

Study of landslide run-out and impact on protection structures with the Material Point Method

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ABSTRACT

Reliable estimates of the impact forces induced by flow-like landslides on existing structures is of great importance for hazard assessment. This is customarily obtained by means of empirically based relationships but, significant differences may be encountered using the existing approaches. Large scale experimental studies are expensive and difficult to set up; for this reason a numerical technique able to simulate the material flow and its interaction with structures would be helpful for the hazard assessment as well as for the design of mitigation measures. This paper shows the applicability of the Material Point Method (MPM), a meshless method specifically developed to describe large deformations of bodies, to the study of granular flow propagation and impact forces on rigid structures. Complex shapes of the structure as well as different soil-structure interface properties are considered. It is shown that the MPM may represent a suitable tool to support the design of landslide mitigation measures.

KEYWORDS

MPM; granular flow; impact forces

INTRODUCTION

Several studies carried out in the past focused on the determination of the impulsive force produced by debris flows on vertical rigid structures, e.g. Armanini & Scotton (1993), Hübl et al. (2003), Moriguchi et al. (2009), but only a few have considered the shape of the structure (e.g. Shieh et al. 2008; Zanuttigh & Lamberti, 2006) or its flexibility (e.g. Canelli et al. 2012; Leonardi et al. 2014). Moreover, there are significant differences between the proposed approaches which render their practical use rather difficult.

A numerical technique able to capture the key features of the debris flow and its interaction with a complex structure can contribute to assess the damage to existing structures and guide the design of protection measures. To this end, this paper investigates the potentiality of the Material Point Method (MPM) for these applications.

The MPM has been specifically developed for large deformations of history dependent materials. It simulates large displacements by Lagrangian points moving through an Eulerian grid as shortly described in the next section.

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A 3D MPM code is applied in this study, thus complex geometries can be handled with ease. It features a specific algorithm to model soil-structure interaction and frictional sliding. The non-linear behaviour of soil is simulated by an elastoplastic model with Mohr-Coulomb failure criterion. The description of the flow propagation with a geomechanical model is quite unusual. Its use is customarily limited to small deformations such as the study of the landslide trigger mechanism, when the failure surface develops. Most of the numerical studies of flow propagation uses rheological models but it is important to note that it is very difficult to link geomechanical and rheological parameters under both small and large deformations. The MPM might close the gap between these approaches.

In the following sections, it is shown that the MPM can reproduce the run out of a dry granular flow with good agreement with experimental results leading to the estimate of the impact forces on a vertical rigid wall, that are shown to be in good agreement with empirical observations. In addition to this, alternative shapes and surface characteristics of the structure are considered.

THE MATERIAL POINT METHOD

The MPM is a particle-based method developed since the 90's for large deformations of history dependent materials (Sulsky et al. 1994). Recently, the method has been extended to coupled problems in order to simulate the soil-water interaction (Bandara & Soga, 2015; Jassim et al. 2013) and unsaturated conditions (Yerro et al. 2015). The MPM has been successfully applied to the simulation of a number of geotechnical problems such as landslides (Andersen & Andersen, 2010), collapse of dams (Alonso & Zabala, 2011) and river-banks (Bandara & Soga, 2015).

The continuum body is discretized by a set of Lagrangian points, called material points (MP). They carry all the information of the continuum such as density, velocity, acceleration, stress, strain, material parameter as well as external loads. The MP do not represent single soil grains, as in Discrete Element Methods (DEM), but a portion of the continuum body. Large deformations are simulated by MP moving through a fix computational finite element mesh which covers the entire region of space into which the solid is expected to move. This grid is used to solve the system of equilibrium equations, but does not deform with the body like in Lagrangian Finite Element Method.

The MPM code used in this study is being developed to solve 3D dynamic large deformation problems in geotechnical and hydromechanical engineering (Vermeer et al. 2013). The code features a contact formulation as presented by Bardenhagen et al. (2001) to model soil-structure interaction and frictional sliding.

SIMULATION OF A GRANULAR FLOW

The capability of the MPM to simulate the propagation of a dry granular flow is evaluated considering the result of a physical model test by Denlinger and Iverson (2001). The experiment used a small flume with a bed surface inclined 31.4° adjoined to a horizontal runout plane.

The non-linear soil behavior of loose sand is described with an isotropic elastic-perfectly plastic model with Mohr-Coulomb failure criterion. The input parameters are summarized in Table 1. A static friction angle $\varphi=40^\circ$ and a static basal friction angle $\varphi_b=29^\circ$ were measured by Denlinger and Iverson. However, the dynamic values of these parameters can be significantly lower. Sensitivity analyses showed that the displacements decrease by increasing φ and φ_b , but the latter has a greater effect on the final run-out (Fig. 1). The best agreement with the experimental results is obtained with a basal friction angle of 26.6° .

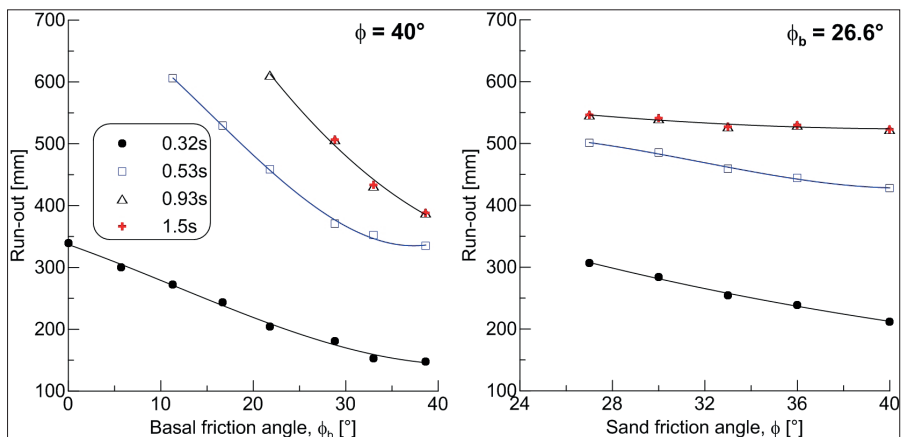


Figure 1: Run-out as function of the basal friction angle (left) and sand friction angle (right) for different time

After material release, the flow accelerates gradually spreading and reaching the end of the inclined plane with a maximum velocity of 0.88 m/s, then the sand mass decelerates and stops. Figure 2 compares the propagation of the granular flow predicted by the MPM with that observed in the experiment. The maximum runout is observed after 1.50 s and the numerical prediction is in good agreement with the experiment.

Table 1: Material properties of sand

Bulk density [kg/m³]	ρ	1600	Dilatancy [°]	ψ	0
Initial porosity [-]	n	0.4	Young's modulus [kPa]	E	1
Friction angle [°]	ϕ	40	Poisson's ratio [-]	ν	0.3

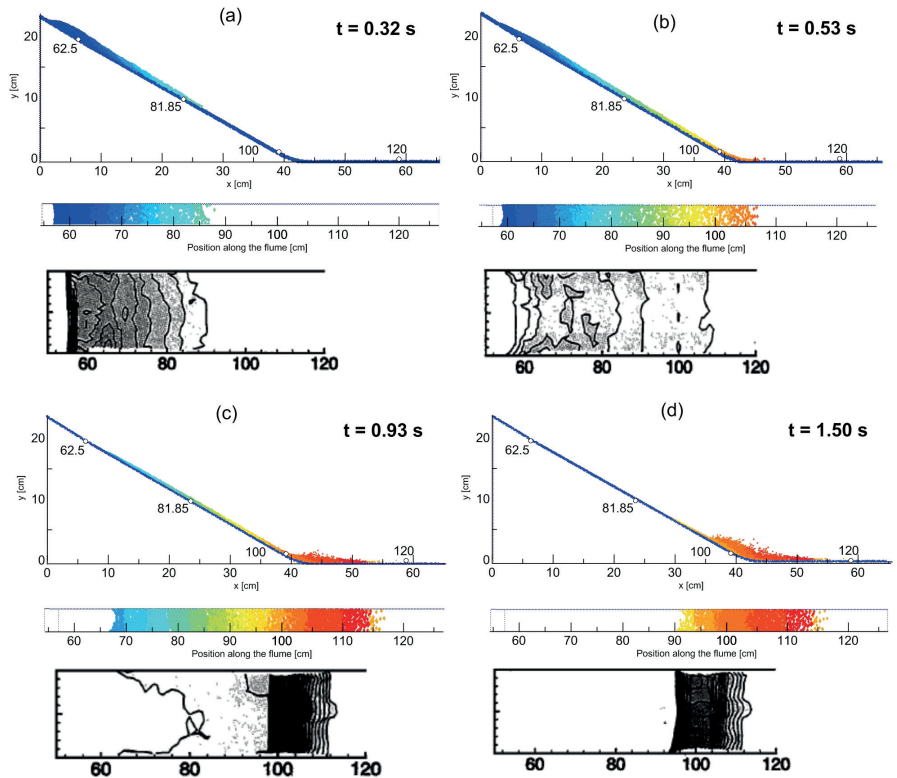


Figure 2: Granular flow at $t=0.32\text{s}$ (a), $t=0.53\text{s}$ (b), $t=0.93\text{s}$ (c) and $t=1.50\text{s}$ (d): front view, top view and comparison with experimental results

SIMULATION OF THE IMPACT ON A RIGID STRUCTURE

This section discusses the impact of a granular flow on a structure in terms of forces and amount of material passing beyond the structure. The slope geometry and soil material parameters coincide with the previous section. The structure is placed at the end of the inclined plane and the basal friction angle is zero, thus maximizing the impact velocity. The discretization of the numerical model has been determined through preliminary analyses as a compromise between accuracy and computational cost. The maximum size of the elements is 8 mm along the sliding surface and 3 mm on the structure surface, 6880 MP are used to discretize the sand.

Three different shapes of the structure are investigated: vertical dam, slanted dam and curved dam. For each shape, three values of the structure friction coefficient are considered to simulate various revetment materials: $\mu_s=0, 0.3$ and 0.6 .

Considering the free granular flow without any obstruction, at a cross section at the location of the structure, a maximum velocity of 1.96 m/s and a maximum flow height of 8.7 mm are observed, thus a Froude number $Fr = v/(gh)^{1/2} = 6.7$ characterizes the flow. $Fr > 2$ characterizes most of the small-scale tests, while real debris-flows usually show $Fr < 2$ (Hubl et al. 2009). The vertical wall and the curved dam deviate the flow vertically (Fig. 3a-b). The sand passes beyond the wall and only a small amount of material is retained in front of the dam. The

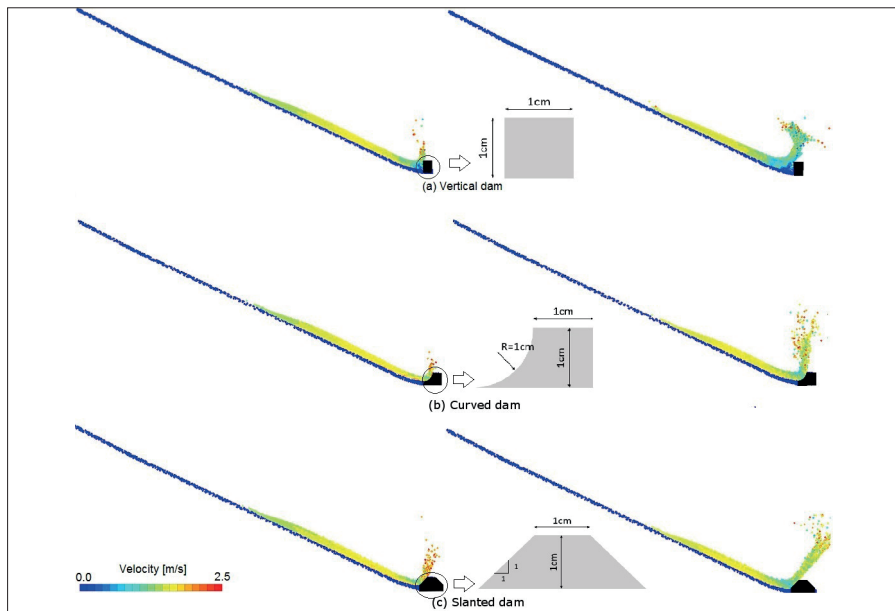


Figure 3: Dynamic of the impact of the granular flow on vertical (a), curved (b) and slanted (c) dams

slanted dam deviates the granular flow by an angle of 45° (Fig. 3c). The thickness of the flow in front of the dam increases much less than the previous shape; moreover a larger amount of material overpasses the dam and with higher velocities.

Figure 4a shows the fraction of soil mass which overtop the wall, thus it is not retained by the structure. The vertical wall is the most effective shape (30% of the material is retained) and the slanted dam is the less effective as almost all the material pass beyond the structure. Figures 4b and 4c show the horizontal (F_x) and vertical (F_y) forces per unit of length on the wall surface. The forces increase rapidly up to a peak, and then decreases to a static value which corresponds to the pressure of the soil in front of the wall.

Figure 5 shows the maximum pressure normalized both by the hydrostatic pressure (ρgh) and the hydrodynamic pressure (ρv^2) obtained from field measurements and miniaturized tests as

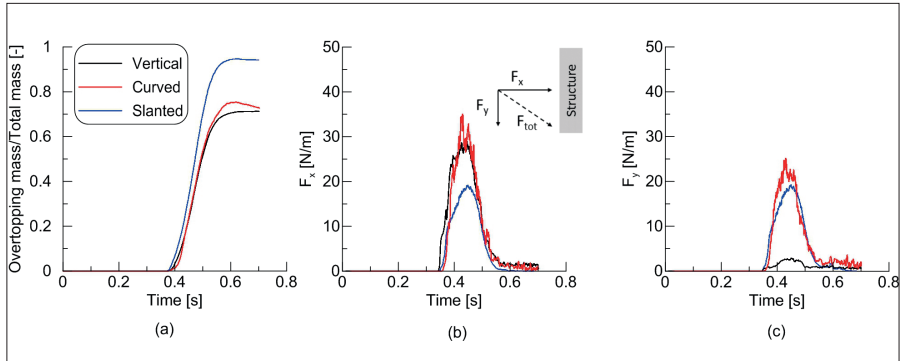


Figure 4: Fraction of san mass overtopping (not retained by) the wall (a), horizontal forces (b) and vertical forces (c) for different shapes of the dam

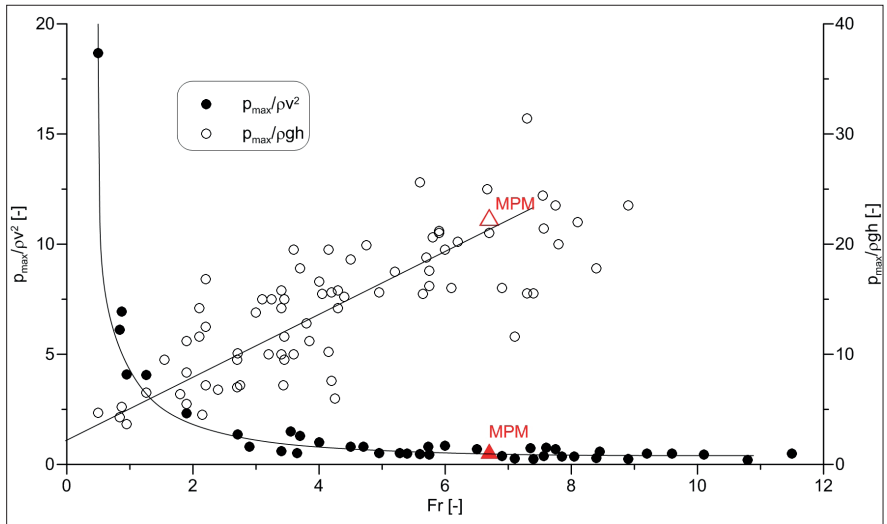


Figure 5: Maximum impact pressure as function of Froude-number; comparison between MPM results and other experimental results collected by Hübl et al. (2009)

reported by Hübl et al. (2009). The obtained $p_{max} = Fx_{max}/h$ (h =height of the dam) for the vertical wall is in good agreement with reference values for similar Froude numbers. The vertical and curved dam show similar values of the horizontal force, but the latter with a significant vertical force whereas the slanted dam shows similar values of the horizontal and vertical forces. The vertical component improves the stability of the dam against sliding and toppling.

Increasing the structure friction coefficient the impact forces reduce. This effect is small for the vertical wall, but very important in case of slanted dam. In particular, F_y decreases, thus reducing its stabilizing effect (Fig. 6). Because of the friction between the soil and the dam, the flow loses energy and the fraction of mass retained by the dam increases with μ_s .

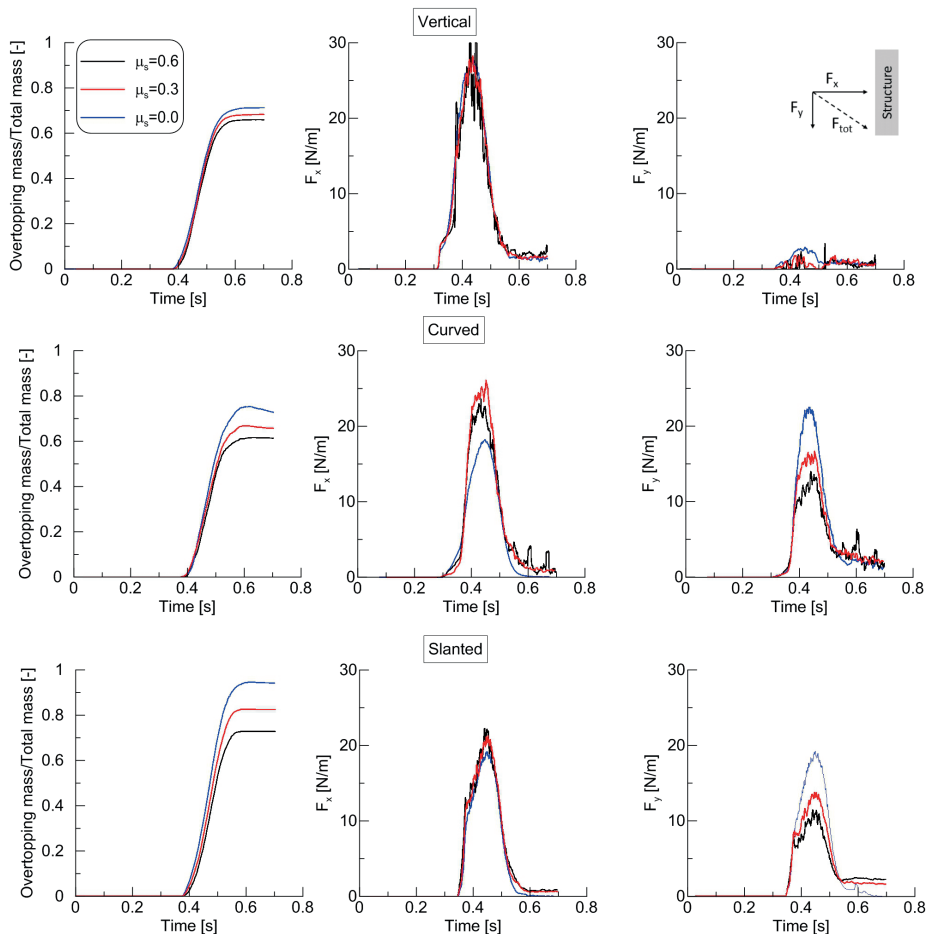


Figure 6: Effect of structure friction coefficient on overtopping mass (left column) and forces (central and right columns) for different shapes

CONCLUSIONS

The MPM is a powerful tool to study landslides of the flow type and their interaction with structures. The method reproduces with good agreement the runoff of a granular flow observed in a small scale experiment.

The impact forces on structures of different shape can be calculated; moreover, the roughness of the surface can be included. This makes the MPM a valuable tool to support the design of mitigation measures. Indeed, simplified methods cannot evaluate the impact forces taking into account the 3D structure geometry and surface properties.

For the considered example, it is shown that the vertical wall is the most effective shape in limiting soil overpassing, but the high horizontal impact forces might compromise its stability. In contrast, the curved and the slanted dam benefit of a stabilizing vertical component of the impact force.

This study considers dry granular flows interacting with rigid structures, further developments of the research will include the soil-water interaction in saturated flow as well as flexible and permeable structures.

REFERENCES

- Alonso, E. E., & Zabala, F. (2011). Progressive failure of Aznalcóllar dam using the material point method. *Géotechnique*, 61(9), 795–808.
- Andersen, S., & Andersen, L. (2010). Modelling of landslides with the material-point method. *Computational Geosciences*, 14(1), 137–147.
- Armanini, A., & Scotton, P. (1993). On the dynamic impact of a debris flow on structures. In *Proceedings Of The Congress-international Association For Hydraulic Research*.
- Bandara, S., & Soga, K. (2015). Coupling of soil deformation and pore fluid flow using material point method. *Computers and Geotechnics*, 63, 199–214.
- Bardenhagen, S. G., Guilkey, J. E., Roessig, K. M., Brackbill, J. U., & Witzel, W. M. (2001). An Improved Contact Algorithm for the Material Point Method and Application to Stress Propagation in Granular Material, 2(4), 509–522.
- Canelli, L., Ferrero, a. M., Migliazza, M., & Segalini, a. (2012). Debris flow risk mitigation by the means of rigid and flexible barriers - Experimental tests and impact analysis. *Natural Hazards and Earth System Science*, 12(5), 1693–1699.
- Denlinger, R. P., & Iverson, R. M. (2001). Flow of variably fluidized granular masses across three-dimensional terrain: 2. Numerical predictions and experimental tests. *Journal of Geophysical Research*, 106(B1), 553.
- Hübl, J., Holzinger, G., & Wehrmann, H. (2003). Entwicklung von Grundlagen zur Dimensionierung kronenoffener Bauwerke für die Geschiebemanagement in Wildbächen: Kleinmaßstäbliche Modellversuche zur Wirkung von Murbrechern. WLS Report 50 Band 3. Im Auftrag Des BMLFUW VC 7a.
- Hübl, J., Suda, J., Proske, D., Kaitna, R., & Scheidl, C. (2009). Debris Flow Impact Estimation. *International Symposium on Water Management and Hydraulic Engineering*, 137–148.
- Jassim, I., Stolle, D., & Vermeer, P. (2013). Two-phase dynamic analysis by material point method. *International Journal for Numerical and Analytical Methods in Geomechanics-numerical and Analytical Methods in Geomechanics*, 37, 2502–2522.

- Leonardi, A., Wittel, F. K., Mendoza, M., Vetter, R., & Herrmann, H. J. (2014). Particle-fluid-structure interaction for debris flow impact on flexible barriers. *Computer-Aided Civil and Infrastructure Engineering*, in press.
- Moriguchi, S., Borja, R. I., Yashima, A., & Sawada, K. (2009). Estimating the impact force generated by granular flow on a rigid obstruction. *Acta Geotechnica*, 4(1), 57–71.
- Shieh, C. L., Ting, C. H., & Pan, H. W. (2008). Impulsive force of debris flow on a curved dam. *International Journal of Sediment Research*, 23(2), 149–158.
- Sulsky, D., Chen, Z., & Schreyer, H. L. (1994). A particle method for history-dependent materials. *Computer Methods in Applied Mechanics and Engineering*, 118(1-2), 179–196.
- Vermeer, P. A., Sittoni, L., Beuth, L., & Wieckowski, Z. (2013). Modeling soil-fluid and fluid-soil transitions with applications to tailings. In *Tailings and Mine waste* (pp. 305–315). Banff, Alberta, Canada.
- Yerro, A., Alonso, E. E., & Pinyol, N. M. (2015). The material point method for unsaturated soils. *Geotechnique*, 65(3), 201–217.
- Zanuttigh, B., & Lamberti, A. (2006). Experimental analysis of the impact of dry avalanches on structures and implication for debris flows. *Journal of Hydraulic Research*, 44(4), 522–534.