Storage, Conveying and Dosing of Bulk Solids

2019

Bulk Solids – Introduction

➢ What are bulk solids?

Bulk solids consist of a huge number of single particles respectively identity elements.
Bulk Solids – Introduction

Examples for bulk solids are
- Gravel, sand, brash,
- Coal, coke, ore,
- Salt, ceramic raw materials (oxides),
- Active pharmaceutical ingredients,
- Synthetic granules, pigments, filling material,
- Animal feed, fertilizer,
- Cereals, flour, sugar,
- Pills, tablets,
- Cleaning agents, laundry detergent,
- Tee, coffee,
- Packaging materials,
- Paints, lacquer.

Bulk Solids – Introduction

Why should we concern ourselves with bulk solids?

Knowledge of the behavior of bulk solids is important for
- Storage,
- Transport,
- Filling and emptying of bins, silos and hoppers,
- Process enhancement in plants,
- Packaging of intermediate or final products.
Storage, handling and transport of bulk solids are poorly respected in the value creation chain.

The (usually unchanged) product maintains its value during storage.

Investments are made at other processes of the value creation chain.

Disadvantages are often not perceived …
Storage, Conveying and Dosing of Bulk Solids

**Bulk Solids – Problems**

- **What has happened?**

  - Bridging
  - Ratholing
  - Demixing
  - Mass flow
  - Stagnant zones
  - Core flow

- **What else might happen?**

  - Stagnant zones
  - Core flow

*Based on: D. Schulze, Powders and Bulk Solids*
Results of Flow Problems

Personal motivation
system safety
low product quality
complaints
lower plant throughput
higher cost

Avoiding Flow Problems

flow property
process
engineering design
design
steady flow
FIFO
mass flow
Examples for Damaged Silos

explosion

collapse

History

- Janssen (Germany)
  - 1895: pressure of cereals investigated with silo experiments
  - Pressure slope trends to a limit value

- Jenike (USA)
  - 1960; design fundamentals for mass flow and core flow in silos
  - Based on experiments
Content of this Lecture

- Flow and load of bulk solids
- Stress-strain behavior
- Measurement of flow properties
- Flow of bulk solids in silos
- Outflow in silos
- Stresses in silos

Behavior of Bulk Solids

- Mechanical behavior of bulk solids is
  - Determined by inter-particulate forces (e.g. adhesion forces, normal forces, friction forces).
  - Currently described by methods of continuum mechanics.
  - Necessary to be known for the design of silos, hoppers and conveyors.
  - Examined for classification of flow properties (quality control, e.g. pharmaceutics).
  - Increasing application of the discrete element method (DEM).

- Flow properties of bulk solids particularly depend on
  - Particle size distribution,
  - Particle shape,
  - Chemical composition of the particles,
  - Humidity,
  - Temperature.
Pressure and Stress in a Bin

The friction between the bulk solids and the surface (wall) material results for non-ideal horizontal surfaces in shear stresses, which act on the bulk solids.

Importance of Shear Stress
Forces and Stresses

- Forces on the periphery of single volume elements (sufficient large compared to particle size) are considered.
- Force $F$ acting on surface $A$ is being divided into
  - Normal force $N$ (force perpendicular to surface $A$),
  - Shear force $S$ (force parallel to surface $A$).

Sign Convention and Units for Stresses in Bulk Solids Handling

- Definitions in bulk solids handling:
  - Compression forces and compression stresses are positive
  - Tensile forces and tensile stresses are negative

- Appropriate unit for stresses is pascal (Pa):
  - $1 \text{ Pa} = 1 \text{ N/m}^2$
  - $1000 \text{ Pa} = 1 \text{ kPa}$
  - $100,000 \text{ Pa} = 10^5 \text{ Pa} = 100 \text{ kPa} = 1 \text{ bar}$
**Stress-strain Behavior of Bulk Solids**

- Definition of the horizontal stress ratio:

\[ \lambda = \frac{\sigma_h}{\sigma_v} \]

**Force Equilibrium**

- Volume element with triangular cross section
- Normal stresses in vertical and horizontal direction acting on sample surface
- Shear stresses just act on sectional plane
Mohr-Coulomb Yield Criterion

- Cohesionless bulk solid
- Cohesive bulk solid

Uniaxial Compression Test

- Hollow cylinder with frictionless walls filled with fine grained bulk solids

\[ \sigma_1 :\text{ consolidation stress (here the major principal stress)} \]
\[ \sigma_c :\text{ unconfined yield strength} \]
Question I
Uniaxial Compression Test

➢ How does the unconfined yield strength (resistance to plastic deformation) of a bulk solid change when the consolidation stress is increased?

Flow Functions of Bulk Solids

![Flow Functions Diagram]

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Measurement of the Unconfined Yield Strength in the $\sigma, \tau$-Diagram

- Circle A: consolidation
- Circle B: shear to failure
- Circle C: only possible when supported in horizontal direction

Relationship between Mohr’s Circle, Failure Plane and Yield Limit
Flowability of Bulk Solids

- $f_f < 1$: not flowing
- $1 < f_f < 2$: very cohesive
- $2 < f_f < 4$: cohesive
- $4 < f_f < 10$: easy-flowing
- $10 < f_f$: free-flowing

Question II
Time Dependency of Flow Properties

- How does the unconfined yield strength change when bulk solids are stored under a sustained static load?
Caking

- Increase of the unconfined yield strength $\sigma_c$ during storage time
- Time flow function $\sigma_{c,t} = f(\sigma_c, t)$

Yield Loci for the Description of Flow Properties
Setup of the Jenike Shear Tester
(Translational Shear Tester)

Setup of the Schulze Ring Shear Tester
(Rotational Shear Tester)
Advantages and Disadvantages

- **Ring shear tester**
  - Unlimited shear displacement
  - No preconsolidation required
  - Minor influence of performing personnel on experimental results
  - Complete yield locus with one specimen

- **Jenike shear tester**
  - Limited shear displacement
  - Complex sample preparation
  - Several specimen necessary to obtain yield locus
  - Performing personnel gains experience in bulk solids handling

Strain, Shear Stress and Density of an Under-consolidated Specimen
States of Preconsolidation

- $\tau_i = 0$
- $\tau_i = 0$
- $\sigma_{II} = \sigma_{II}$
- $\tau_{II}$
- $\sigma_{III} = \sigma_{II}$
- $\tau_{III}$
- $\sigma_{III} = \sigma_{II}$

Question III
Performance of Shear Tests

➢ How can the measurement of a sample, which has been preconsolidated with a specified normal stress, be continued to acquire a data point of the yield locus?
Yield Loci for Different Bulk Densities

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Consolidation and Flow of Bulk Solids in the \( \tau,\sigma \)-Diagram

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Question IV
Performance of Shear Tests

- How can a shear testing device be used to measure the time consolidation of bulk solids?

Measurement of Time Consolidation

- In between the preshear and the shear (to failure) procedure the sample is stored under a static normal load $\sigma_{n,t}$. This normal load is selected to equal the consolidation stress $\sigma_1$ during preshear.
Time Yield Loci

Time Flow Functions
Measurement of Wall Friction

- Shear displacement of bulk solids specimen on a wall material sample under defined normal loads.
- In a Jenike shear tester the basis ring is replaced with a wall material sample.

Determination of Wall Friction Angle
Question V
Flow Problems

➢ Which different flow problems appear in hoppers?

➢ And in which type of hoppers might these problems occur?

Janssen’s Approach –
Slice Element of the Vertical Silo Section
Axial-symmetric and Planar Flow

(a) Axial-symmetric flow
(b) Planar flow

Conditions at the Outlet
(Radial Stress Field)
Question VI
Hopper Shapes

Why may a wedge-shaped mass flow hopper be flatter than a conical mass flow hopper?
Major Principal Stress, Consolidation Stress and Stable Bulk Solid Arch

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Determination of the Flow Factor

- For a known set of values $\varphi_e$, $\varphi_x$ and $\theta$ the flow factor can be read (interpolate if necessary)
Silo Design to Avoid Arching

Consider:

- The outlet diameter results from the required discharge rate and the chosen discharge device.
- Mechanical blocking or bridging in the outlet \( (d > 3 \ldots 10 \cdot x_{\text{max}}) \) has to be strictly avoided.

Rule No. 1
No Horizontal Borders
Rule No. 2
Design Surfaces Sufficient Steep

- Quotient of the length and the height of the outlet slot < 1

Rule No. 4
Principle of Increasing Capacity

- Quotient of the length and the height of the outlet slot < 1
Rule No. 5
Discharge Over the Whole Outlet Diameter

Caution:
- Problems if hanging hopper is completely filled with bulk solids
- Discharge of bulk solids just from a partition of the outlet
- Drive hanging hopper at intervals, check filling level if possible

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Time Yield Loci

Time Flow Functions

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Improvement of Flow Properties

- Possibilities to improve the flow properties of bulk solids:
  - Fluidization of the bulk solids (compare discharge aids)
  - Production of micro granules
  - Addition of dispersants
    - Very fine particles (e.g. Aerosil)
    - Chemical spacer molecules (e.g. diatomaceous earth)

- Very fine particles act as dispersants!

Very Fine Particles as Dispersants

- $H$ – adhesion force between particles
  - $R$ – radius of curvature in the particle contact
  - $n$ – number of particle contacts per unit volume

- Mixture of relatively coarse and relatively fine particles

- $\alpha$ – large
  - $n$ – small
  - $H$ – large

- $\alpha$ – larger
  - $n$ – smaller
  - $H$ – small

- $\alpha$ – small
  - $n$ – large

- $\alpha$ – small
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- $\alpha$ – large
  - $n$ – large
Further Methods for the Determination of Flow Properties

- Measurement of the discharge rate
- Measurement at different hopper outlet diameters
- Angle of repose
- Carr flowability index
- Stirrer
- Compactability
- Warren Spring Bradford cohesion tester
- Penetration test
- Power bed tester
- Johanson Hang up Indicizer