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Flow behaviour of grains through the dosing station of spacecraft under low gravity environments

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ABSTRACT

For the design of the grain-processing stations of spacecrafts, such as EXOMARS 2020, reliable estimates are required on the internal and bulk flow characteristics of granular media under the low gravitational environments. Using theoretical and computational modelling, here we present results on the generic flow behaviour of granular materials through flow channels under different gravity levels. For this, we use three approaches, viz., (i) a simple one-dimensional discrete layer approach (DLA) based on hybrid-Lagrange continuum analysis (ii) three dimensional Kirya structural continuum model and (iii) three dimensional discrete element modelling (DEM). Each model has its merits and limitations. For the granular simulant considered here, a good level of agreement is obtained between the results of Kirya model and DEM simulations on the flow properties of the grains. Some qualitative comparisons are also reported favourably on the flow characteristics of grains between the results of the experimental parabolic flight campaign and the DEM simulations. The theoretical and DEM simulations presented here could help to minimise relying on the complex experimental programmes, such as the parabolic flight campaign, for evaluating the processing behaviour of grains under low gravitational environments in future.

INTRODUCTION

Space agencies of the world conduct extraterritorial ground exploration operations to explore human life beyond the earth. For example, the European Space Agency (ESA) aims to launch the EXOMARS rover mission to Mars in 2020, which involves operating a rover for the subsurface soil sampling and analysis. Using several electro-mechanical systems within the rover, samples acquired would be mechanically processed and dispensed to different instruments. In the design of the grain processing stations of such spacecrafts, a key requirement is understanding the flow behaviour of granular materials under low gravitational environments (Squyres et al. 2004; Yen et al. 2005; Antony et al. 2016).

Granular materials consist of discrete grains (Duran 1999). Micromechanical behaviours of granular materials have been studied extensively in the past, and they differ from that of conventional solids, liquids and gases states of matter (de-Gennes 1999; Schulze 2007; Lumay et al. 2009; Nguyen et al. 2014). For example the microscopic origin of shear strength is attributed to the contribution of a limited group of contacts, referred to as strong contacts, which depend on their particle-scale properties (Antony 2007, Kruyt and Antony 2007). Recent experimental studies using Digital Particle Image Velocimetry (Albaraki and Antony 2014) provide information on how grain-scale properties influences on the flow behaviour of granular media at both micro and bulk scales under the earth gravity. However, such details are scarce in the literature for the low gravitational environments.

For simulating the processing characteristics of granular materials, DEM is used more commonly in the recent times (Cundall and Strack 1979). DEM models the interaction between contiguous grains as a dynamic process and the time step is advanced using an explicit finite difference scheme (Cundall and Strack 1979). The method enables to predict both the microscale (internal) and bulk scale mechanical characteristics of granular materials under different loading and environmental conditions. So far, investigations on the mechanical behaviour of granular materials are widely reported under the earth gravity conditions, but relatively to a small extent under other gravitational conditions (Liu and Li 2010; Hofmeister et al. 2009). Under the low-gravitational conditions, certain material properties such as the cohesion of the grains could influence on the macroscopic flow properties relatively more with that of the earth gravitational condition (Walton et al. 2007). This is due to potential changes in the chemical activity of the grains under low gravitational environments. For example, the lunar granular surfaces could be chemically more active and result more surface energy when compared with the same minerology of the grains under the earth gravity (Walton et al. 2007). This could also result the formation of the grains (or their agglomerates) in non-spherical shapes. For simulating the mechanical behaviour of granular assemblies, some DEM studies account for the non-spherical shape of the grains by considering them as a collection of prolates, oblates (Antony and Kuhn 2005), or by fusing individual spheres to construct any non-spherical shape of the grains (Walton and Braun 1993, Chung and Ooi 2007). Theoretical analysis have been also reported in the past to determine the bulk flow properties of the grains, for example using the simple Beverloo equation (Beverloo et al. 1961) comprising an empirical correlation coefficient. Some studies (Chung and Ooi 2007) on the bulk flow rate of the grains have reported that such predictions depend on the selection of the correlation coefficient. The value of this correlation coefficient is not yet well defined to different terrestrial grains and environments. Furthermore, Beverloo equation does not directly account for the inter-particle friction of the grains (Beverloo et al. 1961).

In general, DEM simulations are computationally expensive, especially under the low gravity conditions (Brucks et al. 2008). It would be desirable to evaluate the flow properties of grains under the low gravity conditions using DEM and to compare the outcomes with relatively less-expensive continuum approaches where feasible. The current research focuses on this by evaluating the influences of grain-scale properties of the non-cohesive grains on their flow properties under a range of gravitational environments, including that of less than the earth gravity (low gravity). The study involves applying simple theoretical models and more extensive discrete element modelling depending on different scenarios.

THEORETICAL AND NUMERICAL METHODS

The theoretical methods adopted here are of two types namely: Discrete Layer Approach (DLA) by considering one-dimensional granular flow through a two-dimensional hopper, and the three-dimensional Kirya's structural model. Results from the three-dimensional DEM simulations are compared with corresponding Kirya's structural model at later stages.

Theoretical Analysis using discrete layer approach (DLA)

In the DLA approach, the particles are represented as discrete layers (Fig. 1). Hence this comes with the simplification, in which instead of considering individual particles 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 (Fig.1). For a given steady-state flow rate Q of the grains through the hopper of a given throat angle, the model helps to estimate the discharge completion time, the position of the particles with time (Lagrange coordinate) and the velocity of granular layers within the hopper. Though the model does not explicitly take into account the gravity term in the final equations, it helps to evaluate the flow trajectories of the layers and the completion time required to empty flow funnels under a steady flow rate (Q m^2/s) condition by assuming that when other conditions are identical, proportionately higher steady flow rates corresponds to flow of materials under a relatively high level 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 which is also called as a 'large particle element' with thickness $h \ll H$ (Fig. 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 Fig. 1. Hence that the boundary conditions are:

$$\begin{cases} t = t_0 : y = \xi \\ t > t_0 : y = f(\xi, t) \end{cases} \quad (1)$$

where *y* is the Euler coordinate of centre of large particle element.

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

$$y = f(\xi, t) \quad (2)$$

For incompressible media, the area of elementary volume (*S*) will be constant. Using this condition together with the geometrical dimensions of the hopper, the following relations are obtained to develop computational schemes for the subsequent analysis:

$$y = \frac{h}{h_1}\left(\xi + \frac{a}{2\tan\alpha_1}\right) - \frac{a}{2\tan\alpha_1} \quad (3)$$

$$h_1 = (h_{11} - h_{12}) / \tan\alpha_1, \quad \alpha_1 = \alpha / 2 \quad (4)$$

where, h_1 is the thickness of the particle element at time *t* (Fig.1) and h_{11}, h_{12} are defined as

$$h_{11} = \sqrt{\left(\xi\tan\alpha_1 + \frac{a}{2} + \frac{h}{2}\tan\alpha_1\right)^2 - (t - t_0)Q\tan\alpha_1} \quad (5)$$

$$h_{12} = \sqrt{\left(\xi \tan\alpha_1 + \frac{a}{2} - \frac{h}{2}\tan\alpha_1\right)^2 - (t - t_0) Q \tan\alpha_1} \quad (6)$$

Analysis of factors influencing the granular flow using DLA

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

At first, the theoretical results were analysed by tracking the motion/position ‘*y*’ of the topmost thin discrete layer (h=0.001 m, Fig. 1) with respect to time as presented in Fig. 2. T_{empty}, which is the emptying time (i.e., time required to complete the flow of granular material through the container. This would correspond to the time when *y* tends to zero). Hence, the value of T_{empty} can be extracted from Fig. 2 and presented in Fig. 3 as a function of granular flow rate. From these results, it is evident that the time required to empty the container (T_{empty}) decreases for an increase in the flow rate as one could expect (Schulze and Schwedes 1990). However, From Fig. 3, it is interesting to note that this decrease in T_{empty} occurs at a rapidly decreasing rate for the 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, in general, the low gravity effects are more likely to slow down the flow of grains in the selected dosing funnel (hopper) 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 hopper angle α (Fig. 1) 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 Fig. 4. It is evident that the time required to empty the containers due to granular flow increases for increase in the hopper angle. This is qualitatively in agreement with the recent experimental studies though conducted under the earth gravity (Antony and Albaraki 2014) in which increase in the hopper angle resulted an increase in the completion time of the granules. This behaviour is more noticeable for the hopper throat angle between π/2 and π/3, as well as more significantly when the height of the container in relatively high (ξ=0.3). Hence for designing the dosing container, hopper throat angle of less than π/3, where feasible, is desired 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 0.2m (ξ>0.2). This could be attributed to the favourable direction of the resultant velocity of the grains during the flow. Experimental granular flow studies conducted using Digital Particle Image Velocimetry (DPIV) under the earth gravitational condition (Antony and Albaraki 2014) have also shown that, for a smaller hopper angle (e.g. π/6), the direction of the resultant velocity of the grains align along the direction of the gravity almost throughout the hopper and favours a uniform flow. This trend diminished significantly in the case of a higher hopper angle (e.g. π/2) and resulted a non-uniform funnel flow (Antony and Albaraki 2014) with a relatively more time to complete the flow through the hopper.

The DLA model was also used to monitor the velocity profile of the particle during granular flow in the hopper. The velocity of the particle can be evaluated as:

$$v = \frac{dy}{dt} = -\frac{1}{2}\frac{hQ}{h_1 h_{11} h_{12}}\left\{\xi \tan\alpha_1 + {}^{a}/_{2}\right\} \qquad (7)$$

Fig. 5 shows the typical velocity distribution of the particle inside the hopper (ξ=0.3, α=π/3, a=0.1m). The velocity is at a maximum at the exit of the hopper (*y*=0) during granular flow in agreement with other studies (Cox and Hill 2005). The above presented DLA analysis helps to evaluate some useful flow characteristics of granular media in a simple manner. However, for studying more rigorous three-dimensional flow of grains under the low gravitational environments, the following analysis is presented.

Analysis of the discharge rate of grains under low gravity using Kirya's structural continuum model

Here, the aim is to study on when other conditions are identical between different cases, to what extent the steady state granular flow rate (Q) of frictional grains (inter-particle friction) varies if the gravitation field of the container is different from that of earth gravity g_0 (reference gravity level). For selected cases, DEM simulations are reported later for the purpose of comparisons. Such an analysis would provide beforehand indications of the variations in the 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 three-dimensional structural continuum model and the details can be found elsewhere (Kirya 2009). As the original description of this model is in Russian, and for the benefit of the wider audience of this journal, we describe the key developments of Kirya's model here. In brief, the flow trajectories of the grains inside a smooth hopper is divided into different zones A-E (Fig.6a). In zone A, the granular medium particles are interconnected and move at a low speed parallel to the walls of the hopper. In zone B, the particles slide relative to each other, and their trajectories are bent towards the axis of the hopper. In zone C, the granular particles form movable vaults moving downward, while the particle velocities increase substantially, and their trajectories approach vertical lines. In the zone of collapse (mixing) D, connections between particles are destroyed, while they are in continuous chaotic motion, colliding with each other, and their speed increases due to gravity. In zone E, the particles are stationary (Kirya 2009). In the present case, the objective is to focus on the exit flow rate of the grains from the hopper. Hence the description of exit flow zone-D bounded by a parabola (Fig. 6b) is considered here. In this zone, the granular particles collide with other particles continuously and in a chaotic movement. The grains are in a free disperse state and their movement can be described by the Navier Stokes equations for granular materials (Kirya 1999, Kirya 2009). The boundary between the dynamic arc C, and the exit flow zone D could be represented in the form of a parabola (Fig. 6b) in the following form (Kirya 2009):

$$y = h_c \left[1 - \left(\frac{2x}{a}\right)^2\right] \tag{8}$$

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

$$h_c = \frac{a}{4}\frac{1+sin\varphi}{cos\varphi} = \frac{a}{4}\left(\mu + \sqrt{1+\mu^2}\right) \tag{9}$$

$$\mu = tan\varphi \tag{10}$$

In which μ is the coefficient of inter-particle friction, φ is the angle of internal friction and a is the size of the opening (Fig.6b).

The parabola shown in Fig. 6b can be substituted by linear sections. The equation of the linear boundary has the following form:

$$y = h_c\left[1 - \frac{2|x|}{a}\right] \tag{11}$$

in which $-a/2 \leq x \leq a/2$. By using Bernoulli equation to the cross-sections 1-1 and 2-2 for considered triangle, we obtain

$$y_1 + \frac{p_1}{\gamma} + \frac{v_1^2}{2g} = y_2 + \frac{p_2}{\gamma} + \frac{v_2^2}{2g} + \zeta\frac{v_2^2}{2g} \tag{12}$$

where y_1, y_2 are levels of sections 1-1 and 2-2 respectively; p_1, p_2 are normal tensions at the points of interceptions of sections 1-1 and 2-2 with lateral sides of the triangle; v_1, v_2 are corresponding velocities of particles at the above said points; g is gravitational acceleration; γ

is the unit weight of granular material; ζ is Darsy-Weissbakh coefficient of local loss characterizing the loss of mechanical energy of granular flow by collisions between particles (Shterenliht, 1984). By substituting $y_1=y$, $y_2=0$, $p_1=0$, $p_2=0$, $v_1=v_d$, $v_2=v_e$ in to Eq. (12) and after transformations, the value of velocity of particles of granular material on the chink exit from the tank can be written as

$$v_e = \frac{1}{\sqrt{1+\zeta}}\sqrt{2gy + {v_d}^2} \tag{13}$$

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

$$v_d = \sqrt{\frac{2g\sigma_2}{\gamma}} \tag{14}$$

$$\sigma_2 = \gamma\left(\frac{1}{\mu} + \mu - \sqrt{1+\mu^2}\right)x \tag{15}$$

Substituting Eqs.(14) and (15) into Eq.(13) results as:

$$v_e = \frac{1}{\sqrt{1+\zeta}}\sqrt{2g\left(y + \frac{\sigma_2}{\gamma}\right)} \tag{16}$$

The volume expenditure of granular material per unit length through the chink is defined as:

$$Q = \int_{-a/2}^{a/2} v_e dx \tag{17}$$

$$\mathrm{Q} = \frac{2}{3}a^{3/2}\sqrt{g}\frac{1}{\sqrt{1+\zeta}}\frac{K_1^{3/2}}{K_1-\chi'}\left[1-\left(\frac{\chi'}{K_1}\right)^{3/2}\right] \tag{18}$$

where,

$$K_1 = \frac{1}{2}\left(\mu + \sqrt{1+\mu^2}\right) \tag{19}$$

$$\chi' = \mu + \frac{1}{\mu} - \sqrt{1+\mu^2} \tag{20}$$

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

$$\zeta = K_2\frac{\kappa^2 d^2 h_c}{a^3} \tag{21}$$

where K_2 is unit dimensionless coefficient dependent on the conditions of flow out from the tank (≈1); d is the diameter of the particle (average size in the analysis); a is width of the exit flow channel in zone D; and κ (=10) is the kinetic coefficient which characterizes the loss of mechanical energy flow by collisions between particles (Kirya 2009). The size of the opening a is kept as 10mm (Fig.6b) for the analysis. Furthermore, from Eqs.(9) and (19) it follows that $h_c = K_1 a/2$. Hence Eq.(21) can be written more generally as:

$$\zeta = K_1 K_2 \frac{\kappa^2 d^2}{2a^2} \tag{22}$$

Using Eq.(18), the effects of friction coefficient on the flow properties (Nedderman 1992) of grains (uniform grain size 100μm) are studied here under a range of gravity levels. The friction coefficient was varied from 0.1 – 0.5 and gravity from 20– 200% of earth gravity and the results are presented in Fig.7. In this, the flow rate (Q) under a given gravity level (g) is normalised with respect to that of earth gravity condition (Q_0, g_0). The results show that the flow rate increases with the gravity (Sun and Sankaran 2012). However this increase is more dominant in the case of low frictional materials ($\mu \leq 0.3$) and under relatively high gravity ($g > g_0$). For particles with friction coefficient greater then 0.3, interparticle friction does not have a dominant effect on the granular flow rate under the low gravity environments ($g < g_0$).

DEM modelling of gravity effects on flow rate (Q) of the grains

The objective of this section is to evaluate the macroscopic flow rate Q of the sandstone grains passing through a typical spacecraft flow channel of the grain-processing station using DEM simulations. The results are also compared with corresponding continuum analysis using the Kirya's continuum model as described in the previous section. DEM models the interaction between individual grains as a dynamic process and the time advancement is based on Newton's law of motion and 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. However, in the present paper, the DEM simulations are presented for three-dimensional conditions. The dimensions of the three dimensional flow channel (hopper) are presented in Fig.8. Discrete spherical particles (normal size distribution with an average size of 100μm, and the ratio of maximum to minimum size of the grains=1.6) were initially created in a random static packing inside the hopper assembly with typical material properties of sandstone grains and hopper (Table 1). After generating the initial random assembly of the grains inside the hopper geometry to the required initial porosity, they were allowed to flow through by opening the throat of the hopper.

Fig.9 shows the time required to empty the sandstone grains from the hopper under different gravity levels. This presents on the strong influence of gravity plays on the flow characteristics of the grains, i.e., at the low gravity levels (about $g<0.6g_0$) the flow of the grains is significantly slow when compared with that of earth gravity. The emptying time tends to be inversely proportional to the level of gravity. Similar generic trends are also reported earlier in the experimental investigation using grains passing through the hourglass (Le Pennec et al. 1995, Hofmeister et al. 2009).

To understand on the extent to which the DEM simulation results agree with continuum analysis under different gravity levels, Kirya's model (as described in the previous section) is used for the geometrical conditions and material properties used in the present DEM simulations. The average flow rate obtained from the DEM simulations is compared with the flow rate obtained from the Kirya's model in Fig.10. Interestingly, a good level of agreement is obtained between these results based on the two different approaches, especially when $g \leq g_0$. This helps to assess the bulk flow rate of grains through the hopper flow devices under low gravity more easily using the Kirya's model as DEM simulations are computationally more expensive (Cundall and Strack 1979). However, DEM simulation data could give more information on the internal and discrete behaviour of the grains inside the flow devices, which is outside the scope of the current work.

The flow characteristics of sandstone using DEM is compared qualitatively with the observations made from a parabolic flight test (Thomson, 1986) and presented in Fig.11. For this, a preparatory experiment involved studying the mass flow of grains through the hopper, and then to increase the gravity level rapidly to $2g_o$ to completely evacuate the grains quickly (without any particles sticking to the wall surfaces to avoid potential contaminations). In this case, flow of the sandstone material through the funnel geometry was observed and a significant level of blockage of the grains occurred in the funnel under the lunar gravity level. This was also quantified using corresponding DEM simulations (as described earlier). The containment of the particles in the funnel was observed (Fig.11). Further tests were carried out by simulating a $2g_0$ gravity environment with the remaining stuck in the hopper. Also, the gravity environment of the experiment was suddenly increased to $2g_0$ level which completely ejected the blocked grains and this agreed with the DEM simulation results as well. The total mass of grains ejected from the funnel increased drastically under the $2g_o$ gravity environment and within a short simulation time-steps, all the particles were discharged out of the hopper (Fig. 11). However, further experimental studies are required to make detailed measurements and their quantitative comparisons with the results based on the DEM and theoretical analysis, although creating a long duration low-gravitational environmental for experimental testing is a stiff challenge yet.

CONCLUSIONS

Both continuum and discrete 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, the results on the bulk flow properties under low gravitational levels of the grains based on the Kirya's approach agreed well with that of the DEM simulations. A simple continuum approach such as Kirya's model could help to estimate the three dimensional flow behaviour of frictional 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. The present analysis helps to estimate the granular flow measures at different gravity levels including low gravity. The approaches outlined here could help to minimise using parabolic flight campaigns (which are more expensive with respect to manpower, flight costs and managing the risks) for evaluating the flow properties of cohesionless and frictional grains. Further detailed studies are required and underway to understand on the internal mechanics, physics and bulk dynamic flow characteristics of more realistic granular simulants, and suitable mechanisms to enhance granular flow under the low gravitational environments.

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Table 1. Material properties used in the DEM simulations

wall normal stiffness = 1e8 N/m	wall shear stiffness = 1e8 N/m
grain normal stiffness = 1e8 N/m	grain shear stiffness = 1e8 N/m
grain contact normal strength= 1e8 Pa	grain contact shear strength= 1e8 Pa
grain contact friction coefficient = 0.6	initial porosity = 0.36
wall friction coefficient = 0.6	grain density = 2900 kg/m^3

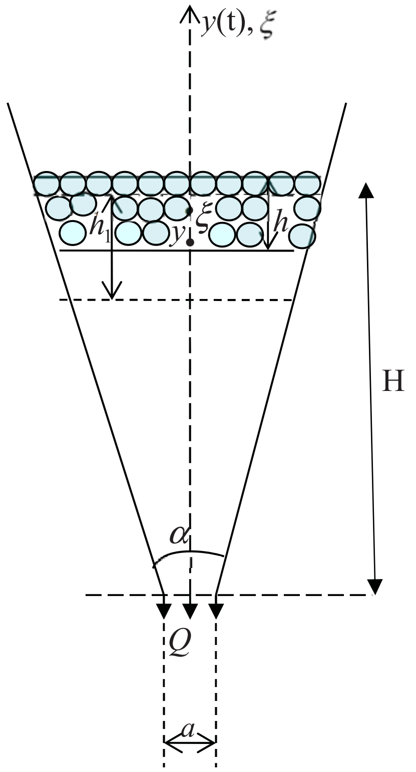


Fig. 1: Schematic diagram of a typical discrete layer of grains used in DLA

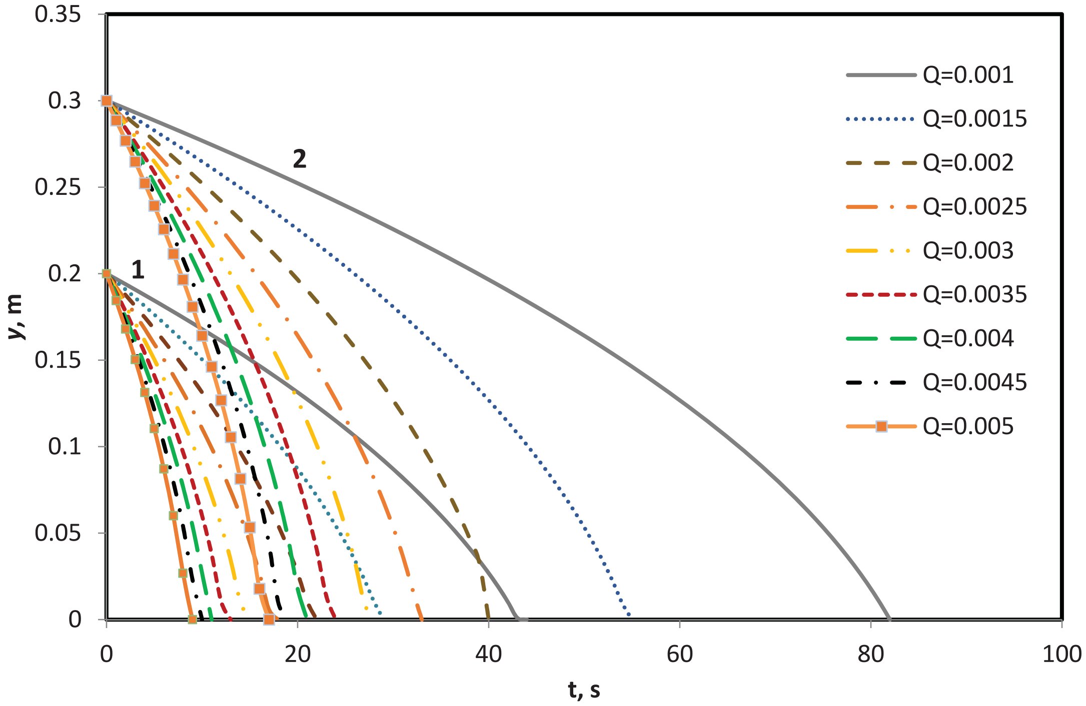


Fig. 2: Location of the top most discrete layer (*y* in Fig.1) with time (t) under different flow rates Q (m^2/s) (case-1: H=0.2m, case-2: H=0.3m)

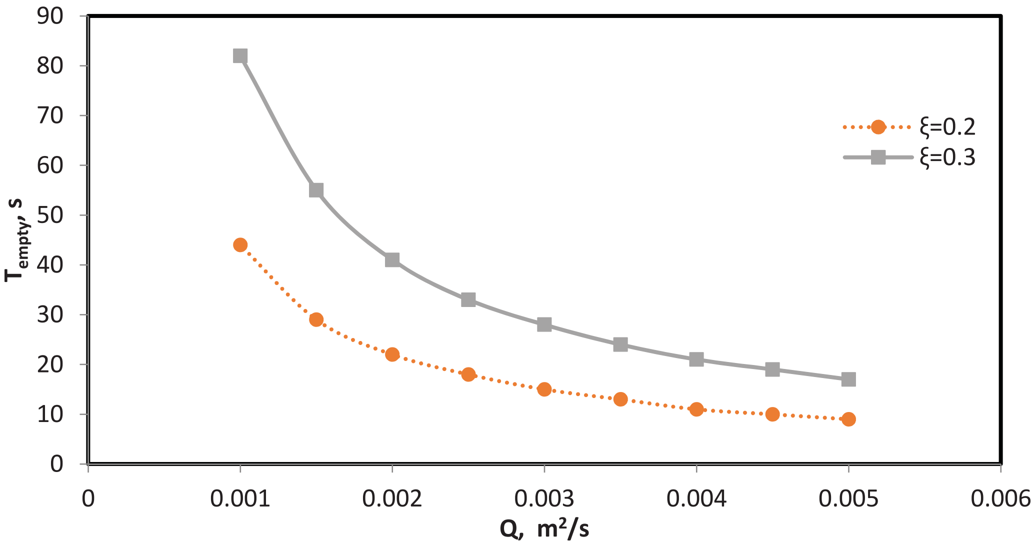


Fig. 3: Variation of the time to empty the hopper with the granular flow rate (Q)

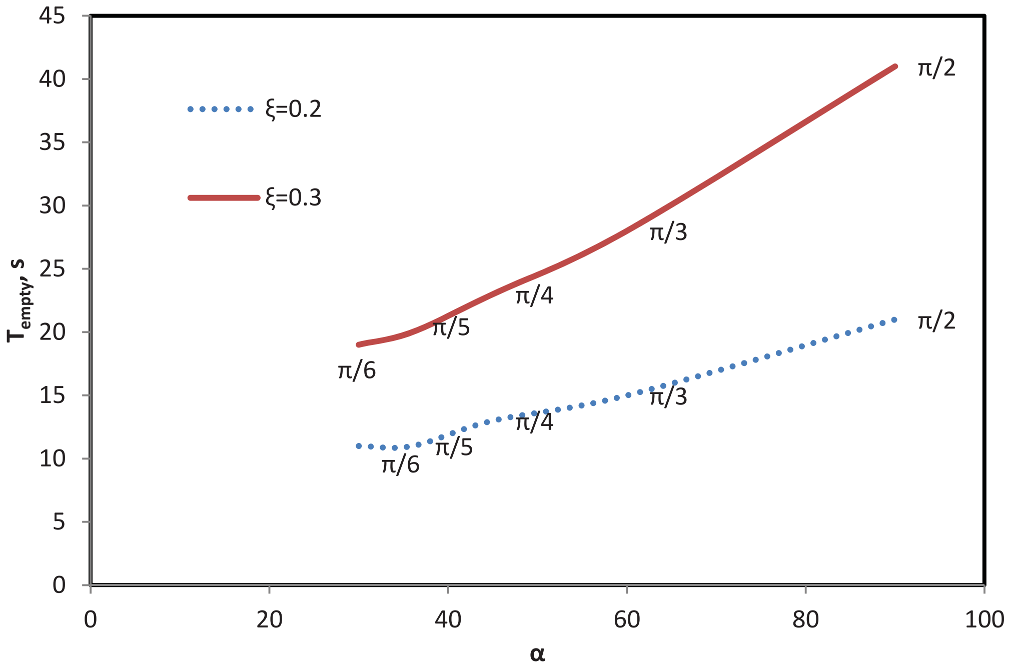


Fig. 4: Time to empty the particles from the hopper in relation to the hopper angle (α)

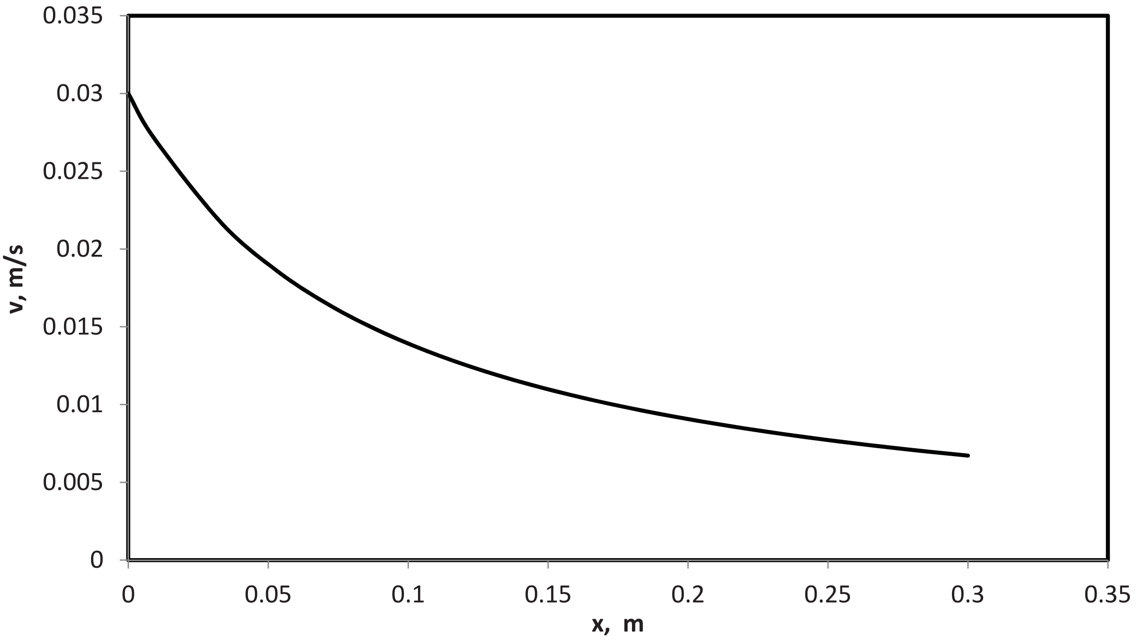
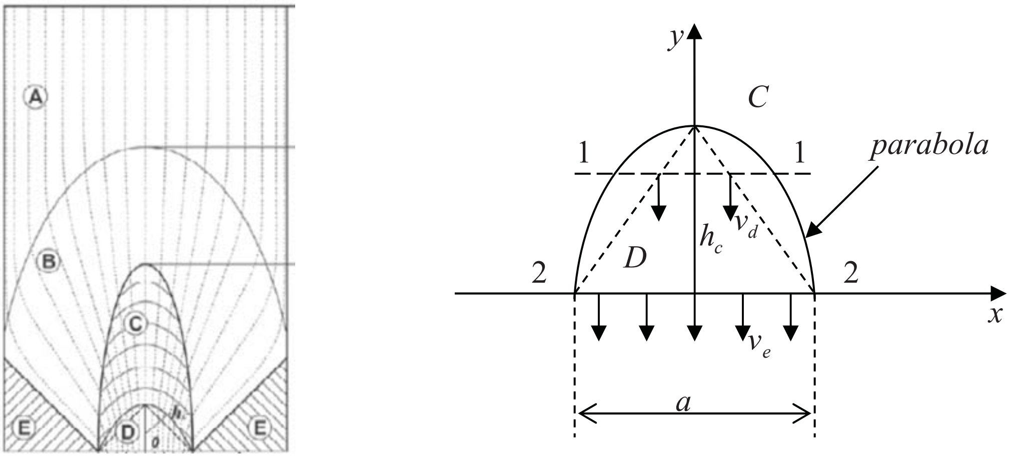


Fig. 5: Variation of the normal velocity of the particles with x ($\xi = 0.3$)



(a) (b)

Fig. 6: (a) Zones of flow of the granular particles inside a hopper (Kirya, 2009) (b) expanded diagram of Zone D

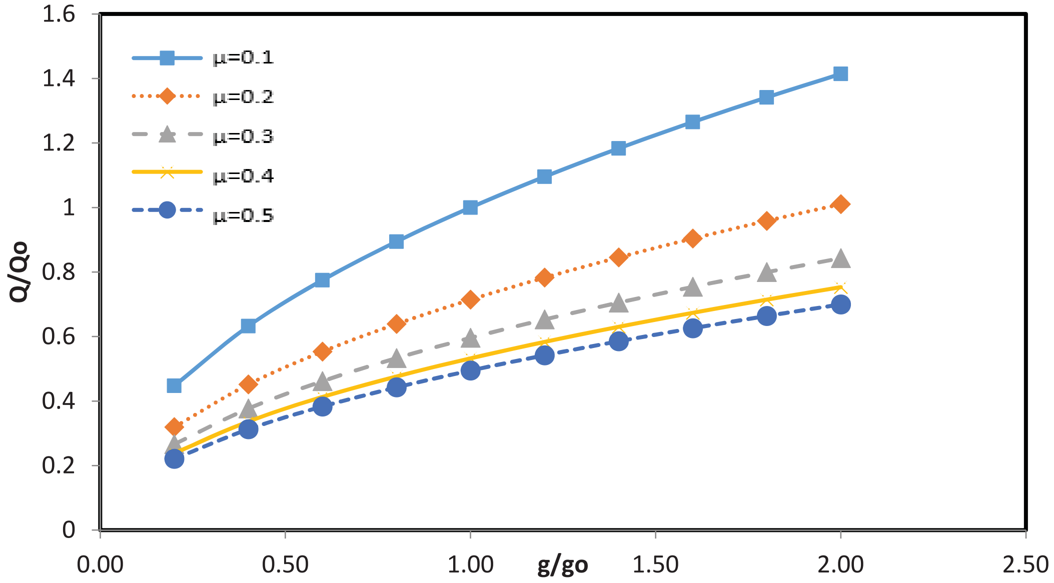
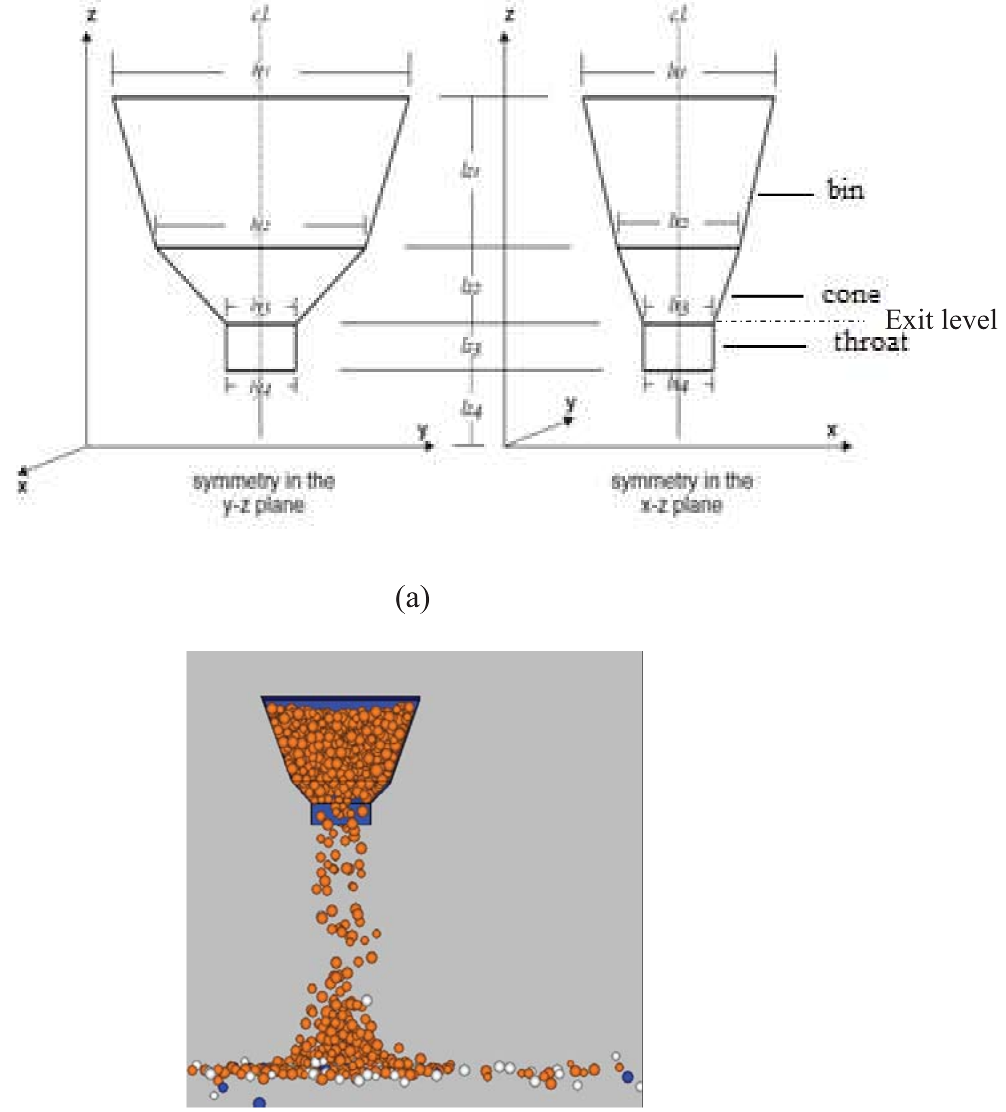


Fig. 7: Effects of friction coefficient and gravity on the granular flow rate using Kirya's structural model



(a)

(b)

Fig. 8: (a) Dimensions of the granular flow container scaled to slit opening width $l_{x4} = l_{y4} = 10$ mm. lx1 = ly1 = 35mm; lx2 = ly2 = 22mm; lx3 = ly3 = 10mm; lx4 = ly4 = 10mm; lz1 = 18mm; lz2 = 4mm; lz3 = 4mm. (b) a typical snap shot of the flow of sandstone grains from the DEM simulation.

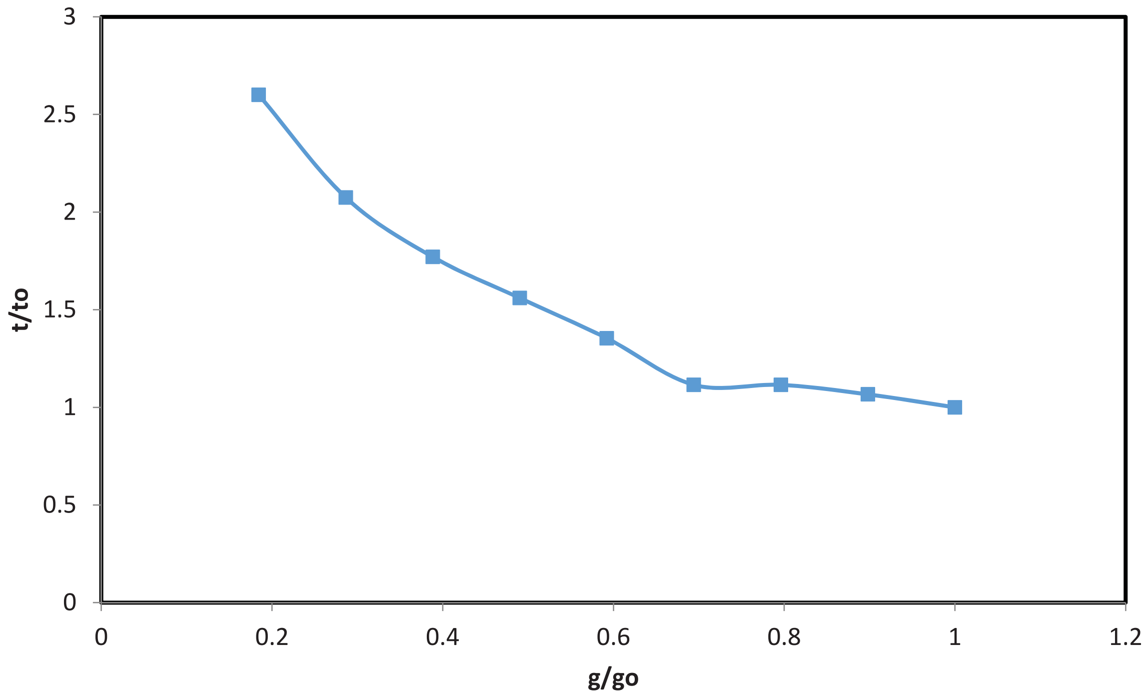


Fig. 9: Variation of the emptying time of the grains with gravity

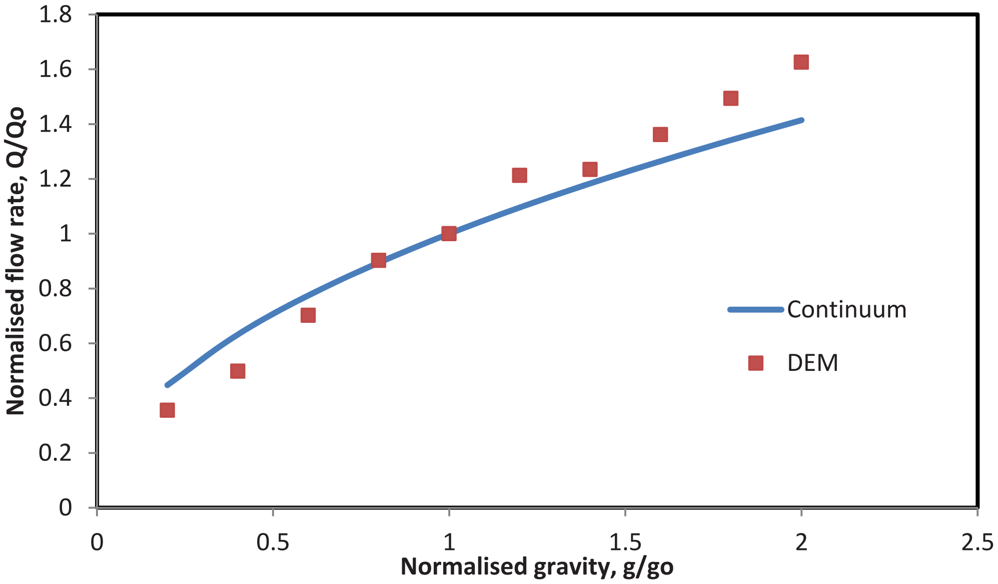


Fig. 10: Comparison of the flow rate (Q) of the sandstone grains obtained from DEM simulations and Kirya's continuum model under different gravity levels (g)

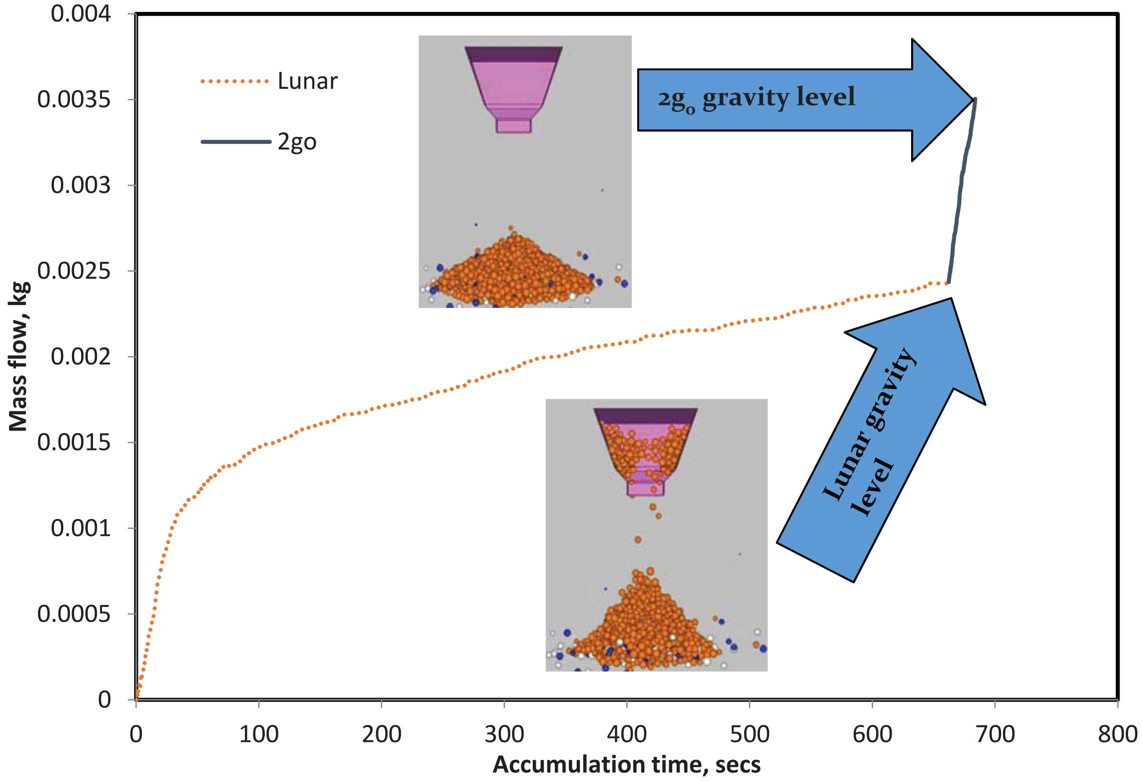


Fig. 11: Mass of sandstone grains exited from the flow chamber under the lunar gravity (1/6th of g_0) and $2g_0$ gravity levels

FIGURE CAPTIONS

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