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IMPACT OF SATURATED GRANULAR MASSES AGAINST RIGID OBSTACLES: THE ROLE OF FLUID COMPRESSIBILITY AND FRONT INCLINATION

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Summary. In recent years, the impact of saturated granular flows against rigid obstacles has been studied by using different numerical approaches. The very low compressibility of water causes numerical instabilities when impact problems are simulated. In this work, a sensitivity analysis has been done by using a Material Point Method code to assess the influence of fluid compressibility and front inclination on numerical results. When the mass front is inclined, fluid bulk modulus does not significantly affect the solution and can be reduced to speed up the computations and reduce spurious numerical oscillations.

1 INTRODUCTION

Flow-like landslides are extremely dangerous phenomena, characterized by (i) massive amounts of material involved, (ii) high velocities, and (iii) long distances travelled. These events often involve saturated granular masses, typically triggered by rainfall, glacial melting, or dam breaks. During their propagation, they can impact obstacles such as sheltering structures (walls, embankments, etc.), buildings, or bridge piers, transmitting high impact forces.

Recently, numerical approaches capable of dealing with both large displacements and dynamic problems have allowed the numerical simulation of impacts, individuating the factors influencing the maximum impact force and its temporal evolution (e.g. [1,2])

When dealing with saturated granular masses, the high bulk modulus of water ($K_l = 2200 MPa$) can pose difficulties in solving the boundary value problem. If an explicit integration scheme is considered, assuming water as a very low compressible fluid makes necessary the use of a very low critical timestep. To speed up calculations, some authors have proposed to treat the water as incompressible [3] or to assume a reduced bulk modulus [4,5].

In this work, the influence of fluid compressibility and front inclination on the dynamic flow-obstacle interaction is discussed. Despite more advanced constitutive relationships for saturated granular media under dynamic actions are available in literature (e.g. [6]), in this work, the role of water compressibility is discussed by considering both a simplified single-phase binghamian rheology and a simplified double phase elastic-perfectly plastic model.

2 NUMERICAL MODEL

The numerical analyses were performed by using the open-source code ANURA3D, considering both single and double point MPM formulations [7]. As in [2], the impacting granular mass is generated just behind the obstacle with an initial uniform porosity $n_0 = 0.45$. and velocity for both the solid and the fluid phases $u_0 = 8m/s$. It is assumed to be prismatic $15m$ long and $3m$ high, with vertical or inclined front ($\alpha_0 = 90 - 75°$, respectively). Plane strain conditions were assumed. The state of stress in the granular mass is initialized through a K_0 procedure and water pressure is assumed to be initially hydrostatic ($K_0 = 1$ is considered since the material is assumed to initially behave as a fluid). Base and wall are imposed to be rough by constraining both horizontal and vertical displacements along them, since the implemented contact algorithm in ANURA3D is not compatible with the double point formulation.

The MPM discretizations used are shown in Figures 1 and 2. An unstructured mesh was employed with 6 material points (MPs) per element initially occupied by the granular mass. For the double point formulation, 6 MPs per phase per element were considered, and initially, the positions of both liquid and solid MPs were assumed to coincide.

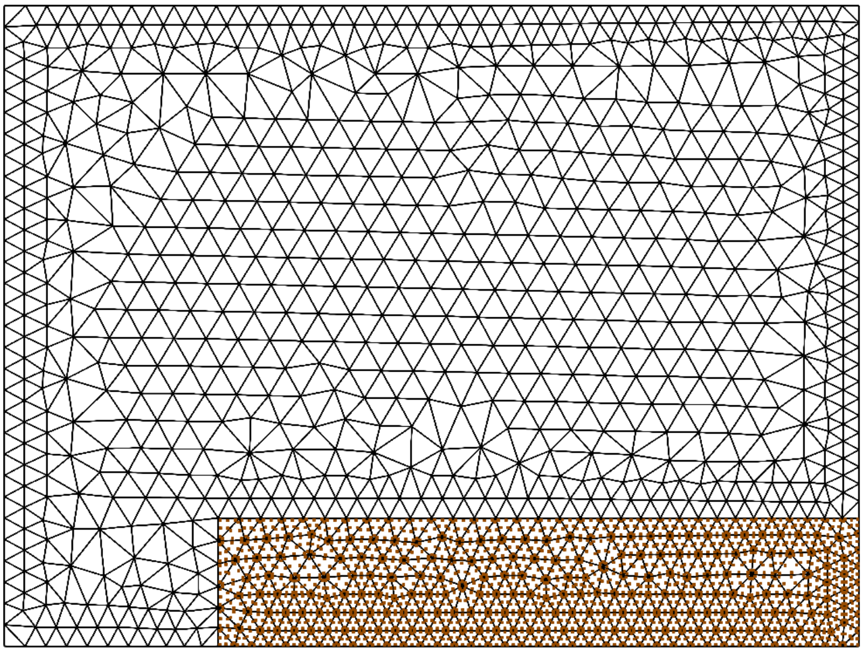

Figure 1: MPM discretization of the model considering vertical front: mesh and MPs distribution.

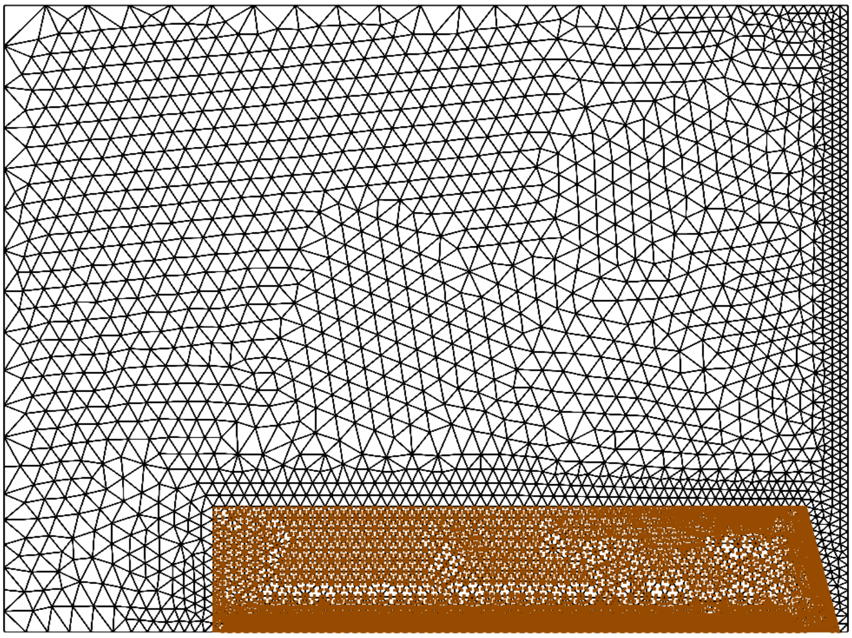

Figure 2: MPM discretization of the model considering inclined front: mesh and MPs distribution.

The analyses of the impact of saturated granular masses have been performed by considering the mixture to be:

- single-phase (SP). A compressible Bingham model has been used;
- double-phase (DP). An elastic-perfectly plastic Mohr-Coulomb model for the solid phase coupled with a compressible Newtonian model for the liquid phase, implemented considering a double point formulation (MC), has been employed.

In both cases, the fluid bulk modulus K_l (corresponding in the SP case to the mixture volumetric stiffness and in the DP case to the water volumetric stiffness) has been varied, whereas the others constitutive model parameters have been fixed as follows.
The yield stress τ_0 and the viscosity μ_0 for the Bingham SP model have been fixed according to the empirical relationships proposed by [8], assuming that both these two parameters increase exponentially with solid concentration ν_0:

$$\tau_0 = 0.251 \cdot e^{0.132\nu_0} \tag{1}$$

$$\mu_0 = 0.0112 \cdot e^{0.163\nu_0} \tag{2}$$

In this case, since $\nu_0 = 1 - n_0 = 0.55$ was assumed, the two parameters result $\tau_0 = 357Pa$ and $\mu_0 = 87.63Pa \cdot s$.
In the DP case, for the solid phase, a linear elastic law has been assumed (Young modulus $E = 24\ MPa$ and Poisson coefficient $\nu = 0.2$), whereas the yield function is assumed to be purely frictional (friction angle $\phi' = 35°$) and plastic volumetric compliance is assumed to be null (dilatancy angle $\psi' = 0°$). For the liquid phase viscosity $\eta_0 = 0.001\ Pa \cdot s$ is imposed.

3 NUMERICAL RESULTS

In this Section, the influence of the choice for K_l is discussed. Impact tests considering both SP and DP models have been performed considering the real water bulk modulus ($K_l = 2200MPa$) and a reduced one ($K_l = 22MPa$). Numerical results have been used to discuss the influence of fluid compressibility on the evolution with time t of impact force F in the case of both vertical and inclined fronts (Section 3.1) and to highlight the numerical issues arising from this choice (Section 3.2).

3.1 The role of fluid bulk modulus K_l

In Figures 3 and 4, numerical results in terms of total horizontal force F versus time t are reported for the case of vertical ($\alpha_0 = 90°$) and inclined ($\alpha_0 = 75°$) fronts, respectively.
It is evident that the maximum impact force value is significantly larger in the case $\alpha_0 = 90°$. In addition, in case of vertical fronts (Figure 3), the maximum impact force is significantly larger in case $K_l = 2200MPa$, whereas in case of inclined fronts (Figure 4) the impact force only slightly depends on fluid compressibility. This is because in case $\alpha_0 = 90°$, the granular mass maintains contact with the vertical obstacle along its entire height. Consequently, the impacting mass is travelled by a compressive wave, mainly inducing a material volumetric compaction. Differently, in case $\alpha_0 = 75°$, the initial contact between impacting mass and obstacle takes place in a single point at the base and only gradually the contact area expands with time. This implies that, in this second case, the mechanical behaviour of the impacting mass is governed by not only its volumetric stiffness, but also by its deviatoric one.
Additionally, for vertical fronts with $K_l = 22MPa$, the initial SP $F - t$ curve slope is significantly lower. This is because in the SP case the reduction in K_l directly modifies the volumetric stiffness of the mixture; in contrast, in the DP case, the reduction in K_l reduces the contribution of wáter but does not modifies the volumetric stiffness of the solid. This is confirmed by Figure 5, in which for the DP case, the contributions of wáter and solid are illustrated separately.
As was expected, in case of inclined fronts (Figure 6), the weight of wáter and solid contributions markedly changes: since deviatoric stiffness becomes important, the solid contribution seems to be dominante even for a not negligible inclination ($\alpha_0 = 75°$).

3.2 Numerical observations

In case of inclined fronts (Figure 4), spurious numerical oscillations are observed in the temporal evolution of the impact force, which are not present in the case of vertical fronts (Figure 3). These oscillations are due to the grid-crossing error [9], known for affecting MPM numerical results. In the case of vertical fronts, this error seems not to affect numerical results since initial impacting mass/obstacle contact area does not change over time, and Material Points (MPs) do not pass from one element to another.
In case of inclined fronts, the reduction in fluid bulk modulus is shown to be beneficial for reducing these spurious oscillations (Figure 4). In the DP case, oscillations affect the pore wáter pressure value. Analogously to what observed in the SP case, a reduction in K_l mitigates these oscillations but does not change severely the global response (Figure 6a).

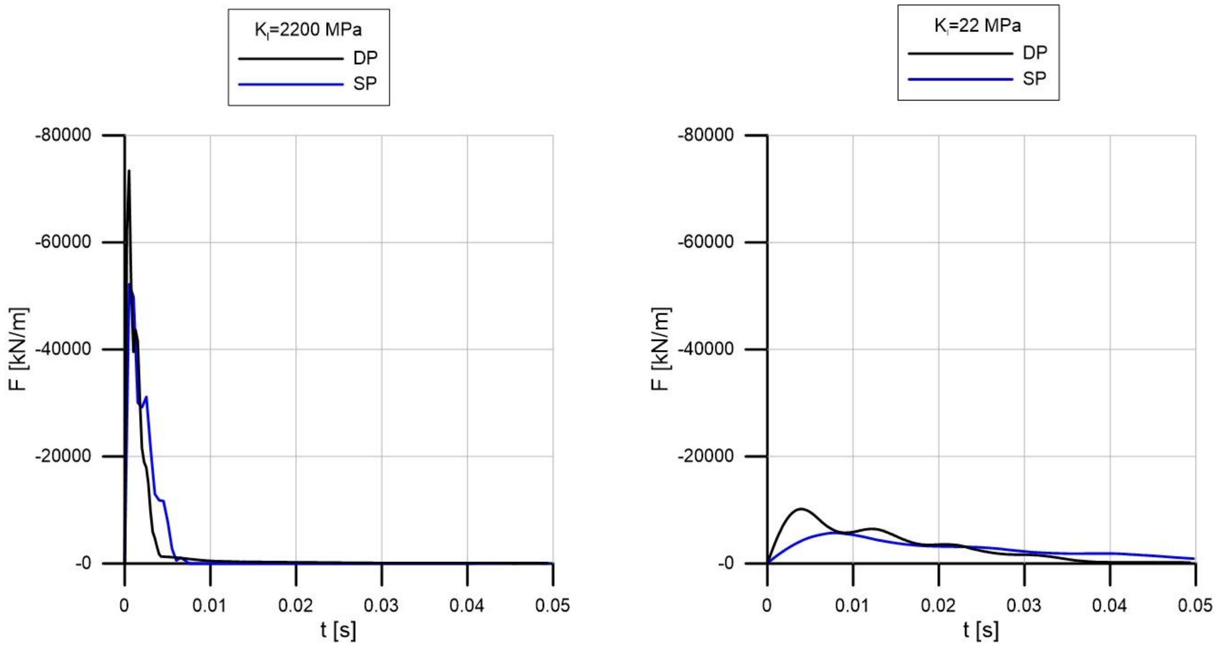

Figure 3: Temporal evolution of the impact force: influence of fluid bulk modulus in case of vertical fronts a) real and b) reduced fluid bulk modulus.

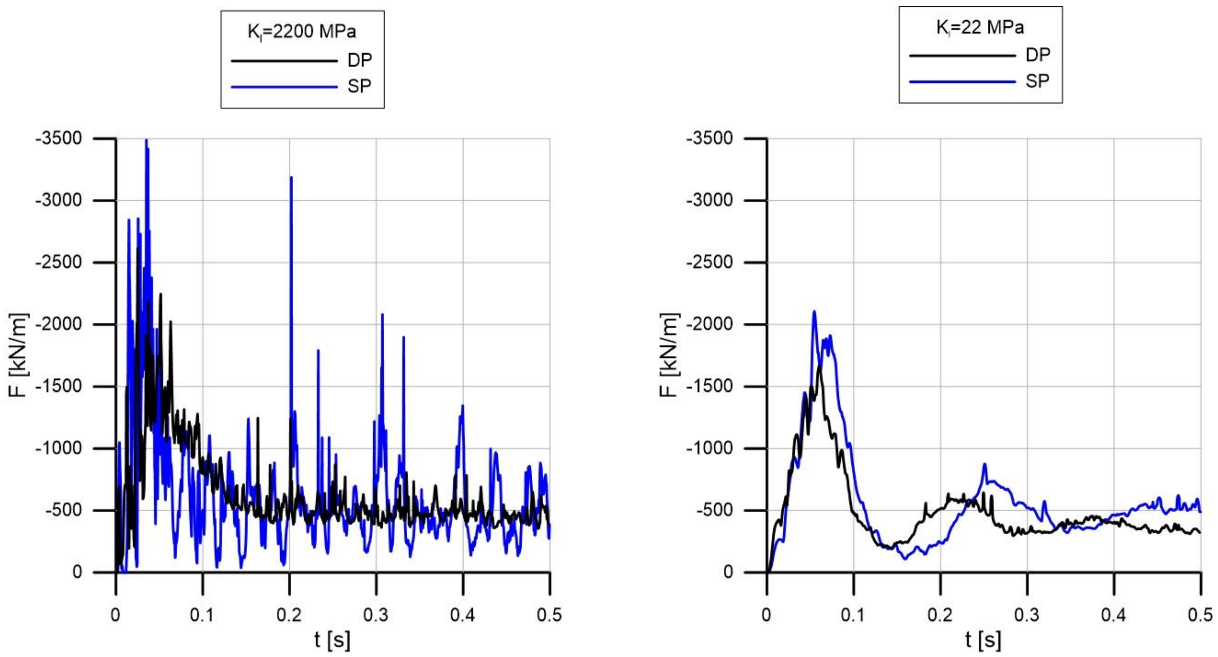

Figure 4: Temporal evolution of the impact force: influence of fluid bulk modulus in case of inclined fronts a) real and b) reduced fluid bulk modulus.

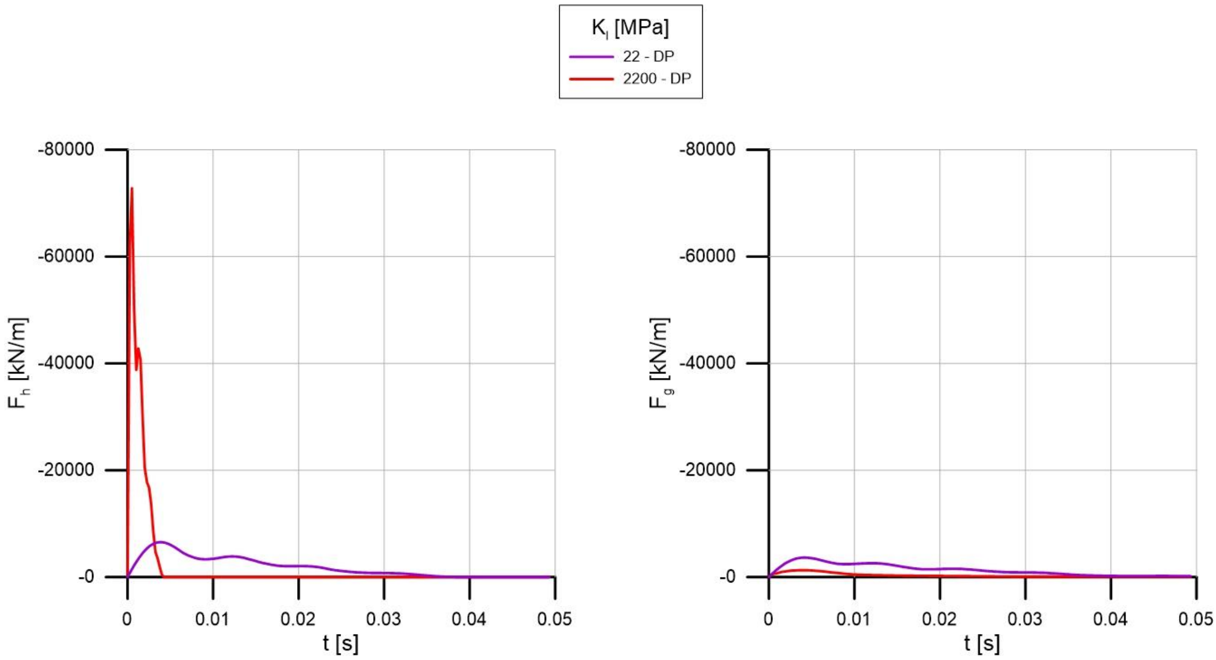

Figure 5: Temporal evolution of the impact force: influence of fluid bulk modulus in case of vertical fronts a) liquid and b) solid contributions to the total impact force.

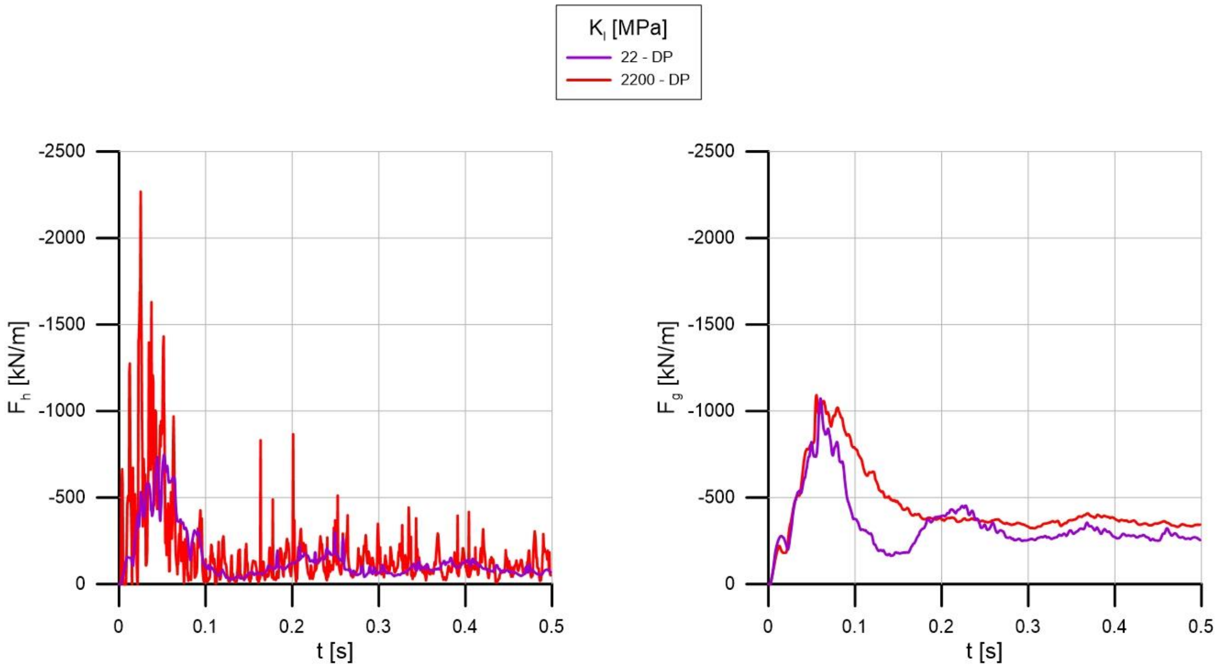

Figure 6: Temporal evolution of the impact force: influence of fluid bulk modulus in case of inclined fronts a) liquid and b) solid contributions to the total impact force.

4 CONCLUDING REMARKS

In this work, by employing the Material Point Method and considering simplified constitutive models/rheologies, a sensitivity analyses has been done to assess the influence of fluid compressibility and front inclination on numerical results concerning saturated granular masses impacting against rigid obstacles.

The numerical results have revealed that, in case of saturated masses, front inclination affects severely the maximum impact force, since the role of mixture volumetric stiffness changes according to mass front inclination. For vertical fronts, the role of solid phase, when a double-phase approach and real water bulk stiffness are employed, is negligible, since deviatoric phase stiffnesses do not influence the maximum impact force. In contrast, for inclined fronts, water and solid contributions become comparable.

In case of inclined fronts, the numerical results are affected by non-physical oscillations, due to grid crossing. Such a numerical instability has been shown to be reduced for smaller values of water volumetric stiffness, in case of DP model, and for smaller mixture volumetric stiffness, in case of SP model.

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