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## Relation between free surface shape and local vertical force in the relaxation of granular materials poured into a container

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### Abstract

The free surface which results from the filling of a container by a dry granular material, takes the shape of a heap. This shape is induced by the particle properties like their size and their restitution coefficient but also by their kinetic energy induced by the filling conditions. The stabilization of the intergranular contact network inside the heap leads to the formation of a local stress field. For five wheat-based powders of same origin but with contrasted properties, beds are formed in a 2D semi-confined cell with a funnel of small outlet (localized source). Captures of the bed free surface are realized from pictures taken at different filling states. The local vertical force is measured in the center of the cell at different depths in the heap. This work highlights a correlation between the local vertical force profile and the shape of the heap during the filling. Two modes of force distribution can be distinguished and classified according to a parameter of uniformity and the gap from a pseudo-hydrostaticity. These distinctions are linked to the different shapes of the heap, quasi-layering or dune. Our experimental study demonstrates that the history of the powder filling directly impacts on the resulting local force profile.

**Keywords:** ensiled granular medium, vertical force profile, heap free surface, wheat-based powders.

### 1. Introduction

During the filling of a container by a dry granular material (ex. storage in a silo, mixer container, packaging), the powder flow interacts with the side walls and the bottom. It leads to the creation of a semi-confined free surface in the ‘feeding zone’ and particle jamming under the free surface (Grasselli *et al.*, 2000). The resultant free surface takes the shape of a heap and the surface raises upward the container with the powder filling. The stabilization of the intergranular force network inside the heap leads to the formation of a local stress field (Vanel *et al.*, 2000; Silbert *et al.*, 2002). The knowledge of the local stress field is important for a mechanical stability of storages (Sperl, 2006) or a grain re-mobilization under the influence of a shear stress (mixing, flowing) or a compression stress (packing, tapping, compaction). This work concerns the experimental identification of relationships between the static mechanical state within an ensiled granular bed and its free surface formation during filling. Different wheat-based powders of same origin, but with contrasted properties (durum wheat semolina and agglomerates) have been considered in order to elucidate a potential relation between the structure of the free surface, which results from the local granular arrangements, and the local distribution of the vertical forces.

### 2. Materials and methods

#### 2.1 Materials

Five different wheat powders were selected. The main raw material was the durum wheat semolina of industrial quality (Panzani group, France). The fine fraction of durum wheat semolina was collected by sieving, under a metallic sieve (315  $\mu\text{m}$  mesh). To investigate larger particle size, agglomerated grains of durum wheat semolina (i.e. couscous grains) were selected. Fine size couscous grains and medium size couscous grains came from an industrial production (Zakia, France). The large size couscous grains were collected by sieving the medium size couscous grain over a metallic sieve (1250  $\mu\text{m}$  mesh). Particle diameters were characterized using laser granulometry (Mastersizer 2000, Malvern, England).

The mean diameter ( $d_{50}$ , the volume-equivalent diameters for which the number of particles is respectively inferior to 50%) and the size width ( $d_{90}-d_{10}$ ; the volume-equivalent diameters for which the number of particles is respectively inferior to 10% and 90%) for all granular media were respectively: 0.210 mm and 0.321 mm for fine semolina, 0.298 mm and 0.434 mm for semolina, 0.676 mm and 0.645 mm for fine couscous, 0.953 mm and 0.517 mm for medium couscous, 1.095 mm and 0.406 mm for large couscous. We observe a large range of mean diameters with a factor of five between the smallest and the largest particles and a large size distribution of widths with lower values for sieved powders (i.e. fine semolina and large couscous).

## 2.2 Methods

The local weight profile was defined as the vertical contribution of the force network acting above the surface of a probe immersed in the granular bed. This weight was measured using an original device developed by Mandato *et al.* (2012) and composed of an open glass cell container (51 x 100 x 160 mm), a flat and rectangular steel probe (0.97 mm thickness, 44.8 mm length, 19.7 mm width) which was screwed on a rod that was linked to a load cell of a texture analyzer (TAXT Plus, Table Micro System), used as a force sensor for which the sensitivity is of the order of about 1 N (Figures 1a and 1b). The probe was first placed inside the cell container, at 0.2 mm from the front side, in the middle ( $x = 0$  mm), and at the desired distance from the bottom of the cell (Figure 1c). The probe position was defined according to the depth ( $z$ ) in the powder bed, from the powder surface ( $z = 0$  mm) to the front side of the cell ( $z = H = 140$  mm). The powder was sprinkled inside the glass cell container with a funnel until to reach 140 mm height  $H$  of the powder bed. We ensured that the granular flow depends on the outlet diameter (Beverloo *et al.*, 1961). Force measurements were performed at each probe position during 2 sec. For a same position, mean values and standard deviation were determined at least from triplicates.

The pictures of the powder bed formation in the cell were obtained with a Nikon D4 camera equipped with a macro lens of 105 mm. The converted images were then treated by Image J ® software to determine the free surface of the bed and its change as a function of the depth  $z$  in the bed.

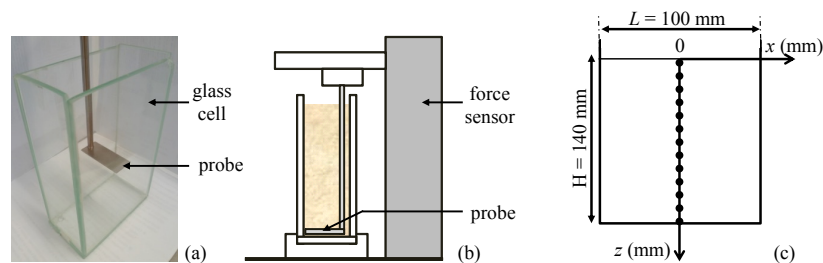


Figure 1. Picture of the experimental glass cell and the probe (a), schematic representation of the experimental set-up (side view) (b), and schematic representation of the probe positions in the cell (front view) (c).

## 3. Results and discussion

### 3.1 Bed formation

For each selected powder, the powder bed formation has been studied by analyzing their free surface evolution in 2D configuration. From pictures, the slope of the free surface was captured as numerical data and then plot at different steps of the filling (different depths  $z$ ). Examples of pictures and captured free surfaces are given in Figure 2 for semolina and large couscous.

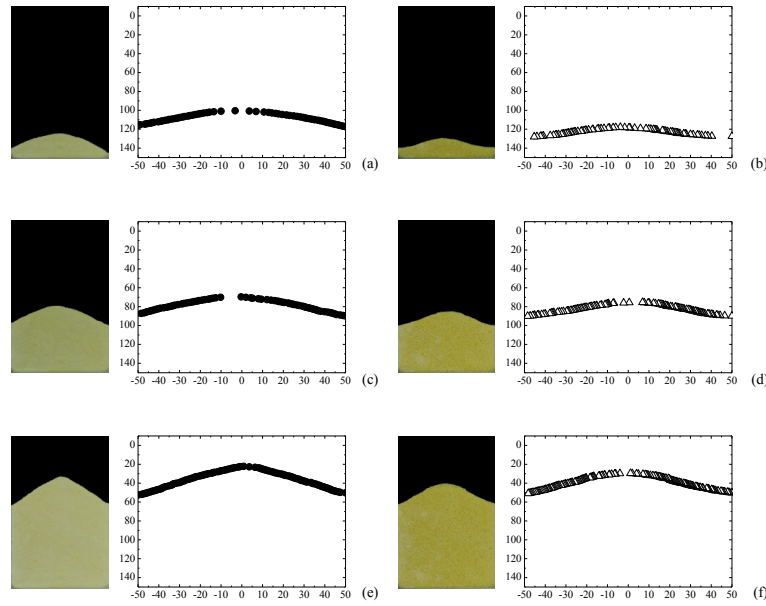


Figure 2. Picture and capture of the free surface of semolina (a, c, e) and large couscous (b, d, f) beds for a depth (at the wall) of 20, 70 and 120 (from the bottom to the top).

Whatever the wheat-powder and the depth, the shape of the free surface of the heap is globally the same. As shown in Figure 3b, this shape is not an ideal prism defined by  $\tan(\beta) = 2f/L$  (where  $L$  is the width of the cell,  $\beta$  is the ‘ideal’ angle of repose, and  $f$  is the deflection) because the top and the base of the heap are rounded off. It is directly connected with the particle properties (size, friction coefficient, restitution coefficient...) and the energy provided by the particle pouring mode (Grasselli et Herrmann, 1997; Grasselli *et al.*, 2000). We observe that the shape of the heap depends on the depth (Figure 2) and the properties of the powder (Figure 3a). In order to compare all the shape of the heaps, we have selected two representative criteria of these curves, the deflection of the heap ( $f$ ) and the angle of repose ( $\alpha$ ), deduced from the Gaussian fit of the free surface data (Figure 3b). The Gaussian equation used is  $p(x, z) = z + f(z)e^{-\frac{x^2}{2\omega(z)^2}}$ , where  $p(x, z)$  is the position of the heap according to  $x$  (horizontal coordinate for each depth  $z$ ),  $f(z)$  is the deflection of the heap at a depth  $z$ , and  $2\omega(z) = \omega_1(z)/\sqrt{\ln(4)}$ ;  $\omega_1(z)$  is the width of the Gaussian fit at a position equals to  $f(z)/2$ . Thanks to this representation, it is possible to define the angle of repose,  $\alpha$ , corresponding to the value of the slope when the inflection of the free surface is changed (Grasselli and Herrmann, 1997). At each depth  $z$ , this angle is calculated from the Gaussian equation by the relationship  $\tan(\alpha) = fe^{0.5}/\omega$ .

For each granular media, the deflection and the angle of repose are non-constant during the filling step due to the position of the powder filling which is fixed during time (Figure 3a). The fall’s height of particles decreases then with time and slows down their kinetic energy on the surface of the heap. This phenomenon is well described by Grasselli *et al.* (2000).

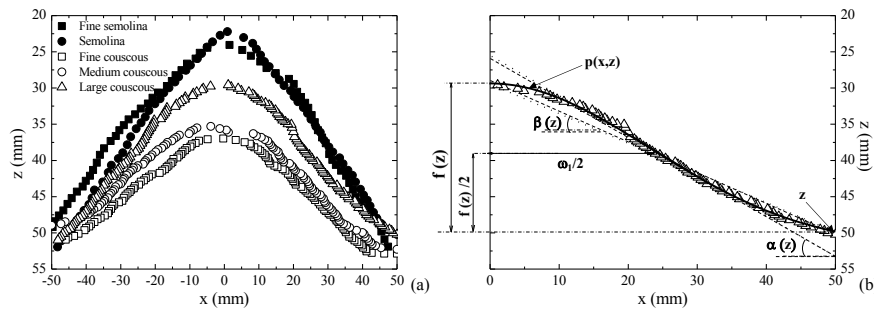


Figure 3. Free surface at about 50 mm depth (at the wall) for all granular media (a). Half-free surface (scatter) and Gaussian fit of equation 1 (line) with fit parameters.

For each granular media, the deflection is correlated to the angle of repose (Figure 4). For couscous powders, the angle of repose is higher than the ‘ideal’ angle which means that the shape of the free surface is clearly different from a prism. We observe that the top and the base of the heap are large meaning that the shape of the free surface is close to a step function ( $f \times \omega_1$ ). The low deflection can be associated with the layer configuration of the bed. As the deflections is smaller for couscous than semolinas (Figure 3a and 4), then couscous are spread into a horizontal layer (heap of low amplitude) whereas the semolinas are distributed into sloping heap (as a ‘dune’), constituted of oblique layers.

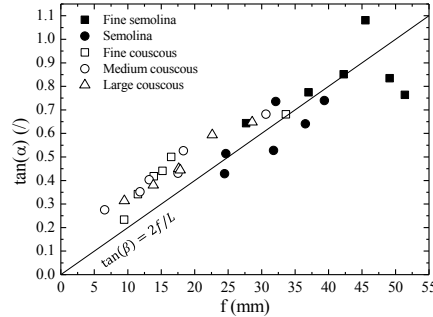


Figure 4.  $\tan(\alpha)$  for all granular media (scatters) and  $\tan(\beta)$  for an ‘ideal’ angle of repose (line) as a function of the deflection,  $f$ .

### 3.2 Vertical force profiles in the center of the cell

The both modes of the heap formation (layer or dune) have an impact on the distribution of the forces within the granular medium and measured in the center of the cell at different depths ( $F(x = 0, z)$ ) for the different selected wheat powders (Figure 5). Whatever the selected wheat powder, it presents a similar shape which is comparable to the one of Mandato *et al.* (2012). From the surface, the values of the vertical force increase until to reach a maximum and then decrease until the bottom due to the the capacity of the bottom to redirect the vertical force laterally (Vanel *et al.*, 1999; Ovarlez and Clément, 2005; Mandato *et al.*, 2013; Zhu *et al.*, 2013). The vertical force profile could be compared to the Janssen description (Ovarlez and Clément, 2005; Sperl, 2006). Janssen’s model, based on three major hypotheses (Sperl, 2006), gives the normal stress at the bottom of an ensiled granular medium versus the height of the grain bed. This model introduces a characteristic length, the Janssen length ( $\lambda_j$ ), which allows to distinct a linear dependence of the pressure, consistent with a hydrostatic behavior (defined as the total weight of the granular bed which would weigh on the bottom.), for heights lower than  $\lambda_j$  and a constant ‘saturation’ normal stress, induced by the walls which absorb the vertical force deflection (Silbert *et al.*, 2003; Ovarlez and Clément, 2005), for higher heights.

Figure 5 shows that for each wheat powder the local vertical force profile,  $F_z$ , is linear until a characteristic depth of about 70 mm which could be assimilated to the Janssen length (Mandato *et al.*, 2013). Considering this linear part from the bed surface, the vertical force profile is well fitted by a linear trend (Figure 5), where the gradient ( $S^{-1}$ ) is comprised between  $53 \cdot 10^{-4}$  N/mm for fine semolina and  $97 \cdot 10^{-4}$  N/mm for fine couscous (Table 1). The values are higher than the gradient of the equivalent hydrostatic state,  $\phi \rho_s g \Omega$ , defined as the weight of the granular column acting on the surface of the probe. In fact, it corresponds to a ‘pseudo’-hydrostatic weight (Mandato *et al.*, 2012) taking into account all the contribution of forces acting on the probe and coming from the different parts of the force network (Vanel *et al.*, 2000; Silbert *et al.*, 2003). For higher depths each profile deviates from a linear dependence (Figure 5). This deviation is positive for semolinas (*i.e.* the vertical force becomes higher) and negative for the couscous grains.

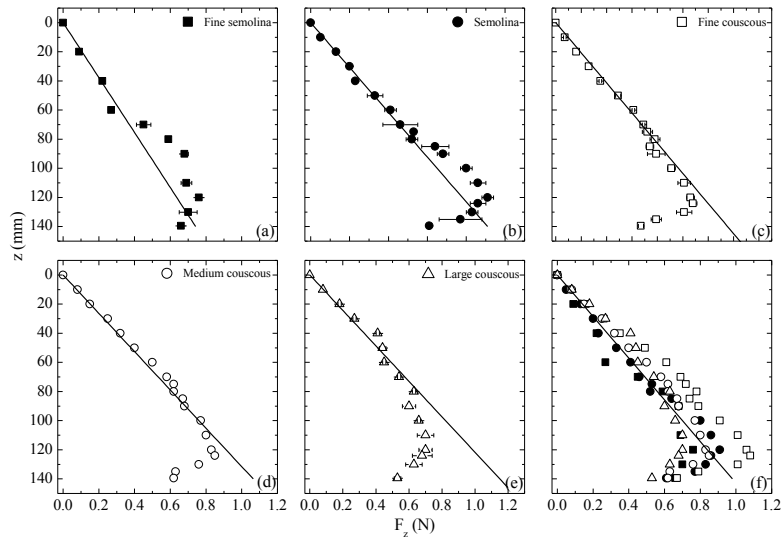


Figure 5. The vertical force for fine semolina (a), semolina (b), fine couscous (c), medium couscous (d), large couscous (e), and all wheat-powders(f) as a function of the depth. The ‘pseudo’ hydrostatic profile is represented by a line.

Table 1. Compactness of the bed ( $\phi$ ), gradient of the linear fit of the vertical force ( $S^{-1}$ ), and gradient of the equivalent hydrostatic force ( $\phi\rho_s g\Omega$ ) for all granular media.

Name	$\phi$	$S^{-1}$ (N/mm)	$\phi\rho_s g\Omega$ (N/mm)
Fine semolina	0.416	$(53 \pm 3) \times 10^{-4}$	$49 \times 10^{-4}$
Semolina	0.446	$(65 \pm 2) \times 10^{-4}$	$53 \times 10^{-4}$
Fine couscous	0.578	$(97 \pm 3) \times 10^{-4}$	$69 \times 10^{-4}$
Medium couscous	0.573	$(76 \pm 1) \times 10^{-4}$	$68 \times 10^{-4}$
Large couscous	0.578	$(82 \pm 3) \times 10^{-4}$	$69 \times 10^{-4}$

To compare the whole data coming from the free surface and the local vertical force, we defined an adimensional parameter for each depth  $z$ ,  $D(z) = \frac{F(x=0,z)}{f(z)S^{-1}}$ . This parameter highlights the correlation between the normalised force (by the pseudo-hydrostatic state) measured in the center of the cell and the height of the heap which has contributed to the establishment of the local mechanical state.

Excepted close to the bottom, where the interaction of the first poured particles leads to different organizations according to their relaxation property (Vanel *et al.*, 1999), the behaviour of the powders seems to follow a coherent distribution. Indeed, the dependence of the parameter  $D$  with the depth, indicates that the level of local vertical force is correlated with the shape of the free surface (Figure 6). For couscous grains, the particle organization into a flat heap (small  $f$  values), which can be assimilated to a quasi-layer distribution, is in agreement with the hypothesis of Janssen (Sperl, 2006) on the lateral uniformity of the stresses highlighted by a ‘pseudo’-Janssen profile, characterized by a lateral deflection of the force and therefore large values of  $D$  parameter. On the other hand for semolina, the particle organization into a sloping heap (large  $f$  values) reduces the capacity of the lateral deflection inducing smaller values of  $D$ .

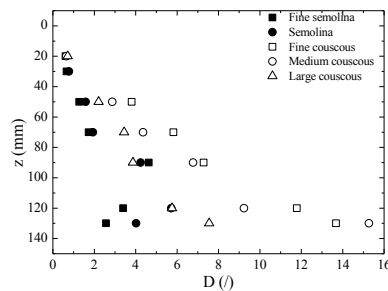


Figure 6. Parameter  $D$  as a function of the depth for all granular media.

#### 4. Conclusion

This work deals with the experimental analysis of the impact of a granular medium ensiling history on the distribution of the local forces. For a 2D experimental configuration, the powder filling is characterized by the free surface evolution of the granular medium whereas the static intergranular contact network is represented by the vertical force measured in the center of the cell. The width of the cell, the filling conditions, and the particle properties (size and shape, coefficient of restitution), are the parameters which lead to define at least two different modes of heap formation: the horizontal layer mode and the oblique layer mode. For all wheat-powders, the vertical force acting on a probe placed in the center of the cell is ‘pseudo hydrostatic’ until a characteristic depth of about 70 mm. Below this depth, the lateral deflection of the force is correlated with the shape of the heap formed during the implementation of the column. The more the heap is sloping, the more the intensity of the local force is high with regard to its local ‘pseudo’-hydrostatic state. Such a result allows considering more explicitly the history of the bed implementation on the force distribution within an ensiled granular medium.

#### References

- Beverloo, W. A., Leniger, H. A., Van de Velde, J., 1961, The flow of granular solids through orifices, *Chemical Eng. Science* 15, 260-269.
- Grasselli, Y., Herrmann, H.J., 1997, On the angles of dry granular heaps, *Physica A*, 246, 301-312.
- Grasselli, Y., Herrmann, H.J., Oron, G., Zapperi, S., 2000, Effect of impact energy on the shape of granular heaps, *Granular Matter* 2, 97-100.
- Mandato, S., Cuq, B., Ruiz, T., 2012, Experimental study of vertical stress profiles in a confined granular bed under static and dynamic conditions, *Eur. Phys. J. E*, 35: 56.
- Mandato, S., Cuq, B. Ruiz, T., 2013, What is Janssen’s length doing in an agglomerator? *Powder Technology*, Vol. 238, 56-63.
- Ovarlez, G., Clément, E., 2005, Elastic medium confined in a column versus the Janssen experiment, *Eur. Phys. J. E*, 16, 421-438.
- Silbert, L.E., Grest, G.S., Landry, J.W., 2002, Statistics of the contact network in frictional and frictionless granular packings 66, 0 61303.
- Sperl, M., 2006, Experiments on corn pressure in silo cells—translation and comment of Janssen’s paper from 1895, *Granular Matter* 8, 59–65.
- Vanel, L., Howell, D., Clark, D., Behringer, R. P., Clément, E., 1999, Memories in sand: Experimental tests of construction history on stress distributions under sandpiles, *Phys. Rev. E* 60, 5, 5040-5043.
- Vanel, L., Claudin, Ph., Bouchaud, J.-Ph., Cates, M. E., Clément, E., Wittmer, J. P., 2000, Stresses in Silos: Comparison Between Theoretical Models and New Experiments, *Phys. Rev. Letters* 84, 7, 1439-1442.
- Zhu, J., Liang, Y., Zhou, Y., 2013, The effect of the particle aspect ratio on the pressure at the bottom of sandpiles, *Powder Technol.* 234, 37–45.

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## **Relation entre la forme de la surface libre et l'état sthénique local au sein d'un milieu granulaire versé dans une cellule**

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### **Résumé**

La surface libre, qui résulte du remplissage d'un matériau granulaire dans un récipient, prend la forme d'un tas. Cette forme est induite par les propriétés des particules comme leur taille et leur coefficient de restitution mais aussi par leur énergie cinétique induite par les conditions de remplissage. La stabilisation du réseau de contact intergranulaire à l'intérieur du tas conduit à la formation d'un champ local de contrainte. Pour cinq poudres de blé de même nature mais aux propriétés contrastées, les lits sont formés dans une cellule 2D semi-confinée à l'aide d'un entonnoir de faible ouverture (source localisée). Les captures de la surface libre du lit sont réalisées à partir de photos prises à différents états de remplissage. La force verticale locale est mesurée au centre de la cellule à différentes profondeurs dans le tas. Ce travail met en évidence une corrélation entre le profil local de la force verticale et la forme du tas pendant le remplissage. Deux modes de distribution de force peuvent être distingués et peuvent être classés selon un paramètre d'uniformité et leur écart à une pseudo-hydrostaticité. Ces distinctions sont reliées à la forme du tas, quasi en couche ou en dune. Nous avons trouvé dans cette étude expérimentale que l'histoire du remplissage de la poudre impacte directement sur le profil local de la force.

**Mots clés :** milieu granulaire ensilé, profil de force verticale, surface libre d'un tas, poudres de blé.

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