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History-dependent structure in granular piles

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ABSTRACT: The pressure distribution under heaps has found to be dependent on the building history of the heap both in experiments and in simulations. Up to now, theoretical models and analysis assume that the packing of the heap is homogeneous. We show new experimental and simulational results which indicate that the packing is inhomogeneous and that this packing property is likely causing the pressure minimum under the heap.

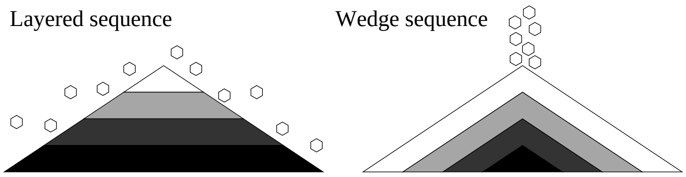

Figure 1: Possible construction history of heaps.

1 Introduction

In recent years, the rather unintuitive existence of a pressure minimum under granular heaps created some attention the community involved in granular research. Heaps with without pressure minimum in the middle have been reported in the literature (see references in [1]). This was interpreted by one of the authors (H.-G. M. in Ref. [2]) as an effect of the construction history and was corroborated by molecular dynamics simulations[2], which have recently been verified experimentally[3]. Wedge sequences, where the heap is poured from a point source, in general exhibit a pressure minimum, in contrast to layered sequences, where the particles are rained uniformly onto the heap (for the terminology of the construction history, see Fig. 1). Arching as a "prime suspect" for the formation of the pressure dip was already mentioned in the experimental papers on the pressure dip[4]. Arching has been a long standing topic in granular materials research, with the first references of "Bogenbildung" (arching) in Terzaghi's textbook on "Erdbaumechanik" (geotechnics) [5] going back to the last quarter of the nineteenth century.

We assume that the bottom of the heap is not deformed by external mechanism. If not otherwise noted, all heaps in the experiments and simulations are built in a wedge-sequence, the grains are poured from a point source. All heaps are constructed on a smooth ground. In the simulations, the Young's modulus of the ground is the same as for the grains and the friction coefficient between ground and particles is the same as between the grains to simplify matters. The simulation method is described in Ref. [2], the setup of the experiments will be explained in a further publication.

2 Grain properties

For heaps of monodisperse smooth grains in the absence of cohesion, no pressure minimum in the middle is observed, see. Fig. 2.

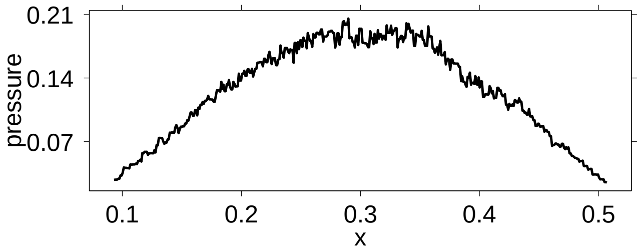

Figure 2: Pressure distribution for a simulation of monodisperse round particles (less than 8 % deviation in diameter) under a heap set up in a layered sequence.

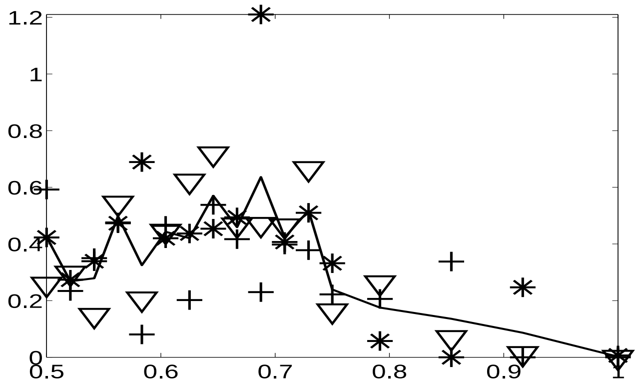

Figure 3: Pressure distribution for small glass beads and an average grain diameter of about 230 μm diameter, monodisperse (210-250 μm).

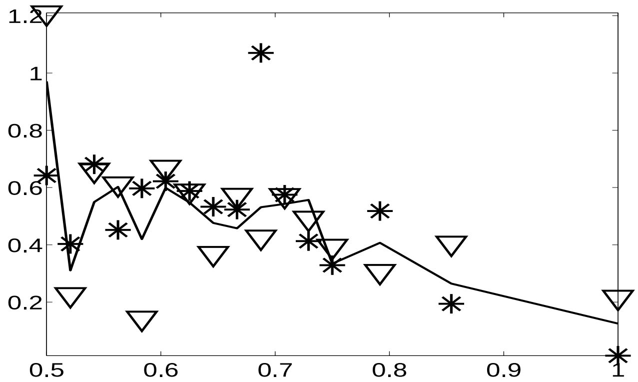

Figure 4: Pressure distribution for glass beads with 463 μm average diameter, monodisperse (425-500 μm).

2.1 Polydispersity

One of the more puzzling experimental results in the experiments in Ref. [6] is the fact that for monodisperse small glass beads (180 μm diameter) a pressure minimum exists, but not for monodisperse large beads (560 μm diameter). The pressure dip for small glass beads seems also to contradict simulation results[2], and the experimental rape seed pressure distributions in [4], where the pressure dip for "nearly" monodisperse systems practically vanishes. For monodisperse particles of about 230 μm diameter (Fig. 3) the pressure dip is well developed, whereas for monodisperse particles of about 463 μm diameter (Fig. 4) no pressure dip exists. On the other hand at about 460 μm particle diameter and a deviation of the particle radius of up to a factor of 3.3 in the deviation of the particle diameter, the pressure dip for glass beads is already well developed, as can be seen from Fig. 5. In general, our data are more noisy than the ones in Ref. [6], because we used a smooth steel ground with standard pressure gauges, so that the bottom was not roughened by the measurement devices.

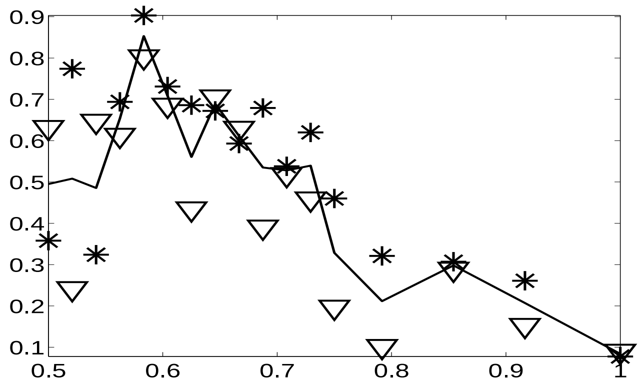

Figure 5: Pressure distribution for glass beads and an average grain diameter of about 460 μm diameter and large polydispersity (210–710 μm).

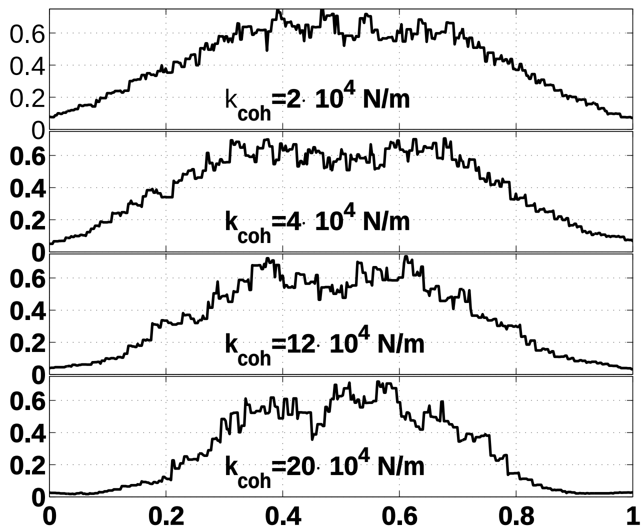

Figure 6: Pressure distribution under heaps for simulations of monodisperse particles (7 corners) and different cohesion strength. The pressure dip develops with increasing cohesion.

2.2 Cohesion and Roughness

From the previous section, we can assume that the pressure dip for particles below 180 μm diameter in Ref. [6] were not caused by some polydispersity on the micrometer scale. The pressure dip seems to occurs only for glass bead with grain diameters below 460 μm. Cohesion changes the movement of grains from single particles to clusters of correlated particles. This was conjectured by experiments in Ref. [7] and corroborated by micromechanical simulations in Ref. [8]. In the Hosokawa powder tester (as proposed by Carr [9]), the strength of the cohesion and the surface roughness of the particles is classified by a single parameter, the flowability. This flowability seems to be responsible why a system with 460 μm diameter glass beads and less than 8 % deviation (Fig. 4) in diameter behaves is a monodisperse system and exhibits no pressure

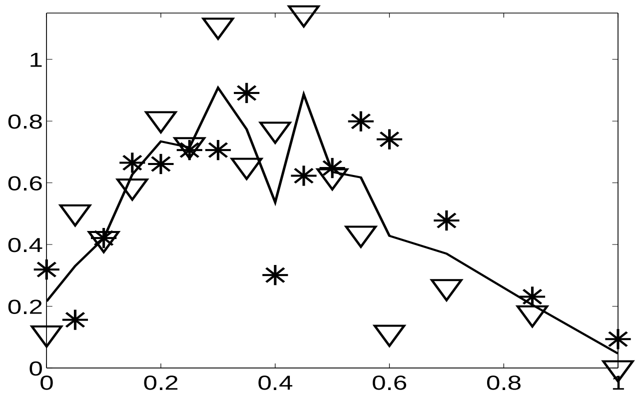

Figure 7: Pressure distribution for sand with 463 μm average diameter, monodisperse (425-500 μm).

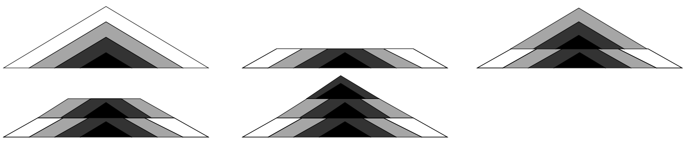

Figure 8: Sketch of the building history of the lopped cone.

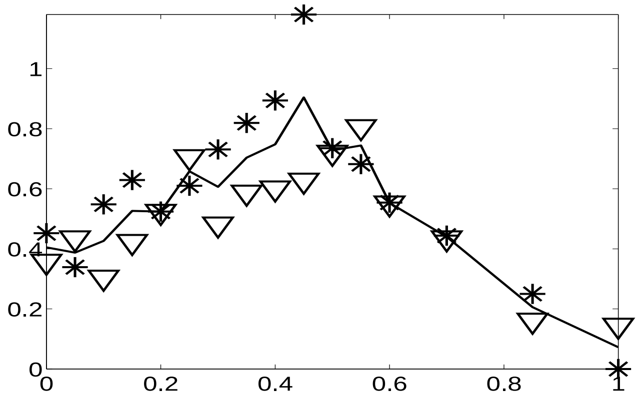

Figure 9: Pressure distribution under the lopped and rebuild cone of Fig. 8.

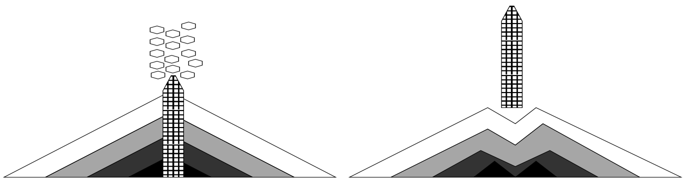

Figure 10: Sketch of the building history of the wedge sequence with a rod inserted in the middle.

dip, whereas sand with the same diameter and size dispersion shows a pressure dip (Fig. 7). For the same reason, the monodisperse frosted glass beads in Ref.[6] with about 1 mm diameter diameter showed a pressure minimum.

3 Stability

An experiment to test the stability of the pressure distribution under the heap was performed by building up a heap from a point source. Afterwards, this cone was lopped via a vacuum cleaner to a frustum, see Fig. 8. On the frustum, the heap is rebuilt, the cone is again lopped via vacuum cleaner and again rebuilt and the pressure distribution is measured.

The pressure minimum for the wedge sequence is present before the first reduction and, as can be seen in Fig. 9, after the final buildup. The width of the dip is rather larger than for "conventional" wedge sequences.

We further investigated a wedge sequence with a rod of 12 mm diameter in the middle of the heap. After the heap was piled up, the rod was removed, and the heap filled up with grains. It turned out that the pressure distribution corresponded largely to the pressure distribution of the wedge sequence. The depth of the crater after the removal of the rod was so small that the change in the total pressure was insignificant. As can be seen in Fig. 11, the pressure minimum had significantly larger diameter than the immediate neighborhood of the rod.

4 Heap density

The experimental findings of the previous sections indicate that the pressure minimum is a rather stable phenomenon, suggesting a rather macroscopic mechanism for the pressure minimum. For 10 heaps built in a wedge sequence with a pressure minimum (Fig. 12), the pressure curves for different heights do not scale. This is consistent with the fact that at the top, where the particles impact, the building history corresponds to a "layered sequence", whereas the ideal "wedge sequence" is only realized far away from the impacting particles. The result that the pressure distribution is not the same throughout the heap is in contrast to assumptions and results in several theoretical investigations. The averaged density of these heaps (Fig. 13), in the middle region exhibits higher density than the rest of the heap. This core of higher bulk density existed for all heaps that showed a pressure minimum in the middle. These density deviations in the simulations with a "funnel" of about 4-8 % higher density in the middle of the pile correspond reasonably well with the increased bulk density in the packing distribution of a catalyst bed filled from a point source in Ref. [10].

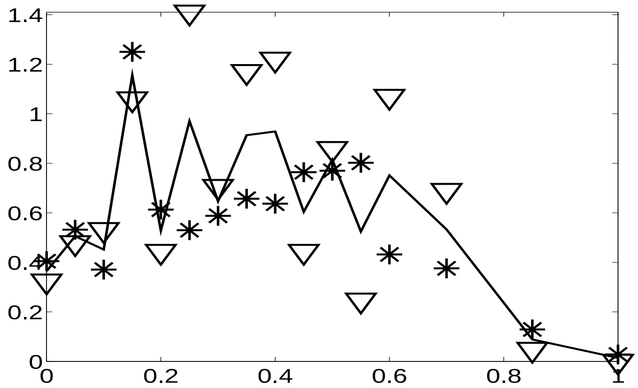

Figure 11: Experimental pressure under a heap built with a wedge sequence around a rod.

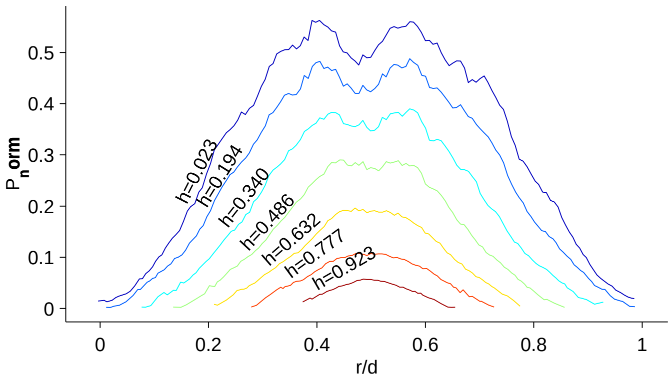

Figure 12: Pressure distribution averaged from 10 heaps with polydisperse particle size distribution and wedge sequence. The pressure is measured at various heights and the curve does not scale for pressures in higher regions.

We did not find any significant density differences for the heap build in a layered sequence, and for such a "rainy" uniform filling method, also experimentally no density differences were observed in Ref. [10].

5 Conclusions

We have shown computational evidence that for heaps with a pressure dip in the middle the density is not homogeneous, which is in agreement with experimental findings. An arch is created by the density inhomogeneity of the pile. Size polydispersity, shape polydispersity or reduced "flowability" by high surface roughness or cohesion prohibit a reordering of the density by impacting particles. Static friction is a necessary condition, disorder alone is not sufficient.

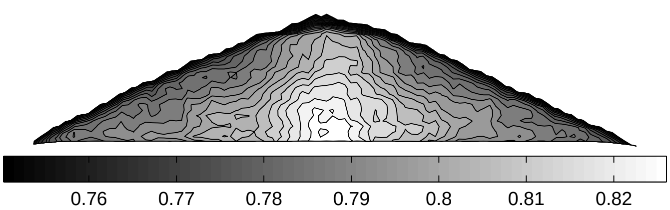

Figure 13: Averaged bulk density of Fig. 12.

Acknowledgments

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