



Universiteit
Leiden
The Netherlands

Granular flows : fluidization and anisotropy

Wortel, G.H.

Citation

Wortel, G. H. (2014, November 19). *Granular flows : fluidization and anisotropy*. *Casimir PhD Series*. Retrieved from <https://hdl.handle.net/1887/29750>

Version: Not Applicable (or Unknown)

License: [Leiden University Non-exclusive license](#)

Downloaded from: <https://hdl.handle.net/1887/29750>

Note: To cite this publication please use the final published version (if applicable).

Cover Page



Universiteit Leiden



The handle <http://hdl.handle.net/1887/29750> holds various files of this Leiden University dissertation

Author: Wortel, Geert

Title: Granular flows : fluidization and anisotropy

Issue Date: 2015-11-19

Granular Flows: Fluidization and Anisotropy

PROEFSCHRIFT

ter verkrijging van
de graad van Doctor aan de Universiteit Leiden,
op gezag van Rector Magnificus
prof. mr. C.J.J.M. Stolker,
volgens besluit van het College voor Promoties
te verdedigen op 19 november 2014
klokke 11.15 uur

door

Gerrit Herman Wortel
geboren te Zoetermeer
in 1985

Promotiecommissie:

Promotor: Prof. dr. M.L. van Hecke

Overige leden: Dr. O. Dauchot (*ESPCI-ParisTech, Frankrijk*)

Prof. dr. E.R. Eliel

Dr. D.L. Henann (*Brown University, VS*)

Dr. D.J. Kraft

Prof. dr. T.H. Oosterkamp

Prof. dr. M.A.J.G. Orrit

Prof. dr. H. Schiessel

Nederlandse titel:

Granulaire Stroming: Fluïdisatie en Anisotropie

Cover image: Sand Dunes, Huacachina, Peru cc by N. Whitford

Casimir PhD series, Delft-Leiden 2014-26

ISBN 978-90-8593-199-7

Dit werk maakt deel uit van het onderzoeksprogramma van de Stichting voor Fundamenteel Onderzoek der Materie (FOM), die financieel wordt gesteund door de Nederlandse Organisatie voor Wetenschappelijk Onderzoek (NWO).

*If we stand on the shore and look at the sea,
we see the water, the waves breaking, the foam,
the sound, the air, the winds and the clouds,
the sun and the blue sky, and light.
There is sand and there are rocks.
There are animals and seaweed,
hunger and disease,
and the observer on the beach.*

*Any other spot in nature has a similar variety of things.
It is always as complicated as that, no matter where it is.
Curiosity demands that we ask questions,
that we try to understand this multitude of aspects as resulting from
the action of a relatively small number of elemental things,
and forces acting in an infinite variety of combinations.*

*Is the sand other than the rocks?
Is the moon a great rock?
Is the sand perhaps nothing but a great number of very tiny stones?*

– Richard P. Feynman
The Feynman Lectures on Physics, p2-1

Contents

| | | |
|----------|---|-----------|
| 1 | Introduction to Granular Matter | 1 |
| 1.1 | Granular Materials | 1 |
| 1.2 | Examples | 4 |
| 1.2.1 | Grain Silo | 4 |
| 1.2.2 | Brazil Nut Effect | 5 |
| 1.2.3 | Quicksand | 5 |
| 1.2.4 | Soft Robotic Gripper | 6 |
| 1.2.5 | Shear Thinning and Thickening | 6 |
| 1.3 | Shear and Vibration | 7 |
| 1.4 | This Thesis | 8 |
| 2 | Introduction to Flow of Weakly Vibrated Granular Media | 9 |
| 2.1 | Introduction | 9 |
| 2.2 | Setup and Protocol | 10 |
| 2.3 | Phenomenology | 14 |
| 2.3.1 | $\Gamma = 0$ | 14 |
| 2.3.2 | $\Gamma > 0$ | 15 |
| 2.3.3 | Simplest Model | 15 |
| 2.3.4 | Hysteretic Transition | 16 |
| 3 | Vibration Dominated Flow in Weakly Vibrated Granular Media | 19 |
| 3.1 | Introduction | 19 |
| 3.2 | Protocol | 20 |
| 3.3 | Phenomenology | 23 |
| 3.4 | Vibration Dominated Flows | 25 |
| 3.4.1 | Torque Minimization Model | 26 |
| 3.4.2 | Frictional Model for $\Gamma > 0$ | 29 |
| 3.4.3 | Fluidized Region | 33 |

| | | |
|----------|--|-----------|
| 3.5 | Conclusion | 37 |
| 4 | A Nontrivial Critical Point in Granular Flows | 39 |
| 4.1 | Introduction | 39 |
| 4.2 | Setup and Protocol | 43 |
| 4.2.1 | Protocol | 45 |
| 4.3 | Theoretical Framework | 46 |
| 4.4 | Flow Curves | 49 |
| 4.5 | Fluctuations | 53 |
| 4.5.1 | Phenomenology | 54 |
| 4.5.2 | Determination of the Velocity | 55 |
| 4.5.3 | Autocorrelation | 57 |
| 4.5.4 | Statistics of $\Delta\theta$ | 64 |
| 4.5.5 | Locating the Critical Point | 66 |
| 4.5.6 | Scaling of Fluctuations | 69 |
| 4.A | Appendix | 74 |
| 4.A.1 | Collective Behavior | 74 |
| 4.A.2 | T -Control Flow Curves | 74 |
| 4.A.3 | Towards a Simple Model | 76 |
| 5 | The Role of Anisotropy in Granular Flow | 77 |
| 5.1 | Introduction | 77 |
| 5.2 | Protocol | 79 |
| 5.3 | Steady State Relaxation | 81 |
| 5.3.1 | Relaxation Speed | 81 |
| 5.3.2 | Dependence on (Ω, Γ) and (T, Γ) | 83 |
| 5.3.3 | Conclusion | 85 |
| 5.4 | Dynamics of Anisotropy | 85 |
| 5.4.1 | Relaxing from Preshear to Steady State | 86 |
| 5.4.2 | Two Stage Relaxation | 87 |
| 5.5 | Conclusion and Discussion | 92 |
| 5.5.1 | Outlook | 94 |
| 6 | Giant Heaping in Sheared Anisotropic Granular Media | 95 |
| 6.1 | Introduction | 95 |
| 6.2 | Setup and Methods | 98 |
| 6.2.1 | Setup | 98 |
| 6.2.2 | Methods | 100 |

| | | |
|-----------------------------|--|----------------|
| 6.3 | Phenomenology | 103 |
| 6.3.1 | Growth Evolution | 103 |
| 6.3.2 | Aspect Ratio, Shape and Material | 105 |
| 6.3.3 | Heap Location | 105 |
| 6.3.4 | Filling Height Dependence | 105 |
| 6.4 | The Mechanism behind the Heaping | 108 |
| 6.4.1 | Heap Removal | 108 |
| 6.4.2 | Reversal | 110 |
| 6.4.3 | Convection | 111 |
| 6.4.4 | Conclusion | 112 |
| 6.5 | 3D X-ray CT Tomography | 113 |
| 6.5.1 | Setup and Methods | 113 |
| 6.5.2 | Results | 115 |
| 6.5.3 | Origin of the Convection | 117 |
| 6.5.4 | Conclusion | 122 |
| 6.A | Appendix | 123 |
| 6.A.1 | Outlook | 123 |
| Bibliography | | 125 |
| Samenvatting | | 137 |
| Summary | | 139 |
| Publication List | | 141 |
| Curriculum Vitae | | 143 |
| Acknowledgements | | 145 |

