Some remarks about SPH propagation modelling of flow-like landslides

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Abstract: Smooth Particle Hydrodynamics (SPH) models have been increasingly used in the last years for the numerical simulation of the propagation stage of flow-like landslides and similar phenomena. The paper discusses some recent numerical results and outlines the potential and drawbacks of SPH method. Remarks are proposed about the influence of Digital Terrain Model, the role of pore water pressure, soil rheology and bed entrainment. It is concluded that new frontiers should be addressed for pore water pressure and 3D formulation.

Key-Words: DTM, water, entrainment, rheology, mixture, coupled, depth-integrated.

1 Introduction

Propagation analysis of flow-like landslides is a difficult, but relevant engineering task. Different numerical approaches have been proposed in the last ten years, which can be broadly distinguished in Eulerian and Lagrangian. The Eulerian-based models [1] are time-consuming, because the unknowns are computed at each point (or cell) of the Digital Terrain Model (DTM), at each time step. This also entails a huge quantity of memory required to store the results of the model. In a Lagrangian model, e.g. [2], the variables are computed only for the propagating mass, and this drastically reduces the computational cost.

Numerical methods used to solve the governing equations range from Finite Differences [3], Finite Elements [1], Material Point Method [4], Finite Element Lagrangian Integration Point [5] up to Smooth Particle Hydrodynamics, SPH [2], [6], [7]. The latter method will be discussed herein with reference to real case histories and experimental flume tests.

In the paper, a series of recent experiences based on the application of a Lagrangian SPH approach will be discussed with reference to the key factors for landslide propagation: DTM, pore water pressure, soil rheology and bed entrainment phenomena. The outline of the paper consists in a brief description of the basics of the hydro-mechanical coupled GeoFlow_SPH Madrid model for landslide propagation. Then, the discussion is focused on some recent numerical results aimed to provide a new contribution to the topic.

2 Basics of “GeoFlow_SPH” model

The model was proposed by Pastor et al. [2] and it schematises the propagating mass as a mixture of a solid skeleton saturated by water; the unknowns are the velocity of the solid skeleton (v) and the pore water pressure (pw).

The governing equations are: i) the balance of the mass of the mixture combined with the balance of the linear momentum of the pore fluid, ii) the balance of the linear momentum of the mixture, iii) the rheological equation relating the soil stress tensor to the deformation rate tensor, and iv) the kinematical relations between the deformation rate tensor and the velocity field.

The model assumes that pore water pressure dissipation takes place along the normal to ground surface; the velocity of the solid skeleton and pressure fields are computed as the sum of two components related to two separate processes: propagation and consolidation, (for further details, [2]). The initial pore water pressure normalized to soil liquefaction pressure (p_{rw}=p_w/\gamma_{sat}h, where p_{rw} is the so-called ‘normalized pore water pressure’ and \gamma_{sat} is the soil unit weight, and h is the flow thickness) is an important input, which can be obtained from the analysis of the triggering stage inside the landslide source area(s).

The above equations are integrated along the vertical axis and the resulting 2D depth-integrated model presents an excellent balance of accuracy and simplicity. The potential of this approach is appreciable for the flow-like landslides, which have small average depths in comparison to their lengths.
or widths.

The model also accounts for bed entrainment along the landslide path, and the elevation of the ground surface consistently decreases over time. In particular, different empirical bed entrainment laws are implemented in the GeoFlow_SPH model (e.g. [8], [9]).

The Smoothed Particle Hydrodynamics (SPH) method is used; this numerical technique discretises the propagating mass through a set of moving ‘particles’ or ‘nodes’. Information, i.e. unknowns and their derivatives, is linked to the particles, and the SPH discretisation consists of a set of ordinary differential equations whose details are provided by the literature [2].

The accuracy of the numerical solution and the level of approximation for engineering purposes depend on how the nodes are spaced and how the digital terrain model (DTM) is detailed, as recently reviewed by Cuomo et al. [10].

An automatic adaptive time stepping is used for time discretisation [1], and the Runge-Kutta algorithm is used for numerical time integration, as suggested by Pastor et al. [2].

3 Digital Terrain Model (DTM)

The DTM plays an important role in the performance of any type of numerical analysis of the propagation stage of landslides. The overall quality of the numerical simulation is dramatically lowered if the main propagation path is misinterpreted due to a poor DTM. In general, for shallow landslides – which are triggered in areas some tens of meters large and few meters thick, and propagate over paths some kilometers long – the identification of the travelling path and the accurate estimate of the final deposition height are the two fundamental issues to be dealt with.

However, the propagation of a flow-like landslide is a very complex process because: the front part of fluidized mass mostly follows the local topography of the ground surface; conversely, the rear part of the landslide body is also highly affected by what happened to the front part. For instance, whether the front of the propagating mass stops at the piedmont areas, the rear part may propagate above this deposit or divert elsewhere, or to be stopped. In addition, it is well-known that flow-like landslides are multiple-surges-like phenomena. It means that more than one single mass propagate downslope within the same event: i) this is because multiple areas may fail in the same areas delayed few minutes (or hours) in time; ii) this is also related to the kinematic of each unstable mass which tends to the behave like a viscous-like fluid, with the front part, body and rear part travelling at a different velocity.

In a sense, the specific role of the DTM can be only assessed when a single soil mass propagate in a “simple” propagation path. This is the case of laboratory flume tests. Among those available in the literature, the experiments performed by Iverson et al. [11] in a 1.0 m long flume were selected and simulated through the SPH model of section 2.

Figure 1 shows an example of the results achieved by changing the size of the DTM square cells (1.2 cm, 0.6 cm, 0.4 cm, 0.2 cm respectively for the original DTM and for the refined DTMs A1, A2 and A3). In this specific case, the original DTM is poor into describing the experimental the slope geometry and the final height (about 1.4 m) is badly reproduced. Whereas, the results obtained for the finer DTMs well match the experimental evidence.

Thus, the effect of a different DTM schematization is evident and, on the other hand, an excessive refinement of the DTM does not improve significantly the estimate of the final height of flow. It is a matter of fact that in a real case, a high quality of the DTM is a necessary, not sufficient, condition to achieve reasonable results either for the back-analysis (model calibration) or forecasting analysis (model exportation). About this issue, Lidar technique, terrestrial laser scanner (TLS) and images taken from unmanned aerial vehicle (UAV) may significantly enhance the quality of the DTM.

4 Rheology

The stress-strain behavior of the mass moving downslope a catchment is highly idealized in engineering analysis of propagation. First, each
surge of a flow-like landslide is a mixture of solid and water, whose concentrations change in space and time. Secondly, the internal deformations and the average velocity of the whole mixture highly change from the inception to the deposition. This means that the internal friction angle of the material should be determined: i) in static geotechnical laboratory tests, and ii) in dynamic propagation tests in flume devices. In addition, pore water pressure variations, bed entrainment, partial local deposition and local hydraulic boundary conditions may change the stress-strain behavior of the mixture.

An example of numerical analysis is herein discussed because it was clearly found that an earthflow reactivated in fine-grained soils of Southern Italy can be properly simulated only if a change of the rheology is admitted between two successive reactivation episodes. This is the Montaguto earthflow case study, firstly analyzed by Cascini et al. [12] and then numerically simulated by Cascini et al. [13].

Figure 2 shows the effects of the rheological parameters on the simulated thickness of soil during the propagation of the Montaguto earthflow. The higher is the shear strength ($\tau_0$), or viscosity ($\mu$), the higher is the final deposition height. But, what is quite interesting noting is that the propagation stage of the landslide is well simulated between two successive reactivation episodes. This is the Montaguto earthflow case study, firstly analyzed by Cascini et al. [12] and then numerically simulated by Cascini et al. [13].

In this specific case, the Bingham rheological model was used by Cascini et al. [13]. The first stage of Montaguto earthflow propagation is well simulated assuming the viscosity, $\mu$ (Pa·s), equal to 5'000 ÷ 6'000, and shear resistance, $\tau_0$ (Pa), equal to 1'500 ÷ 1'700. Conversely, this same set of rheological parameters is completely misleading for the interpretation of the remobilization of the earthflow from the previous deposition zone to the final stopping area. Field observations in the landslide remobilization zone highlighted that superficial water runoff and groundwater convergences in this area determined severe hydraulic boundary conditions in terms of water supply and high pore water pressures. Thus, the numerical modelling is capable to reproduce the landslide remobilization only considering a material “degradation”. The latter is principally related to: i) the higher pore water pressures, which are implicitly taken into account in the rheological model with reduced strength parameters; ii) the propagation of the material along a steep slope also including a fall of the material from 20 m high vertical bedrock outcrop, which weakened. Both these factors cause a significant lowering of the rheological parameters. The viscosity, $\mu$ (Pa·s), is found to be equal to 300 ÷ 500, and shear resistance, $\tau_0$ (Pa), equal to 50 ÷ 100.

This case history is of interest to outline how simplified are the engineering analyses whether: i) boundary conditions change in time, or ii) the propagating mass interact with different boundary conditions in different portion of a hillslope, or iii) the mass suffer of a degradation process during the propagation stage of the landslide. In all the mentioned cases, a variation of rheology is expected, and this issue is still not included in the available numerical models. A variation of rheology can be also expected in coarse-grained mixtures, which have enough kinetic energy to entrain huge quantities of debris and even boulders from the bed of the propagation path.

Until the issue of the rheology variation is not properly tackled, simplified models will be used like for the discussed case history of Montaguto earthflow.

### 5 Pore water pressures

What has been recently treated suitably well is the role of water pressures inside the propagating mass. The model based on the twofold approach of propagation and consolidation was set up by Pastor et al. (2009), and then validated for benchmarks and case histories. Fig. 3 proposes a significant example of numerical model performed for the Tuostolo-Sarno debris flows. The simulated run-out distance is plotted against the time, depending on different hypotheses made for pore water pressure: i) dry material, ii) saturated mixture, iii) higher initial basal pore water pressure, iv) higher water table in
the landslide source areas, and v) higher consolidation coefficient.

The higher the pore water pressure, the lower is the shear strength at the base of the material. This is a simple mechanism. Nevertheless, the changes of pore water pressure in time and space are regulated by complex processes. Among these, vertical consolidation is only one important mechanism. A recent development was proposed by Pastor et al. [13] for the computation of the vertical profile of pore water pressure based on a finite different scheme. Such an approach allows also including in the model a hydraulic boundary condition at the bottom of the propagating mass. This is the case a drainage material above which the landslide may propagate.

However, other mechanisms are of interest: i) relative movements of water to the solid skeleton, ii) overpressure due to mixture deformations, and iii) extra-pressures at the base of the mixture due to vertical segregation. All these processes are still far to be modeled as it would be desirable.

6 Bed entrainment

In many types of flow-like landslides, non-channelized (known as Debris Avalanche, DA) or channelized (usually known as Debris Flow, DF), the propagation is a non-constant-mass-process due to bed entrainment. The latter includes either the soil entrained from below the ground surface or the trees, the vegetation and the debris driven from above the ground surface.

Bed entrainment is dramatically important for debris avalanches, especially in the upper portions of the propagation path. Cuomo et al. [15] demonstrated via SPH numerical model that bed entrainment – apart from increasing the landslide mass – causes the landslide to: i) decelerate, as a material with nil velocity is added to the propagating mass, and ii) spread laterally, as the front part of the landslide constitutes a sort of obstacle for the rear part of the landslide. The laterally spreading is the most critical consequence of the bed entrainment because the whole propagation path can be completely changed by this mechanism. For instance, Pastor et al. [17] and Cuomo et al. [15] proposed the modeling of debris avalanches bifurcated in two distinct channels with two separate deposition zones. These contributions also demonstrate that without bed entrainment a single propagation path would have been followed.

About the quantitative estimate of the thickness of the entrained material, much was done and much more is still to be done. In many practical applications, the law proposed by Hungr [8] is used, which relates the landslide volume growth rate ($E_r$) to the run-out distance. Figure 4 shows the thickness of the entrained material simulated at a point of a regular open slope, 35° steep, for distinct factors (friction angle $\phi_b$, basal pore water pressure $p_{rw}$, consolidation coefficient $c_v$, erosion coefficient $E_r$). The higher the friction angle, the higher is the entrainment thickness. The lower is the pore water pressure (lower $p_{rw}$ or higher $c_v$), the higher is the entrainment thickness. All these results mean that the higher is the effective shear stress at the bottom of the flow, the higher is entrainment thickness. In addition, independent on the specific case of figure 4, it is clearly outlined that bed entrainment is a highly transient process, which occurs in few seconds.

Interestingly, bed entrainment also affects the deposition and stopping processes of the landslides. To this aim, figure 5 outlines the results of two debris flows occurred in the Sarno-Quindici site in May 1998. Two series of simulations are reported,

![Figure 4. Simulated thickness of the entrained material in a regular open slope, 35° steep, depending on distinct factors (friction angle $\phi_b$, basal pore water pressure $p_{rw}$, consolidation coefficient $c_v$, erosion coefficient $E_r$), (modified from [15]).](image)
one for Sarno, the other for Quindici [16]. For each debris flow, different hypotheses were assumed: negligible bed entrainment (S and Q in figure 5), and increasing bed entrainment (from 2 to 3 to 4, and from 6 to 7 to 8, respectively for Sarno and Quindici).

7 Conclusions

The paper dealt with the application of a Smooth Particle Hydrodynamics (SPH) model for the simulation of the propagation stage of flow-like landslides. After a brief presentation of the basics concepts of the model, some key factors were discussed: the selection of the detail of the DTM, the role of pore water pressure, the selection of rheology and the effects of bed entrainment. Relevant examples of numerical modelling were used to outline the potential of the model to accurately capture the fundamental physical processes of propagation and deposition. On the other hand, the current limitations were outlined and future researches which deserve more attention. The main contribution of this paper was to systematically compare some recent developments and applications through a promising SPH-based model.

Two main conclusions can be drawn as far as the adopted model. From a theoretical viewpoint, the role of pore water pressure is a dominant factor for many types of materials and for many classes of phenomena. The “GeoFlow_SPH” model is capable to combine accuracy and rapidity into the computation of pore water pressures. On the other hand, bed entrainment seems to be a relevant factor only for a specific class of landslides (i.e. debris avalanches) and for unfavorable site conditions, which may eventually cause a bifurcation of a landslide into distinct channels.

As far as the practical application of the model, an accurate DTM and an adequate rheology are two necessary ingredients to well describe the site conditions and material properties. Future research should focus on a more general formulation of the governing equations capable to include the 3D distributions of the unknowns, the velocity of the solid skeleton (v) and the pore water pressure (pw). This is a difficult task to be tackled but the advantages of such a new tool could be much relevant. For instance, the impact of landslides against buildings and control works could be better simulated. In conclusions, the SPH approach provides a powerful tool for the numerical modelling of landslide propagation and it is also very promising for the future developments.

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