Storage, Conveying and Dosing of Bulk Solids

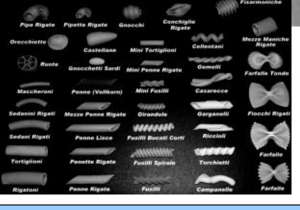
2019

Bulk Solids – Introduction

- What are bulk solids?

very coarse

very fine



convenience product

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.

Bulk Solids – Problems

- 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 …

Bulk Solids – Problems

Bulk Solids – Problems

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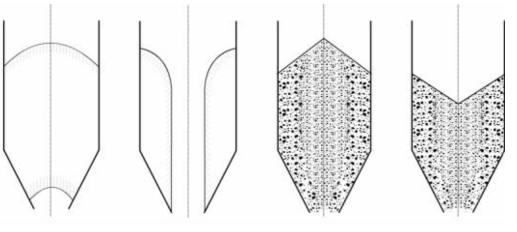
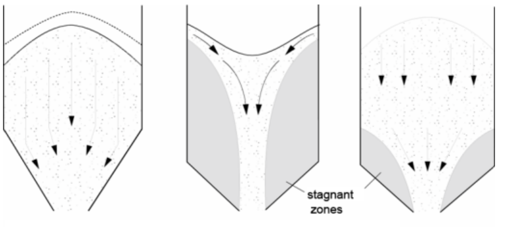
- What has happened?





Bulk Solids – Problems

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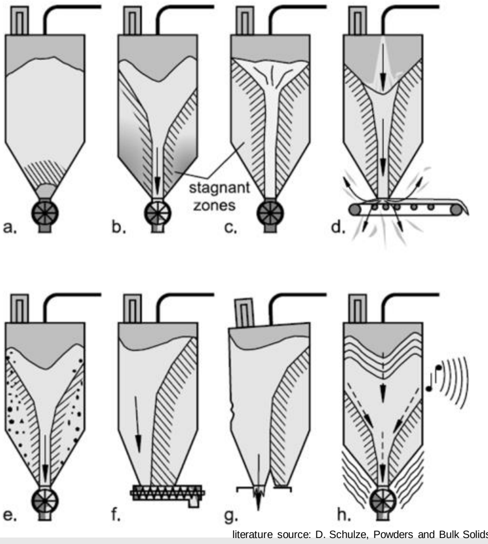
- What else might happen?



literature source: D. Schulze, Powders and Bulk Solids

Results of Flow Problems

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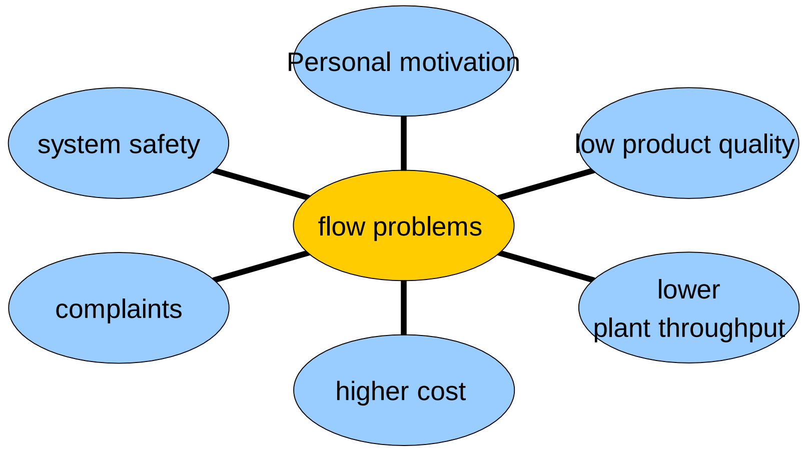

Avoiding Flow Problems

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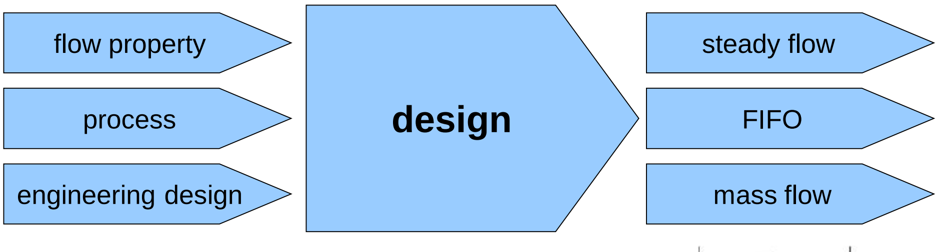

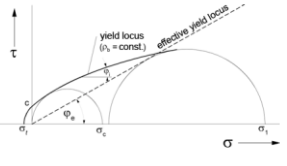

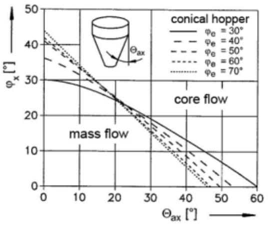

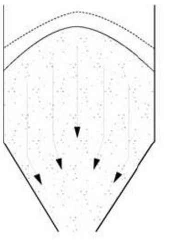

Examples for Damaged Silos

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explosion

collapse

History

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- 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

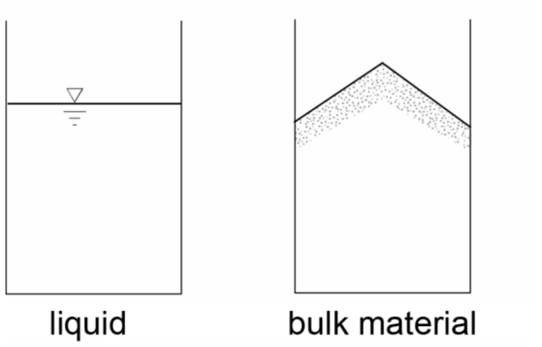
Content of this Lecture

- 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

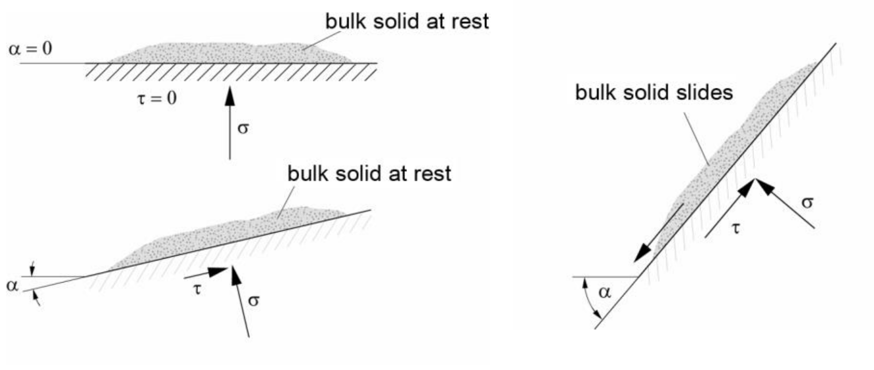
- Mechanical behavior of bulk solids is
  - Determined by inter-particulate forces (e.g. adhesion forces, normal forces, friction forces).
  - Currently described by methods of continuum mechanics .
  - Necessary to be known for the design of silos, hoppers and conveyors.
  - Examined for classification 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



Importance of Shear Stress

- 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.



Forces and Stresses

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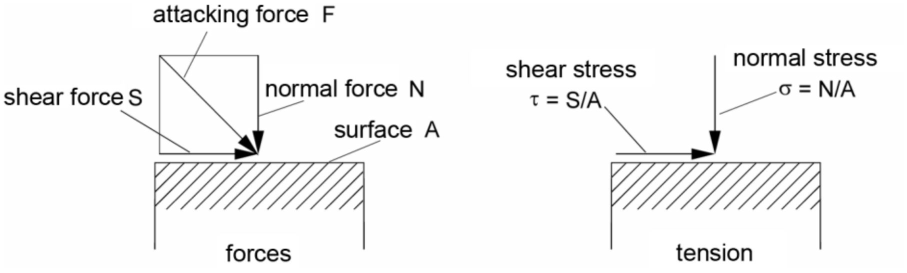
- Forces on the periphery of single volume elements (sufficient large compared to particle size) are considered.
- Force F acting on surface A is being divided into
  - Normal force N (force perpendicular to surface A),
  - Shear force S (force parallel to surface A).



Sign Convention and Units for Stresses in Bulk Solids Handling

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- Definitions in bulk solids handling:
  - **Compression** forces and **compression** stresses are **positive**
  - **Tensile** forces and **tensile** stresses are **negativ**
- Appropriate unit for stresses is pascal (Pa):
  - 1 Pa = 1 N/m^2
  - 1000 Pa = 1 kPa
  - 100.000 Pa = 10^5 Pa = 100 kPa = 1 bar

Stress-strain Behavior of Bulk Solids

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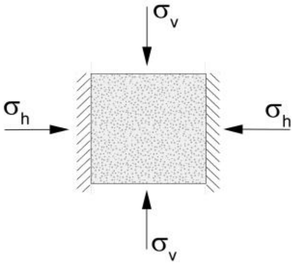
- Definition of the horizontal stress ratio:

$$\lambda = \frac{\sigma_h}{\sigma_v}$$



Force Equilibrium

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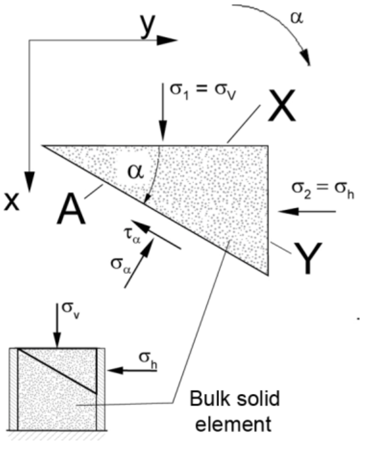

- Volume element with triangular cross section
- Normal stresses in vertical and horizontal direction acting on sample surface
- Shear stresses just act on sectional plane

Mohr-Coulomb Yield Criterion

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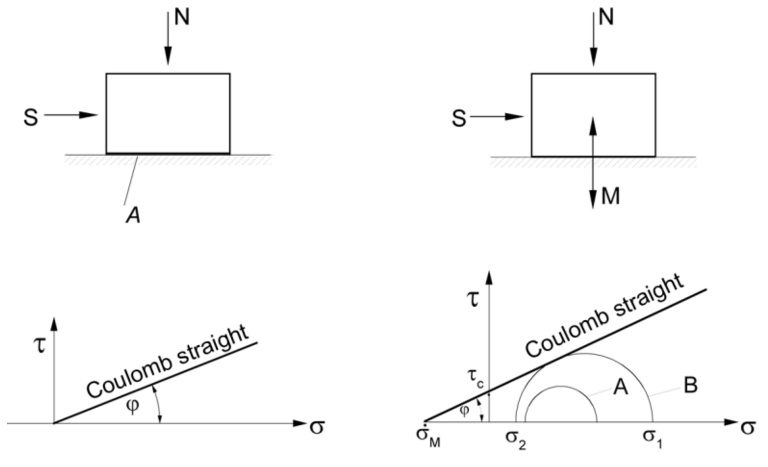
cohesionless bulk solid | cohesive bulk solid



Uniaxial Compression Test

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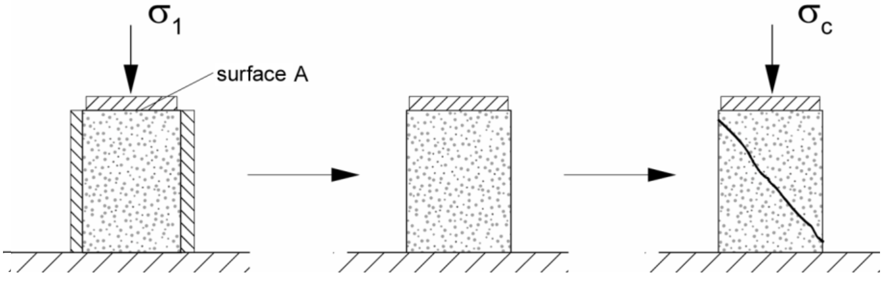
- Hollow cylinder with frictionless walls filled with fine grained bulk solids



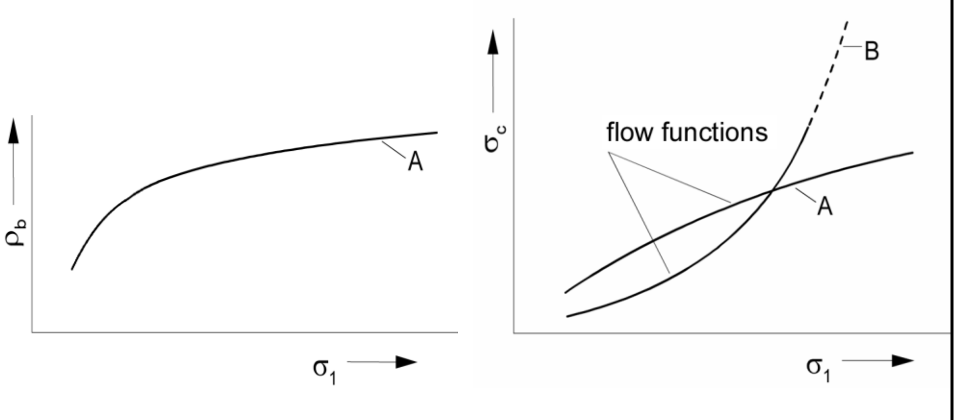
σ_1 := consolidation stress (here the major principal stress)

σ_c := unconfined yield strength

Question I
Uniaxial Compression Test

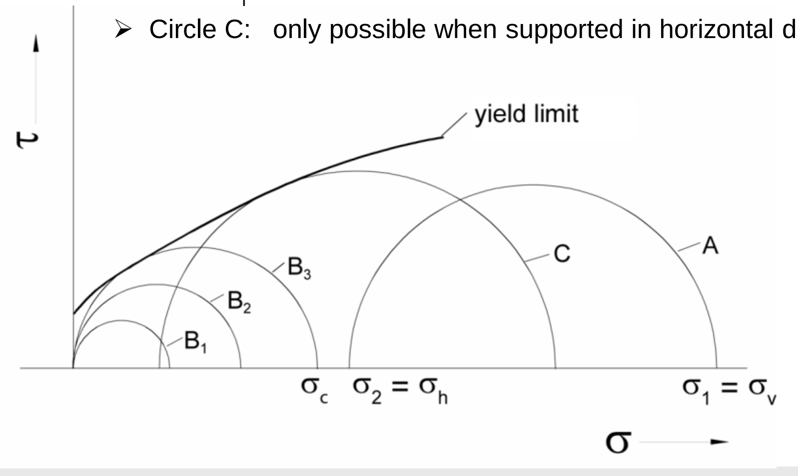
- How does the unconfined yield strength (resistance to plastic deformation) of a bulk solid change when the consolidation stress is increased?

Flow Functions of Bulk Solids

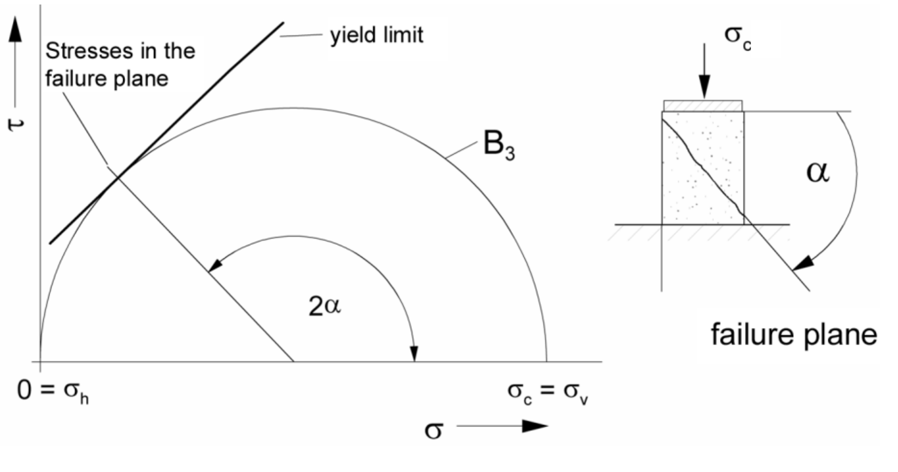


Measurement of the Unconfined Yield Strength in the σ,τ-Diagram

➢ Circle A: consolidation
➢ Circle B_i: 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

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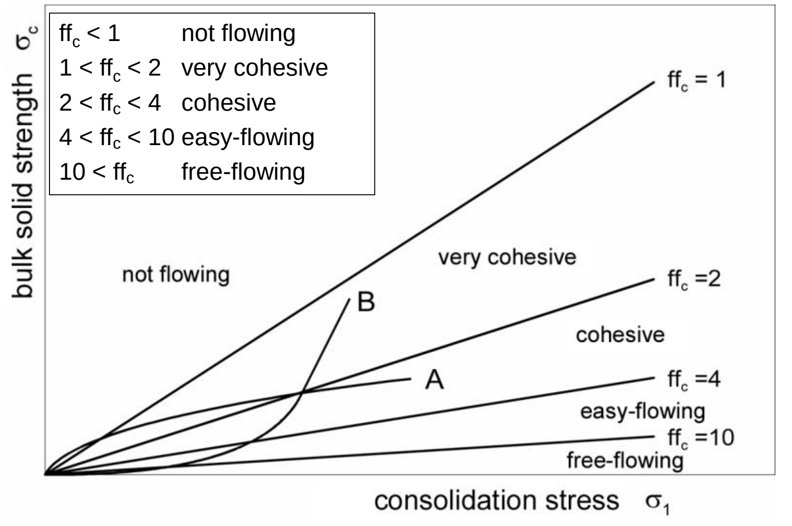

Question II
Time Dependency of Flow Properties

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

Caking

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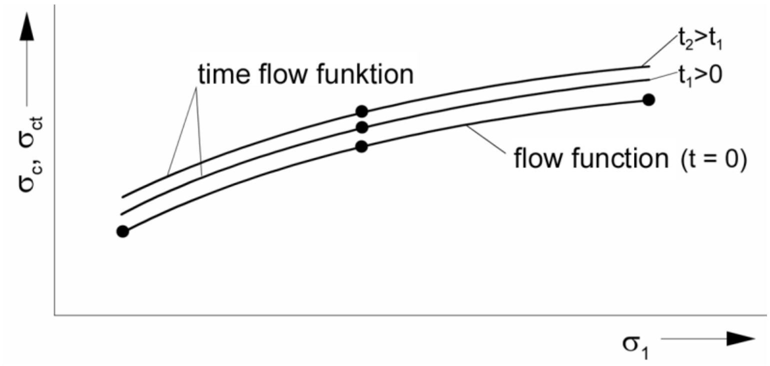
- Increase of the unconfined yield strength σ_c during storage time
- Time flow function $\sigma_{c,t} = f(\sigma_c, t)$



Storage, Conveying and Dosing of Bulk Solids 29

Yield Loci for the Description of Flow Properties

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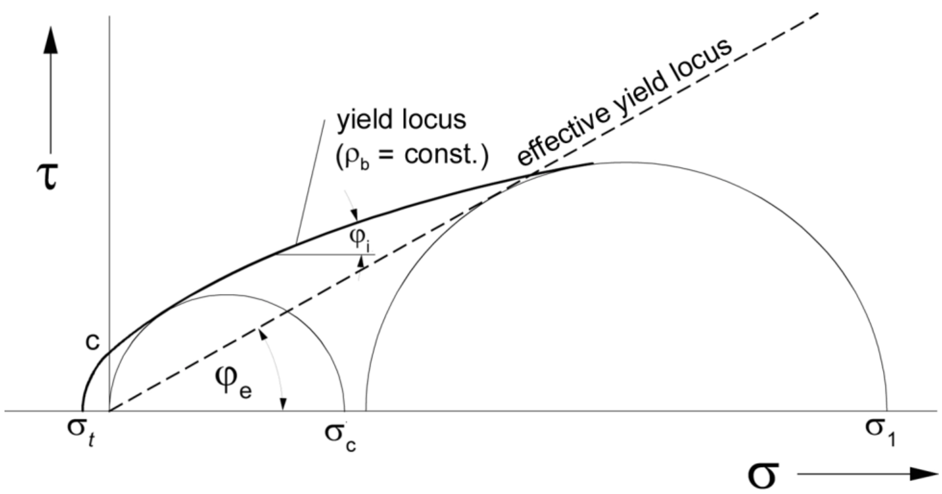

Storage, Conveying and Dosing of Bulk Solids 30

Setup of the Jenike Shear Tester (Translational Shear Tester)

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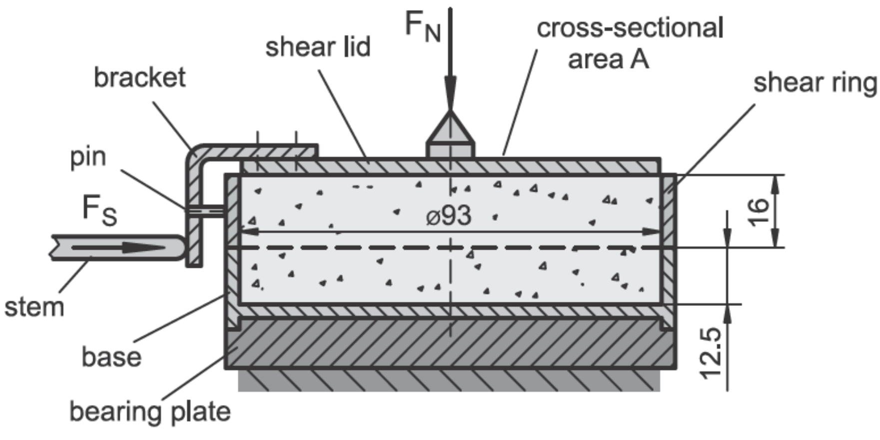

literature source: D. Schulze, Powders and Bulk Solids

Setup of the Schulze Ring Shear Tester (Rotational Shear Tester)

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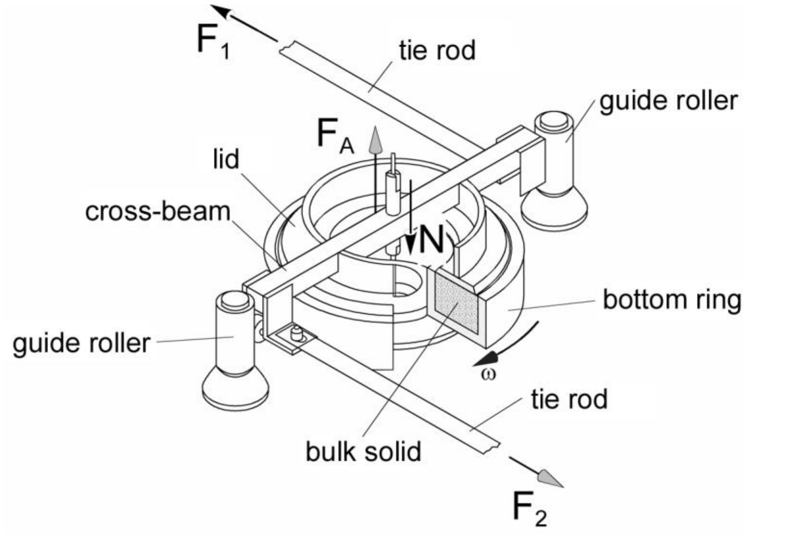

Advantages and Disadvantages

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- 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

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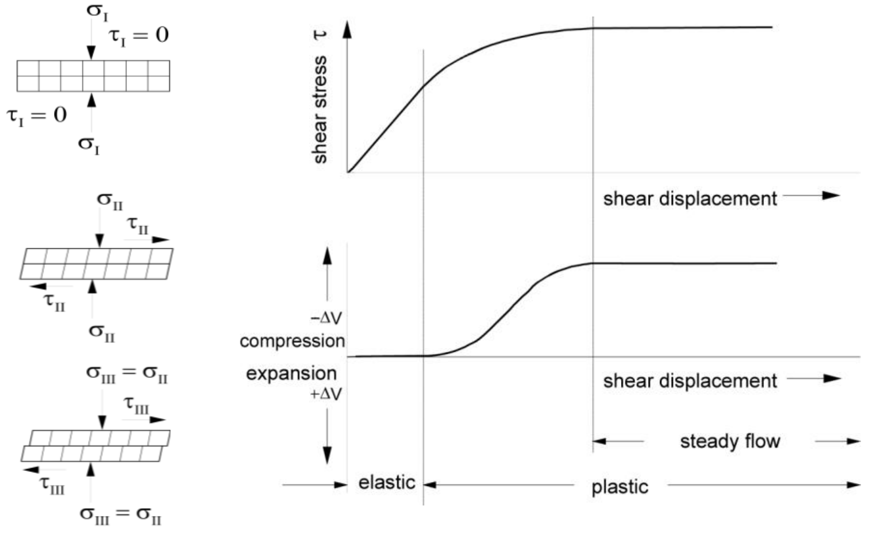
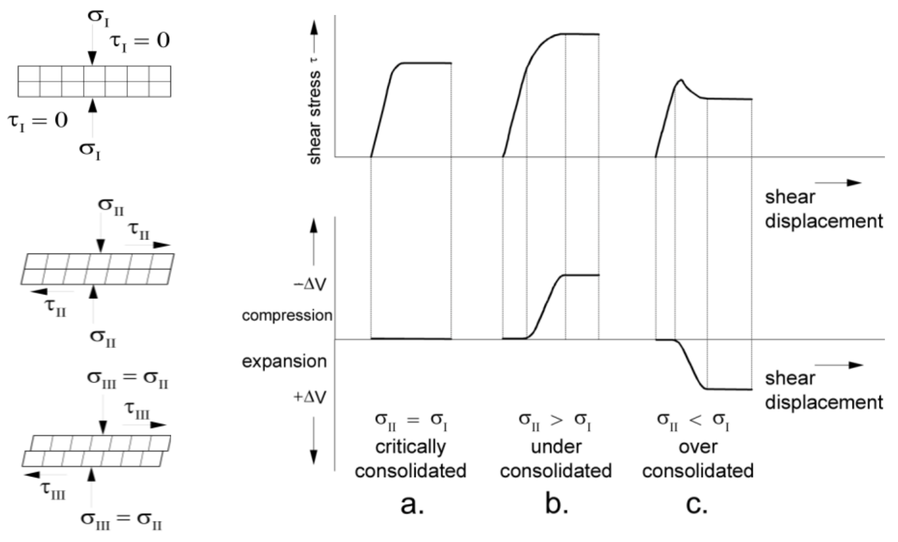


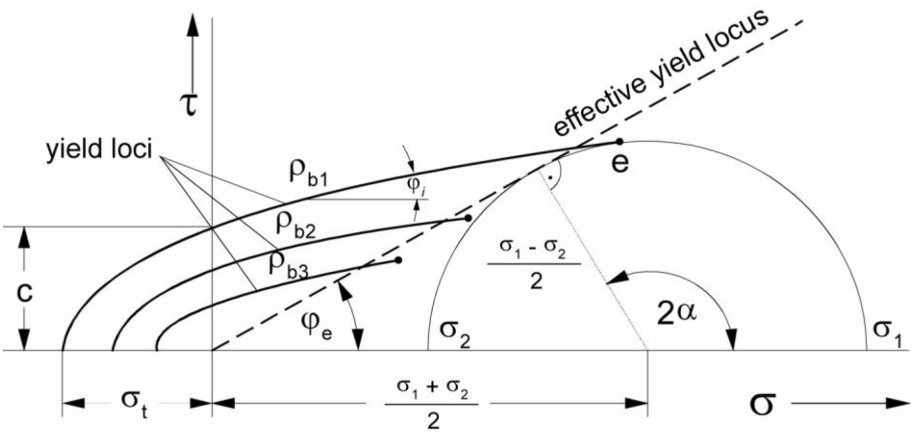
States of Preconsolidation



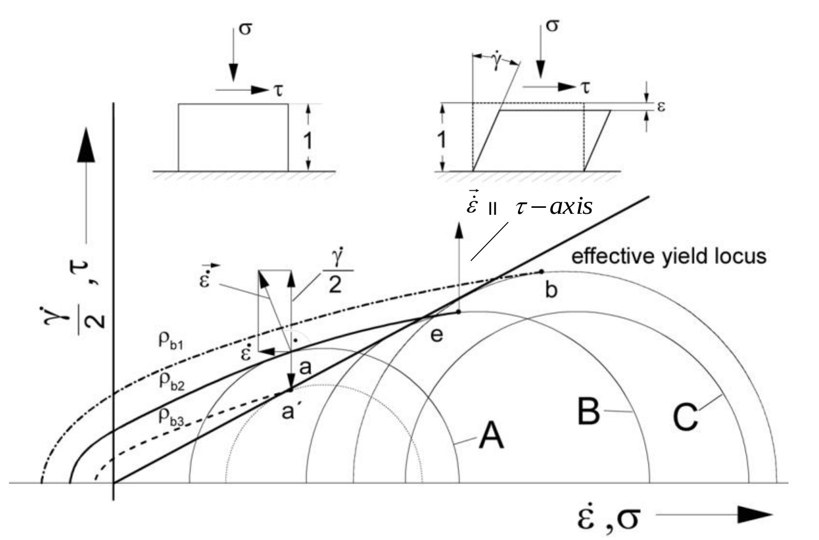
Question III
Performance of Shear Tests

- 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



Consolidation and Flow of Bulk Solids in the τ,σ-Diagram



Question IV
Performance of Shear Tests

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

Measurement of Time Consolidation

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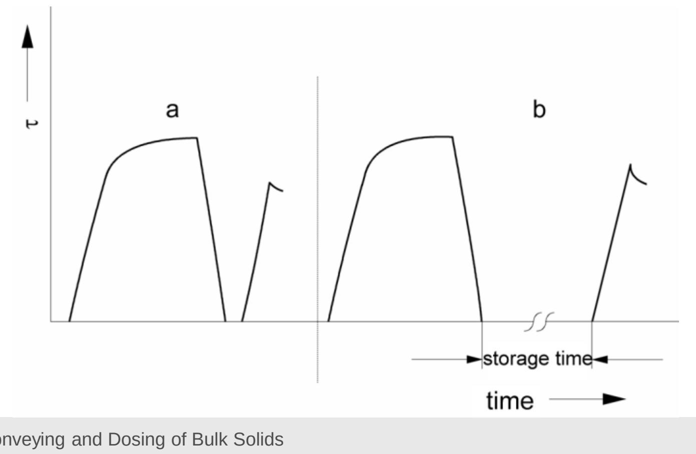
- In between the preshear and the shear (to failure) procedure the sample is stored under a static normal load $\sigma_{n,t}$. This normal load is selected to equal the consolidation stress σ_1 during preshear.



Time Yield Loci

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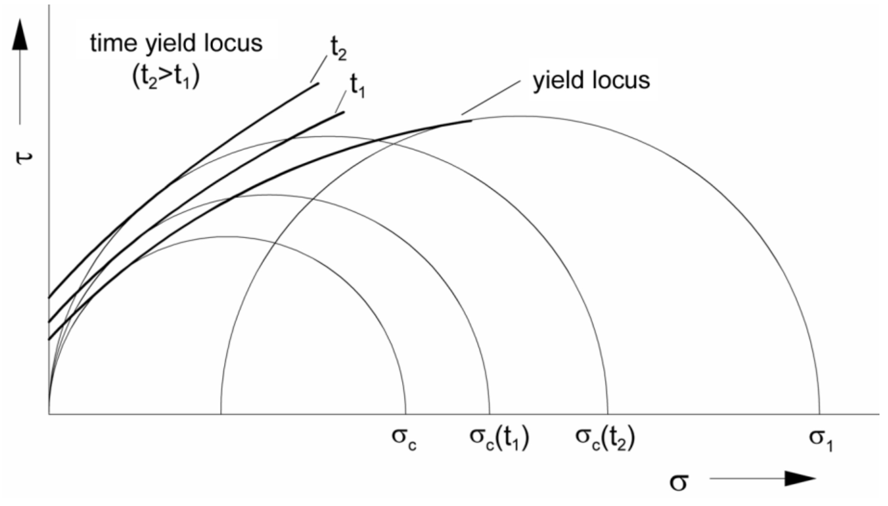

Time Flow Functions

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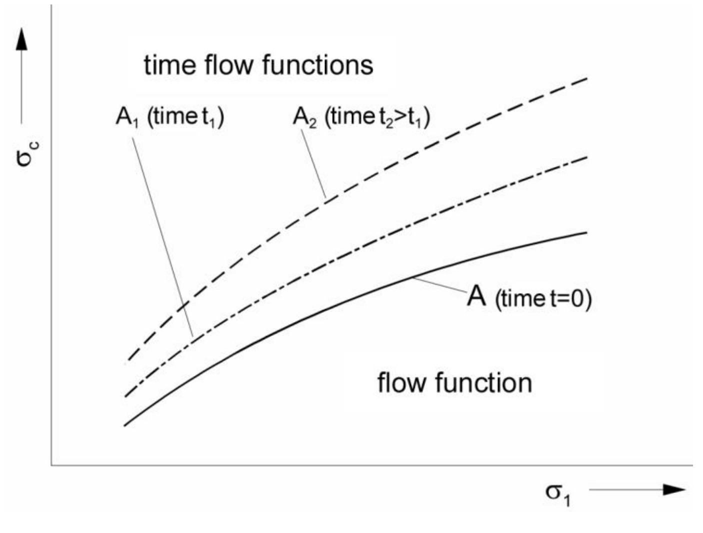

Measurement of Wall Friction

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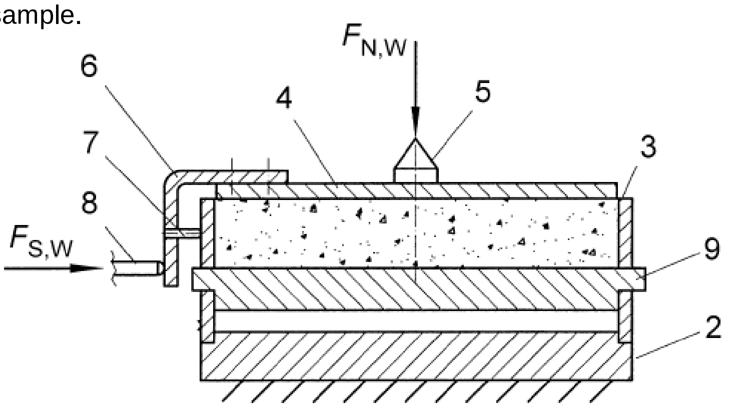
- Shear displacement of bulk solids specimen on a wall material sample under defined normal loads.
- In a Jenike shear tester the basis ring is replaced with a wall material sample.



Determination of Wall Friction Angle

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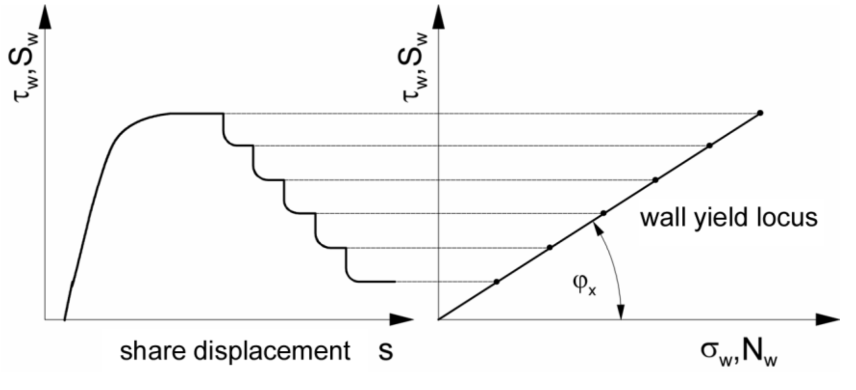
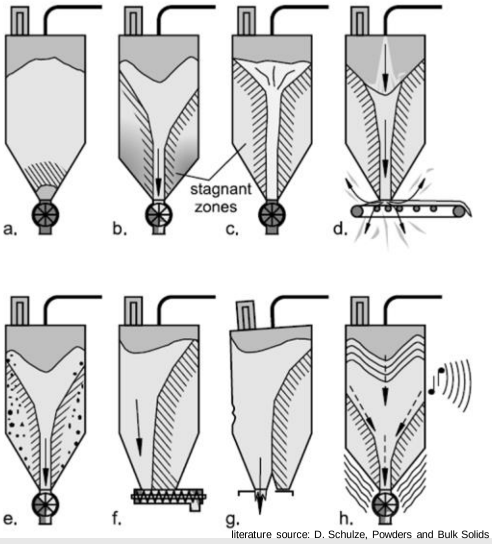


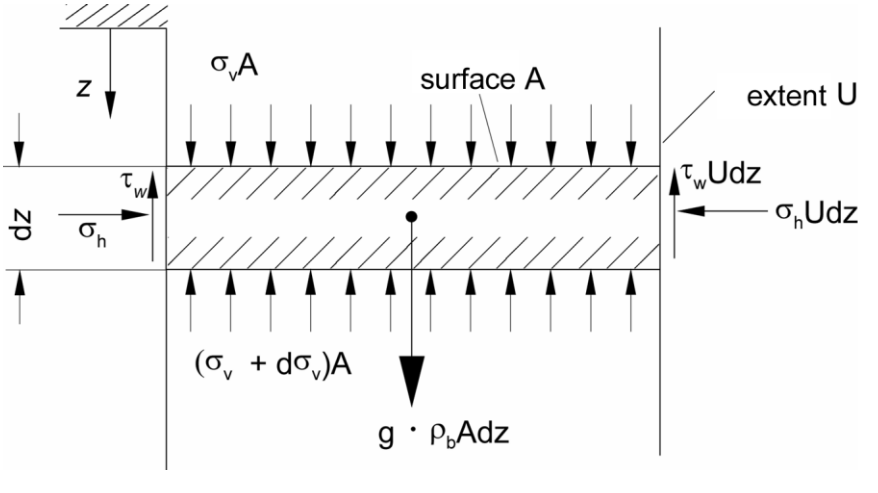
Question V
Flow Problems

- Which different flow problems appear in hoppers?
- And in which type of hoppers might these problems occur?

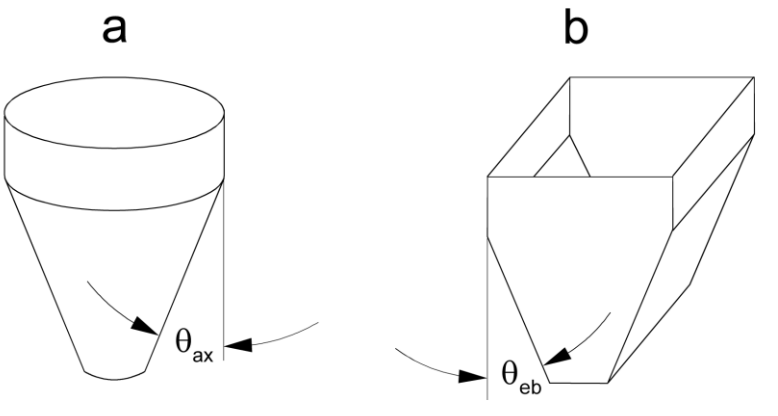


literature source: D. Schulze, Powders and Bulk Solids

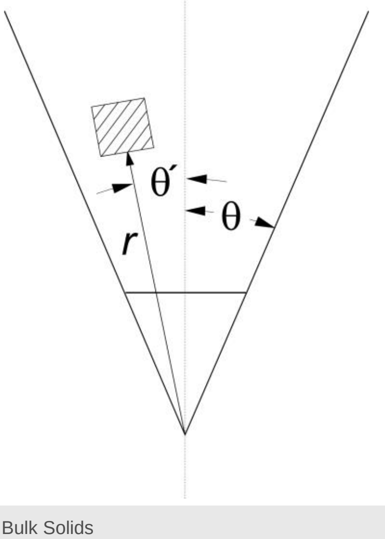
Janssen‘s Approach – Slice Element of the Vertical Silo Section



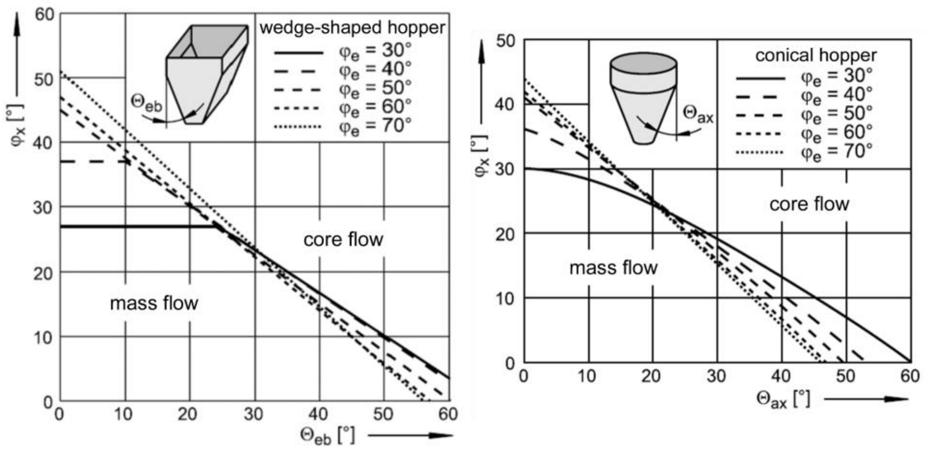
Axial-symmetric and Planar Flow



Conditions at the Outlet (Radial Stress Field)



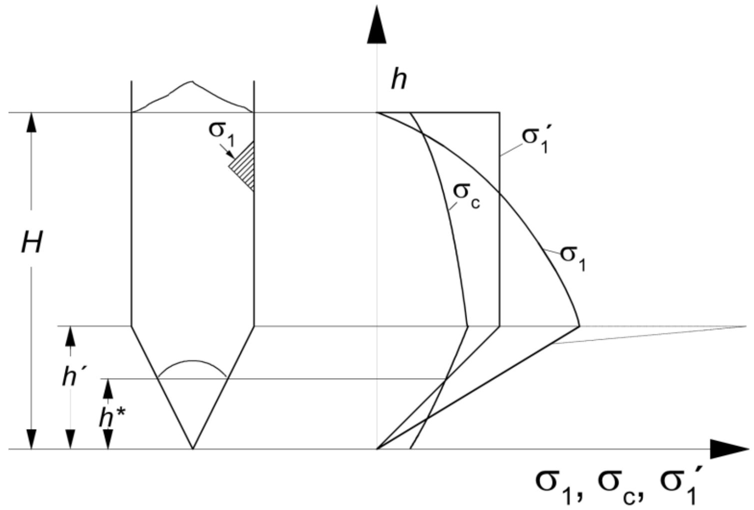
Boundaries Between Mass Flow and Core Flow



Question VI
Hopper Shapes

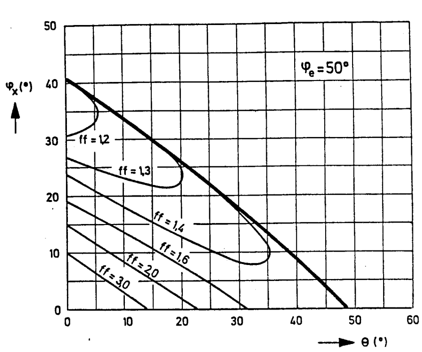
- Why may a wedge-shaped mass flow hopper be flatter than a conical mass flow hopper?

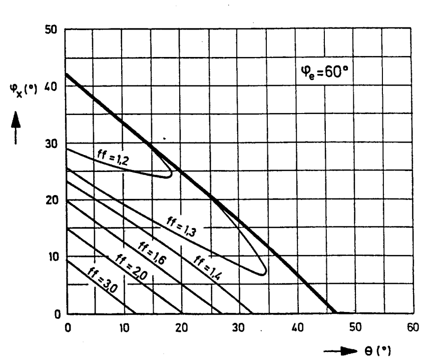
Major Principal Stress, Consolidation Stress and Stable Bulk Solid Arch



Determination of the Flow Factor

- For a known set of values φ_e, φ_x and Θ the flow factor can be read (interpolate if necessary)





Silo Design to Avoid Arching

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Consider:

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

Rule No. 1
No Horizontal Borders

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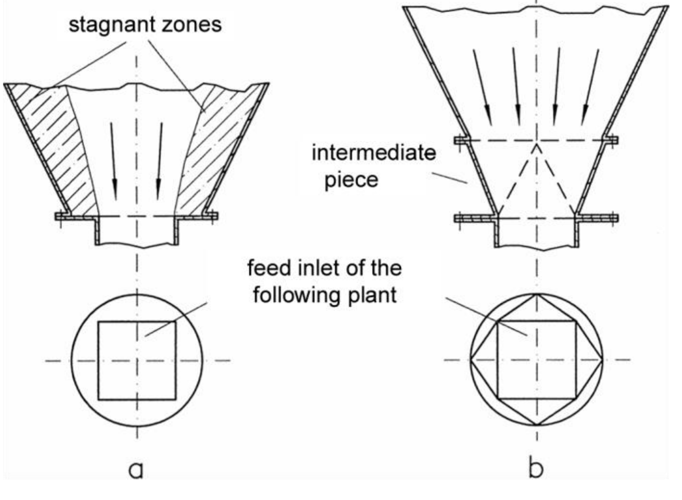
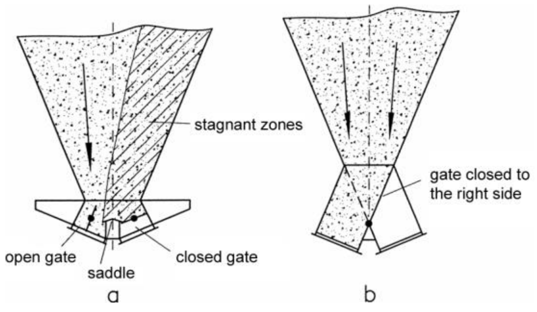
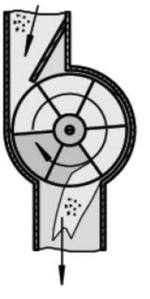


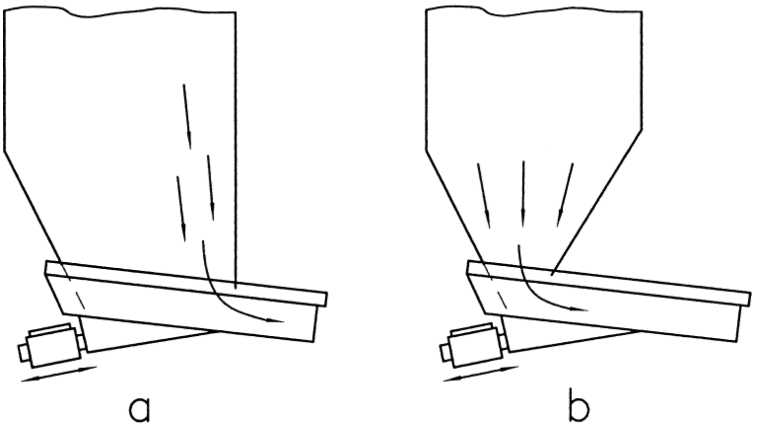
Rule No. 2
Design Surfaces Sufficient Steep





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

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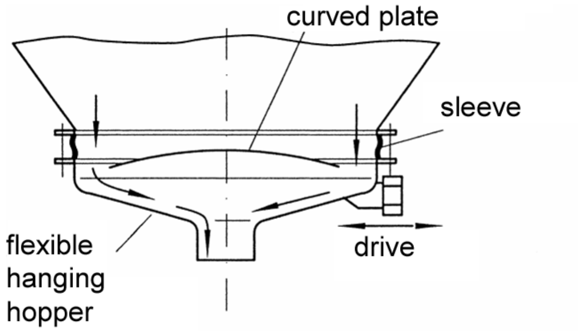

Caution:

- 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

Rule No. 5
Discharge Over the Whole Outlet Diameter

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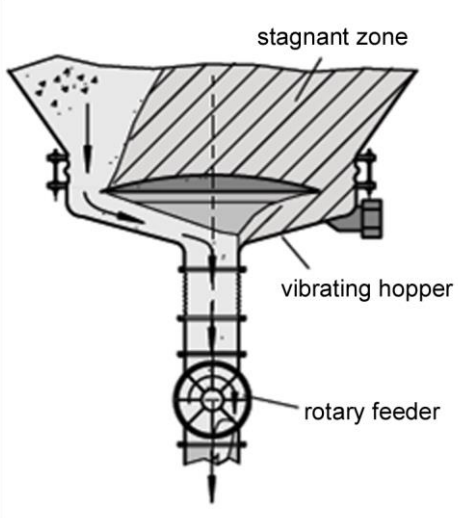

Time Yield Loci

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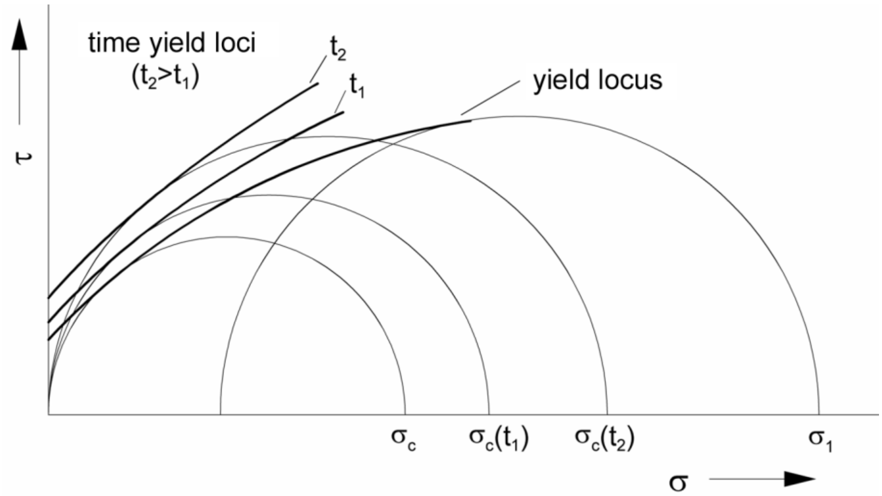

Time Flow Functions

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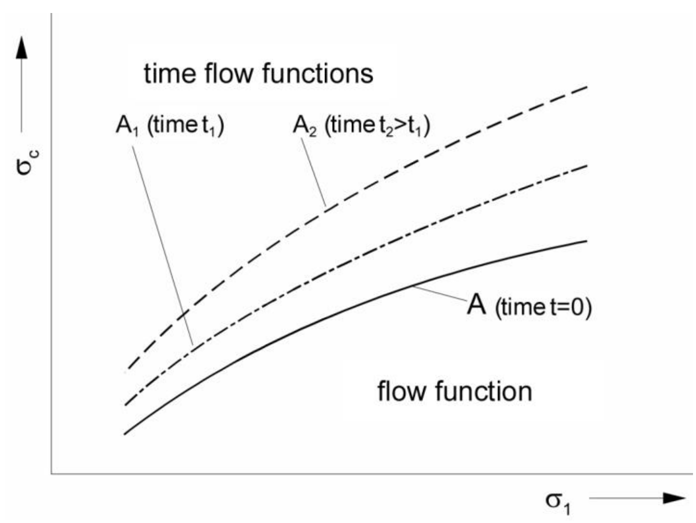

Improvement of Flow Properties

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- 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

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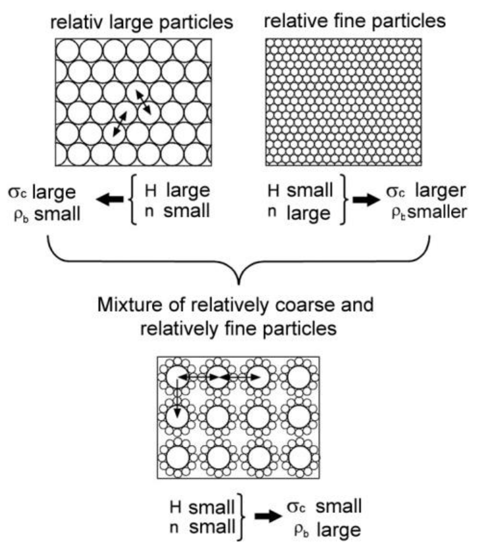
H — adhesion force between particles → $H \sim R$

R — radius of curvature in the particle contact

n — number of particle contacts per unit volume



Further Methods for the Determination of Flow Properties

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- 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