CSMA 2019
14ème Colloque National en Calcul des Structures
13-17 Mai 2019, Presqu'île de Giens (Var)

LMGC90[a] & MigFlow[b]

F. Dubois [1,2], R. Mozul[1,2], M. Constant[3], N. Coppin[3], J. Lambrechts[3], V. Legat[3]

[a] **https://git-xen.lmgc.univ-montp2.fr/lmgc90/lmgc90_user/wikis/home** Open source CECILL license (i.e. GPL).
[b] **https://www.migflow.be** Open source GPLv3 license

[1] *LMGC, CNRS, Univ. Montpellier, Montpellier, France*
{frederic.dubois,remy.mozul}@umontpellier.fr
[2] *Laboratoire MIST, CNRS - IRSN - Univ. Montpellier*
[3] *Institute of Mechanics, Materials and Civil Engineering, UCLouvain*
{matthieu.constant,jonathan.lambrechts,vincent.legat,nathan.coppin}@uclouvain.be

Résumé — LMGC90 is an open platform dedicated to the modelling of large collections of interacting objects (2D/3D). It aims at modelling objects of any shape with various mechanical behaviour and to take into account interaction laws as complex as necessary. Furthermore multiple physics couplings (thermal effects, fluids, *etc*.) are progressively taken into account.

Migflow is a free software aiming at simulating immersed granular flows. It can use either a fast simple library for the grain simulation (only disk/sphere with frictional contact), or use LMGC90 to be able to simulate more complex granular media.
Mots clés — contact, dynamics, multiple physics, DEM, FEM, Open source

1 LMGC90

LMGC90 is an open source research software which developments are coordinated by LMGC. It aims at modelling large collection of objects of any shape with various mechanical behaviour and to take into account interaction laws as complex as necessary.

1.1 Main features

1.1.1 Bulk behaviour of objects

Objects may be rigid or deformable (small, floating frame or large transformation) by means of the finite element method. In this case various behaviour laws are available, mainly provided by Matlib [1] : elastic, hyper-elastic, viscous, elasto-plastic, *etc*.
Couplings with other physics are available among them thermomechanics or poromechanics.
Instead of using the build-in FEM functionalities, it is possible to use an external finite element software/library like Pelicans [2] or Code_Aster.
In the same way, external software simulating Multi-Body-System can provide dynamical systems, as illustrated by the coupling with Robotran software [3].

1.1.2 Shape of objects

Objects may be described with simple convex primitives (disk/sphere, polygon/polyhedron, *etc*), compound of these primitives or general poly-line/triangulated surface.
Contact detection is performed for most combination of primitives and provides a list of binary interactions. There are several possibilities to perform this step which depend on the primitives to detect, especially regarding polyhedra.

1.1.3 Interaction laws

A large set of mechanical interaction law is available either between rigids or deformable bodies. The most fundamental one is frictional contact (with or without restitution). There are also several cohesive laws (capillarity, damage, brittle, etc.) and wire or rod to describe tensegrity structures.

1.1.4 Analysis

Mainly based on the **Non Smooth Contact Dynamics** method, the strategy implemented within the software works like a predictor/corrector scheme. An implicit time integration scheme is used to bodies motion (θ-scheme). Then, after detecting the active interactions, an implicit contact solver is used to determine the reactions used to correct the bodies' velocity. Available contact solvers are Non-Linear Gauss-Seidel (NLGS) or Jacobi, which allow to mix any kind of contact laws in the same simulation. Using Siconos-Numerics library [4] one has access to additional contact solvers (Alart-Curnier global solver, *etc*).
Thanks to a modular architecture other strategies may also be implemented : quasi-static, explicit dynamics.
Applications with a large number of interacting bodies are reachable through multi-threading (OpenMP).

1.2 User features

1.2.1 Pre-processing

A built-in scriptable preprocessor aims at helping to define : geometries, material properties, numerical modelling options, boundary conditions, *etc*.
Specific drivers are available for granular materials, masonry structures and finite element models.
External tools, as Gmsh or Resoblok, may be used. Any software with a Python API can be easily used.

1.2.2 User Interface

All stages of a simulation are finely driven by Python scripts ; moreover Python interface provides an access to LMGC90 database, which offers the possibility to manage complex, customized, simulations.
In the meantime, advanced developments benefit from a Fortran90 modular software design which preserves performance.

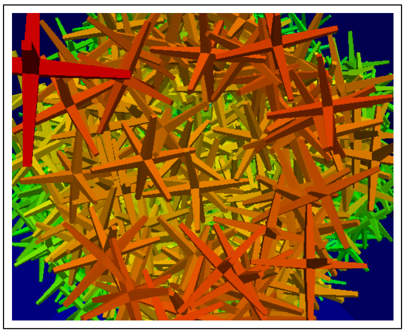
1.2.3 Post-processing and visualization

Extraction of data is managed by LMGC90 ; plots are performed by external tools (MatPlotLib, Grace, *etc*). For visualization, VTK files are written so Paraview, or any other software supporting this format (like Mayavi or Visit), can be used.

1.3 An open platform for research

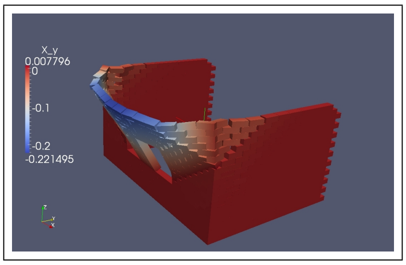
LMGC90 is dedicated to scientists for research developments and applications. LMGC team provides hot-line on the software (through a mailing list), organize free training courses and user days. All these information are available on
`https://git-xen.lmgc.univ-montp2.fr/lmgc90/lmgc90_user/wikis/home`
Past recent years contributors : F. Dubois, R. Mozul, M. Renouf, L. Bichet, F. Peralès, E. Delaume, F. Cherblanc, F. Rozar, D. Ambard, N. Docquier, O. Lantsoght.

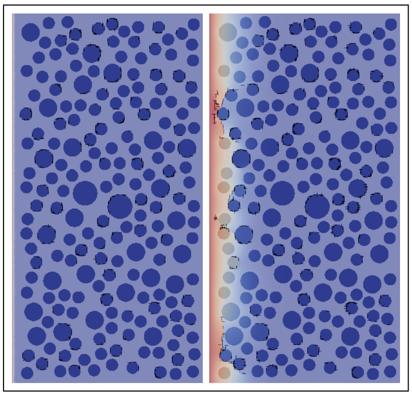
1.4 Some Fields of Application



Granular Material, from rheology to structure : a typical use of LMGC90 concerns the study of the rheology of granular materials. As an example the figure shows a sample made of the deposit of non-convex rigid bodies.

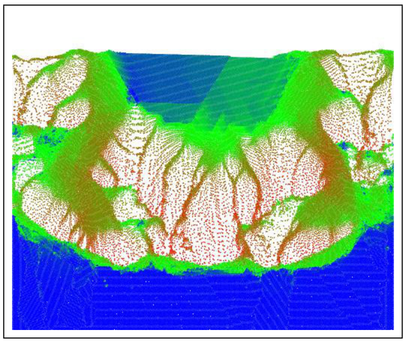
Masonry structures : modelling allows assessing the stability and the safety of masonry structures under static loads or dynamical natural risk (earthquake, landslide, etc) taking into account the influence of the design pattern and the joint behaviour.

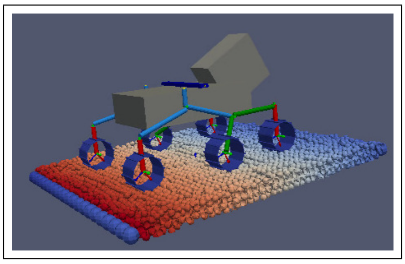




Fracture of heterogeneous media : Using a Frictional Cohesive Zone Model or eigen-erosion method, fracture can be modeled, at microscopic or mesoscopic scale, from initiation to post-failure. Recent developments permits to take into account effects of the thermal solicitations.

Multiple physics couplings : Various physics may be considered at different scales such as thermal coupling, fluid particle interaction, electrical conductivity. Furthermore modeling multiphase flow in deformable porous is also available.





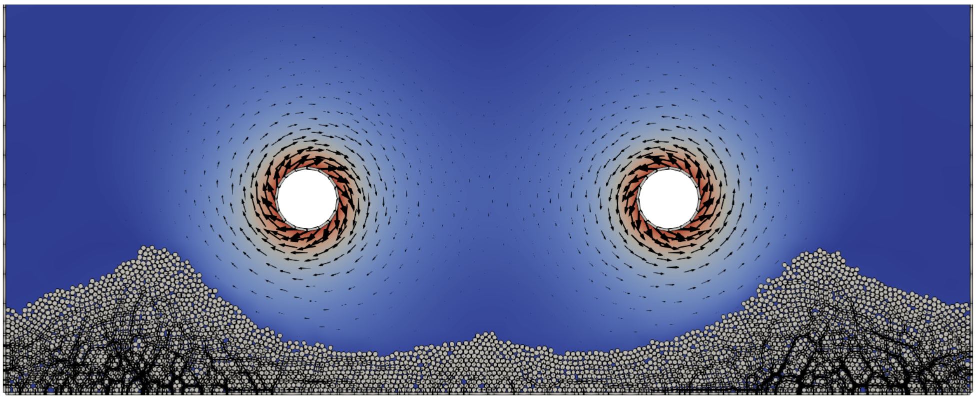
Coupling with Multi-Body-System : simulations with software such as Robotran to correctly simulate the behavior of controlled complex systems in interaction with a large number of particles are also possible.

2 MigFlow

The main goal of the MigFlow Project is to develop a handy and fast free software to simulate immersed granular flows presenting a large discrepancy in the volume fraction of grains, going from pure liquid to dense granular media. Based on a multiscale representation of the mixture media, the MigFlow Software aims to give insights into the influence of microscopic inhomogeneities on the macroscopic flow behaviour [5].

A Coarse scale model for the fluid...

MigFlow makes use of a representation of the fluid at a greater scale than the grain scale. The flow dynamics in the space between the grains is computed from average Navier-Stokes equations. The volume fraction of fluid is computed on control volumes, far bigger than a grain to smooth the spatial distribution of the grains, and it is used to average punctual field values to obtain a continuous representation of the mixture flow.



and a fine scale model for the grains...

Some models represent grains as a continuum phase but grains are able to collide and fill a compact and closed volume in the space. Geometrical microscopic configuration of the granular matrix greatly affects the macroscopic behavior of the medium. In the MigFlow model, grains are considered at their scale as rigid discrete bodies. Forces are computed at grains centre location to compute their dynamics and a contact solver is used to prevent overlapping.

linked with a momentum balance law

The connection between the fine scale representation of the grains and the coarse scale representation of the fluid flow require an empirical force to model the momentum transfer between the discrete and the continuous phases. This closure term is a viscous force taking into account the relative velocity between the grains and the fluid, the presence of neighbor grains and many other physical parameters.

2.1 Complementary numerical methods to ensure speed and accuracy

Industries often requires fast computations to calibrate some processes. Fully continuous representations of immersed granular flows allow fast computations but are unable to give insight to the microscopic flow effects due to the grains configuration (e.g. clog in a pipe) but the numerical cost of fully resolved models often put the brakes on their use. The hybrid multiscale CFD-DEM model implemented in the MigFlow Software conciliates the advantages of the two worlds.

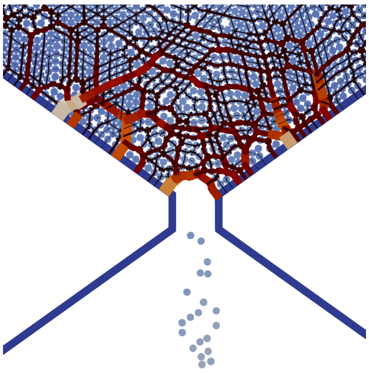
On one hand, the continuous representation of the mixture give the possibility to cover the entire domain with a continuous mesh, preventing the numerical cost of a mesh reconstruction on the fluid phase at each grain displacement or the use of a penalty method. The transition between the pure fluid regime and the granular medium regime is covered by the averaging process in the modified Navier-Stokes equa-

tions. The average variables taking into account the fluid volume fraction enable a continuous transition between the two flow regimes.
On the other hand, grains dynamics can be solved by the Discrete Element Method computing the trajectories and forces in a Lagrangian way. Moving the grains inside the granular matrix requires to know all the forces applied on them, including the contact reaction if they collide their neighbors. MigFlow is provided with a fast and sleek contact solver to compute steady states without interpenetration of moving spheres collections or it can be plugged with LMGC90 to offer a large range of contact laws.

Finite element method for the fluid equations

The discretisation method we choose for the CFD part is the Finite Element Method. Immersed granular flows are encountered in many different fields like geology (mud volcanoes, hydrothermal vents, etc). Natural geometries in which fluid-grain mixtures flow could be just as complex as the industrial geometries in applications like gas cyclone separators, ploughshare mixers, semi-autogenous grinding mills, tower mills, etc. Finite Element Method is easily applicable to complex geometries with which grains interact thanks to the use of unstructured grids. Moreover, it is easy to adapt the mesh in order to refine it around the area of interest to accurately capture flow fields during the grains motion.

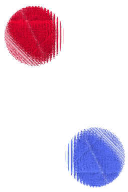
Discrete element method to solve contacts



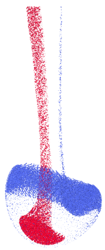
Event-driven methods are not applicable to dense granular media that requires the use of a Time-stepping method, solving all the contacts happening during a given time step. The nonsmooth contact dynamics method totally bans the interpenetration of the grains. Non-linear Gauss-Seidel iterations are used to compute contact reactions to verify the contact laws. The nonsmooth contact dynamics give at each time step the reaction contact network of a grain with his neighbors and the boundaries. This method gives insight into microscopic effects due to grains configuration with a fixed time step conserving the advantage of the coarse scale fluid model.

2.2 Results

Interacting drops made of grains with an horizontal offset

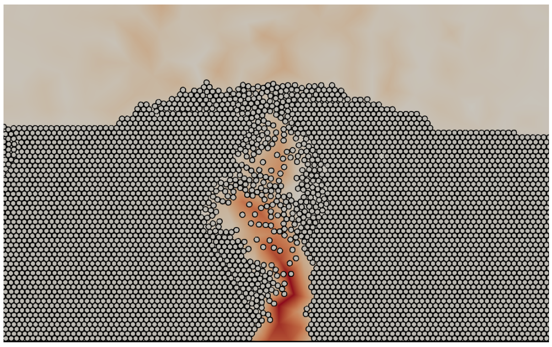


Lets consider two drops made of grains falling one behind another with an horizontal offset in a viscous fluid. The classical evolution of each Stokes drop is perturbed by the presence of the other drop. Initially, each drop interact with the fluid causing a circulating velocity field around them.

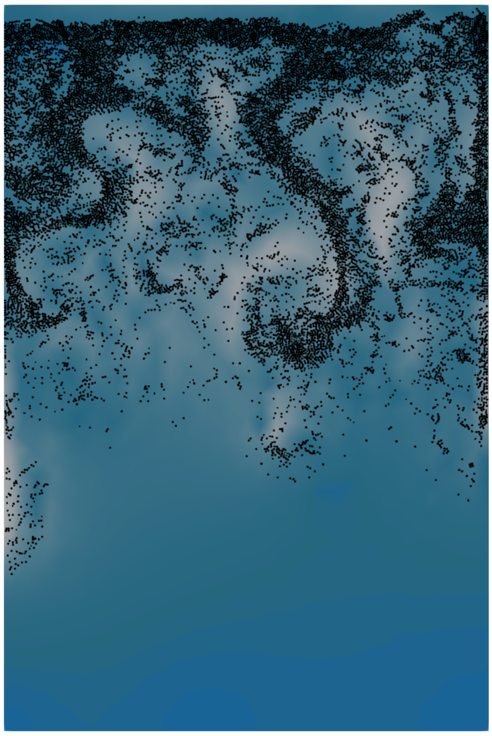


The velocity field of the lower drop attracts the upper drop forcing the upper drop to lengthen while the lower one flattens. The interaction between the two circulating velocity fields forces the upper drop to drill the lower one and cross it. Then, the initially upper drop slows down and wrap the initially lower one. The grains mixed together to form an unstable open torus that could break up into two or three droplets.

Injection of water in immersed granular matrix



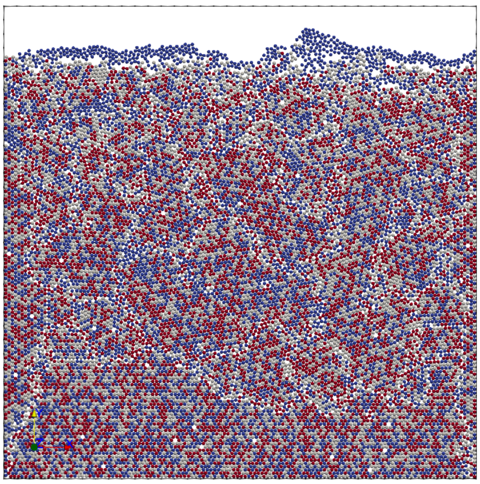
Fluidization of immersed granular flows is an important technique due to its use in drying, segregation, mixing, airing… processes. It is also possible to use air injection to deteriorate contaminants in soil remediation. Numerical simulations are of considerable interest to study injection area and observe invasion patterns. Particularly, it seems to be interesting to estimate, through simulations, what is the injection flow rate required to fluidize the granular bed. Studying the fluidization area, it is possible to observe that the injection flow rate required to fluidize the granular bed is greater than the injection flow rate required to maintain the fluidized area. This hysteretic behavior is often attributed to the friction that creates grains arches in the granular matrix. However, for granular matrices with equal radius grains geometrical effects are in competition with frictional effect. It explains why the hysteresis can also be observed without friction between grains.

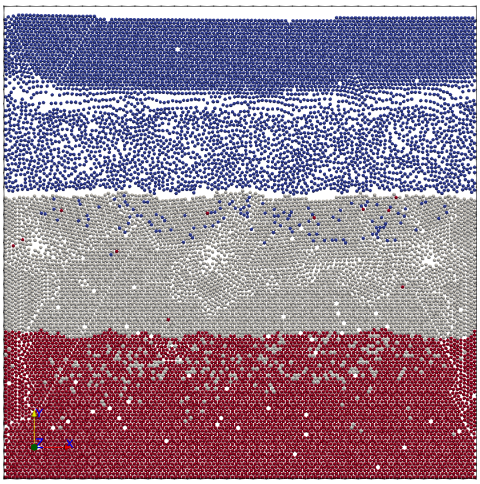


Fall of Grains in Fluid

Pack of grains don't fall linearly in fluid. Viscous effects create Rayleigh-Taylor instabilities. It create circulations and vortices slowing down the settling velocity of the pack. Simulation of deposits can be used in some chemistry processes or in geology to study the deposition of sand or rocks on the ocean floor.

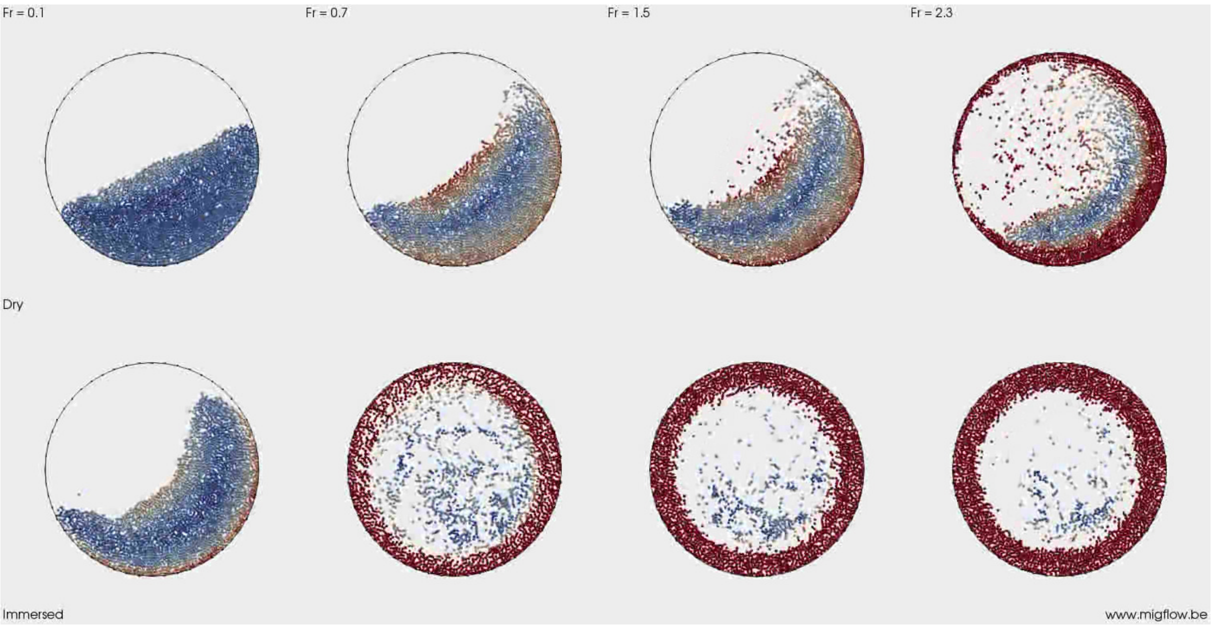
Sorting grains by successive injection of fluid





Grains with different radii and densities have different settling velocities in fluid. It can be used to sort grains with respect to their mass or shape. Industrial processes can make use of this property. Injecting water at the bottom of a deposit suspends grains in the fluid. This process can be repeated indefinitely to artificially create successive settling of grains. Starting from an unsorted granular matrix, it is possible to sort the grains to isolate grains having the desired property.

Granular motion in tumbling mills



Tumbling mills are widely used in the industry in various processes such as mixing, centrifuging or crushing particles. The motion of the granular phase inside the mill has been shown to depend on the Froude number, that quantifies the centrifugal acceleration with respect to gravity. As this number increases, the grains undergo the four different regimes that can be seen in the upper part of the video below (respectively rolling, cascading, cataracting and centrifuging) that have different industrial applications. In the presence of a fluid, shown for the case of sand in ethanol in the lower part of the video below, the transition between the regimes is much faster. Indeed, at a low Froude number (0.1) the grains already are in a cascading regime, and for the above Froude numbers they experience centrifuging, with time to complete solid rotation decreasing with increasing Fr.

Références

[1] Laurent Stainier, Frédéric Dubois, and Robert Peyroux. MatLib, une bibliothèque portable de modèles constitutifs pour la mécanique non-linéaire des solide : concepts et implémentation. In *6ème Colloque National en Calcul des Structures*, 2003.

[2] Frédéric Perales, Frédéric Dubois, Yann Monerie, Bruno Piar, and Laurent Stainier. A NonSmooth Contact Dynamics-based multi-domain solver Code coupling (Xper) and application to fracture. *Revue européenne de mécanique numérique*, 19(4) :389–417, jul 2010.

[3] Olivier Lantsoght, Paul Fisette, Frédéric Dubois, Olivier Brüls, and Nicolas Docquier. Coupling multibody system and granular dynamics application to a 2D benchmark. In *Powder and Grains*, 2017.

[4] Vincent Acary, Maurice Brémond, and Frédéric Dubois. Méthodes de Newton non-lisses pour les problèmes de contact frottant dans les systèmes de multi-corps flexibles. In *13e Colloque National en Calcul des Structures*, pages 1–8, 2017.

[5] Matthieu Constant, Frédéric Dubois, Jonathan Lambrechts, and Vincent Legat. Implementation of an unresolved stabilised FEM–DEM model to solve immersed granular flows. *Computational Particle Mechanics*, 2018.