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S. Idelsohn, M. Papadrakakis and B. Schrefler (Eds)

A PFEM APPROACH TO THE SIMULATION OF LANDSLIDE GENERATED WATER-WAVES

MASSIMILIANO CREMONESI*, CLAUDIO DI PRISCO* AND UMBERTO PEREGO*

*Department of Civil and Environmental Engineering
Politecnico di Milano
Piazza Leonardo Da Vinci, 32, 20133 Milan, Italy
e-mail:cremonesi@stru.polimi.it, claudio.diprisco@polimi.it, umberto.perego@polimi.it

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Abstract. A Particle Finite Element Method is here applied to the simulation of landslide-water interaction. An elastic-visco-plastic non-Newtonian, Bingham-like constitutive model has been used to describe the landslide material. Two examples are shown to show the potential of the approach.

1 INTRODUCTION

Catastrophic landslides impinging into water reservoirs may generate impulsive waves whose propagation can cause considerable damages. This is an exceptional natural hazard, usually associated with erosion, fault movements, earthquakes, heavy rainfalls or storms. The prediction of landslides velocity, runout distance and travelling path is useful for preventing and mitigating the consequences of these events. Recent developments in the simulation techniques for coupled problems have led to efficient analysis procedures allowing for the accurate reproduction of landslide-reservoir interactions (see for example [1, 2]). The numerical analysis of these events requires capabilities for tracking interfaces and free surfaces undergoing large displacements, and accounting for the mixing of different constituents, for complex constitutive behaviours and for multi-physics processes. A recently developed Lagrangian finite element approach formulated in the spirit of the Particle Finite Element Method [3, 4, 5] is here reconsidered and adapted to the specific case of landslide-reservoir interaction.

Owing to its capability of automatically tracking free-surfaces and interfaces, the proposed method is particularly suitable for the simulation of landslide-water interaction problems, which are dominated by fast propagating waves and interfaces.

2 NUMERICAL TECHNIQUE

The Particle Finite Element Method (PFEM) was orginally developed [5, 6, 7] for solving problems involving free surfaces fluid flows and fluid-structure interaction. The method is here revisited and applied to the simulation of landslides, their interaction with a basin and the generation and propagation of water waves.

Both landslide and water motions are governed by Lagrangian Navier-Stokes equations:

$$\rho_0 \frac{D\mathbf{u}}{Dt} = \mathrm{Div}\Pi + \rho_0 \mathbf{b} \quad \text{in } \Omega_0 \times (0, T) \tag{1}$$

$$\mathrm{Div}\left(J\mathbf{F}^{-1}\mathbf{u}\right) = 0 \qquad \text{in } \Omega_0 \times (0, T) \tag{2}$$

In the first equation, expressing momentum balance, ρ_0 is the density of the fluid, $\mathbf{u}$ is the velocity, $\Pi = J\sigma\mathbf{F}^{-T}$ is the first Piola-Kirchhoff stress tensor, σ is the Cauchy stress tensor, $\mathbf{F}$ is the deformation gradient, J is the determinant of $\mathbf{F}$ and Ω_0 represents the initial (and reference) configuration. In the second equation, expressing mass conservation in view of the assumed incompressibility, $\mathbf{u}$ is the velocity vector.

A classical Finite Element procedure is used to discretize the problem in space while a backward Euler scheme is employed for the time integration. In the spirit of the Particle Finite Element Method, to avoid excessive mesh distortion due to the Lagrangian nature of the equations, the domain is frequently remeshed. An index of the element distortion is used to check whether the mesh should be regenerated or not. When a new mesh is to be created a Delaunay triangulation technique is used to redefine the nodal connectivity starting from the current node position. Morever, an "alpha shape" technique is introduced to identify the free-surfaces and the interacting surfaces between water and landslide. Details on the numerical procedure can be found in [2, 3, 4, 5].

3 CONSTITUTIVE LAW

Both the landslide and the reservoir water have been modelled as viscous fluids. The Cauchy stress tensor $\boldsymbol{\sigma} = \boldsymbol{\sigma}(\mathbf{x}, t)$ is decomposed into its hydrostatic p and deviatoric $\boldsymbol{\tau}$ components as $\boldsymbol{\sigma} = -p\mathbf{I} + \boldsymbol{\tau}$ where $\mathbf{I}$ the identity tensor.

Water is assumed to be a Newtonian isotropic incompressible fluid. Focusing on a one-dimensional case, the constitutive law can be expressed as:

$$\tau = \mu\dot{\gamma} \tag{3}$$

where μ is the dynamic viscosity and $\dot{\gamma}$ is the one-dimensional shear rate.

Unlike in standard Navier-Stokes formulations, the landslide material is assumed to obey an elastic-visco-plastic non-Newtonian, Bingham-like constitutive model to be able to consider also the initial phase of static equilibrium which precedes the activation of the landslide motion. The main assumptions are as follows. The landslide material is incompressible. Only small strains take place in the initial static equilibrium phase, so that linear compatibility can be assumed. In this phase, viscous strains are also small since nodal velocities are vanishing and the deviatoric effective stress is in general below the yield limit. When external actions trigger the landslide motion and the elastic limit is exceeded, large viscoplastic deformations take place, so that the elastic part of the strain can be neglected. From now onward, the running landslide behaves as a viscoplastic Bingham fluid. To be able to deal with the static phase, the balance equation (1) contains a stiffness dependent internal force contribution, in addition to the viscous term. The primary variables are as usual nodal velocities and pressures, but nodal displacements are also computed in the static phase through time integration, to allow for the computation of the stiffness contribution.

In the assumed model the deviatoric stress τ can be expressed as:

$$\tau = \begin{cases} \widetilde{\mu}\dot{\gamma} + G\gamma^e & \text{per } \tau < \tau_y \\ \tau_y + \widetilde{\mu}\dot{\gamma} & \text{per } \tau \geq \tau_y \end{cases} \tag{4}$$

where γ^e is the elastic part of the deviatoric strain, $\dot{\gamma} = \dot{\gamma}^e + \dot{\gamma}^p$ is the deviatoric strain rate and τ_y a yield shear stress. $\widetilde{\mu}$ is an apparent viscosity defined as:

$$\widetilde{\mu} = \mu + \frac{p \cdot \tan(\varphi)}{|\dot{\gamma}|}\left(1 - e^{-n|\dot{\gamma}|}\right) \tag{5}$$

where φ is the friction angle. When $\tau < \tau_y$ the behaviour is viscoelastic and dominated by the elastic term $G\gamma^e$, conversely when the yield stress is reached ($\tau \geq \tau_y$)a viscoplastic behaviour is obtained. The exponential term in (5) has only a regularization purpose [2, 8], and has not to be given a constitutive interpretation. The extension to the 3D is straightforward.

This model can be easily used to describe landslides originated from layered slopes. Furthermore, the soil transition from an initial static equilibrium state to an unstable landslide, due to an imposed ground acceleration, can be also accounted for.

4 NUMERICAL EXAMPLE

4.1 Granular flow on a rigid obstruction

The estimation of the impact force of a flowing landslide against a rigid wall is critical for the safety assessement of protection structures such as earth retaining walls. In [9], small-scale tests have been conducted to measure the impact force on a rigid wall of a sand flow. In the same paper, numerical tests have also been performed in an Eulerian framework to analyze and reproduce the laboratory results. The previously described approach has been used to simulate these tests and its results have been validated against both the experimental and numerical results in [9].

Figure 1 depicts a schematic representation of the problem geometry. As suggested in [9], the following physical parameters are used:

$$\rho = 1379\text{Kg/m}^3 \quad \mu = 1\text{Pa s} \quad \varphi = 35^\circ$$

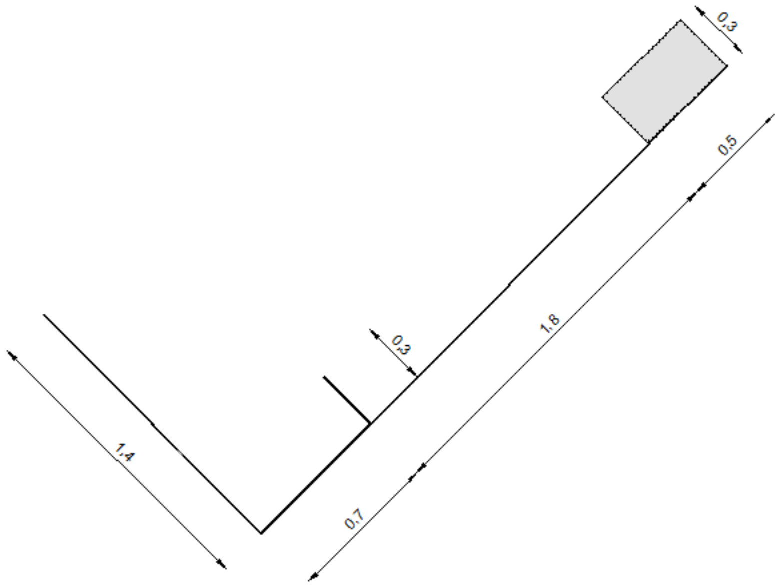

Figure 1: Granular flow on a rigid obstruction: schematic representation of the problem.

Other details about the geometry of the problem as well as about the calibration of the parameters can be found in [9].

Four different tests have been performed varying the flume inclination θ. Figure 2 shows the impact force time histories for the different flume inclinations, compared with experimental and numerical outputs of [9]. In all cases, good agreement is obtained.

Finally, figure 3 shows snapshots of the simulation at different time steps for the case of $\theta = 55°$.

4.2 Landslide interaction with water reservoir

Water waves generated by fast landslides impinging in water basins can be very dangerous for the safety of the surrounding area. To study this phenomenon, the simplified 2D geometry of the Gilbert Inlet, at the head of the Lituya bay, Alaska, considered in [10] and reproducing the experimental setup in [11], has been used to simulate the motion of a landslide along the slope and the formation and propagation of the water waves on the opposite side.

In Figure 4 different snapshots of the simulation are shown. In [11], an experimental landslide run-up on the opposite side of 152 m has been measured, which compares well with the value of 160 m obtained with the present simulation (a run-up height of 226 m was obtained in [10]).

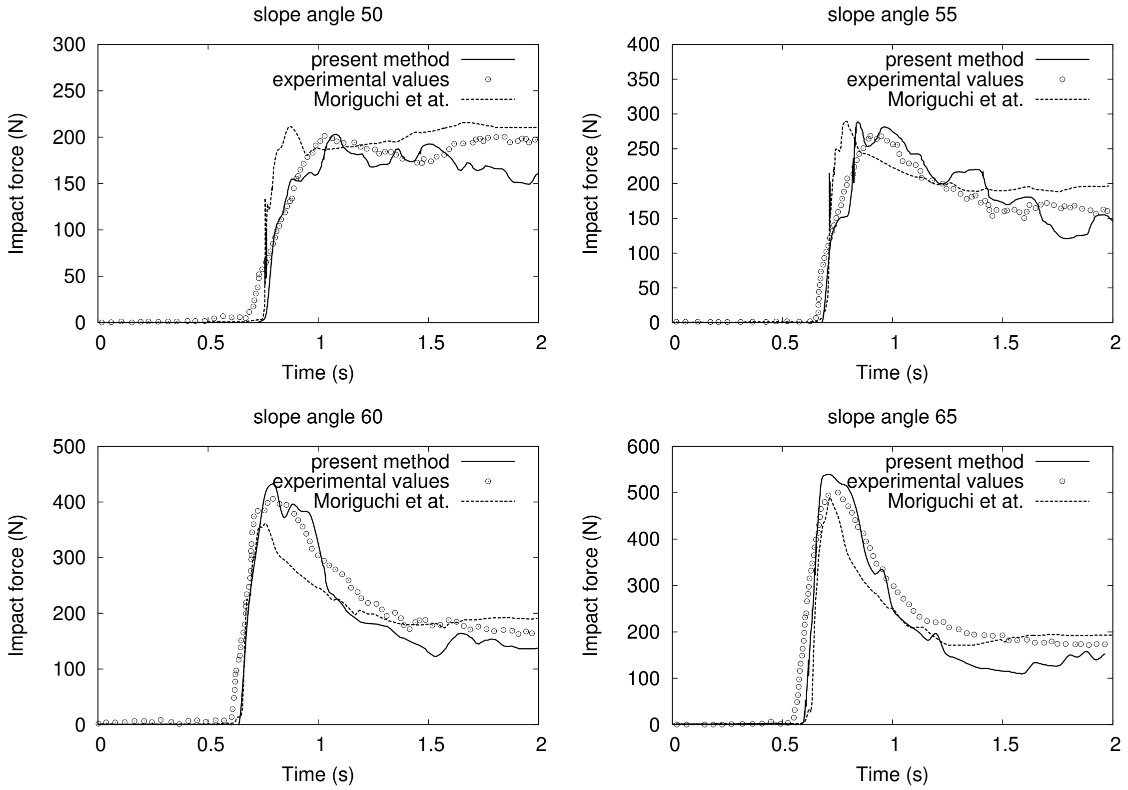

Figure 2: Granular flow on a rigid obstruction: impact force time histories for different flume inclinations.

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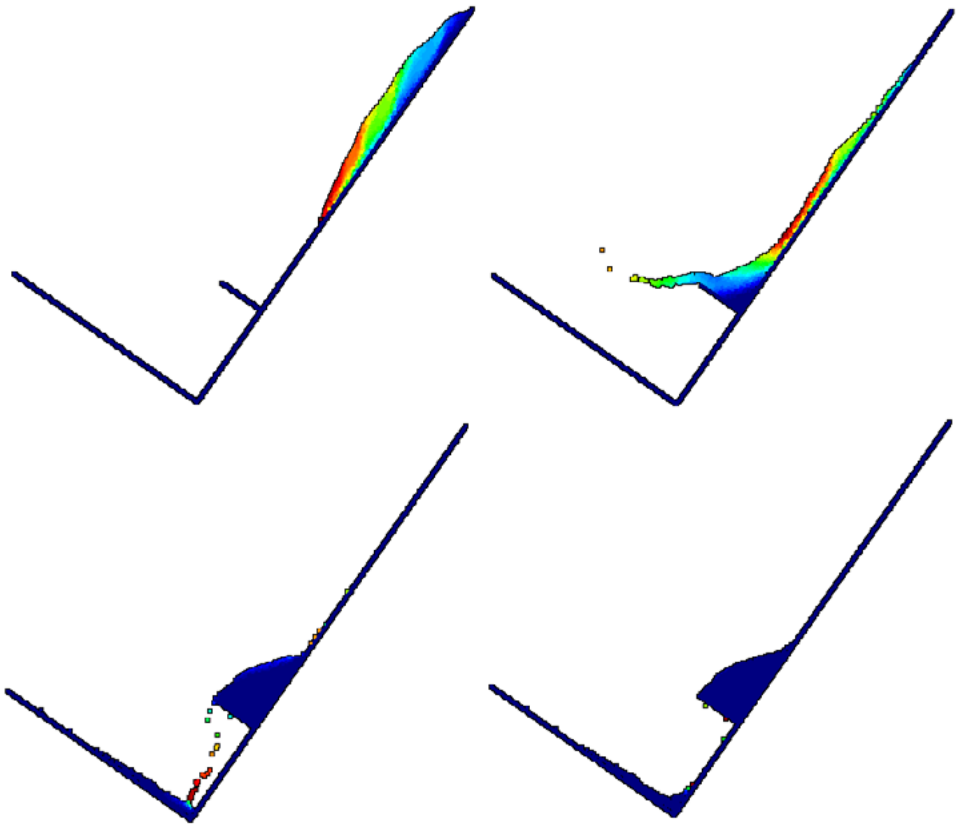

Figure 3: Granular flow on a rigid obstruction: snapshots of numerical flow.

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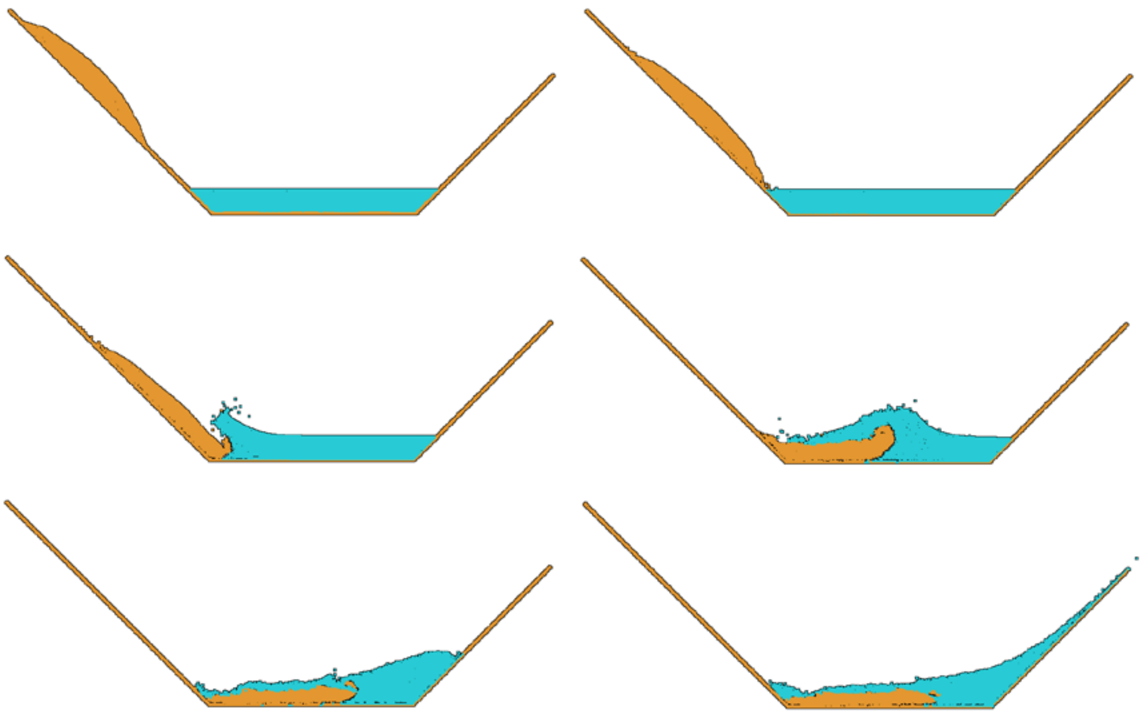

Figure 4: Landslide interaction with water reservoir. From left to right and from top to bottom, different phases of numerical simulation.

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