11.6 Dynamics of granular materials (regolith)

A. Context and state of the art

Asteroids range in size from small (~10 m) boulders to bodies 1000 km across with consequently larger range in mass, from a few thousand tons to 10^{21} kg, which is still only a fraction of a percent of the mass of the Earth. As a result, from planets to asteroids, surface gravities vary by many orders of magnitude. The same can be stated, although to a lesser extent, for bodies like Mars and the Moon, whose surface gravities are also smaller than that of Earth's. Surfaces of planets and small bodies of our Solar System are often covered by a layer of granular material, called regolith, which can range from fine grains to a gravel-like structure of varying depths. Granular material dynamics is a field of intensive research with a range of industrial applications. A variety of laboratory experiments and numerical methods have been developed to study granular dynamics, but the applications of these experiments to problems related to celestial body surfaces have only recently begun. Applications to the preparation of space missions are exposed in Theme 8. Here we present the application to the general understanding of small body and planetary surfaces, which obviously is also crucial to interpret space mission data on surfaces.

The dynamics of granular materials are involved in many events occurring during planetary and small-body evolutions thus contributing to their geological properties. It is therefore important to characterize how granular materials respond to various stresses in various gravitational environments adapted to small bodies and planets. Bodies with low surface gravity can be very sensitive to processes that appear irrelevant in the case of larger planetary bodies. For instance, seismic vibration induced by small impacts can occur throughout a small body and can be at the origin of motion of its granular surface. Such a mechanism has been proposed to explain the lack of very small craters both on the 17 km-size asteroid Eros and the 320 m-size asteroid Itokawa (e.g. Michel et al. 2009). However, the efficiency of these vibrations to generate motion, and the way the regolith will move, are poorly known and require better understanding of granular dynamics in the low-gravity environment. Moreover, understanding how granular materials, as a function of their properties (angle of friction, size distribution of their components, friction coefficients, cohesion etc.), behave on a small body's surface and react to different kinds of stresses is of great interest for the interpretation of surface images sent by spacecraft. For instance, it can allow inferring the unobserved properties of the granular material based on observed features (e.g. the grain size distribution and/or friction coefficients at the origin of a landslide for which the angle of repose is measured) and for the design of landers and sampling devices of space missions (see A8.1, 8.2).

Flow in response to stress can be described by continuum models under certain conditions. For dense granular flows, continuum models (Jop et al. 2006) are able to predict steady complex shear dominated flows (G.D.R. Midi 2004), unsteady free surface flows (Lagrée et al. 2011, Riber et al. 2016) and shear bands due to nonlocal rheology (Henann and Kamrin 2013). However, many processes cannot be captured yet using classical continuum approaches.

Indeed, while constitutive equations linking stress and strain are empirically known for most granular interactions on Earth, they involve a wide range of forces from gravity to air- grain coupling to liquid bridges due to humidity, to electrostatic effects, to surface shape and chemistry-dependent van der Waals forces. However, the inferred scaling of these equations to the gravitational and environmental conditions on other planetary bodies such as asteroids, as discussed in Scheeres et al. (2010), is currently untested.

Various numerical codes have been developed to study granular dynamics (Mehta 2007). Some of these codes are purely hydrodynamic in the sense that the granular material is represented as a fluid or as a continuum (e.g., Elaskar et al. 2000). However, the homogenization of the granular-scale physics is not necessarily appropriate and in most cases the discreteness of the particles and the forces between particles (and walls) need to be taken into account. Other codes, such as soft- and hard-sphere molecular dynamics codes, or codes using the Discrete Element Method (DEM) have also been developed, all of which treat the granular material as interacting solid particles (e.g. Cleary & Sawley 2002; Kosinski & Hoffman 2009; Sanchez & Scheeres 2011, Schwartz et al. 2012).

We implemented the Soft-Sphere-Discrete Element Method (SSDEM) in our N-body code *pkdgrav* in collaboration with collaborators at the University of Maryland in the USA and tested this implementation by confrontation to experiments (Schwartz et al. 2012, 2013). The code was then used for various problems related to regolith dynamics on asteroid surfaces. Here we just describe two examples of applications (those related to space missions can be found in Theme 8).

A first study of the Brazil Nut Effect (BNE) was performed in Earth and low-gravity environment (Matsumara et al. 2014). In effect, out of the handful of asteroids that have been imaged, some have distributions of blocks on their surface that are not easily explained. Therefore, we investigated the possibility that seismic shaking leads to the size sorting of particles in asteroids. Our first study consisted in simulating the evolution of a big intruder within a set of smaller grains, in a confine environment (cylinder). Among other things, we showed that in such a confine environment, the BNE is scalable for low-gravity environments and that the rise speed of an intruder is proportional to the square root of the gravitational acceleration.

Figure 1: Snapshots of a numerical simulation of the Brazil-Nut Effect (BNE), in gravity conditions of the asteroid Eros (17 km in size). Left: initial conditions showing an ensemble of small particles confined in a cylinder with a big red particle at the bottom. Middle: some instant later, as a result of oscillations undergone by the cylinder, the big particle starts rising (it can be seen in at mid-height). Right: at the end of the simulation, the big particle reached the top, showing that the BNE is also occurring in conditions of low-gravity on a timescale that is proportional to the square root of the gravitational acceleration (Matsumara et al. 2014).

We also studied whether planetary close approaches can be at the origin of regolith motion at the surface of a planetary-crossing asteroid. Our first application focused on the asteroid (99942) Apophis that will encounter the Earth at a distance of 5.6 Earth radii in 2029 (Yu et al. 2014). Apophis' close approach will be one of the most significant small-body encounter events with the Earth in the near future and offers a good opportunity for in situ exploration to determine the asteroid's surface properties and measure any tidal effects that might alter its regolith configuration. Resurfacing mechanics has become a new focus for asteroid researchers due to its important implications for interpreting surface observations, including space weathering effects. We developed a two-stage approach to model the responses of asteroid surface particles (the regolith) based on the SSDEM implementation in *pkdgrav*. A full-body model of Apophis was sent past the Earth on the predicted trajectory to generate the data of all forces acting at a target point on the surface. A sandpile constructed in the local frame was then used to approximate the regolith materials; all the forces the sandpile feels during the encounter were imposed as external perturbations to mimic the regolith's behavior in the full scenario. The local mechanical environment on the asteroid surface was represented in detail, leading to an estimation of the change in global surface environment due to the encounter. We found that catastrophic avalanches of regolith materials may not occur during the 2029 encounter due to the small level of tidal perturbation, although slight landslides might still be triggered in positions where a sandpile's structure is weak. Simulations were performed at different locations on Apophis' surface and with different body- and spin-axis orientations; the results showed that the small-scale avalanches are widely distributed and manifest independently of the asteroid orientation and the sandpile location. We also included simulation results of much closer encounters of the Apophis with Earth than what is predicted to occur in 2029, showing that much more drastic resurfacing takes place in these cases.

Members of CP4O include specialists of the granular dynamics involved both in laboratory experiments and numerical models. As we do for the impact process, we aim to enhance existing numerical models and compare them with experiments performed both at micro-g and under Earth-gravity, to validate them. Moreover, once the numerical models show their ability to reproduce those experiments, we will use them to study the dynamics of granular materials under various gravitational environments and contexts that can be encountered in the Solar System and that cannot be addressed by experiments. Our aim is to be able to improve our knowledge of small body's and planetary surface evolutions and histories based on our understanding of the dynamics of regolith at their surface. Moreover, this understanding will allow us to infer unobserved surface properties from observed ones by spacecraft, knowing that a great amount of data is expected in the coming years, thanks to space missions devoted to small bodies (See Theme 8) and planets (see Theme 9.2).

B. Current activity

Scientific issues related to the dynamics of regolith are already the topic of several current activities. In the following we only indicate a few examples along the lines of those indicated in the previous section (see Theme 8 for space mission related activities).

B.1. Brazil Nut Effect

Our previous study of the BNE considered particles in a confined environment represented by a cylinder with the presence of a big intruder. Our interest is in going beyond the classic BNE scheme (a single intruder of bigger size in a granular bed) and in looking into potential size and/or density segregation of regolith materials, and the dependency of the outcomes on material parameters. In order for our simulations to better represent actual asteroid surface conditions, we have introduced periodic boundary conditions, i.e., we have removed the simulated container of the granular bed, and at the same time, any artifacts that may arise by its presence. We have started a small set of simulations that show that the BNE also works when periodic conditions are used. We are now continuing our investigations that should allow us to get conclusions and have a paper submitted to a peer-review international journal in the coming months.

B.2. Numerical simulations of landslides: comparison with experiments

Landslides have been observed at the surface of small bodies (e.g. the asteroid Lutetia observed by the ESA space mission Rosetta). From the characteristics of the landslides (e.g. angle of repose) and simulations of the process in similar gravity conditions, we may be able to infer the properties of the granular material composing the landslides. Before applying our simulations to real asteroid cases, we have begun a long effort with Braunschweig University to build a controlled laboratory experiment of a landslide specifically to serve as a testbed for calibrating our numerical simulations to this problem. The configuration was selected to provide a test environment where particle-particle interactions were dominant, to eliminate uncertainties about how to handle particle-wall interactions. Figure 2 shows an example of a simulation of a landslide using the same conditions as the experiment: an entire box of particles is slowly tilted, and the flow of beads as a function of the angle of the box is measured. Given the simplicity of the configuration and the detailed laboratory measurements, we can explore a wide range of numerical parameters for detailed calibration. Preliminary results reproduce well the experiments and show that flow initiation requires a steeper angle as the static friction parameter is increased from 0.1 to 0.9. We are now looking at the effect of rolling friction, with a new rolling friction model that was recently implemented in our SSDEM code *pkdgrav*. Knowing how the final properties of the landslide depend on the frictional properties and size distribution of the particles will allow us to put constraints on the properties of the regolith at the origin of an observed landslide on asteroid images.

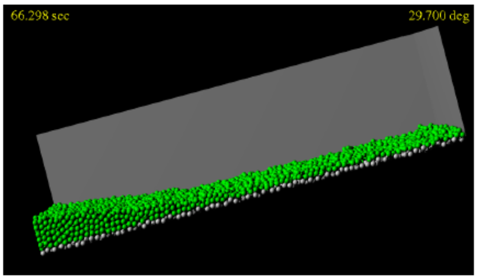

Figure 2: End-state of a simulation of a tilting bed with loose particles (green) on top of fixed particles (gray). Sustained flow initiates at a tilt angle of approximately 24 degrees for this configuration that used about 14,000 monodisperse 5 cm radius particles (half free, half fixed) on a 6 by 9 m bed. For this simulation, the static and rolling friction parameters are set to 0.1 (low friction).

B.3 Small bodies modeled as granular aggregates

Many asteroids are believed to be aggregates bounded by gravity and possibly cohesion (see A11.4). In recent years, we studied how a gravitational aggregates behaves when its spin is increased beyond the limit for losing material, and thus showed that this spin-up mechanism can put particles of a single asteroid into orbit and be at the origin of a binary system (Walsh et al. 2008). We also studied low-speed collisions between gravitational aggregates (see Fig. 3) and showed how the initial rotation influences the outcome by increasing the degree of disruption with respect to that from non-rotating bodies. We are now extending these studies to a larger range of parameter space in terms of friction coefficients (and models) between grains, grain size distribution, and cohesion (when implemented, see C.3) in order to determine how granular aggregates behave when submitted to impacts and spin-up as a function of these parameters.

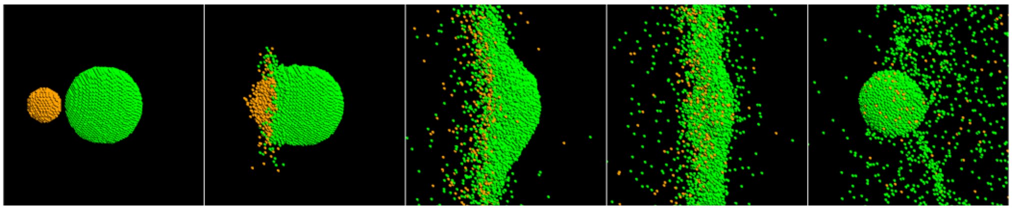

Figure 3: Simulation of a central low-impact-speed collision between two granular aggregates shown with two colors with initial rotation period of 6 hours (mean rotation period of asteroids). Active perturbations are the mutual gravitational attractions between aggregate components and contact forces between particles computed with SSDEM. (Ballouz et al. 2014).

B.4. Numerical framework for modeling of Non-Newtonian multiphase flow

The analysis of multi-materials flows has attracted considerable attention during the past few decades, particularly in view of industrial and environmental applications such as the behavior of heterogeneous granular solids, dust, powders and many others. Indeed, the combination of liquid-like and solid-like behavior, and stress inhomogeneities on the microscale are known to be challenging to simulate and thus different approaches are still investigated. We worked intensively on the alternative continuum approach, developed initially for multiphase flows. It is based on using a robust interface tracking method needed to follow efficiently and accurately the interfaces, but also to consider carefully high jump of different materials properties (different law behavior). Then, to increase accuracy, we combine it with an anisotropic a posteriori error estimator that controls the errors at the interface and in highly physical areas. Finally, a Variational Multiscale approach to solve the Navier-Stokes equations is proposed and modified to account for highly stretched elements with an anisotropic ratio of the order of O(1 : 1000). These improvements have been validated on granular flows from dry state to semi-liquid state, which turns into a Bingham yield stress model (see an example of Fig. 4).

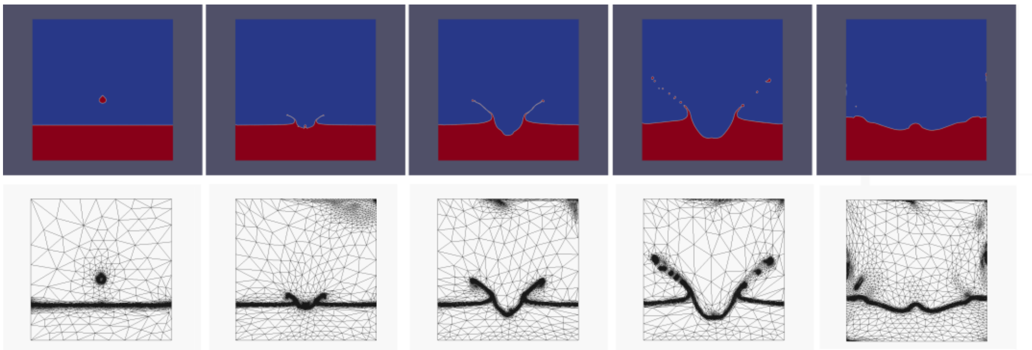

Figure 4: Droplet falling breaks surface tension and makes ripples.

B.5. Granular collapse continuum computations

We have investigated the pertinence of continuum models to predict dry (using a mu(I) model, Jop et al. 2006) and wet (using a Bingham model) granular collapse flows (Riber et al. 2015[1]) subjected to Earth gravity. We used the numerical framework proposed in B.4 to solve regularized viscoplastic flow models at high Reynolds and Bingham numbers (Riber et al. 2015[2]).

Using the same numerical framework, we have demonstrated (Riber et al. 2016) that the mu(I) rheology (Jop et al. 2006) allows predicting 2D and 3D experimental dry granular collapse scaling laws of relative spreading distance vs. initial aspect ratio (Lube et al. 2004, 2005), as shown on Figure 5.

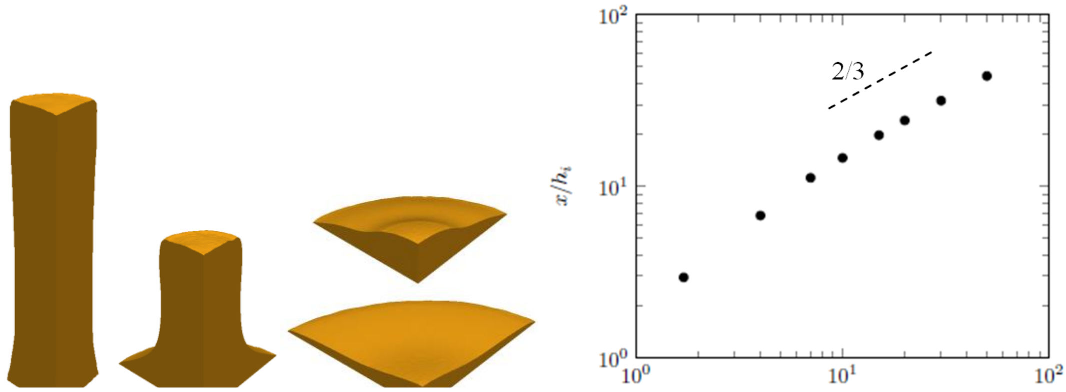

Figure 5: mu(I) computation of the shape of a granular column at t = 20%, 40%, 60% and 80% of total collapse and demonstration of the 2/3 scaling law of 2D relative spreading distance vs. initial aspect ratio.

C. Future steps

C.1 Regolith segregation on small bodies

Going forward, we aim to establish scaling laws for regolith segregation in micro-gravity environments, which take into account material properties. To better apply our results in an asteroid-related context, we plan additionally to use realistic impact-generated seismic profiles (e.g., Garcia et al. 2015) instead of the continuous sinusoidal shaking implemented until now.

C.2 Effect of planetary encounters on small body surfaces

Our previous study focused on the case of the asteroid Apophis and its encounter conditions with the Earth in 2029. However, a generalization of this study is under way, motivated by the fact that several studies speculated that tidally induced resurfacing may explain the spectral properties of near- Earth asteroids belonging to the Q taxonomic type, which appear to have fresh (unweathered) surface colors. Dynamical studies of these objects found that those bodies had a greater tendency to come close to the Earth, within the Earth–Moon distance, than bodies of other classes in the past 500 kyr. The authors speculated that tidal effects during these passages could be at the origin of surface material disturbance leading to the renewed exposure of unweathered material. Although in the case of Apophis, we found that such a global disturbance was unlikely despite its very close encounter to the Earth, we started a similar study as that for Apophis, but considering a wide range of encounter conditions (distance, encounter velocity, body's rotation) and possible surface properties (friction coefficients of the regolith, angle of repose of sandpiles on the surface, etc …). Also, we are investigating whether even slight internal perturbations in the asteroid during tidal encounters may contribute to noticeable surface motions.

C.3 Synergie between OCA and Ecole des Mines de Paris

The dynamics of granular materials can be studied by two approaches, which both have their pros and cons. Members of OCA develop simulations based on the discrete approach, in particular SSDEM, while members of Ecole des Mines de Paris develop simulations based on the continuum approach. The advantage of the latter is that it avoids the complexity of treating contact forces of each constituent of the medium and can thus be performed at low-cost in terms of computation time. The advantage of the former is that it attempts to model the complete physics of the problem, solving for contact forces between grains, which often comes at the expense of a very small time step, a wide range of parameters that need to be fixed, and a high-cost in terms of computation time. Some of the limitations of the continuum approach are already known (see A.), but having within CP4O experts in both approaches and available numerical codes will allow us to investigate deeper the range of applications of the two methods in planetary science problems. For this, we plan to compare nonlocal continuum constitutive models (Henann and Kamrin 2013) to SSDEM methods on a few test cases considering confined and free surface flows. In particular, low speed impacts and penetration in a granular material will be considered. Some of these cases will be provided by experiments in low-gravity in collaboration with SupAero-ISAE (Toulouse) and its drop tower.

We also plan to perform a coordinated project to extend both approaches with cohesive and electrostatic forces, which may be present (even dominant) and thus have an important role in the behavior of granular materials, in particular in a low-gravity environment., and in the spin limit of asteroids modeled as granular aggregates (e.g. Sanchez and Scheeres 2015). A first model of cohesion was introduced in *pkdrgav* and tested against impact experiments on sintered glass beads (Schwartz et al. 2013), but it needs to be improved. Cohesive and electrostatic forces need also to be included in the continuum approach so that we can study within the respective limits of these approaches how regolith behaves in various conditions on small bodies and planets when these forces are present. One of the important objectives is to be able to predict when those forces are needed to explain observations and to interpret images of surfaces obtained by space missions (see Theme 8).

Another multidisciplinary goal will be to couple the continuum and discrete approaches. A hybrid approach is already developed to simulate the collisional disruption of an asteroid, in which the outcome of a continuum impact code (size, mass, positions and velocities of fragments) is used as input in the SSDEM code that models the gravitational phase of the event (fragment interactions and reaccumulations; see A11.4). In the case of the study of granular material dynamics, a possible way forward will be to join the two approaches within a single simulation where the most appropriate approach is chosen along the way. This will allow us to have a tool that is optimized in terms of computational time and heaviness for future applications.

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D. International collaborations

The code *pkdgrav* that includes the Soft-Sphere Discrete Element Method, which is used to simulate the dynamics of regolith in various gravity conditions is developed in collaboration with Prof. D.C. Richardson at the University of Maryland (UMD) in USA. OCA and UMD have signed Memorandum Of Understanding for acooperation in fields of common interest (including planetary science), the development joint projects in these fields, the exchange of faculty and students for research, teaching and study, and of scholars for seminars, conferences and other academic meetings.

E. List of people involved in the project

Patrick Michel, DR2 CNRS
Rudy Valette, MA MINES ParisTech
Elie Hachem, MA MINES ParisTech
Contact: michelp@oca.eu

F. Most significant publications of the team

Hachem E., Rivaux B., Kloczko T., Digonnet H., Coupez T. 2010. Stabilized finite element method for incompressible flows with high Reynolds number, Journal of Computational Physics, Vol. 229 (23), 8643-8665.

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Short CV of participants

Patrick Michel, CNRS research director, leader of the team Theory and Observations in Planetology of the Lagrange Laboratory at OCA, expert in the impact process, granular material dynamics and asteroid physical properties, Co-I of Hayabusa-2 and OSIRIS-REx, science team leader of the space project AIDA (ESA-NASA collaboration), member of the Science Program Committee of CNES, Carl Sagan Medal of the Division of Planetary Science of the American Astronomical Society (2012), Prize Paolo Farinella in Planetary Science (2013), Prize Young Researcher of the French Society of Astronomy and Astrophysics (2006), asteroid (7561) PatrickMichel, more than 90 refereed publications, H-index = 27.

Rudy Valette, MINES-ParisTech Associate Professor, head of the Rheology, Microstructure and Processing group and deputy head of the Computing and Fluids group, expert in complex fluids rheology and non-newtonian fluids mechanics, board member and international delegate of the French Society of Rheology, PhD Prize of the French Society of Rheology (2001)

Elie Hachem, Mines ParisTech, head of the Computing & Fluids research group (CFL), is an expert in computational fluid dynamics with particular focus on multiphase flows. He spent almost a year at Stanford University, invited in 2012 as an assistant professor to work on immersed methods for fluid-structure interaction. His work on computational fluid dynamics with high performance computing was recognized by the IBM Faculty Awards 2015. His PhD was awarded twice, by SMAI-GAMNI (best PhD thesis in applied mathematics in France) and by ECCOMAS (best PhD thesis in CFD in Europe).