Powder Technology 246 (2013) 269–277

Contents lists available at SciVerse ScienceDirect

Powder Technology

journal homepage: www.elsevier.com/locate/powtec

Arching structures in granular sedimentary deposits

L. Kulaviak [a], J. Hladil [b], M.C. Ruzicka [a,*], J. Drahos [a], L. Saint-Lary [c]

[a] Institute of Chemical Process Fundamentals, Department of Multiphase Reactors, Academy of Sciences of the Czech Republic, Rozvojova 135, 165 02 Prague, Czech Republic
[b] Institute of Geology, Laboratory of Geological Processes, Academy of Sciences of the Czech Republic, Rozvojova 269, 165 00 Prague, Czech Republic
[c] National Polytechnic Institute of Chemistry in Toulouse - ENSIACET, Department of Processes and Chemistry, 4 allée Emile Monso - BP 44362, 31030 Toulouse Cedex 4, France

ARTICLE INFO

Article history:
Received 13 December 2012
Received in revised form 15 May 2013
Accepted 17 May 2013
Available online 24 May 2013

Keywords:
Wet granulars
Deposit
Arching structure
Cavity
Voidage pattern

ABSTRACT

Experimental results on arching structures in sedimentary deposits are presented. Polydisperse mixtures of rough non-spherical natural calcite particles (ground limestone) settled collectively in a liquid, in a lab-scale experimental cylinder. At the bottom, layers of sediment were produced. The morphology of the deposit layers was studied with the help of visualization and image analysis. Families of inter-connected arching patterns in the form of voids or cavities were identified, of highly complex geometry. The effect of the mixture composition on the deposit structure was investigated. It was found that arches tend to form under specific conditions. Large and small grains promoted the arch formation, while the medium grains tended to inhibit arching.

1. Introduction

Sedimentation is an omnipresent phenomenon that reflects the general tendency imprinted to our material environment by the gravity field. One can quote Zimmels [1]: "A world without sedimentation phenomena, whether natural or man-made, would be incomprehensible. In some way, sedimentation exists around us every day in the form of natural (i.e. rain, snow, dust, sedimentation of silt in rivers) or artificial (i.e. processing and pollution products) precipitation".

The settling process has been studied for a long time and this important research field is covered by a rich literature. Typically, two limit cases are considered. First, the fall of an isolated particle in a still fluid, because this 'micro-scale' situation is the simplest possible and is amenable to rigorous mathematical analysis. Second, the design of large settling tanks with the help of empirical correlations, because this 'macro-scale' situation is of high practical interest. The missing link between these two extremes, the 'meso-scale' view, is currently under development. It presents the difficult problem of hydrodynamic interactions of individual particles in clusters of various sizes, from which the collective dynamics of larger ensembles of dispersed particles, under hydro-mechanical forces, gradually emerges. It is due to the inherent complexity of the meso-scale approach, that we still lack fully conclusive and easy-to-use practical results, suitable for inclusion in common handbooks on sedimentation. Instead, this challenging subject is being treated in separate research articles, often with ambiguous and even contradictory results.

Unlike the settling process itself, much less attention has been paid to the process of formation of sedimentary deposit (sediment, sludge, slurry) beneath settling layers, on the bottom of the container. This issue is usually addressed only when the deposit is further processed. In this case, only the bulk properties of the sediment are considered (e.g. slurry height descent, total voidage, etc.), since they are easily accessible and help to manage the deposit handling (transport, thickening, disposal). It is well known that a large number of fluid-filled cavities (voids) is produced during deposit formation, which strongly reduce the separation efficiency of the sedimentation process. However, very rarely the internal structure of the deposit layers and their morphology are investigated. It would provide us with an important piece of knowledge about the mechanisms of the cavity formation, their properties and stability, and consequently give us guidance to control their unwanted occurrence.

In technology, sedimentation is a traditional separation process that is used in a large number of applications. It is frequently employed in chemical, biochemical, pharmaceutical, mineral, oil and environmental technologies. Since the amount of the sediment globally produced every day is enormous, even a little increase in the separation efficiency would be welcome. The liquid-filled cavities contribute much to the total liquid content in the deposit and increase the bulk volume of the sediment, which must be handled to the further transport and treatment, for instance through thickening or dewatering of waste disposal and slurries (e.g. Faust & Aly [2], Cheremisinoff [3], Metcalf & Eddy [4], Wang [5], Jewell & Fourie [6]). Thus on the practical side, knowing more about the cavities, as for their occurrence, properties and way of formation, would be useful.

* Corresponding author. Tel.: +420 220 390 299; fax: +420 220 920 661.
E-mail address: ruzicka@icpf.cas.cz (M.C. Ruzicka).
URL's: http://www.icpf.cas.cz (L. Kulaviak), http://www.gli.cas.cz (J. Hladil), http://www.icpf.cas.cz (M.C. Ruzicka), http://www.icpf.cas.cz (J. Drahos).

0032-5910/$ – see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.powtec.2013.05.033

In science, one whole branch of research is fully devoted to exploring the natural sediments (sedimentary geology, sedimentology, e.g. Reading [7], Nichols [8], Bhuiyan [9], Leeder [10]). The petrified sediments contain the complete memory of the geological evolution and conserve the information about the then conditions and events, over a huge span of time. The presence of cavities in the sediment is of a great indicative value, and these cavities and their properties, as well as the mechanism of their formation, are presently the subject of intense study (e.g. Tucker & Wright [11], Middleton [12]). Discovering their formation mechanism can help to identify the specific circumstances prevailing in the given place, at a given time, millions years ago, when these cavities were produced, which is valuable for geologists.

The sedimentary cavities present a highly challenging problem for granular science and relate to the problem of hydro-mechanical particle–particle interactions in wet granular ensembles. These cavities are *arching structures* that form spontaneously at simultaneous settling and depositing of particles. This typically occurs with complex polydisperse mixtures of diverse anisotropic particles, under ill-defined hydrodynamic conditions, as is the typical situation in both nature and technology. Under such circumstances, it is almost impossible to decipher the physical mechanisms underlying the formation of the wide spectrum of highly complex geometrical void patterns, the inter-connected liquid-filled dome-shaped cavities of strongly irregular shape, the bridging constructions covering a wide span of length scales.

The science of granular media, which is a peculiar and independent state of matter, is nowadays a strongly proliferating field of interest, with a number of specific topics; for its vast diversity see e.g. the 'Powders and Grains' conference series. There are valuable handbooks (e.g. Fayed & Otten [13]) and monographs (Feda [14], Seville [15], Antony [16], Hinrichsen & Wolf [17], Mehta [18]), fully devoted to this exciting subject. The problem of *arching* is an old one, shared in common by soil mechanics, building engineering, and granular science. Much inspiration came from the behaviour of hoppers (silos), where both static and dynamic arches are frequently encountered (e.g. Brown & Richards [19], Neddermann [20]). Newly, the arching phenomenon appears also in more physically minded texts (e.g. Duran [21]). The current granular simulations techniques accept the arching challenge too (e.g. Poschel & Schwager [22]).

In the literature, there are not many contributions dealing with the specific problem of arching in sedimentary deposits. The contributions typically use severe *simplifications* (2D system, spherical particles, monodisperse ensemble, low particle number, dry granular system, approximate models, replacing gravity effects with shaking/tapping, etc.). Some results were obtained through models for the *static* granular ensembles, for instance, the geometry-based voidage estimation model for a 3D system of monodisperse spheres (Kelly [23]), spatial correlations model for force-transmission chains in 2D statistical system of monodisperse disks (Nicodemi [24]), typicality of arching in mechanically equilibrated dry 2D granular system model of monodisperse disks (Peralta-Fabi [25]).

More interestingly, the *dynamic* aspect of arching in deposits with help of 2D and 3D *models* were studied too, but likely only in dry monodisperse systems. Here, the natural gravity settling was simulated by shaking/tapping the granular bed to generate the effect of the non-sequential settling, needed for activating the arching potential of the system. Arevalo [26] performed the molecular dynamic type of simulation on the ensemble of granular 2D disks, followed the history of individual particle contacts, and found the stable arrangements—the arches. The effect of the tapping amplitude on the arches properties was tested. Pugnaloni [27] studied the effect of the tapping amplitude on the degree of uniformity of the granular bed and the number and geometry of the arches formed from 2D disks. The order–disorder transition was observed and the number of arches related to the density of packing. The difference between the 2D and 3D coordinate number trends was highlighted too. Carlevaro [28] investigated the contact forces and stress conditions for 2D disk grains in and out of the arches and found the discriminative difference between the iso- and anisotropic stress components. The relation between the force chains and arches is discussed too. Vidales [29] presents a rare exception by using non-circular grains in form of 2D pentagons. The process of compaction under vertical tapping is simulated, with regard for the arch formation, their number and size distribution, to be compared with round disks. The formation of a heap from non-circular grains, convex polygons, was also studied with a 2D model in Matuttis & Luding [30], with the main focus on the internal stress, but not on arching. Other contributions on the effect of particle shape on the basic granular mechanics are e.g. due to Szarf [31] (2D model) and Shamsi [32] (3D model). Similarly, the effect of polydispersity of circular disks was also studied (Ueda [33]). Interestingly, a Tetris-like model for granular dynamics was advocated by Caglioti [34].

Besides these 2D attempts, also 3D modelling efforts were reported. Konstandopoulos [35] employed discrete particle simulation approach to investigate the deposit growth dynamics. The impact dynamics of monodisperse spheres colliding with the deposit layer was resolved and discussed. The incident particle parameters determined the deposit growth rate and morphology. The effect of deposit roughness and hardness on the impact process was studied too. Pugnaloni [36] investigated the structure and spatial distribution of arches produced after shaking the monodisperse spherical granular system. The main focus was on the effect of the packing fraction of the granular bed. The shape and size of the arches was not influenced much, in contrast to the arches location and orientation within the bed.

Even more interestingly, there are also several *experimental* studies somehow related to the deposit growth and arching. The traditional area of interest in both the static and dynamic arching is the behaviour of hoppers (solid–gas system), which is covered by many references. This corresponds more to release of a dry deposit from below of a container, which is not our case of a wet deposit gradually growing from above on the bottom. To briefly reflect the recent progress in hopper arching, let us refer e.g. to the measurements in Garcimartin [37], where the geometry of arches was studied in relation to static friction forces, and to that of Vivanco [38], where the network of contact forces and dynamic arching was directly visualized with the photoelastic method. The stability of static clogged dry granular beds was reported by Duran [39], with a particular respect to the initial condition (sample preparation). The 2D granular system (monosized spheres) remained blocked and suspended in the flat column after gravity reversal. The 3D systems (non-spherical polydisperse sepiolite grains) displayed a range of flow types, depending on the preparing mode. Considerations were suggested about the role of the static friction force in fragmenting the granulate, which relates to a more general problem of force chains stability, hence stability of static arches. On the other hand, purely dynamic arches were observed in Hsiau [40], in vibrating granular bed of dry monodisperse spheres, where these ephemeral structures were related to the velocity field and granular temperature within the shaken bed. To our knowledge, not many experiments concern the detail deposit dynamics in liquid environment (solid–liquid system). For instance, in the work by Furuuchi [41], fine monodisperse spherical particles were observed to form deposit layer, driven by the electrophoretic force field to control their settling speed. The morphology of the dried deposit surface was evaluated, and related to the particle size, speed, and concentration. The ordered and closely packed compact surfaces were preferred, since the motivation came from the ceramic material engineering.

From the above mini-review, it becomes apparent that we lack information about the important and generic arching phenomena under circumstances that are more complex, hence more realistic. The primary motivation of our study is to experimentally investigate the effect of the composition of polydisperse mixtures of real granular geological materials, settling in liquids, on its arching potential (solid–liquid system).