Modelling the flow behaviour of granular media through the dosing station of a spacecraft under low gravitational environments

S.J. Antony*[1], B. Arowosola[1], L. Richter[2], T. Amanbayev[3] and T. Barakat[4]

[1]School of Chemical and Process Engineering, University of Leeds, Leeds, UK
[2] OHB System AG, Munich, Germany
[3]Southern-Kazakh State University, Shimkent, Kazakhstan
[4]School of Physics and Astronomy, King Saud University, Riyadh
* Corresponding author: Tel.: ++44 (0)113 3432409; Email: S.J.Antony@leeds.ac.uk

ABSTRACT

The European Space Agency (ESA) will launch the EXOMARS rover mission to Mars in 2018 which will operate a rover for subsurface soil sampling and analysis. Using several electro-mechanical systems within the rover, samples acquired will be mechanically processed and dispensed to instruments. For designing the grain-processing stations of spacecraft such as EXOMARS require reliable estimates on the internal and bulk flow characteristics of granular media under low gravitational environments. However the micromechanical behaviour of granular materials under low-gravitational environments is still complex to understand. Experimental studies on the flow behaviour of grain under a low gravity, for example using parabolic flight tests to simulate Martian gravity, are difficult to perform and expensive. Using computational modelling, here we present results on the flow behaviour of granular materials through flow channels under different gravity conditions including the low-gravity regime. For this, we use three approaches, viz., (i) one-dimensional discrete layer approach (DLA) based on hybrid-Lagrange continuum approach (ii) three dimensional Kirya continuum model and (ii) three dimensional discrete element modelling (DEM). Each model has its merits and limitations. Some qualitative comparisons are also made between the flow characteristics of grains observed from parabolic flight tests and DEM simulations.

INTRODUCTION

Micromechanical behaviours of granular materials have been studied extensively (de-Gennes, 1999, Schulze 2007, Lumay et al 2009, Nguyen et al 2014), and are strongly influenced by single-grain scale characteristics (Antony, 2007). In granular materials, the mobilization of bulk strength occurs in a non-homogeneous manner (Kruyt and Antony, 2007). For example the shear strength of granular materials originate due to the contributions of a limited group of contacts referred to as strong contacts, which themselves depend on a number of particle-scale properties (Antony, 2007). Recent experimental studies (Albaraki and Antony, 2014) provide information on how grain-scale properties influences on the flow behaviour of granular media under earth gravity using digital particle image velocimetry. Although they emphasise the need to establish clear understandings on the role of grain-scale properties on both the macroscopic and internal characteristics of granular assemblies, such details are scarce in the literature under low gravitational environments. This is important in space engineering applications, for example in the design of grain-processing and dosing stations of spacecraft, where the designs should enable the smooth flow of grains through flow devices during space exploration activities such as the on-site evaluation of the terrain properties of the Martian terrains (Squyres et al, 2004; Yen et al, 2005). The current research focuses on evaluating the influences of grain-scale properties of the grains on their flow properties under a range of gravitational environments. The study involves applying simple theoretical models and more complex discrete element modelling (DEM) depending on different scenarios.

THEORETICAL AND NUMERICAL METHODS

Theoretical Analysis using discrete layer approach (DLA)

In DLA, particles are represented as discrete layers (Figure 1). Hence this comes with the limitation, in which instead of considering individual particles (non-cohesive) as such, group of particles are represented as thin discrete layers of height h and each layer would represent the collective flow behaviour of particles within them based on Lagrange approach. The flow geometry is two dimensional in which the flow of grains occurs along the vertical axis. Though the model does not explicitly take into account the gravity term in the final equations, the models help to evaluate the flow trajectories of the layers and the completion time required to empty flow funnels under the steady flow rate (Q m^2/s) condition assuming that when other conditions are identical, proportionately higher flow rates corresponds to flow of materials under high levels of gravity and vice versa.

For this, it is assumed that the granular material is incompressible – an assumption that in fact is not fully valid for planetary regolith. We select an elementary volume of discrete granular layer (with height h) which is also called as 'large particle element' (Figure 1). The Lagrange coordinate, ξ is employed as the initial coordinate of centre of the large particle element (elementary volume of media) as shown in Figure 1. Hence that the boundary conditions are:

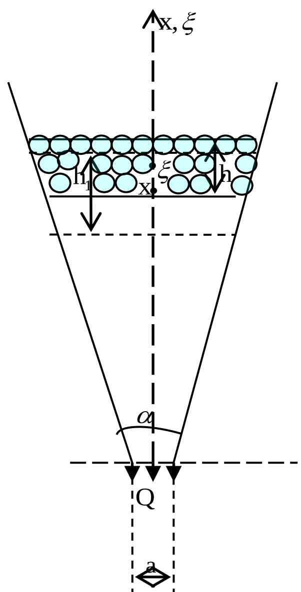

Figure 1: Schematic diagram of a typical discrete layer of grains used in DLA

$$\begin{cases} t = t_0 : x = \xi \\ t > t_0 : x = f(\xi, t) \end{cases} \qquad (2.1)$$

where x – Euler coordinate of centre of large particle element.

It is necessary to find the law of motion of the elementary volume:

$$x = f(\xi, t) \qquad (2.2)$$

For incompressible media, the area of elementary volume will be constant – i.e. S=const. By this condition and by applying geometric conditions we obtain following relations to develop computational schemes for the subsequent analysis:

$$x = \frac{h}{h_1}(\xi + \frac{a}{2\tan\alpha_1}) - \frac{a}{2\tan\alpha_1} \quad (2.3)$$

$$h_1 = (h_{11} - h_{12}) / \tan\alpha_1, \quad \alpha_1 = \alpha / 2 \quad (2.4)$$

where,

$$h_{11} = \sqrt{\left(\xi\tan\alpha_1 + \frac{a}{2} + \frac{h}{2}\tan\alpha_1\right)^2 - (t - t_0)Q\tan\alpha_1} \quad (2.5)$$

$$h_{12} = \sqrt{\left(\xi\tan\alpha_1 + \frac{a}{2} - \frac{h}{2}\tan\alpha_1\right)^2 - (t - t_0)Q\tan\alpha_1} \quad (2.6)$$

RESULTS AND DISCUSSIONS

Analysis of factors influencing the granular flow through the container

We considered two different heights of the container in this study, viz., 0.2m (ξ=0.2-case1) and 0.3m (ξ=0.3-case2) and various values of flow rate Q. Unless mentioned otherwise the size of the slit 'a' is kept as 0.1m and the trap angle α as $\pi/3$ (Figure 1). However, at later stages the analysis has been extended to different combinations of a and α to understand their individual roles on granular flow properties.

First, we analyse the results by tracking the motion/position 'x' of the topmost thin discrete layer (h=0.001 m, Figure 1) with respect to time as presented in Figure 2. T_{empty}, which is the time required to complete the flow of granular material through the container would correspond to when x tends to zero. Hence, the value of T_{empty} can be extracted from Figure 2 and presented in Figure 3 as a function of granular flow rate. From these figures it is evident that the time required to empty the container (T_{empty}) decreases with the flow rate as one would expect. However, From Figure 3 it is interesting to note that this decrease in T_{empty} occurs at a rapidly decreasing rate for flow rate up to about 0.003 m^2/s and this trend tends to diminish beyond a flow rate of 0.003 m^2/s for both cases of the container with different heights (ξ=0.2 and 0.3). Hence we can conclude that, in general, the low gravity effects are more likely to slow down the flow of grains in the selected dosing funnel geometry especially when the processing flow rate is relatively low (approximately the minimum cut off flow rate is 0.003 m^2/s).

The influence of the trap angle α (Figure 1) of the containers on the granular flow behaviour is analysed for a typical value of flow rate 0.003 m^2/s. As discussed above, the corresponding time required to empty the container T_{empty} is also calculated and presented in Figure 4. It is evident that the time required to empty the containers due to granular flow increases for increase in the trap angle. This behaviour if more noticeable for the trap angle between π/2 and π/3, as well as more noticeably when the height of the container in relatively high (ξ=0.3). Hence for designing the container, choosing trap angle not more than π/3 is recommended from the point of view of maintaining good flowability of the grains from the container, especially when the height of the container is more than 20 cm (ξ>0.2).

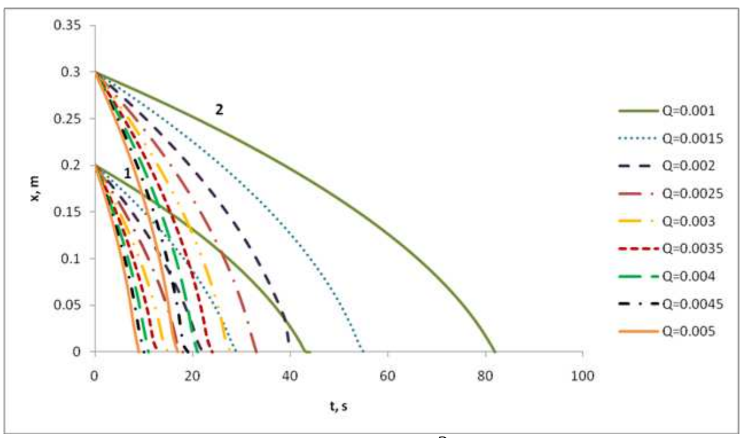

Figure 2: Effect of flow rate Q (m^2/s)

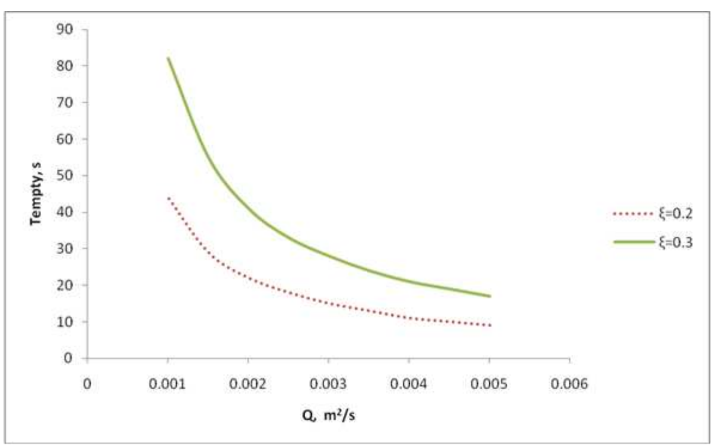

Figure 3: Time to empty the container with the granular flow rate variation

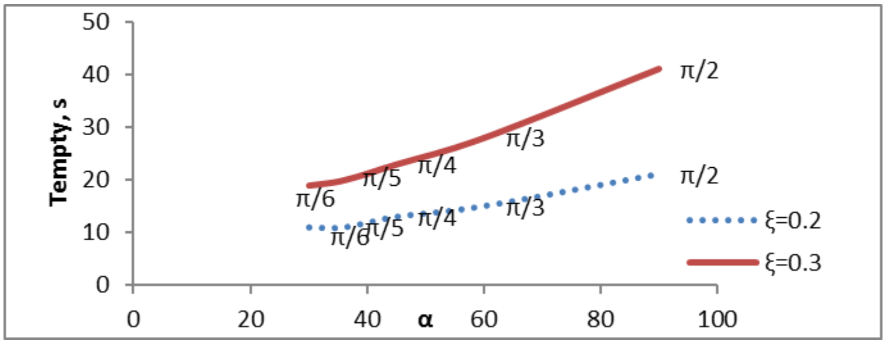

Figure 4: Time to empty with trap angle (α) variation

Theoretical analysis of the effect of gravity on the flow rate of free flowing granular media from a granular container

Here we aim to study, when other conditions are identical between different cases, to what extent the granular flow rate from the container would get affected if the gravitation field of the container is different from that of earthen gravity g_0 (reference level). We expect that such an analysis would provide beforehand indications of the variations in flow properties when actual experiments are conducted to corresponding conditions in the parabolic flight campaign in the future.

The theoretical analysis was performed based on Kirya's structural continuum mechanical model (Kirya, 2009). For this, the inner zones of the region of the container through which granular particles are expected to flow though can be sub-divided depending on their trajectory of motion, viz., A-E (Figure 5a). In the present case, as we are interested to study the exit flow rate, we will only concentrate the description of exit flow zone-D, bounded by a parabola (Figure 5b). In this zone, the granular particles collide with other particles continuously and in a chaotic movement. The granular material in this zone is thus said to be in free disperse state and the movement can be described by the Navier Stokes equations for granular materials. The boundary between dynamic arc C, and the exit flow zone D may be illustrated using the Moor's circle and can be represented in the form of a parabola as shown in Figure 10b in the following form:

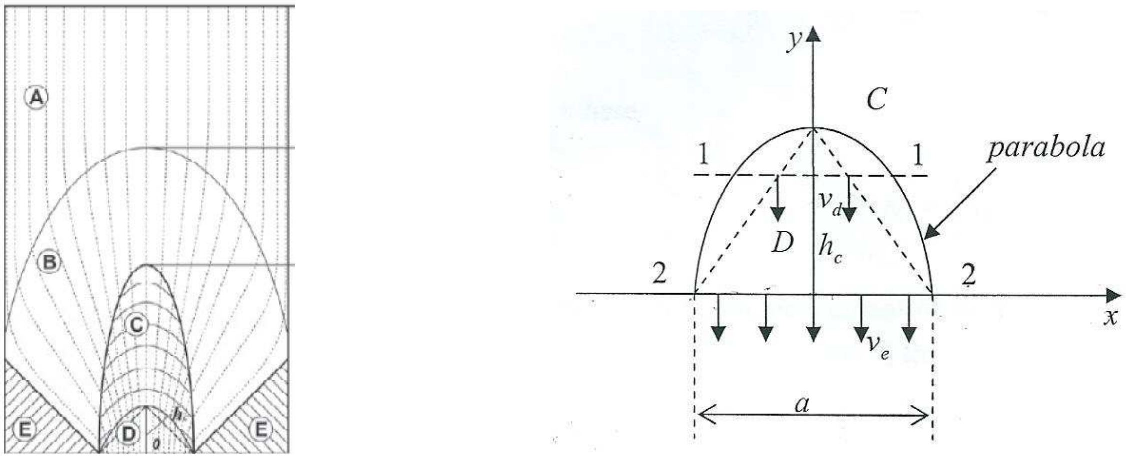

Figure 5: (a) Zones of flow out of the granular particles (Kirya, 2009) (b) expanded diagram of Zone D

$$y = h_c\left[1 - \left(\frac{2x}{a}\right)^2\right] \qquad (3.1)$$

Where h_c is the height of parabola which can also be defined as;

$$h_c = \frac{a}{4}\frac{1+sin\varphi}{cos\varphi} = \frac{a}{4}\left(f + \sqrt{1+f^2}\right) \qquad (3.2)$$

Where,

$$f = tan\varphi \qquad (3.3)$$

In the granular material, f is the coefficient of friction while φ is the angle of internal friction.

The exit velocity can be given as

$$v_e = \frac{1}{\sqrt{1+\zeta}}\sqrt{2gy + v_d} \qquad (3.4)$$

Where v_d is the velocity of particles at a point of intersection and can be expressed as

$$v_d = \sqrt{\frac{2g\sigma_2}{\gamma}} \qquad (3.5)$$

$$\sigma_2 = \gamma\left(\frac{1}{f} + f - \sqrt{1+f^2}\right)x \qquad (3.6)$$

Substituting equation 3.5 and 3.6 into equation 3.4 gives

$$v_e = \frac{1}{\sqrt{1+\zeta}}\sqrt{2g\left(y+\frac{\sigma_2}{\gamma}\right)} \quad (3.7)$$

The volume expenditure of granular material through the chink is given as

$$Q = \frac{2}{3}a^{3/2}\sqrt{g}\,\frac{1}{\sqrt{1+\zeta}}\frac{K_1^{3/2}}{K_1\chi'}\left[1-\left(\frac{\chi'}{K_1}\right)^{3/2}\right] \quad (3.8)$$

Where,

$$K_1 = \frac{1}{2}\left(f+\sqrt{1+f^2}\right) \quad (3.9)$$

$$\chi' = f + \frac{1}{f} - \sqrt{1+f^2} \quad (3.10)$$

The coefficient of loss, ζ at the movement of granular material in the zone of flow out can then be defined as

$$\zeta = K_2\frac{k^2 d^2 l}{h^3} \quad (3.11)$$

Where K_2 is unit dimensionless coefficient dependent on the conditions of flow out from tank; l is the length of channel ($\approx h_c$); k (=10) is the kinetic coefficient which characterizes the loss of mechanical energy flow by collisions between particles (Kirya, 2009).

Computational results and analysis for the granular flow

A computational scheme was developed based on the above said continuum description of the granular flow behaviour and results analysed for indications of the effect of gravitational field in relation to earth gravity (g_0) on the flow rate Q of particles from the container. The scaled dimension of the container is provided in the insert of Figure 7 (the same geometrical condition is used later in the DEM simulations).

For the purpose of the following analysis we considered a typical case of sandstone grains with an average grain size (non-cohesive spheres) 100 microns and friction coefficient 0.3. Figure 7 shows the variation of exit flow rate from the container at different gravity levels in relation to corresponding measures at earth gravity condition g_0 ($Q = Q_0$ at g_0). From this figure, it is evident that granular containers in relatively low gravity environments results low flow rate compared with earth gravity condition and vice versa. For example, with respect to the earth condition (g_0, Q_0), a gravity field of $0.4g_0$ will result will result a flow rate of $0.63Q_0$. A gravity field of $1.8g_0$ will result will result a flow rate of $1.34Q_0$ and so on. Thus this analysis helps to estimate the granular flow measures at different gravity levels and could pre-inform what to expect when corresponding experiments are performed using parabolic flight campaigns which are more expensive with respect to manpower, flight costs and managing the risks.

DEM modelling of bulk flow rate of grains through the granular container

The aim of this section is to evaluate the macroscopic flow rate of the sandstone grains for the same geometry of the granular container presented in section-3. DEM models the interaction between individual grains as a dynamic process and the time advancements are based on Newton's law of motion using an explicit finite difference scheme (Cundall and Strack, 1979). For more details of the DEM simulation methodology for low gravity levels, the readers could refer to the work of Nakashima et al (2011), though their work pertains to two-dimensional conditions for studying the angle of repose of granular materials post-flowing through hopper under low gravity conditions. In the present paper, the DEM simulations are presented for three-dimensional conditions.

Discrete spherical particles (normal size distribution) were initially created randomly inside the hopper assembly with the following specifications of typical material properties of sandstone grains and hopper (Table-1). After generating the initial assembly with grains, they were allowed to flow through equivalent to opening the throat of the hopper.

Table-1: Material properties used in the DEM simulations

Wall normal stiffness = 1e8 Pa	Wall shear stiffness = 1e8 Pa
Wall friction coefficient = 0.7	Ball shear stiffness = 1e8 Pa
Ball normal stiffness = 1e8 Pa	Particle density = 2900 kg/m^3
Ball contact normal strength= 1e8 Pa	Ball contact shear strength= 1e8 Pa
Ball contact friction coefficient = 0.7	Size ratio of maximum to minimum size of grains = 1.6
Porosity = 0.36	

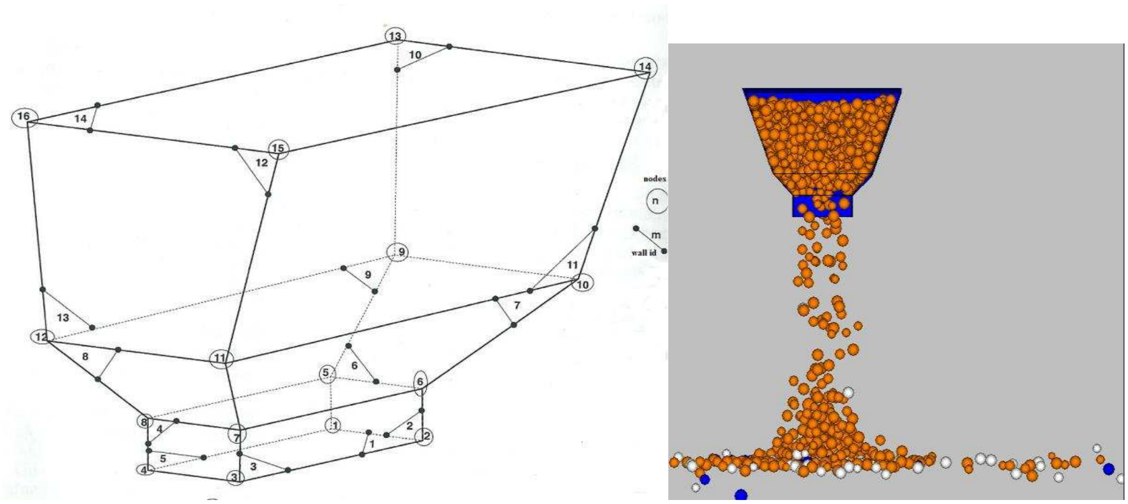

Figure 6: Granular flow container scaled to slit opening width ‘a’ line connecting nodes 7 and 8 as 10 mm. The coloured image shows the snap shot of the container with sandstone during the flow in the DEM simulation.

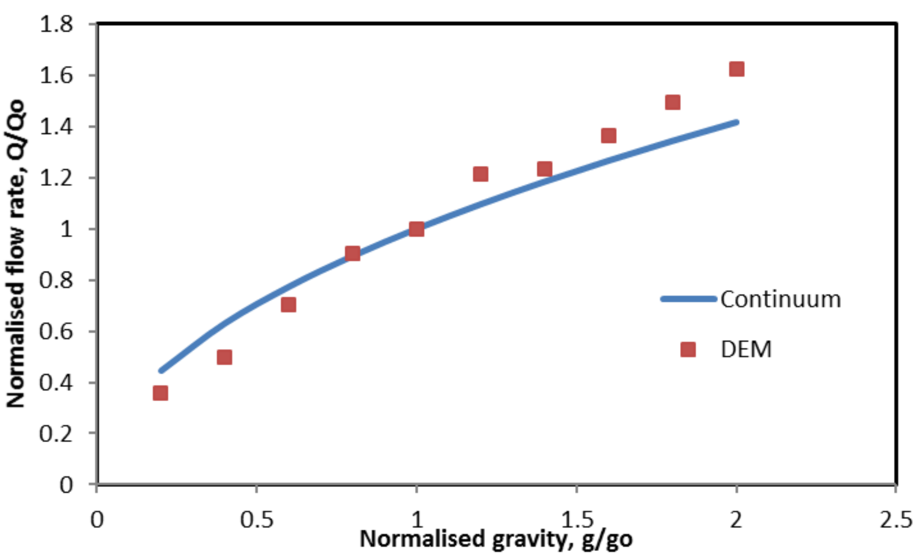

Figure 7: Flow rate Q of the sandstone grains through the 3D geometry evaluated under different gravity levels (g). The results are normalised with respect to that of earth gravity (Q_0, g_0). The results from the three dimensional DEM simulations and the continuum theory presented in section-3 are provided for comparison.

Form the above presented results, it is evident that the bulk flow rate of the sandstone grains decreases significantly for a decrease in the gravity level of the environment. Furthermore, the bulk flow rate predicted by the continuum theory and more rigorous DEM simulations agree fairly well.

CONCLUSION

Three different approaches have been used in this study to understand the flow characteristics of granular materials through flow geometries under different gravitational environments. Though the DLA approach is the most simplest of all, it helps to evaluate the dynamic nature of the grains such as the completion time of the flow under different gravitational conditions. Furthermore, even a simple continuum approach such as Kirya's model could still help to estimate the three dimensional flow behaviour of grains more quickly unlike in the case of DEM simulations which involve a significantly high amount of computational time and resources, especially for studying the low gravitational behaviour of granular materials. Further analysis is required to understand the discrete and non-homogeneous dynamic characteristics of grains within the container during their flow under different gravitational environments, which is outside the scope of the current publication.

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REFERENCES

Albaraki, S. and Antony, S.J. (2014) 'How does internal angle of hoppers affect granular flow? Experimental studies using digital particle image velocimetry', Powder Technology, 268, 253–260

Antony, S.J (2007) 'Link between single-particle properties and macroscopic properties in particulate assemblies: role of structures within structures', Philosophical Transactions of the Royal Society of London, Series: A, 365, 2879-2891

Cundall, P.A., and Strack, O.D.L. (1979) 'A discrete numerical model for granular assemblies', Geotechnique 29(1), 47-65.

De-Gennes, P. G. 1999. Granular Matter: A Tentative View. Rev. Mod. Phys., 71, S374 - S382.

Kirya R.V (2009) ‘The Description of process of flow out of granular material from tank by structural-mechanical models, System technology, 3(62) 3-19.
Kruyt, N.P. and Antony,S.J (2007) ‘Force, relative displacement and work networks in granular media subjected to quasi-static deformation’, Physical Review E, 75, 051308
Lumay, G., Dorbolo, S. & Vandewalle, N. 2009. Compaction dynamics of a magnetized powder. Physical Review E, 80**,** 041302.
Nguyen, T. K., Combe, G., Caillerie, D. & Desrues, J. 2014. FEM × DEM modelling of cohesive granular materials: Numerical homogenisation and multi-scale simulations. Acta Geophysica, 62**,** 1109-1126.
Schulze, D. 2007. Powders and Bulk Solids: Behaviour, Characterization, Storage and Flow, Springer Berlin Heidelberg.
Squyres et al (2004) ‘The Spirit Rover's Athena Science Investigation at Gusev Crater, Mars’, Science, 305(5685), 794 – 799
Yen et al (2005) ‘An integrated view of the chemistry and mineralogy of Martian soils’, Nature, 436, 49-54