r}_{ab} \geqslant 0 \end{cases} \quad (10)$$

with:

$$\mu_{ab} = \frac{h\mathbf{v}_{ab}\mathbf{r}_{ab}}{\mathbf{r}_{ab}^2 + \eta^2}$$

In Eq. (10) $\mathbf{r}_{ab} = \mathbf{r}_a - \mathbf{r}_b$, $\mathbf{v}_{ab} = \mathbf{v}_a - \mathbf{v}_b$; being $\mathbf{r}_k$ and $\mathbf{v}_k$ the position and the velocity corresponding to particle k (a or b); $\bar{c}_{ab} = (c_a + c_b)/2$, $\eta^2 = 0.01h^2$. Artificial viscosity α_v has the main purpose of preventing instability and spurious oscillations in the numerical scheme. For violent phenomena, such as the wave generated by the Vajont slide, α_v has little influence on the main characteristics of the flow [8,19,21], as the stability condition of the numerical scheme is assured. The value of $\alpha_v = 0.2$ was adopted in this work because it is the minimum value that guarantees this condition.

Eq. (9) was used to update the accelerations of fluid particles.