Technische Universität Braunschweig

iPAT Institut für Partikeltechnik

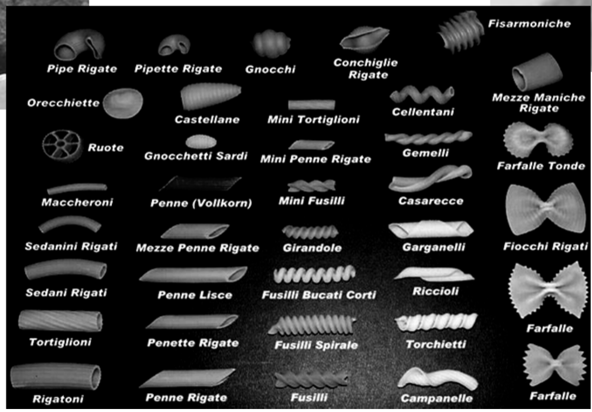
Powder Flow, Measurement, and Silos (Phenomenology, Design, Problems)

Prof. Dr.-Ing. A. Kwade

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 technology – what is involveld?

Cereals

Silos

Avalanches

Food products

Tablets

Building materials

Bulk Solids – Introduction

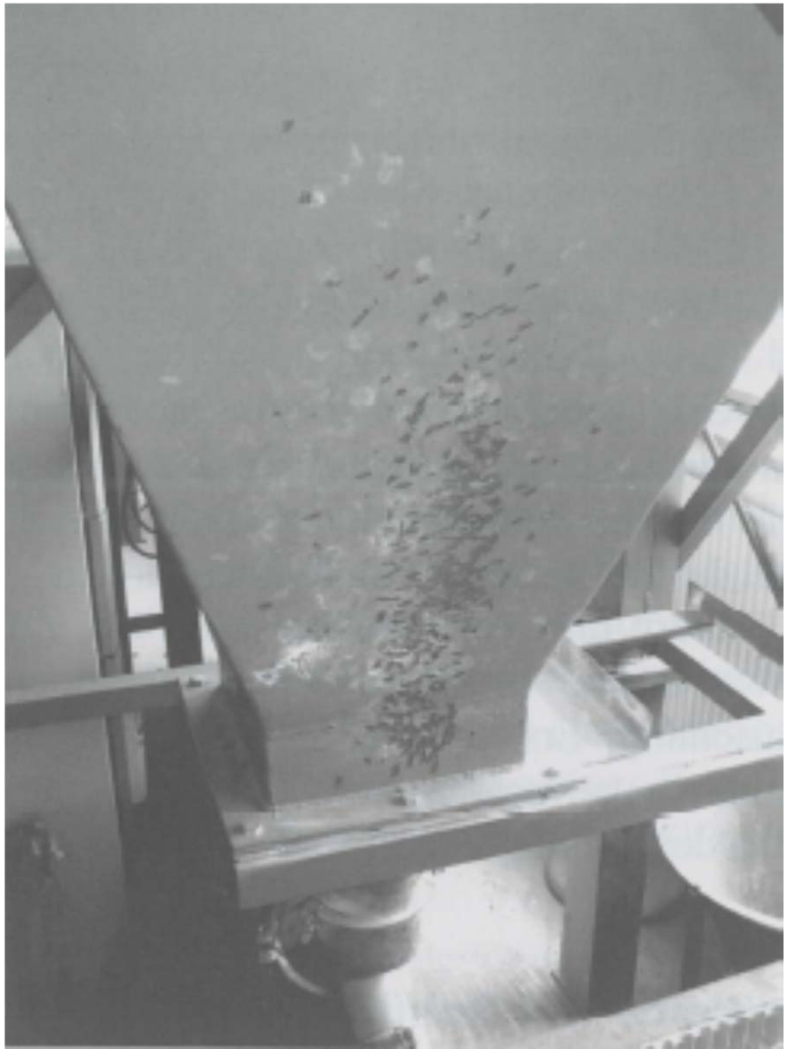
Examples for bulk solids are

- 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.

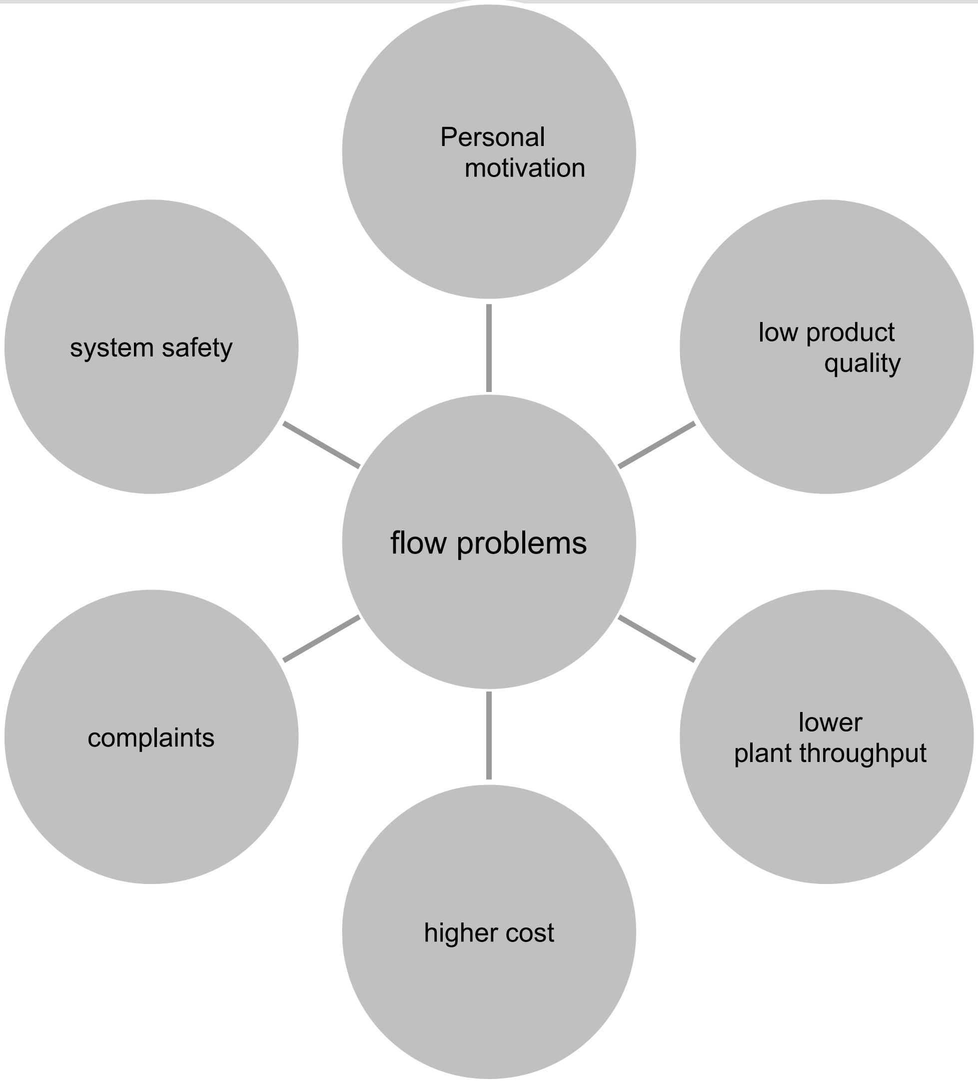
Why should we concern ourselves with bulk solids?

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.

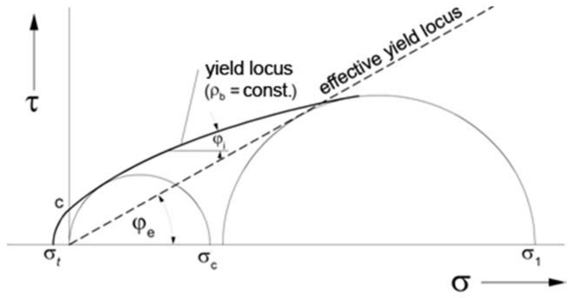


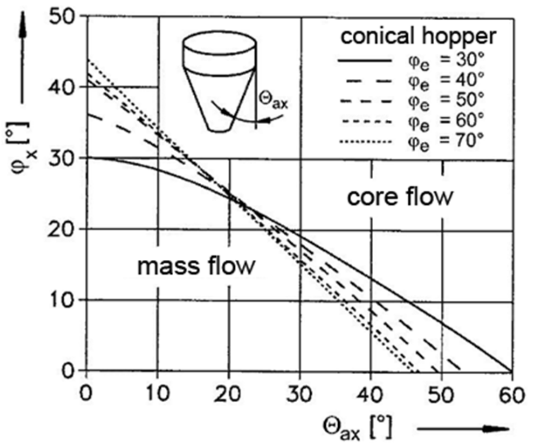
Results of Flow Problems

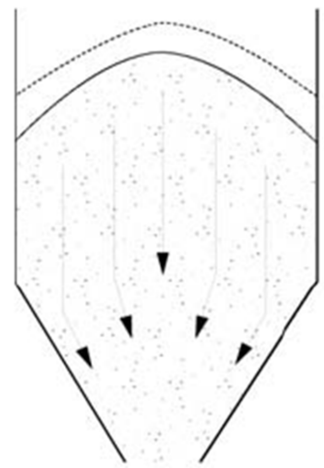


Avoiding Flow Problems

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

Behavior of Bulk Solids

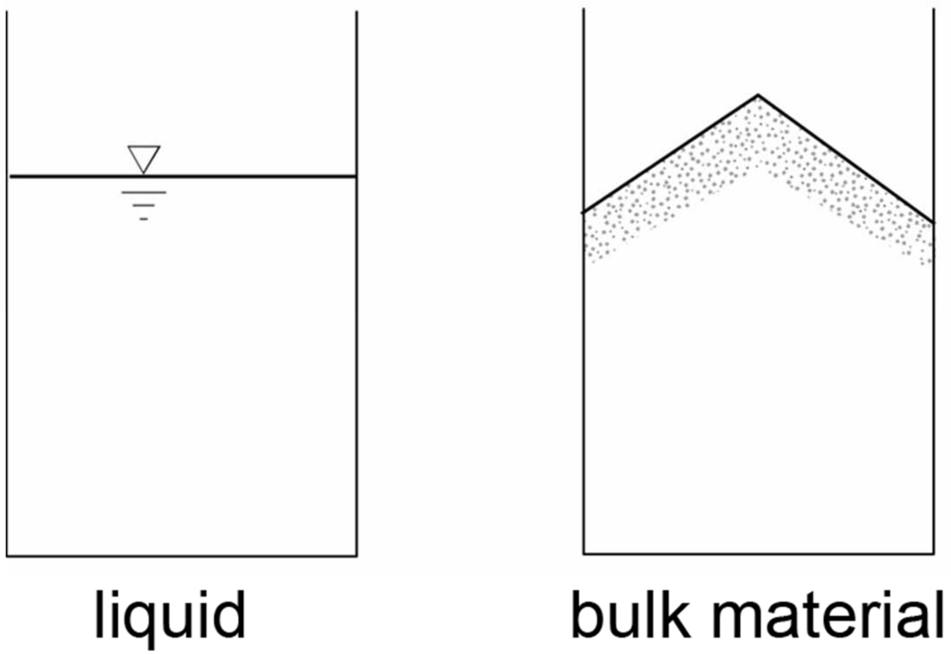
Mechanical behavior of bulk solids is

- 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).

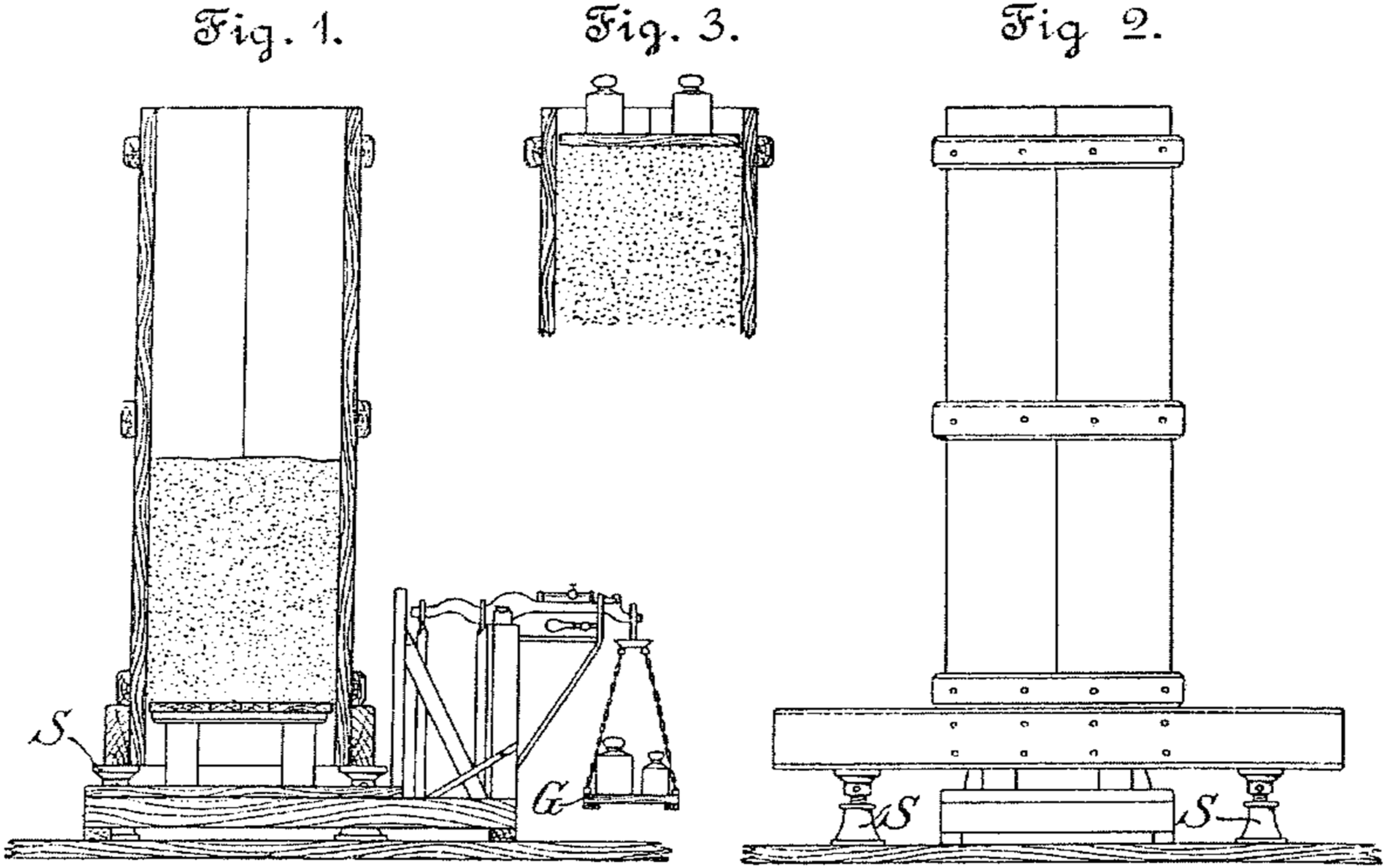
Flow properties of bulk solids particularly depend on

- Particle size distribution,
- Particle shape,
- Chemical composition of the particles,
- Humidity,
- Temperature.

Pressure and Stress in a Bin



Experiment von Janssen (1895)



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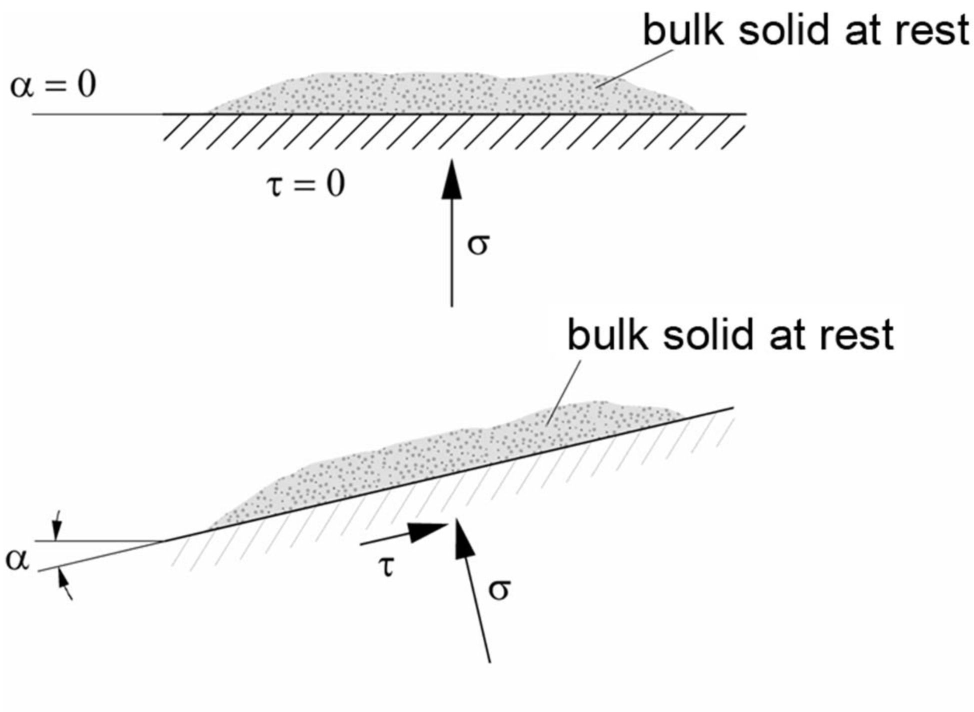
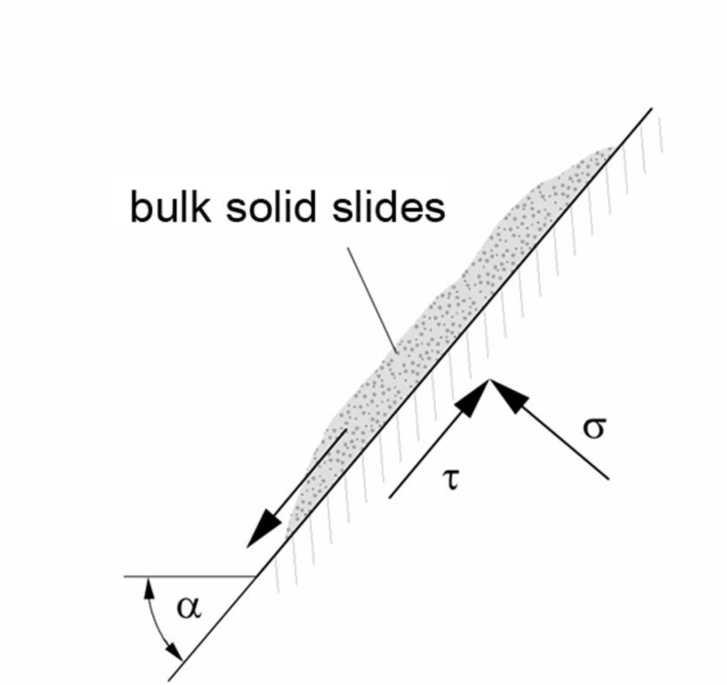
The friction between the bulk solids and the surface (wall) material results for non-ideal horizontal surfaces in shear stresses, which act on the bulk solids.



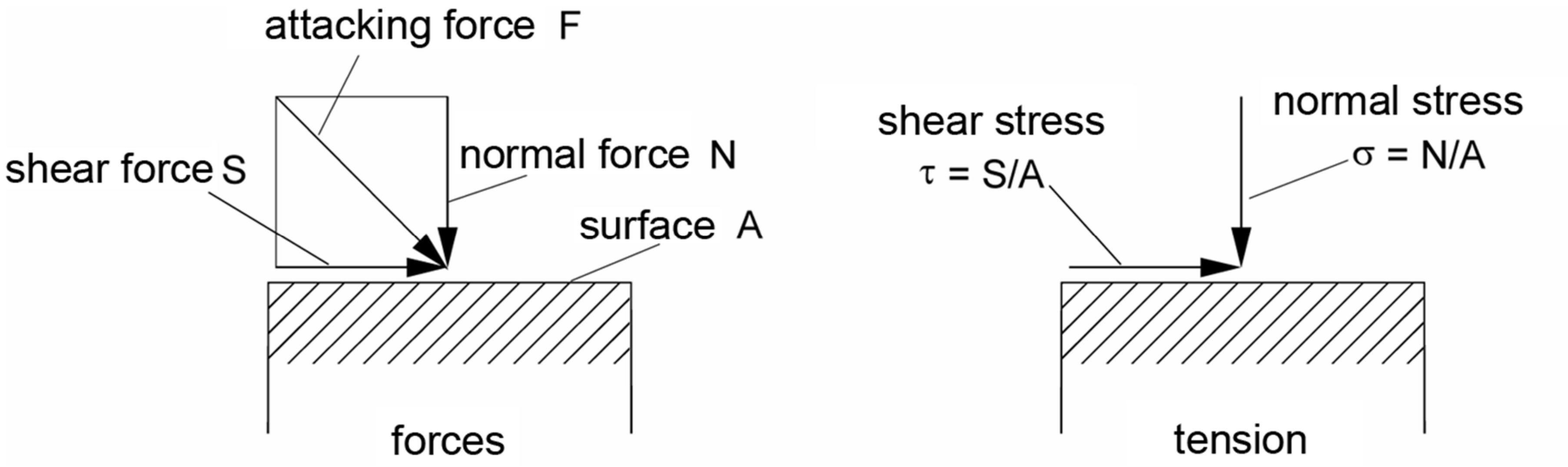


Forces and Stresses

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:

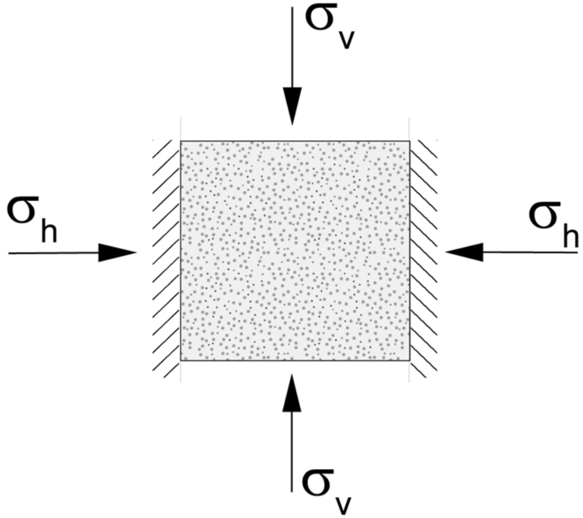
- **Compression** forces and **compression** stresses are **positive**
- **Tensile** forces and **tensile** stresses are **negativ**

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

Definition of the horizontal stress ratio:

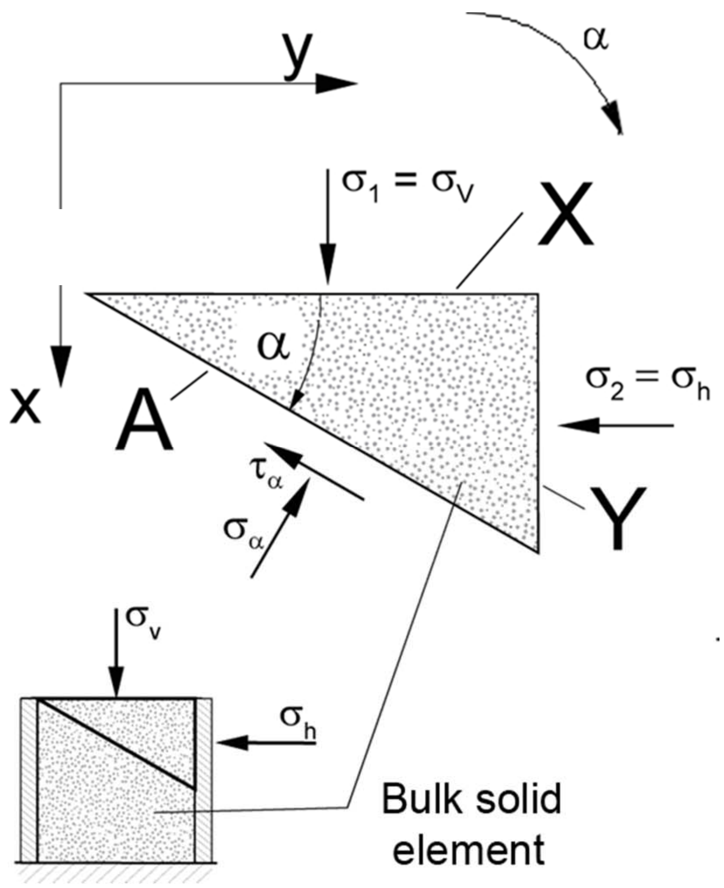
$$\lambda = \frac{\sigma_h}{\sigma_v}$$



Horizontal stress ratio of bulk solids in comparion to fluids and real solids:

Solids:	$\sigma_h = 0$	$\lambda = 0$
Bulk solids:	$\sigma_v > \sigma_h > 0$	$0 < \lambda < 1$; usually $0{,}3 < \lambda < 0{,}6$
Fluids:	$\sigma_v = \sigma_h$	$\lambda = 1$

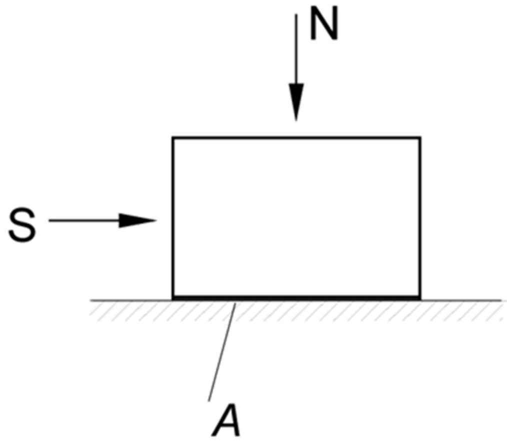
Force Equilibrium

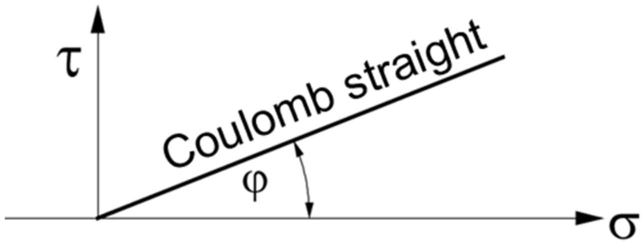


- Volume element with triangular cross section
- Normal stresses in vertical and horizontal direction acting on sample surface
- Shear stresses just act on sectional plane

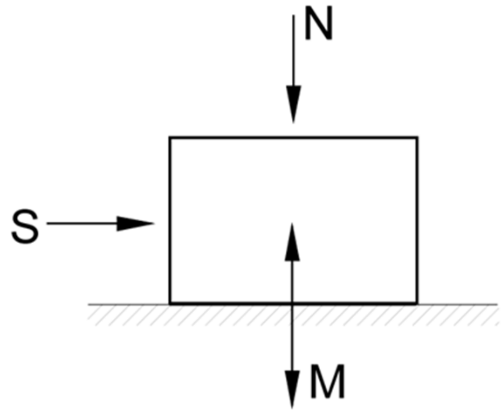
Mohr-Coulomb Yield Criterion

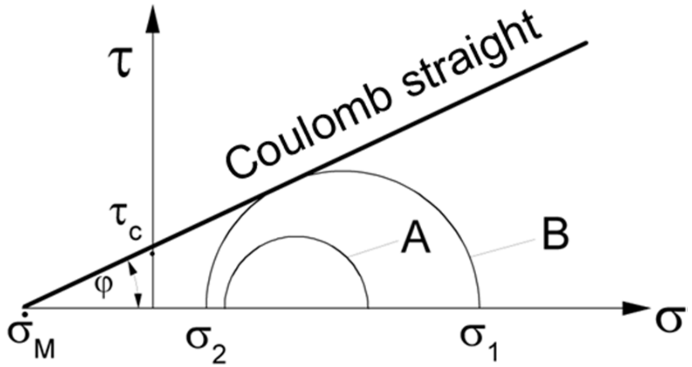
cohesionless bulk solid





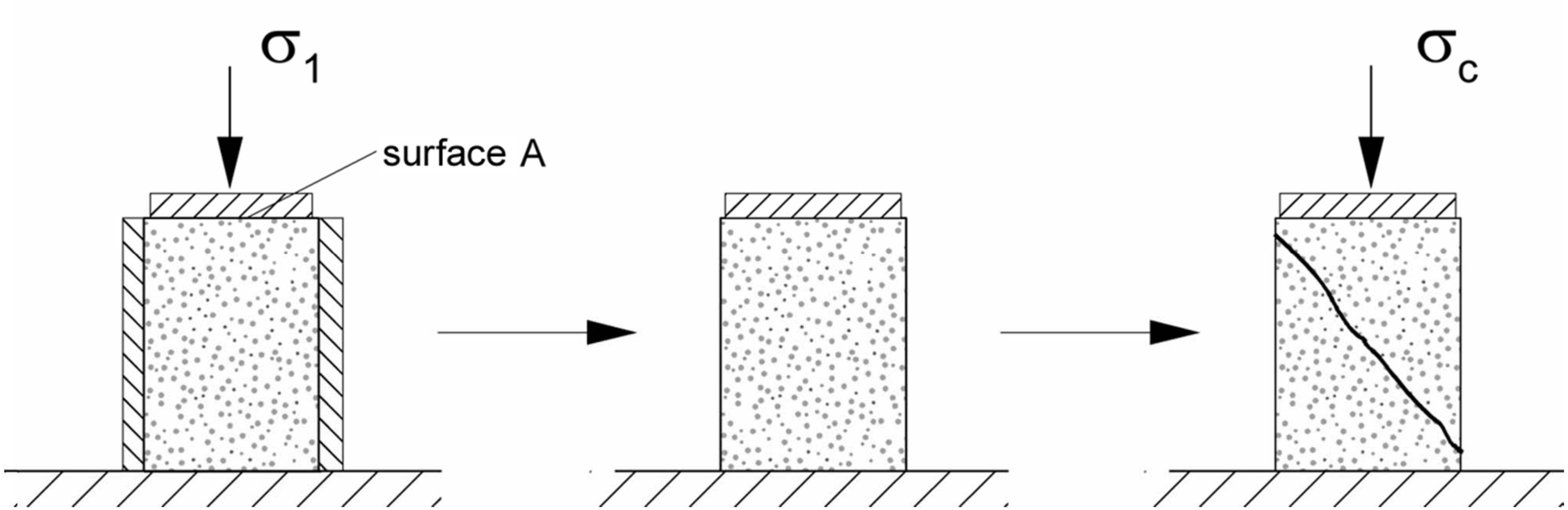
cohesive bulk solid





Uniaxial Compression Test

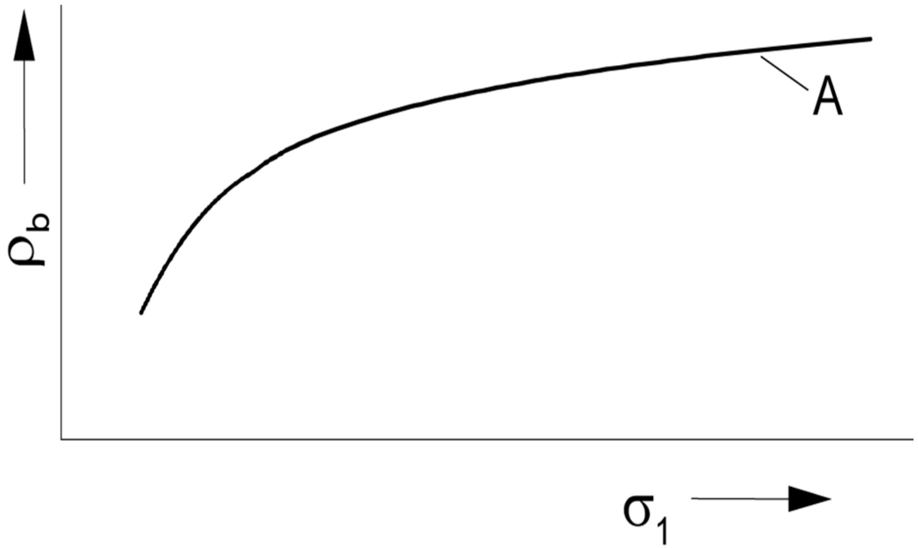
Hollow cylinder with frictionless walls filled with fine grained bulk solids

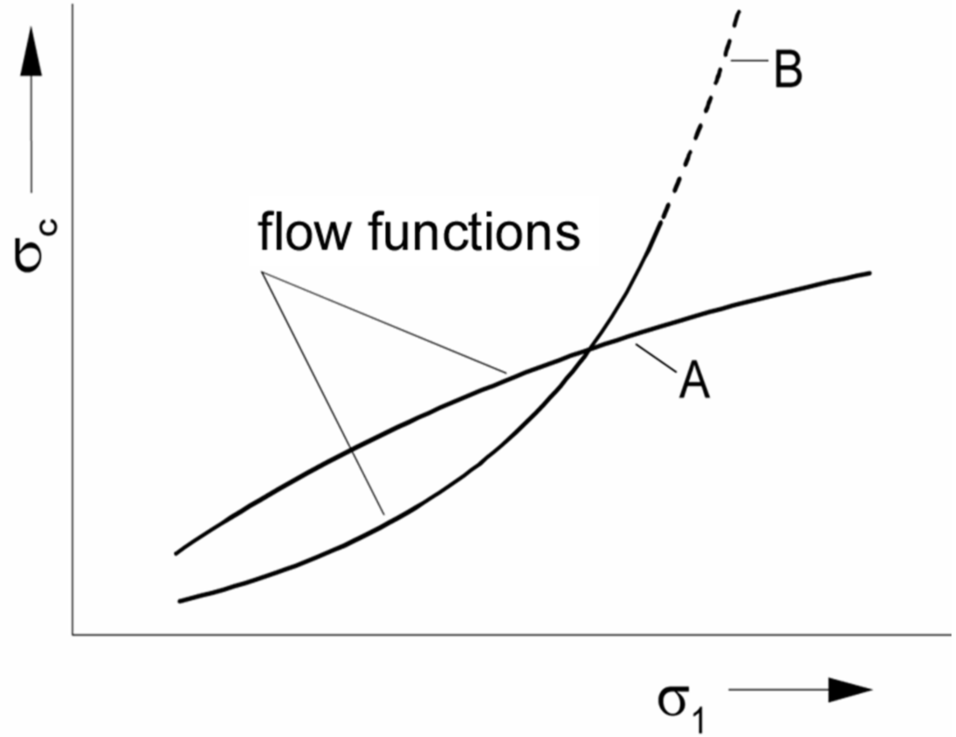


Question I
Uniaxial Compression Test

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

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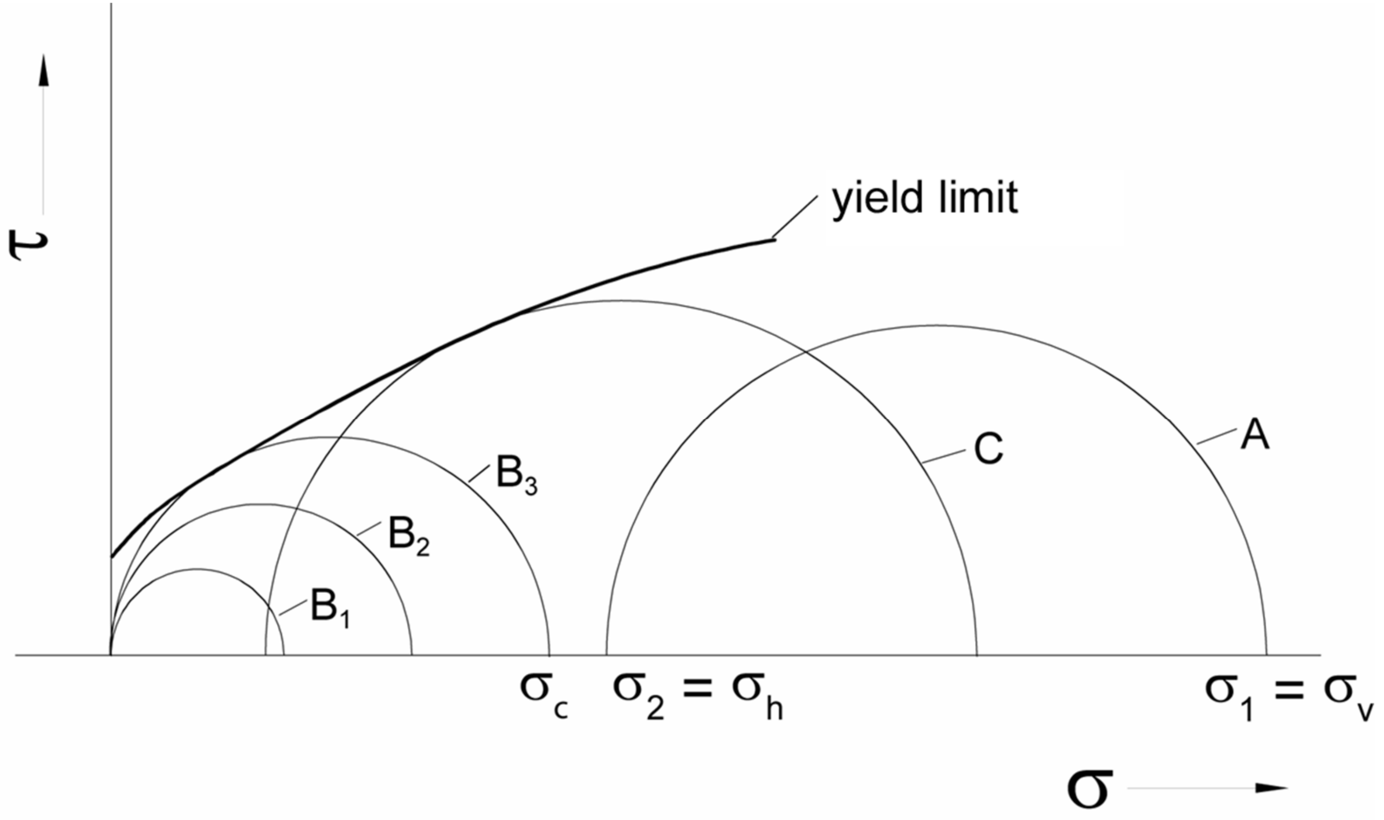
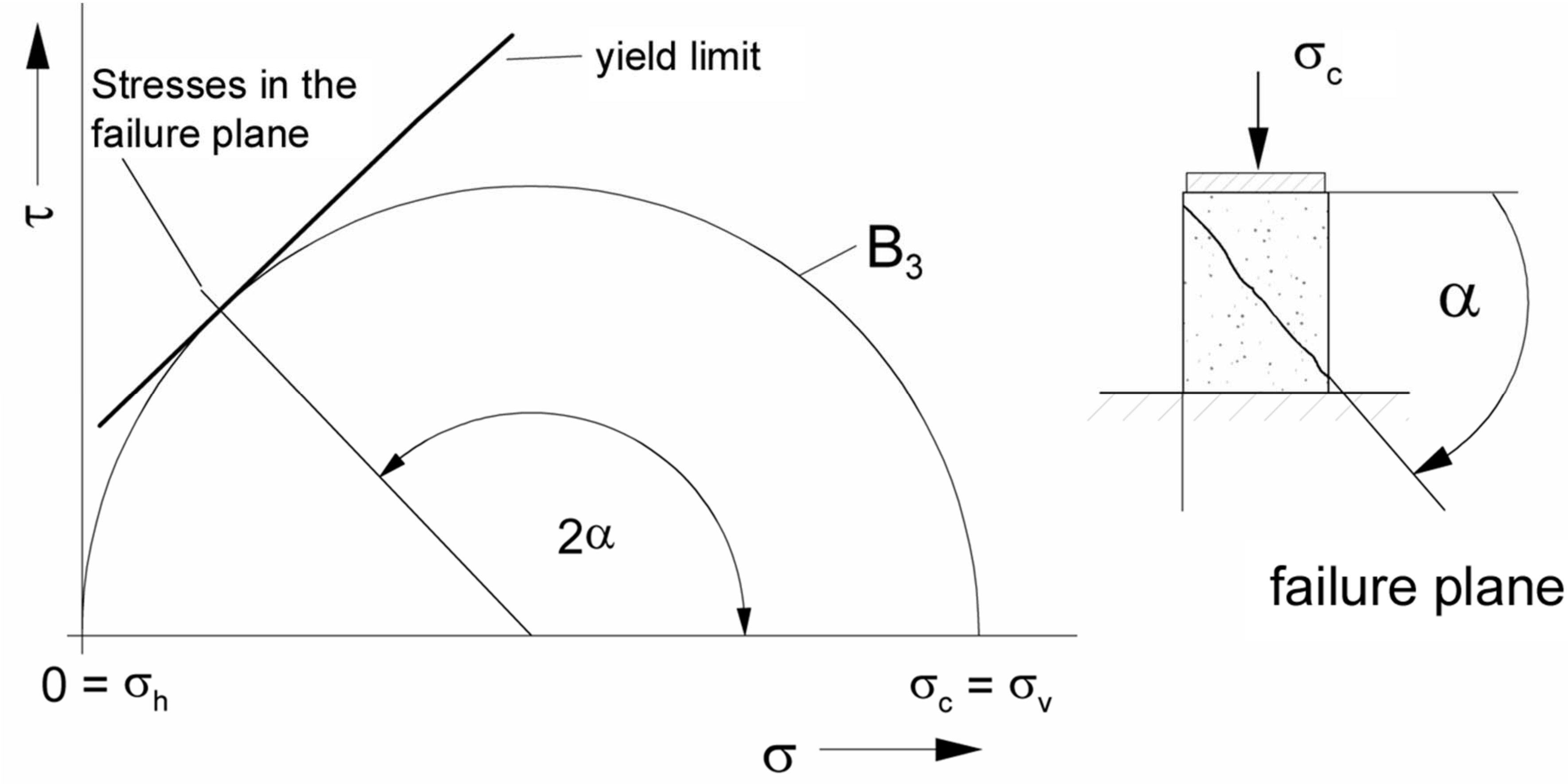
Circle A: consolidation

Circle B_i: shear to failure

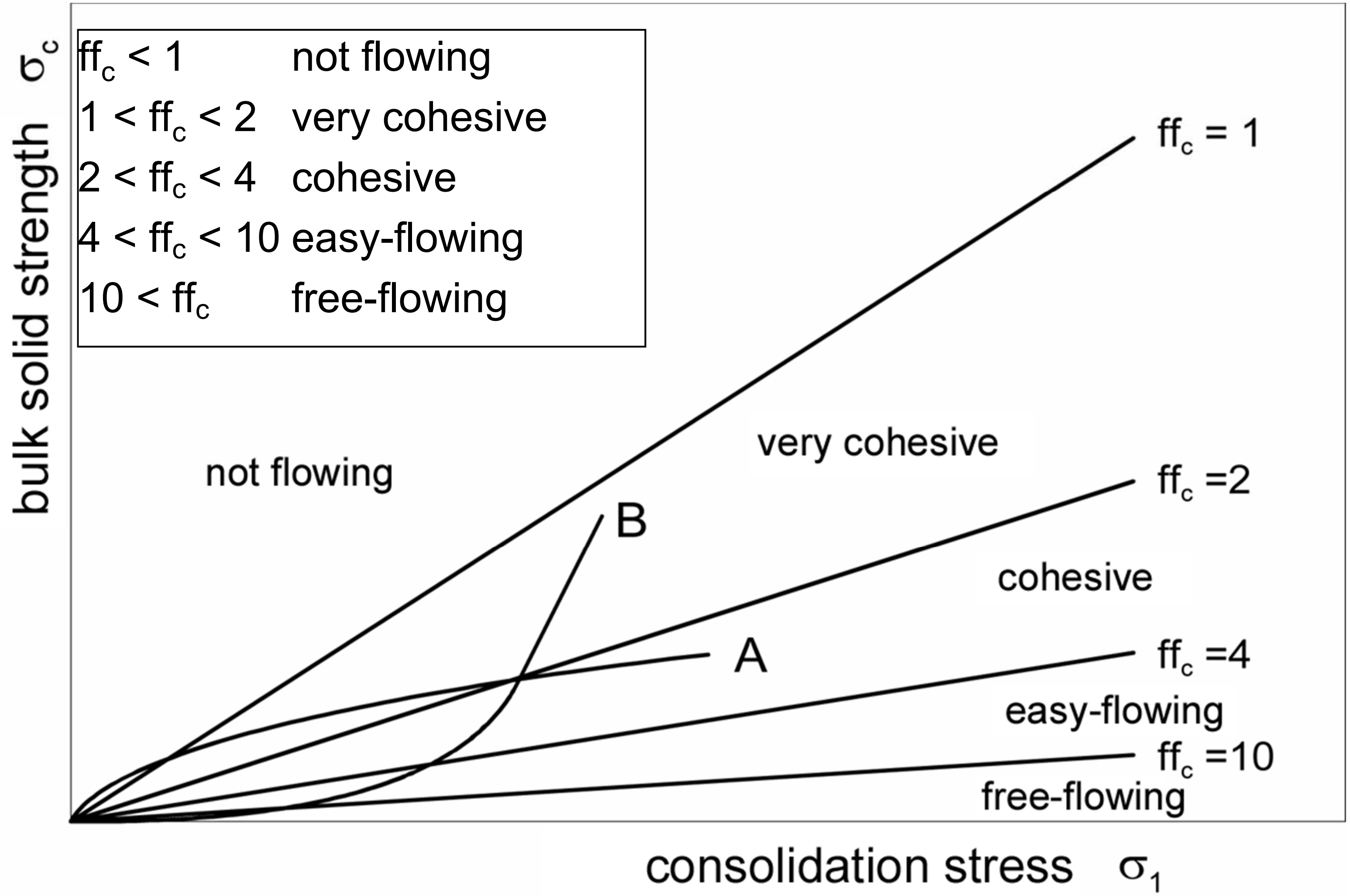
Circle C: only possible when supported in horizontal direction



Relationship between Mohr's Circle, Failure Plane and Yield Limit



Flowability of Bulk Solids



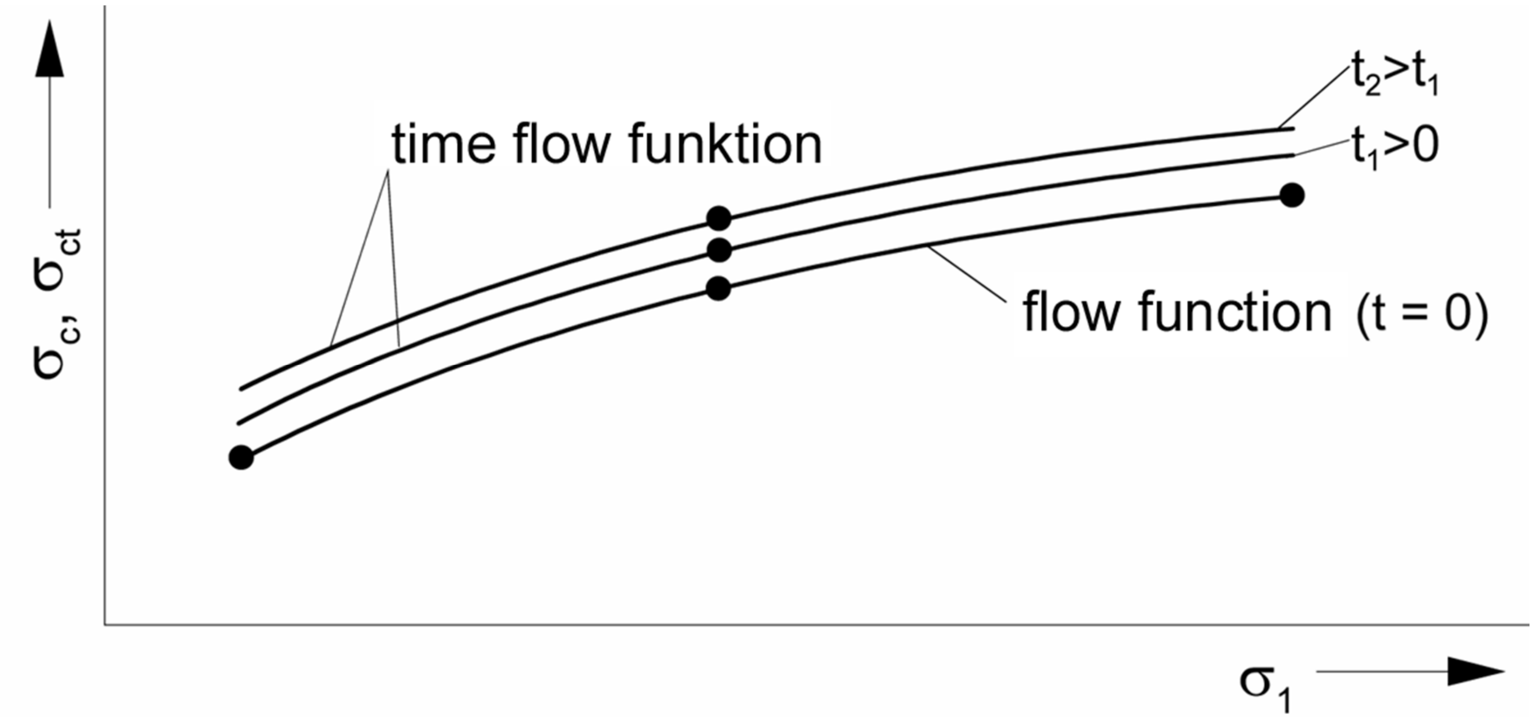
Question II
Time Dependency of Flow Properties

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

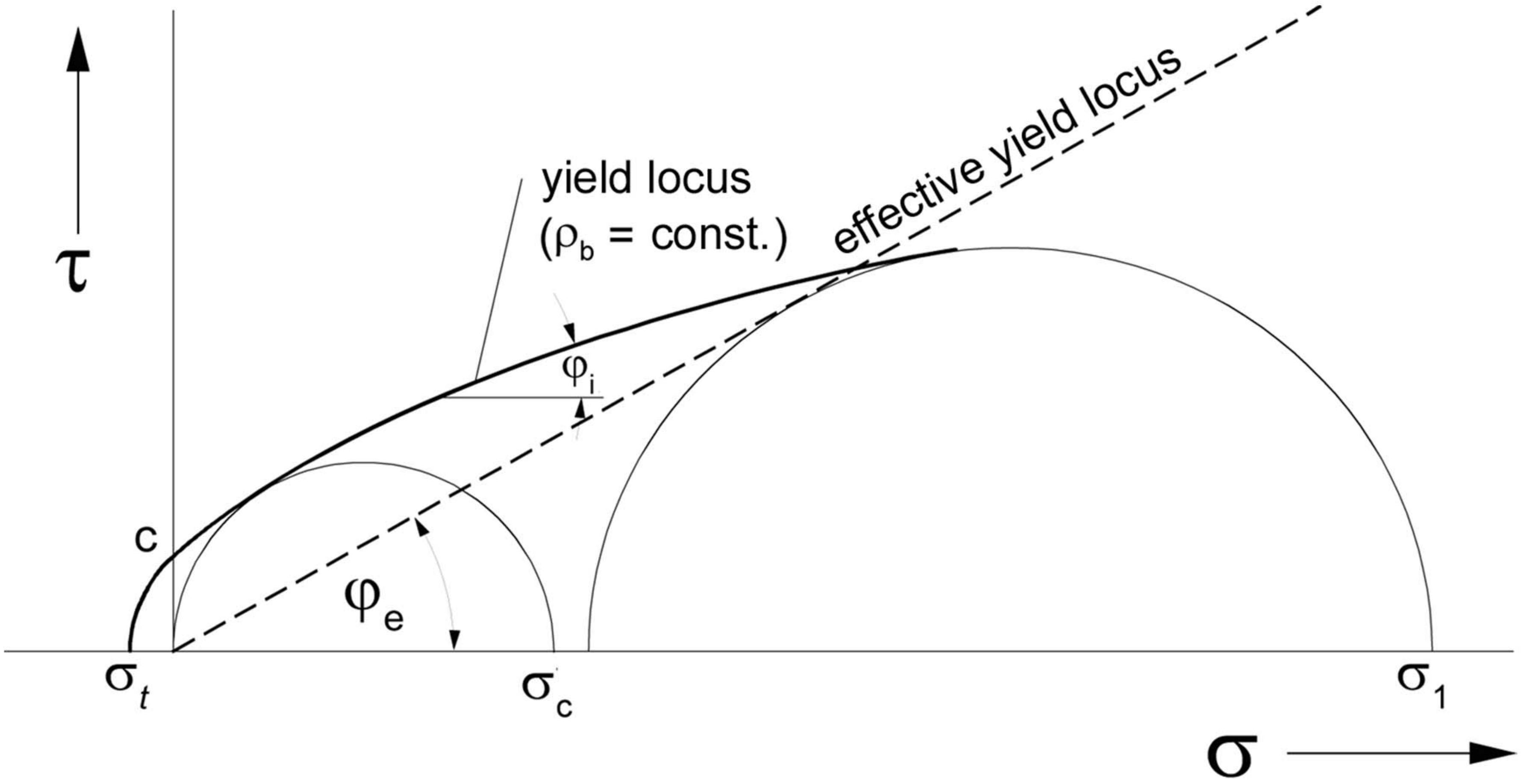
Caking

Increase of the unconfined yield strength σ_c during storage time

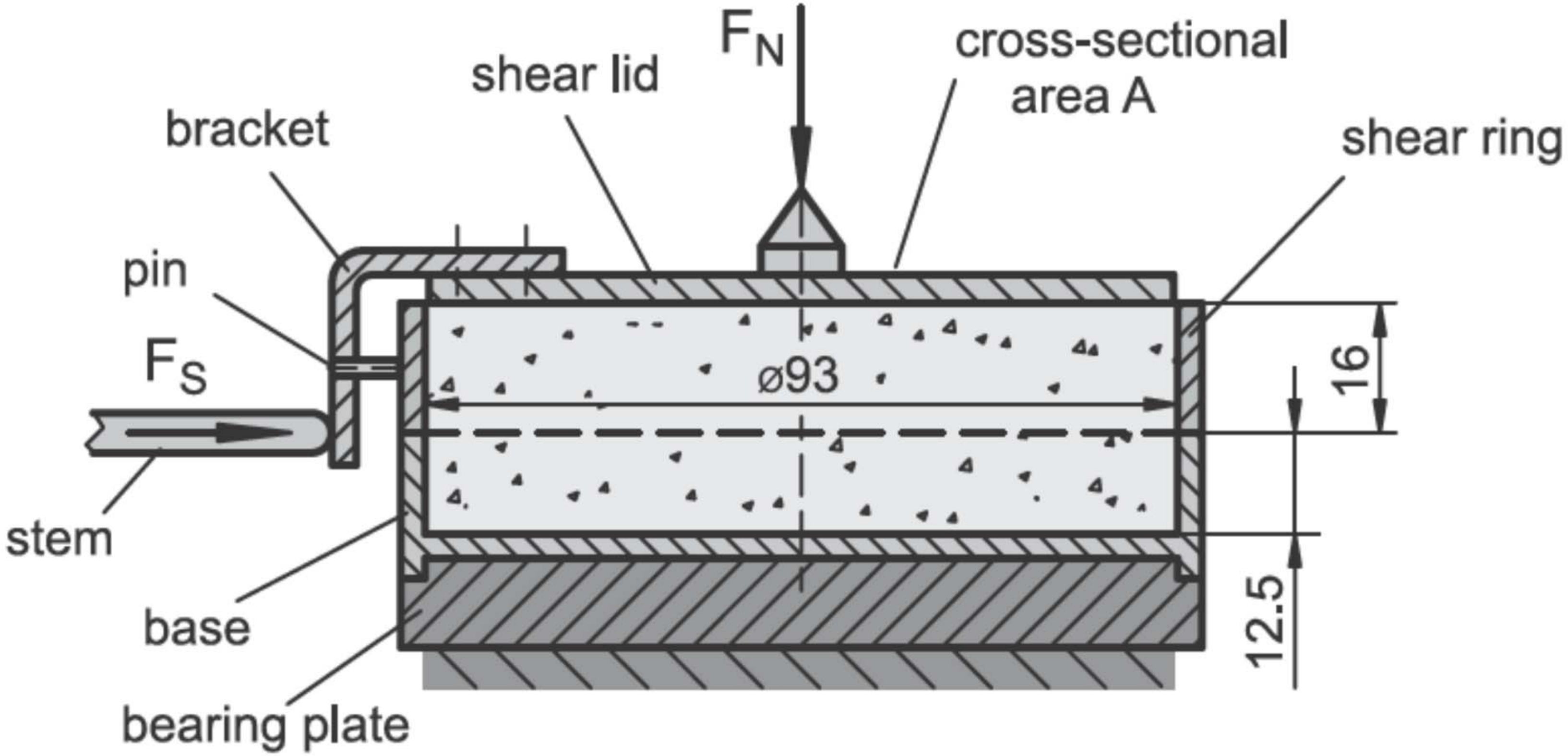
Time flow function $\sigma_{c,t} = f(\sigma_c, t)$



Yield Loci for the Description of Flow Properties

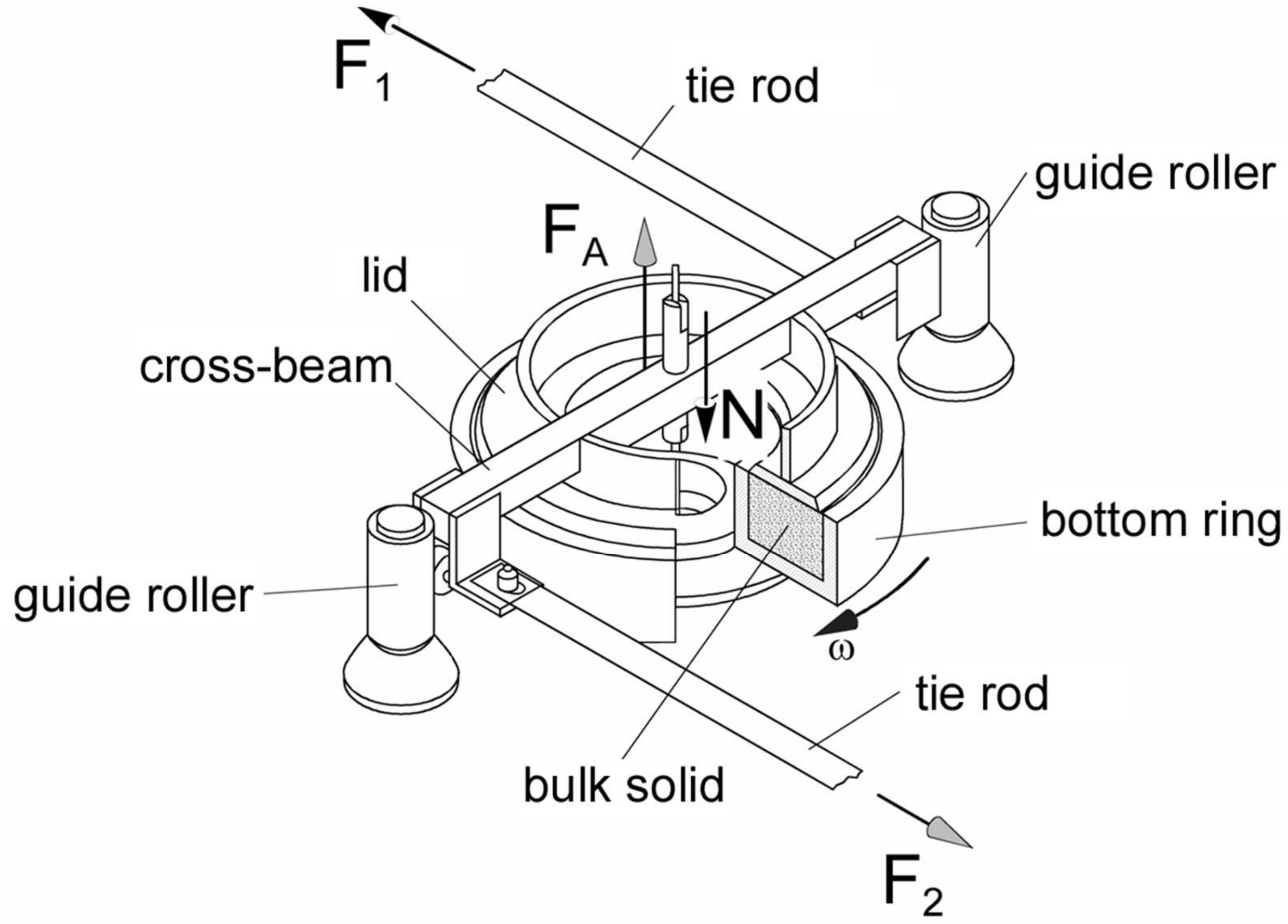


Setup of the Jenike Shear Tester (Translational Shear Tester)



literature source: D. Schulze, Powders and Bulk Solids

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



Advantages and Disadvantages

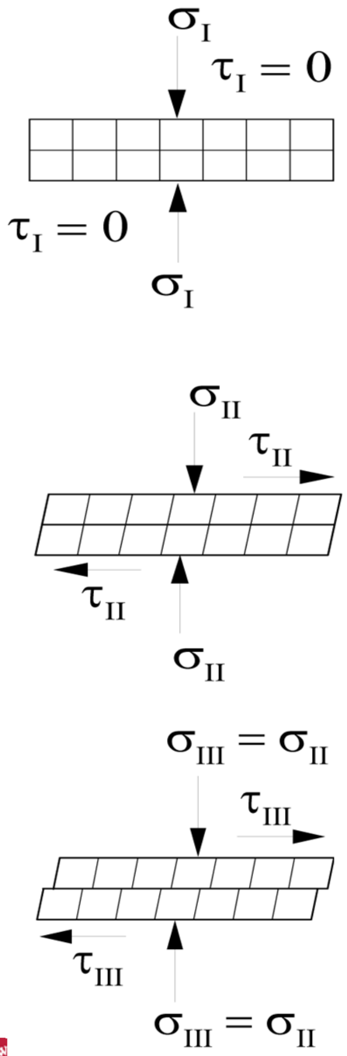
Ring shear tester

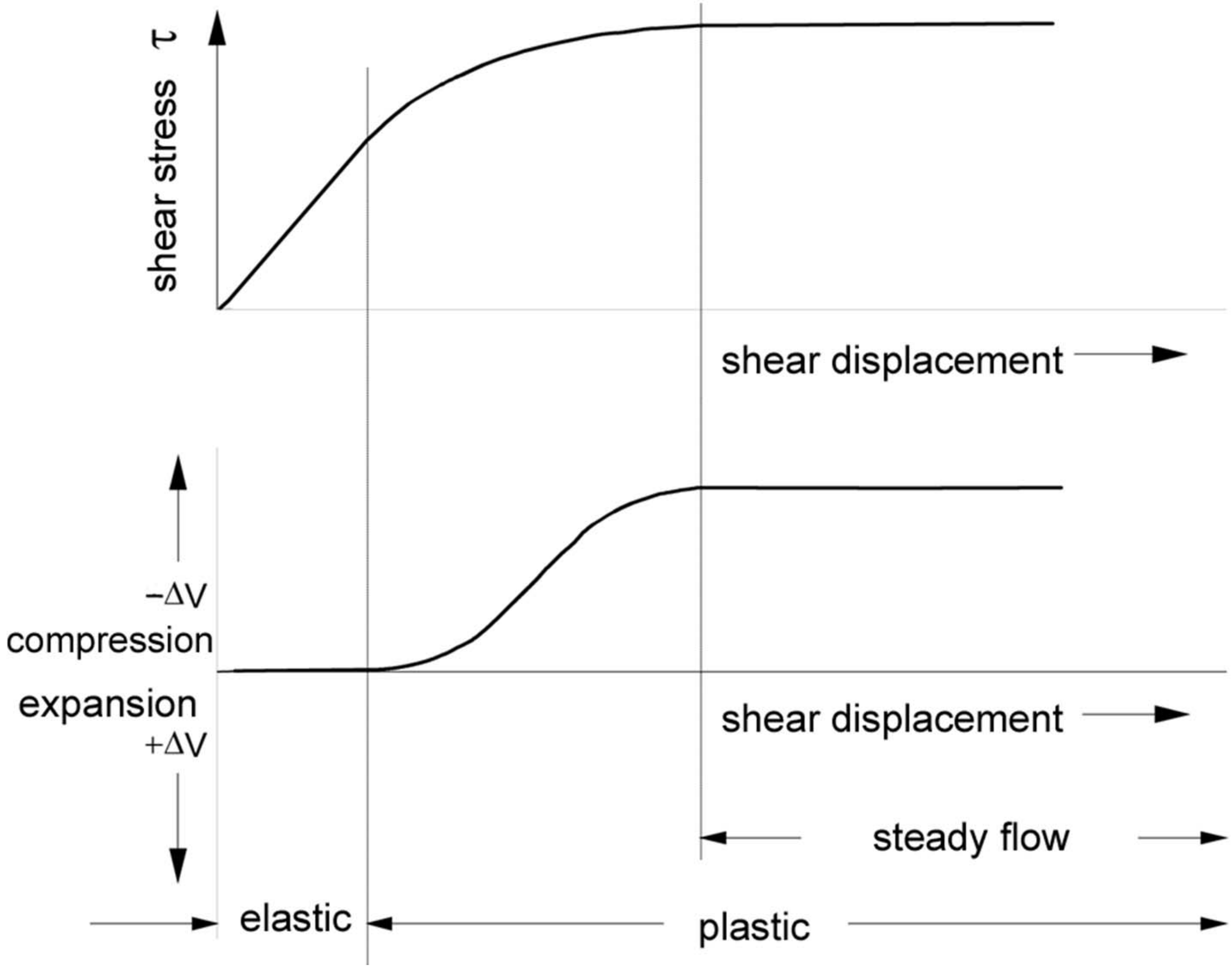
- Unlimited shear displacement
- No preconsolidation required
- Minor influence of performing personnel on experimental results
- Complete yield locus with one specimen

Jenike shear tester

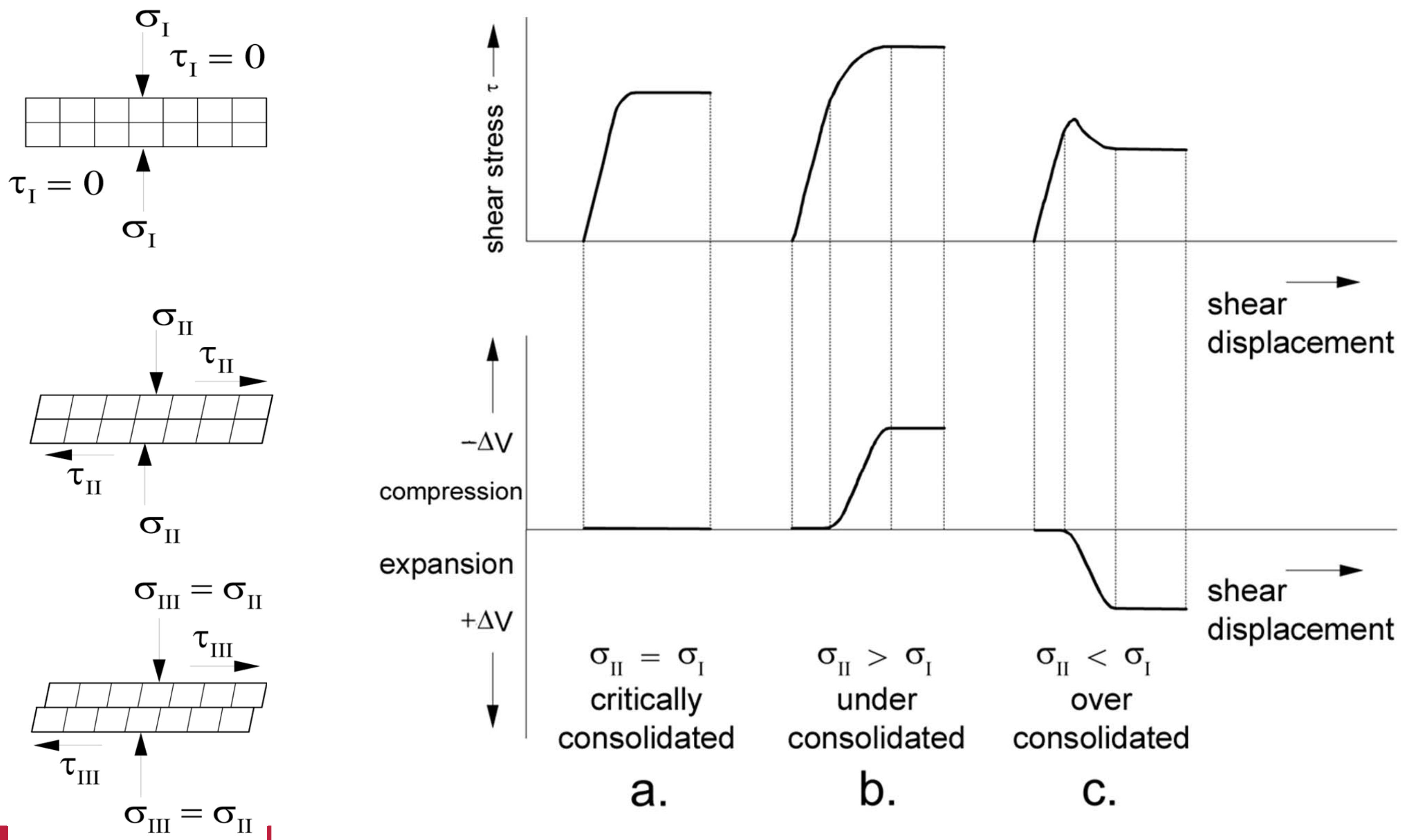
- Limited shear displacement
- Complex sample preparation
- Several specimen necessary to obtain yield locus
- Performing personnel gains experience in bulk solids handling

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





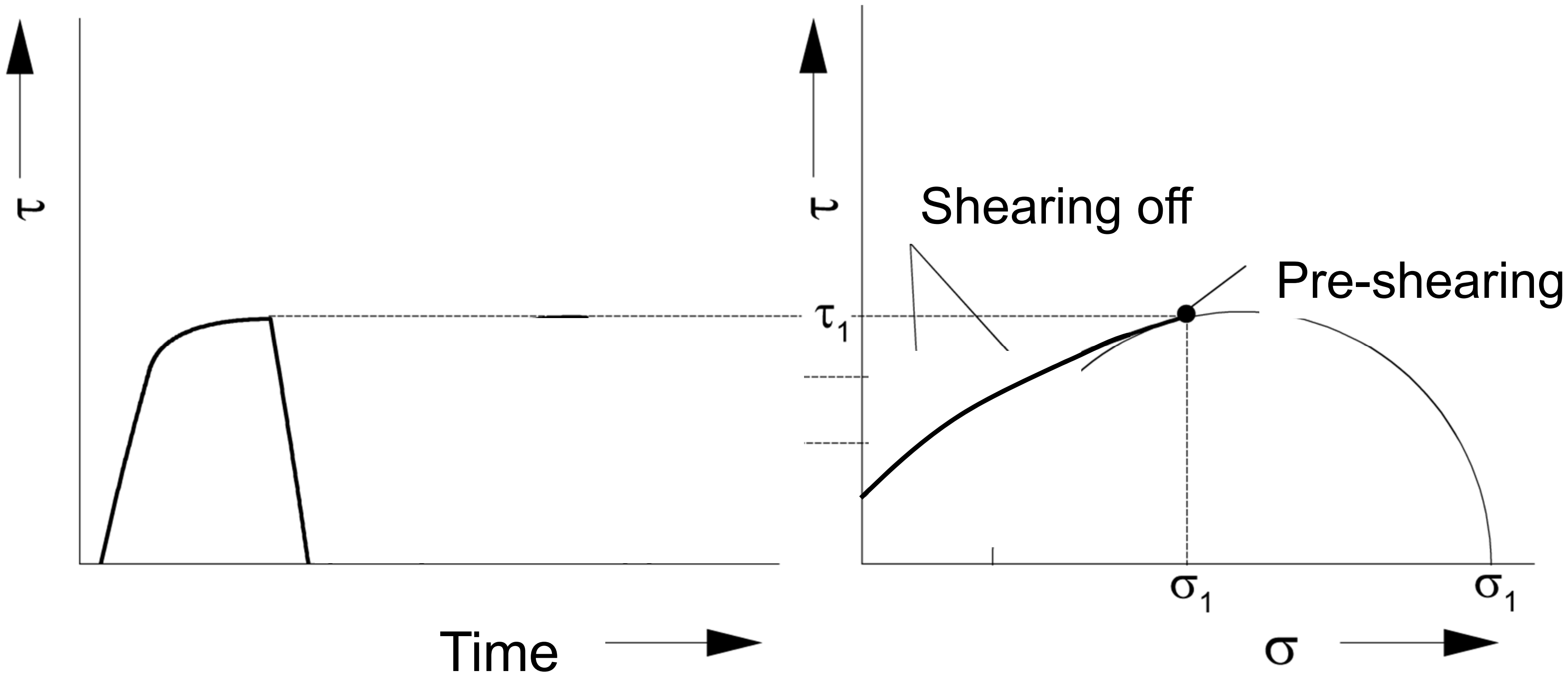
States of Preconsolidation



Execution of a shear test

- Filling of the shear cell with the bulk solid and take-off of the surface (without consolidation of the bulk solid)
- Hang up of the lid
- Eventually placing of shear cell in tester and applying of normal load
- **Pre-Shearing** under fixed normal load until stationary flow is achieved
  ➔ Sample with defined density and defined stress state
  ➔ Endpoint of yield locus is determined

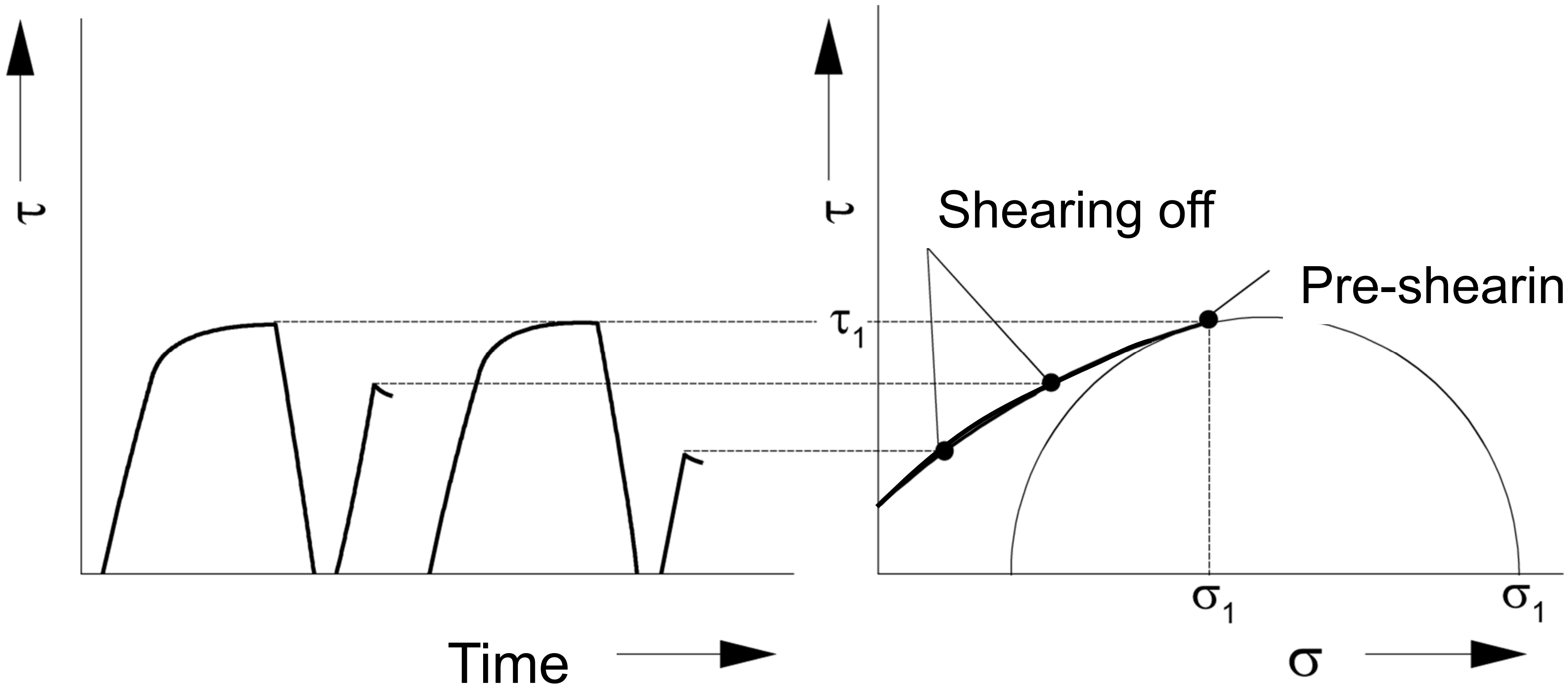
Tensile stress – shear distance – courses for the determination of the yield locus



Execution of a shear test

- Filling of the shear cell with the bulk solid and take-off of the surface (without consolidation of the bulk solid)
- Hang up of the lid
- Eventually placing of shear cell in tester and applying of normal load
- **Pre-Shearing** under fixed normal load until stationary flow is achieved
  ➔ Sample with defined density and defined stress state
  ➔ Endpoint of yield locus is determined
- **Shearing-off** under smaller normal load until flow starts (sample is plastically deformed)
  ➔ Tensile stress decreases, density decreases
  ➔ Point on yield locus is determined

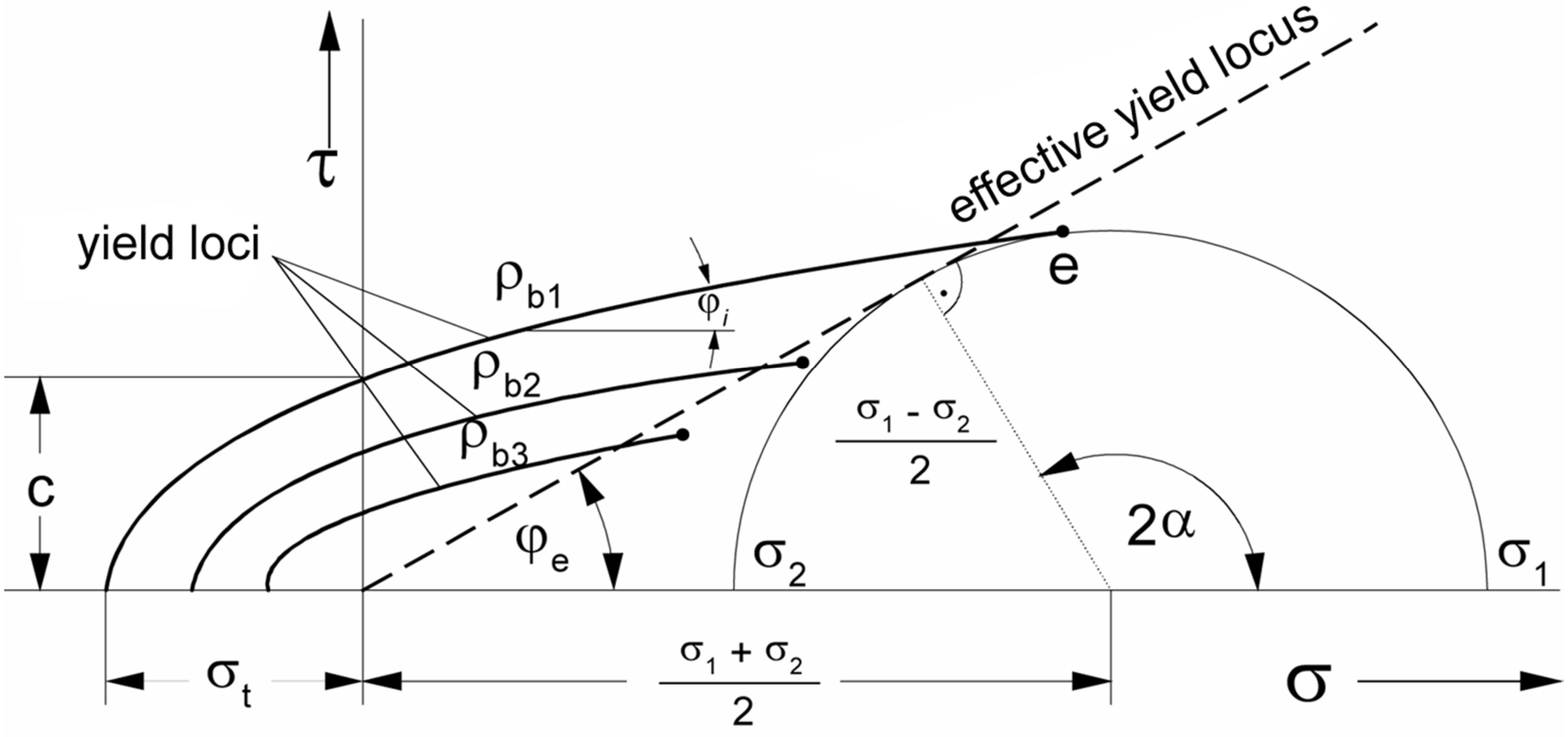
Tensile stress – shear distance – courses for the determination of the yield locus



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



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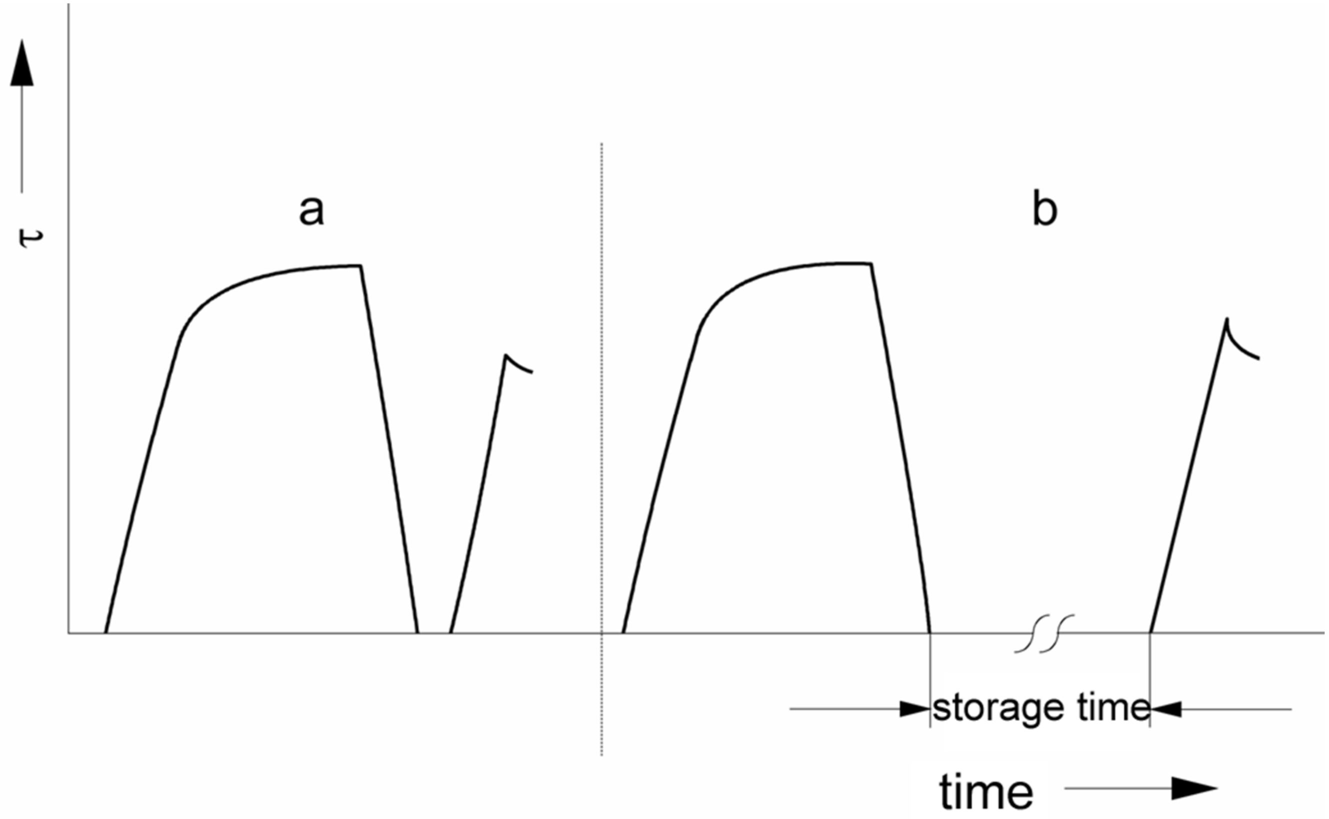
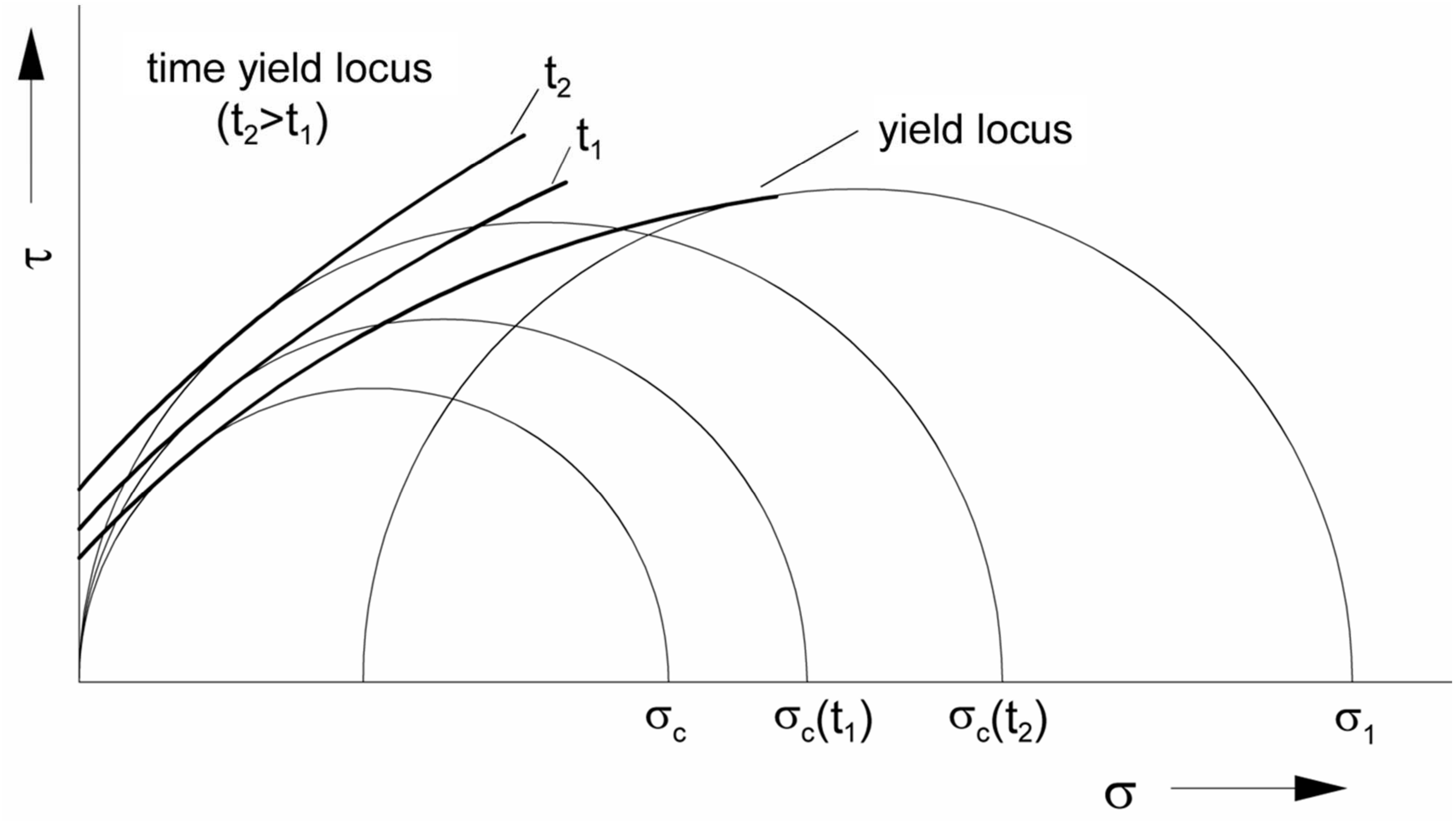
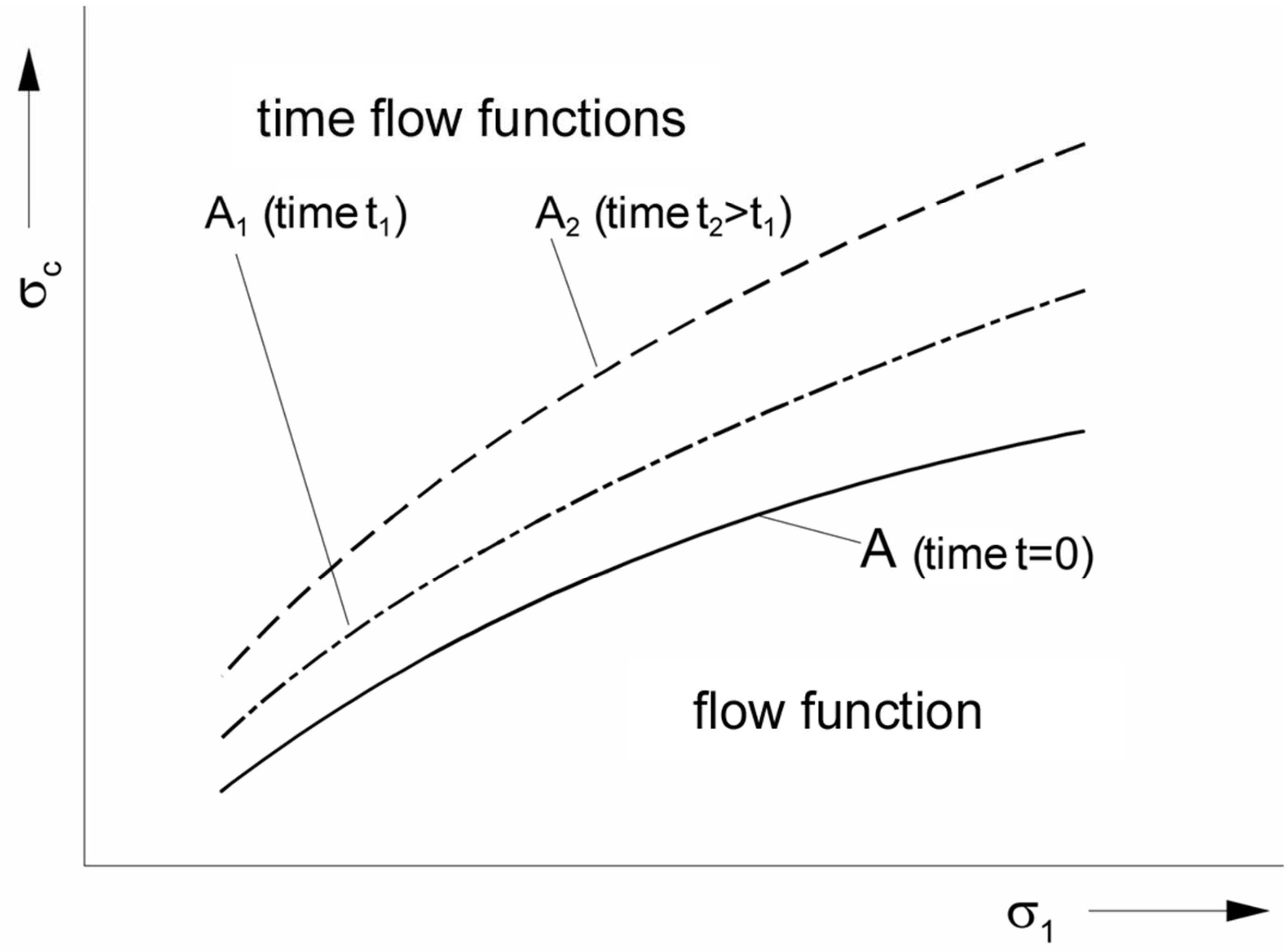
In between the preshear and the shear (to failure) procedure the sample is stored under a static normal load $\sigma_{n,t}$. This normal load is selected to equal the consolidation stress σ_1 during preshear.



Time Yield Loci



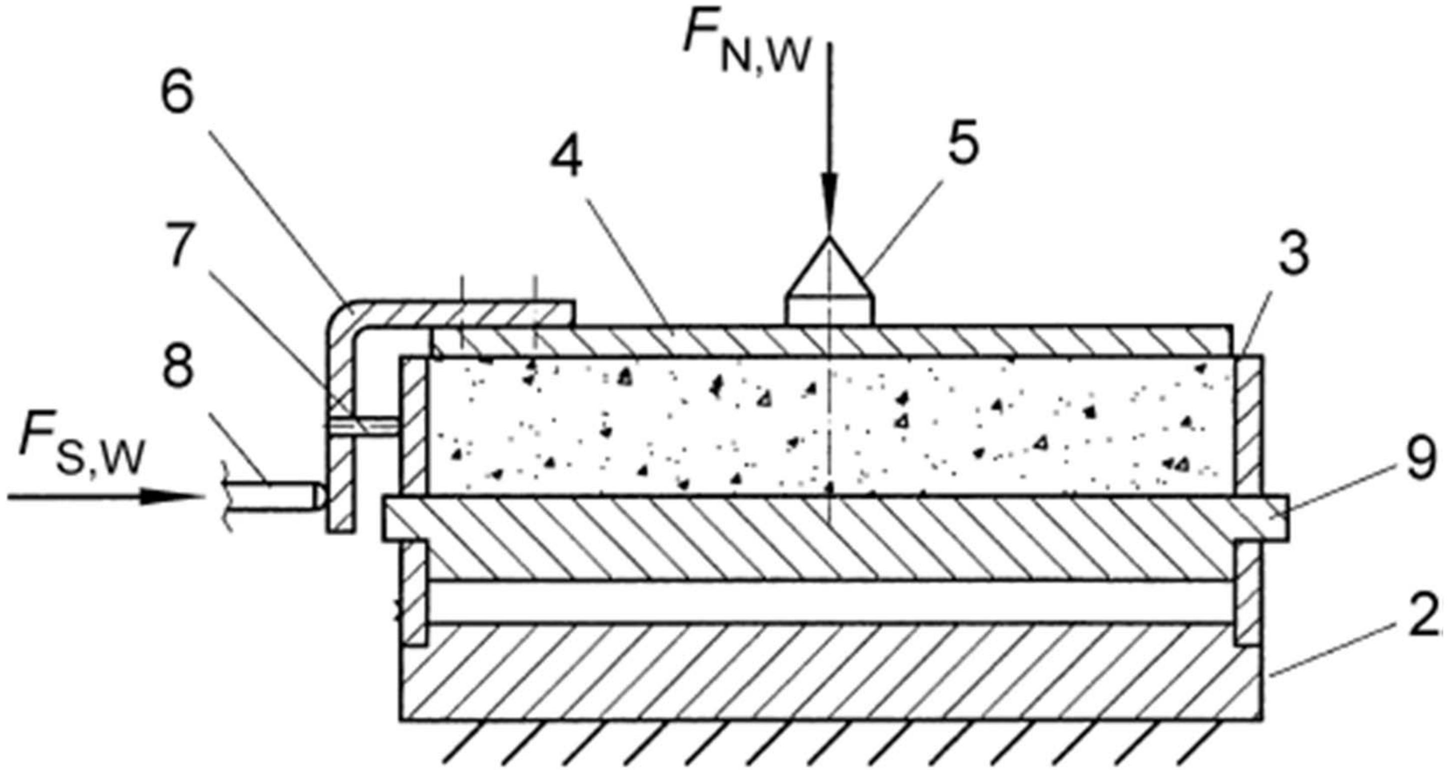
Time Flow Functions



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

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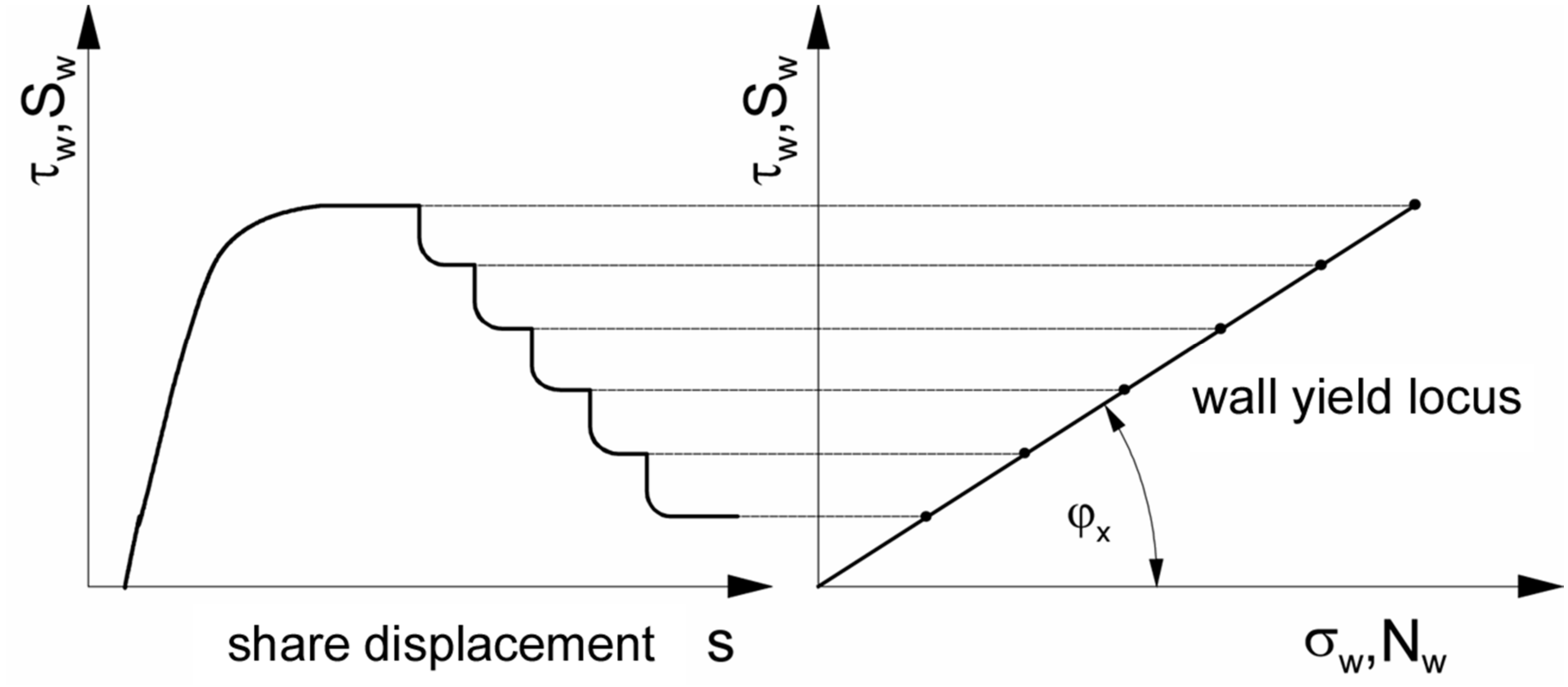
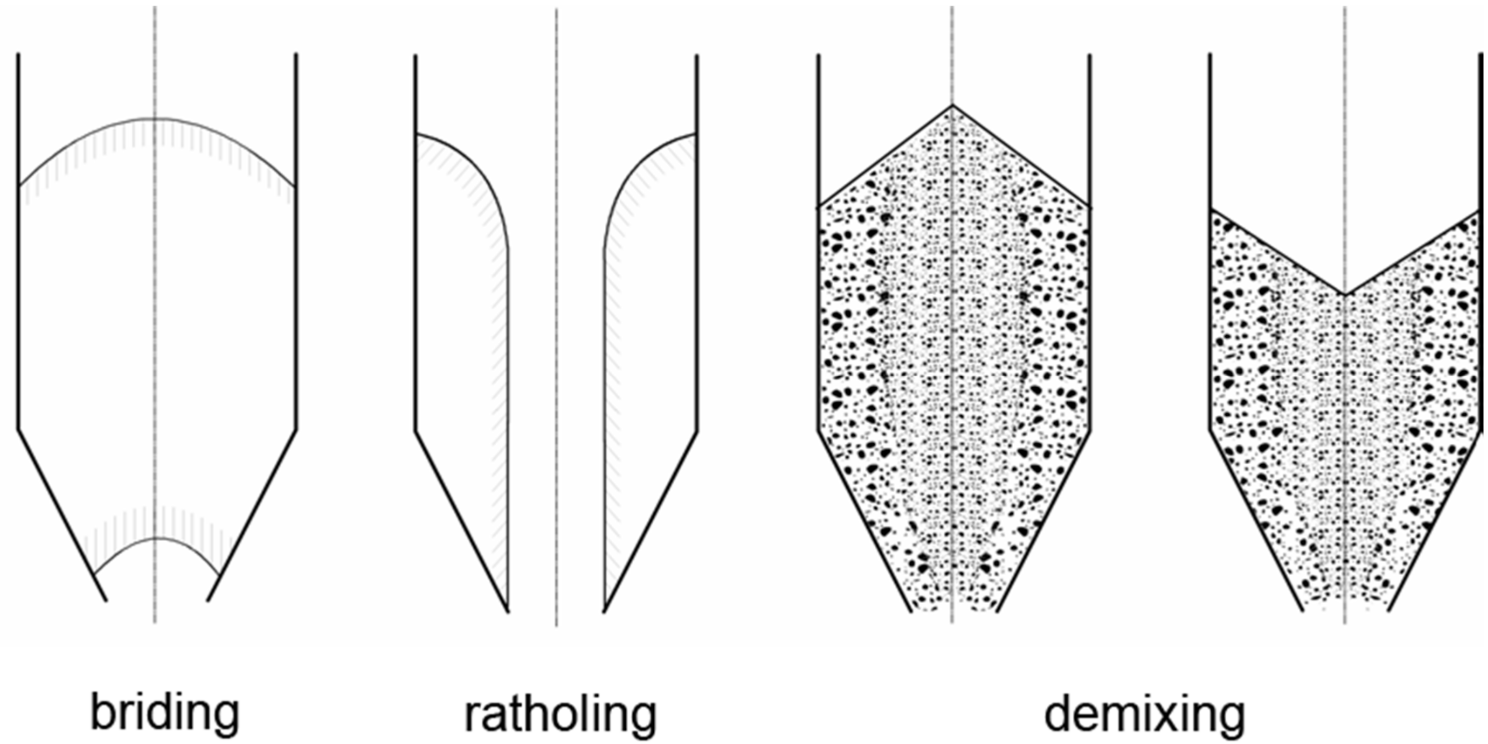


Bulk Solids – Problems

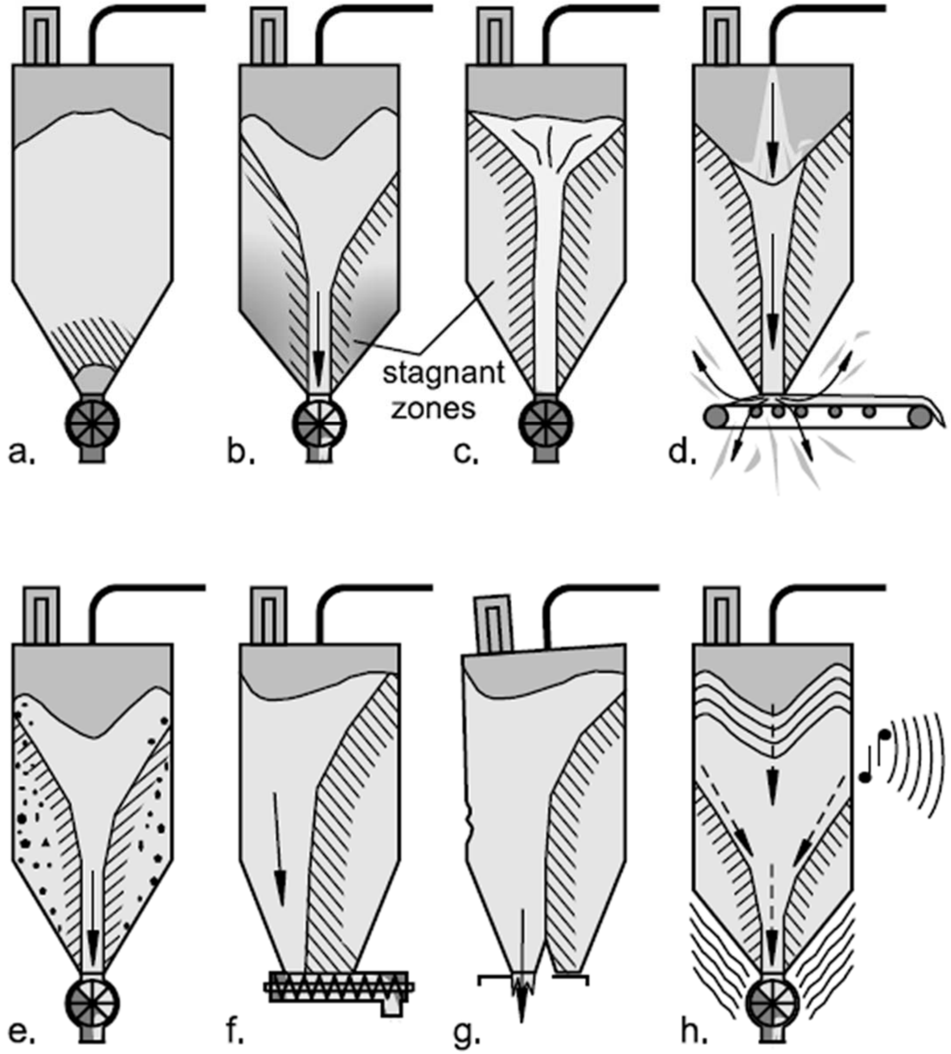
What has happened?



Question V
Flow Problems

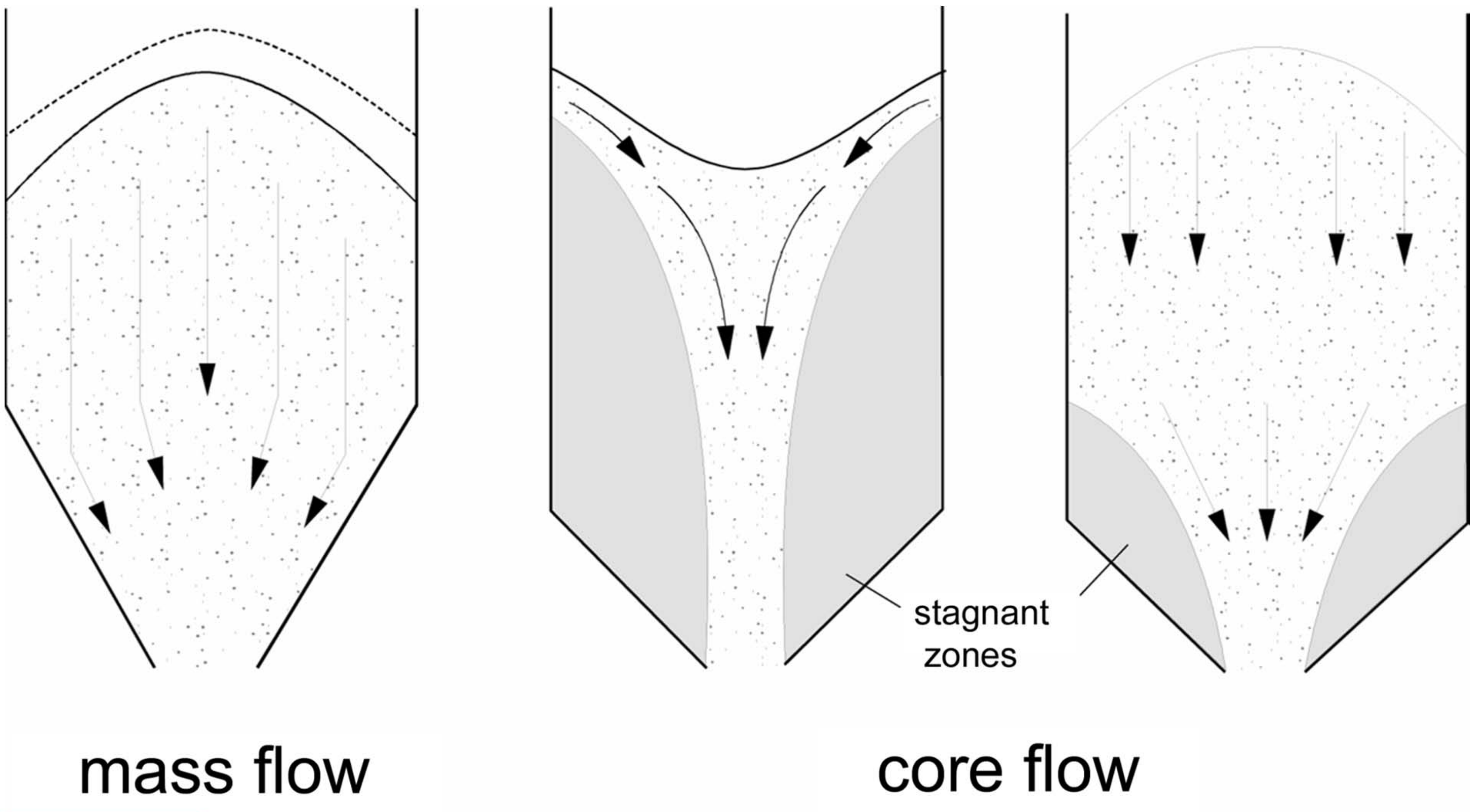
Which different flow problems appear in hoppers?

And in which type of hoppers might these problems occur?



literature source: D. Schulze, Powders and Bulk Solids

Flow Profiles in Silos



Silo design for flow

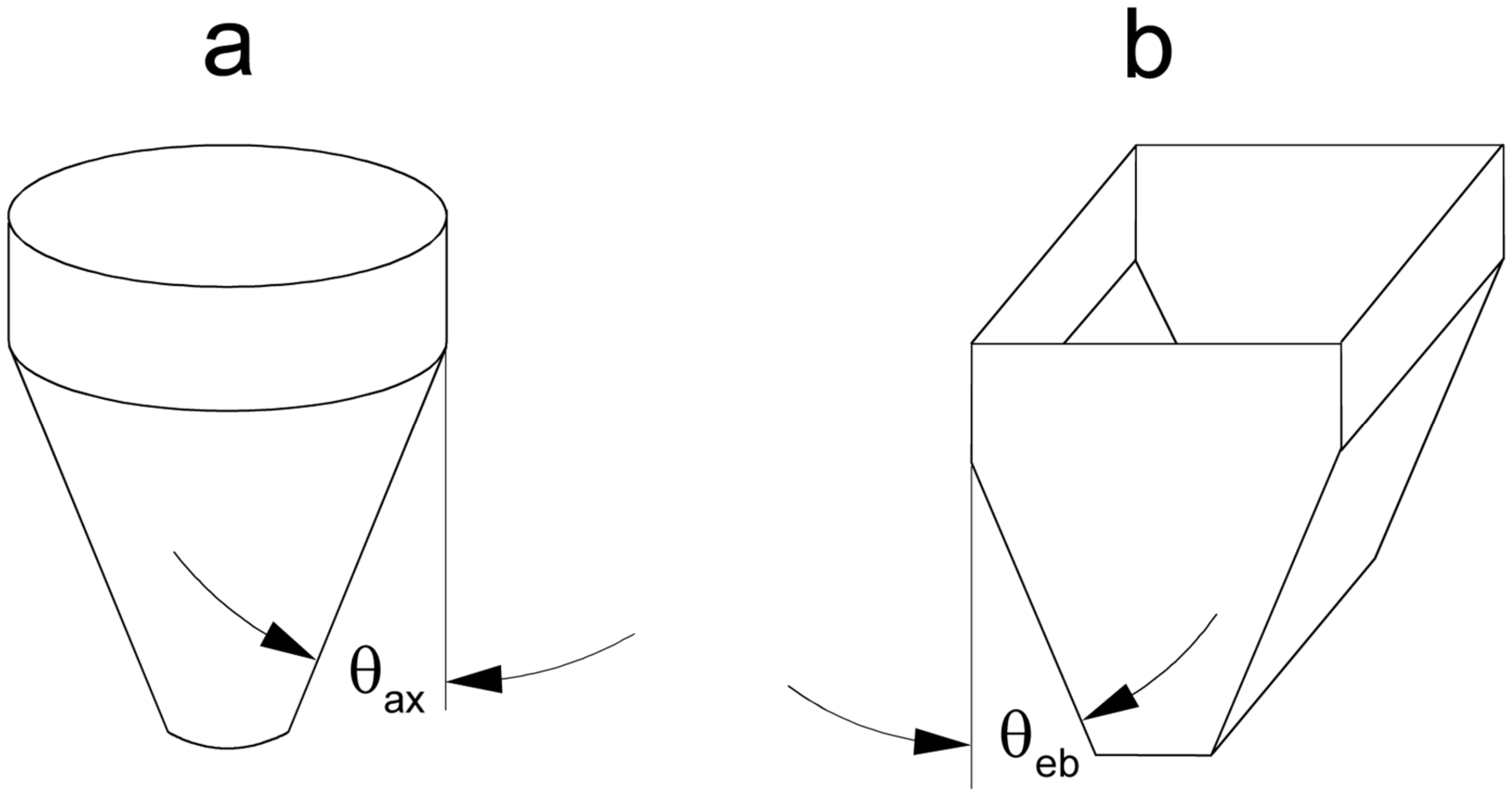
Stresses at the silo outlet determine if

- Mass flow is achieved
- Arching occurs.

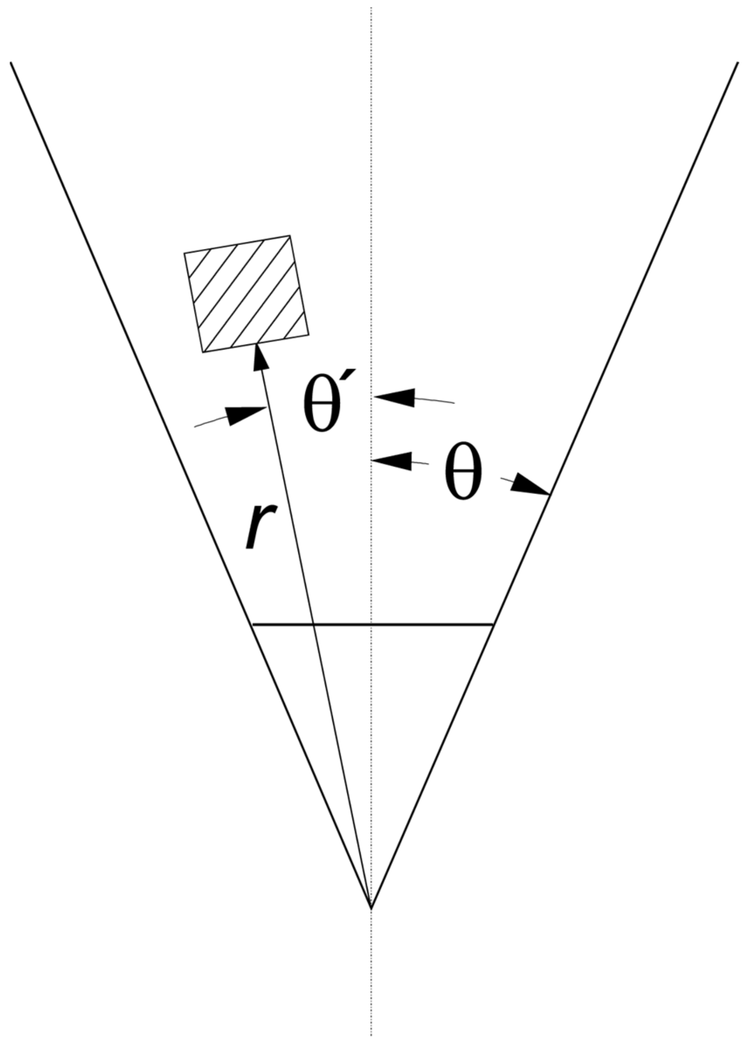
Course of stresses in the hopper has to be determined at passive stress state for

- Wedge-shaped hopper (plain stress and strain state)
- Conical hopper (axial-symmetric stress and strain state)

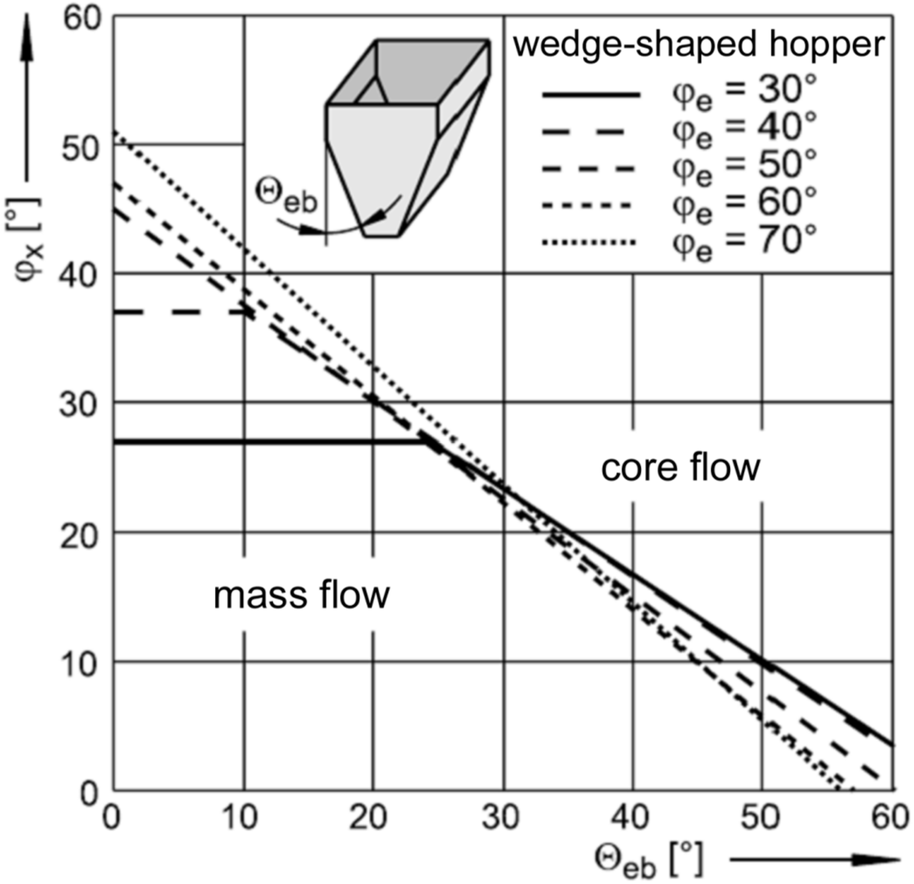
Axial-symmetric and Planar Flow

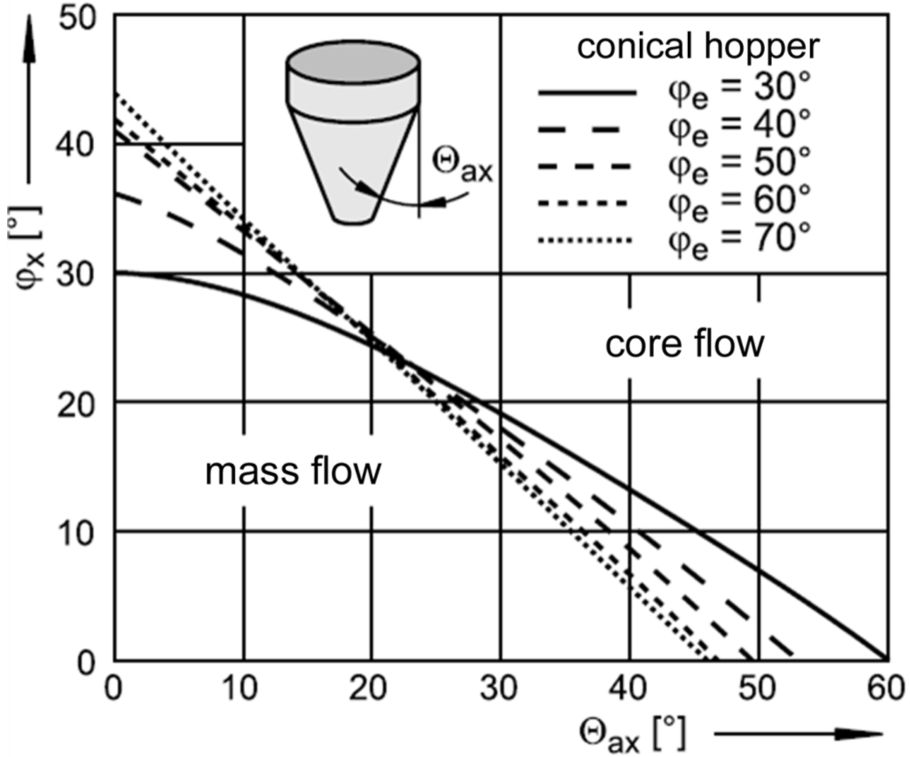


Conditions at the Outlet (Radial Stress Field)



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?

Design against arching (principal method)

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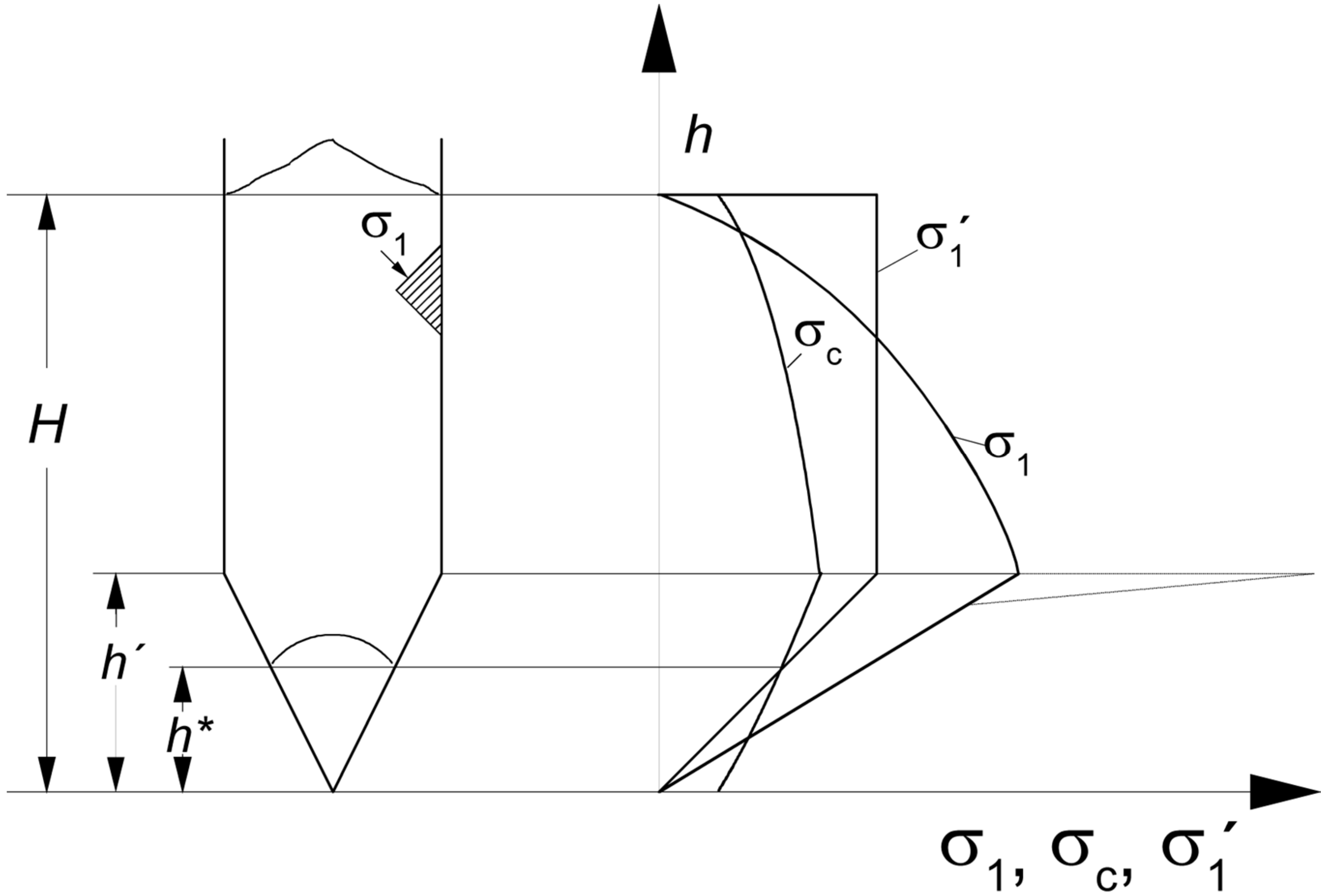
In order to avoid an arch at the outlet the stresses acting on the bulk solid at the outlet must be higher than the strength of the bulk solid. The stresses acting on the bulk solid are determined by the bearing stress

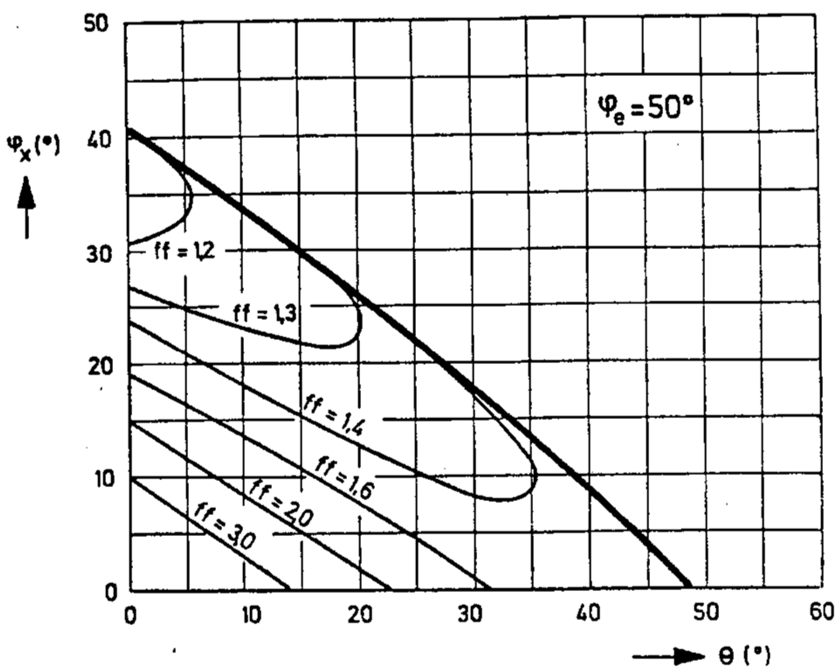
No arch, if bearing stress > yield strength of bulk solid

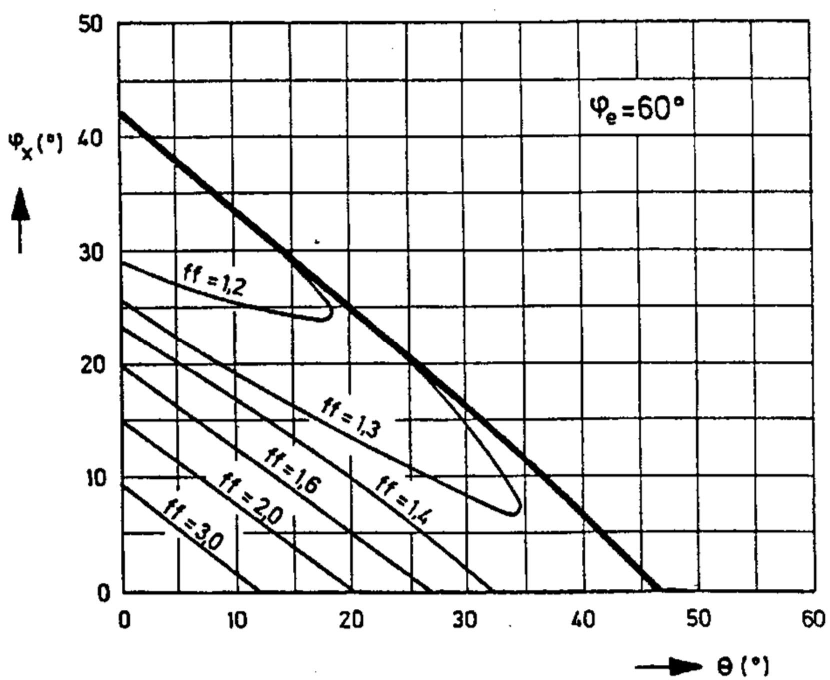
Major Principal Stress, Consolidation Stress and Stable Bulk Solid Arch



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)





Design against arching (principal method)

In order to avoid an arch at the outlet the stresses acting on the bulk solid at the outlet must be higher than the strength of the bulk solid. The stresses acting on the bulk solid are determined by the bearing stress

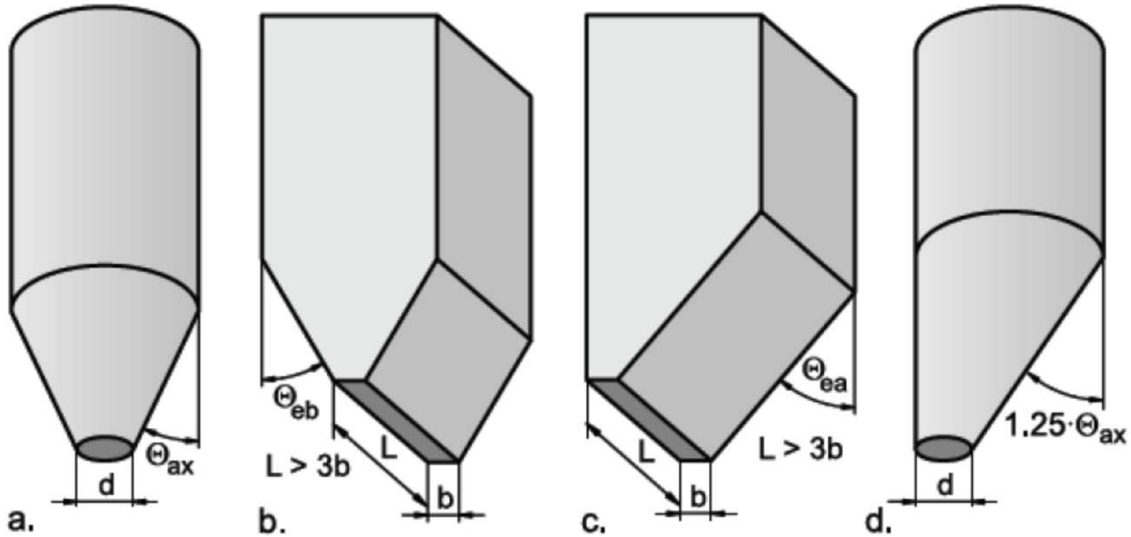
No arch, if bearing stress > yield strength of bulk solid

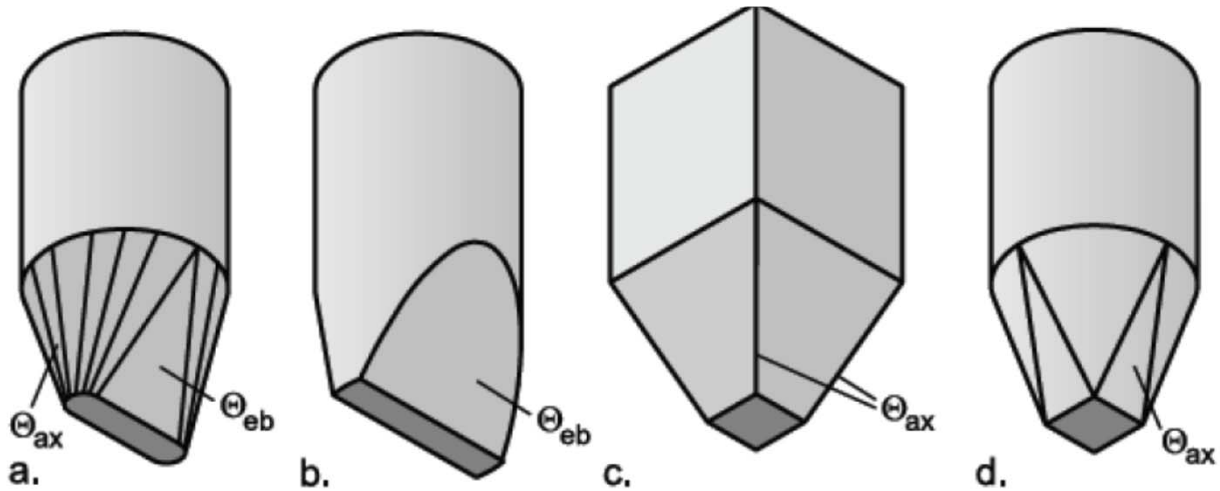
By comparison of bearing stress (= σ_1 / ff) and yield strength of bulk solid as function of major principal stress a critical yield strength or bearing stress respectively can be achieved, at which both stresses have the same value.

With the critical yield strength and an adaption parameter the minimum outlet size of the silos can be determined based on the knowledge of the stress field in the hopper:

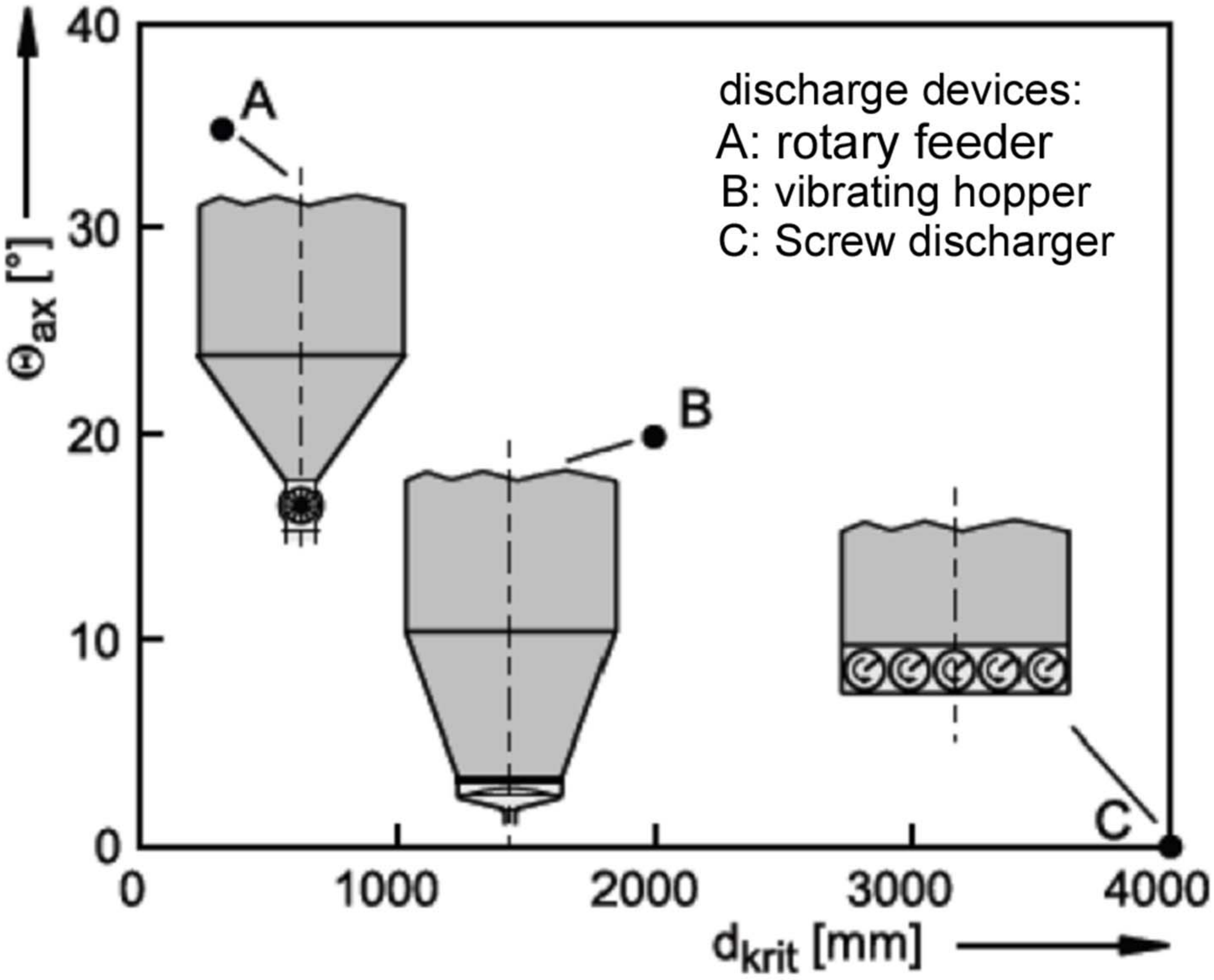
$$d_{krit} = H(\theta) \cdot \frac{\sigma_{c,krit}}{g \cdot \rho_b}$$

Hopper Shapes

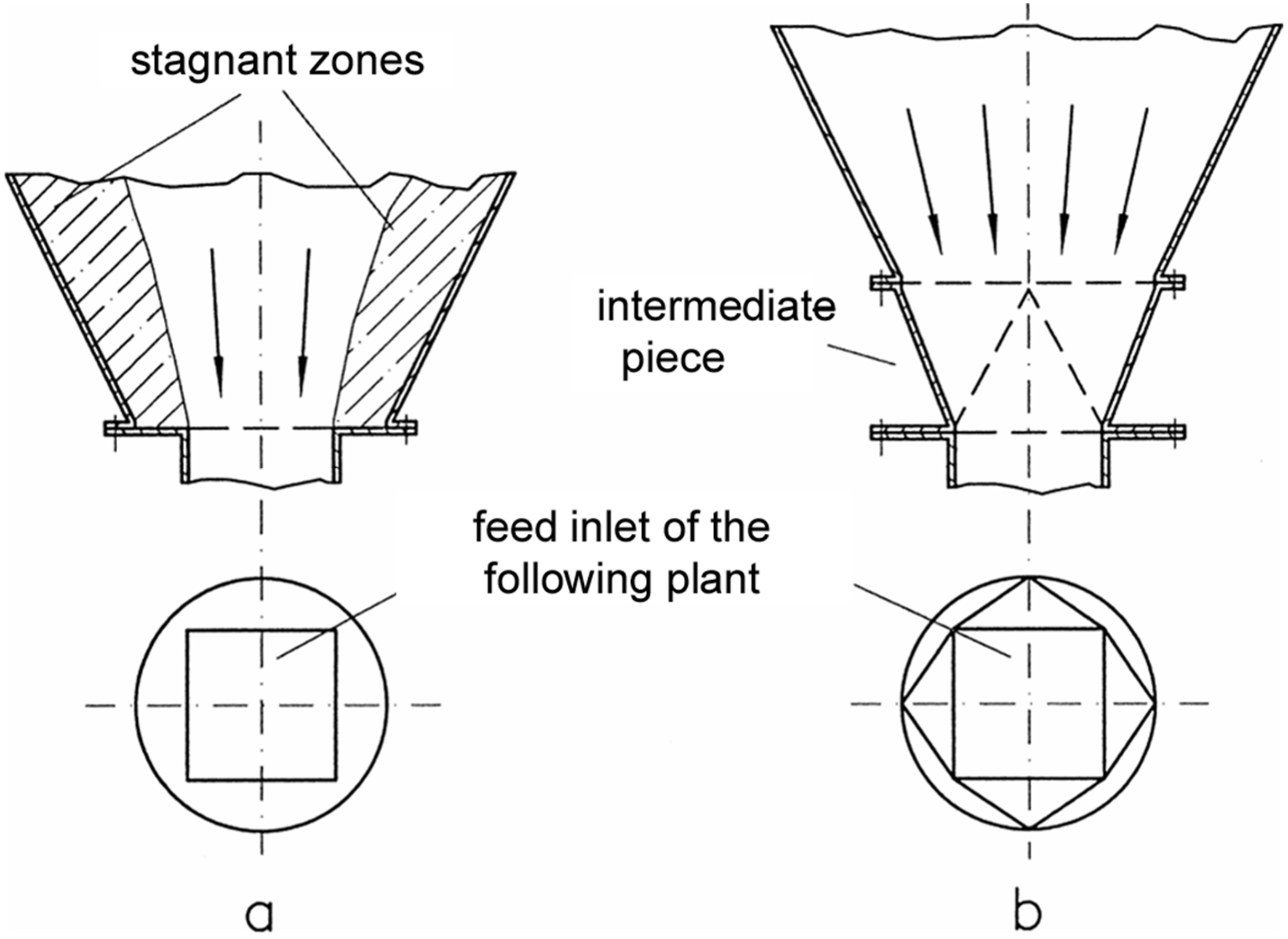




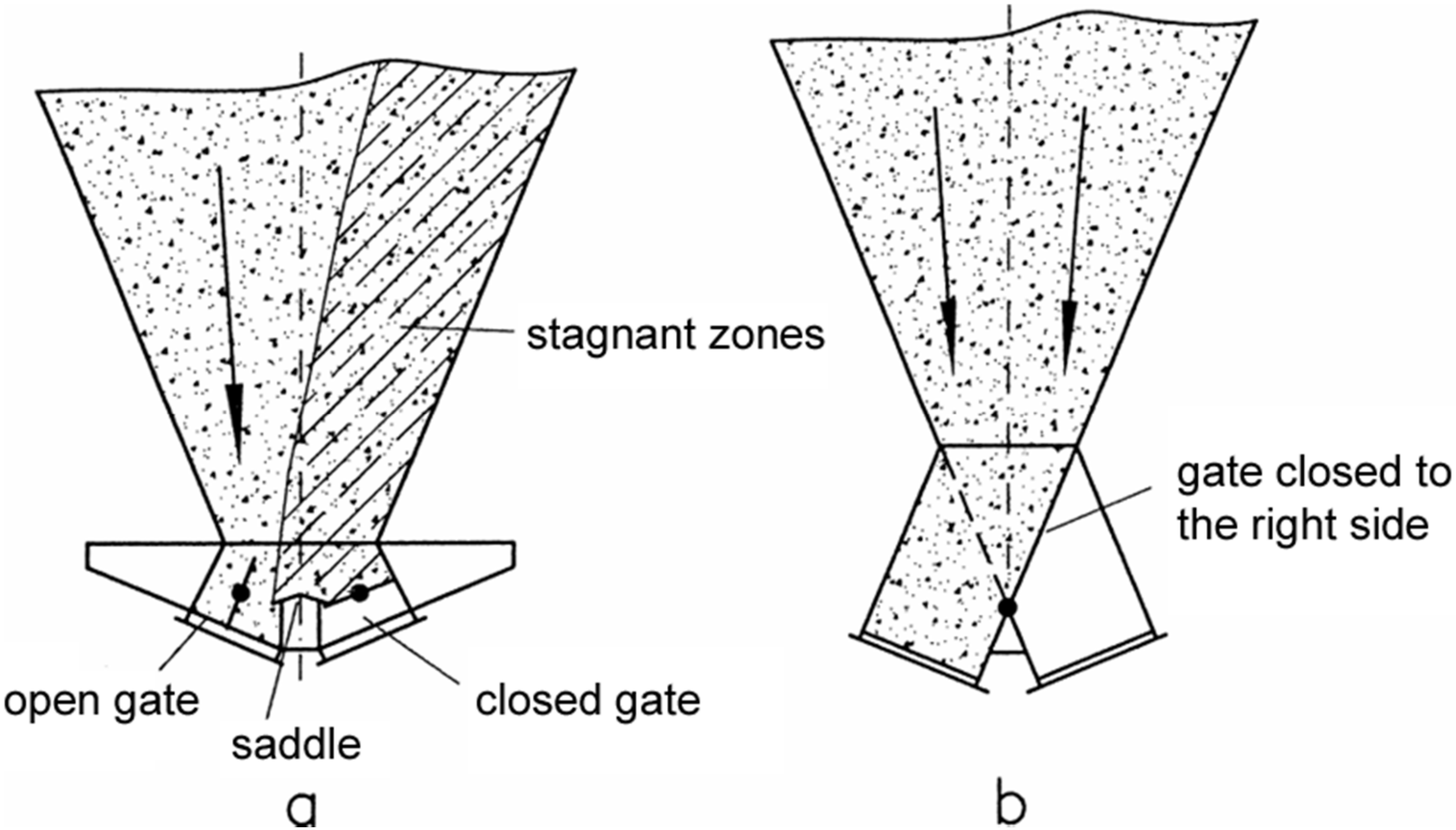
Influence of Flow Properties on Silo Design



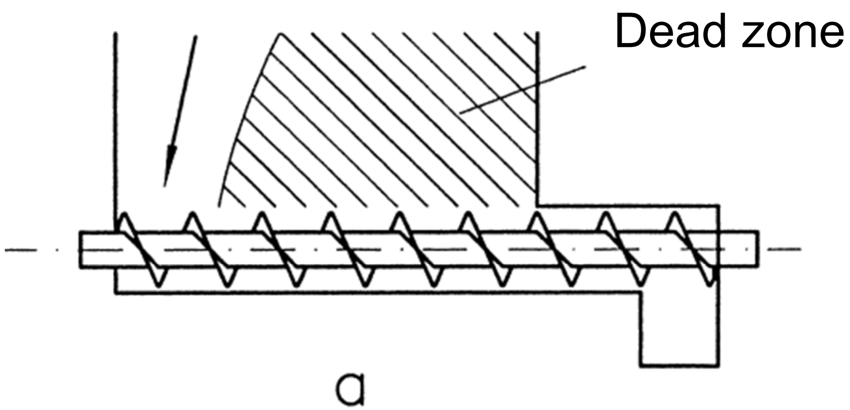
Rule 1 - Junction to Connected Devices



Rule 1 – Example Gate/Flap: Walls has to be designed steep enough for mass flow



Rule 2 – Example Screw conveyor: Principle of increasing capacity



How can screw conveyor be designed to achieve an increasing capacity in direction of flow?

Rule 2 – Example Screw conveyor: Principle of increasing capacity

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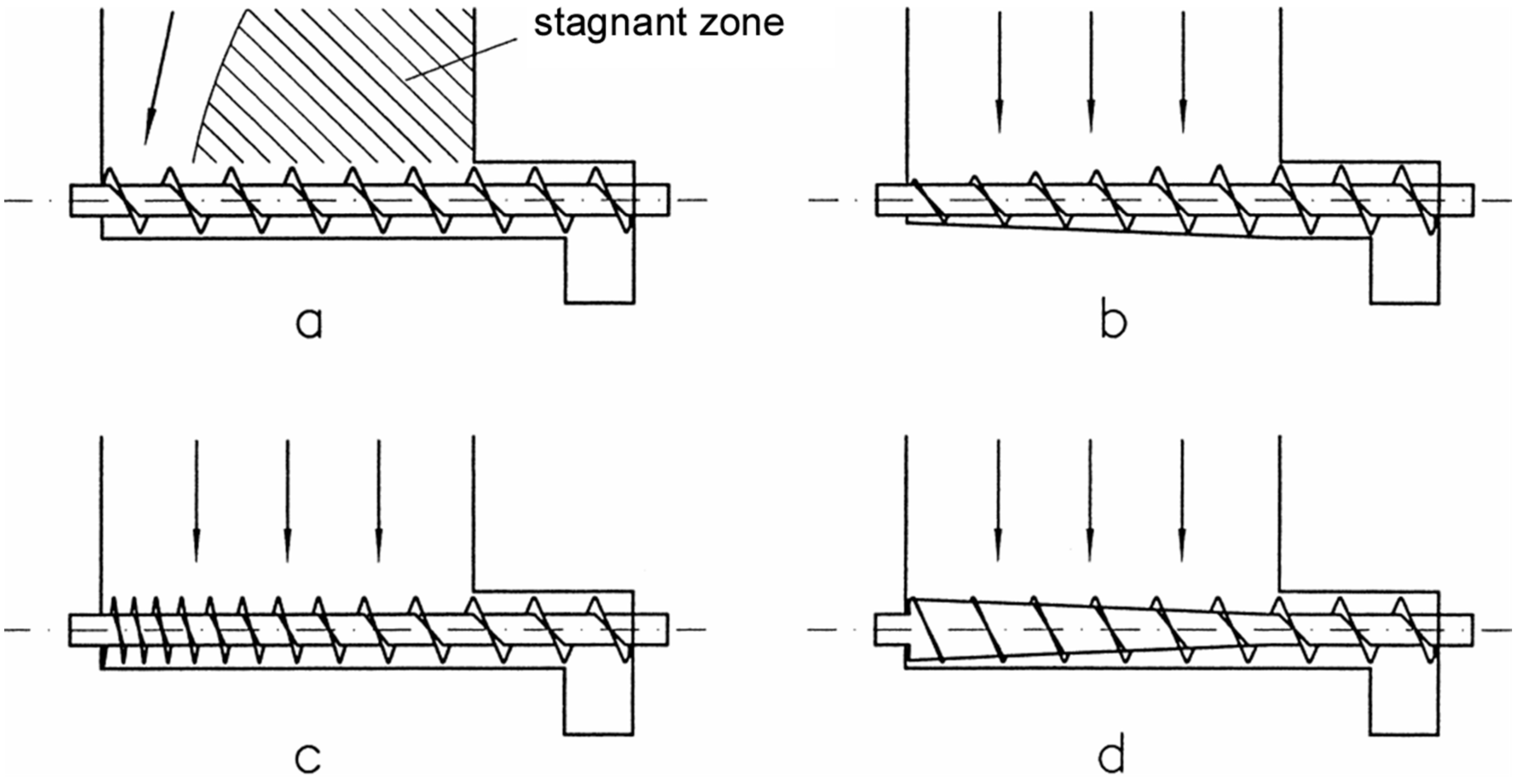
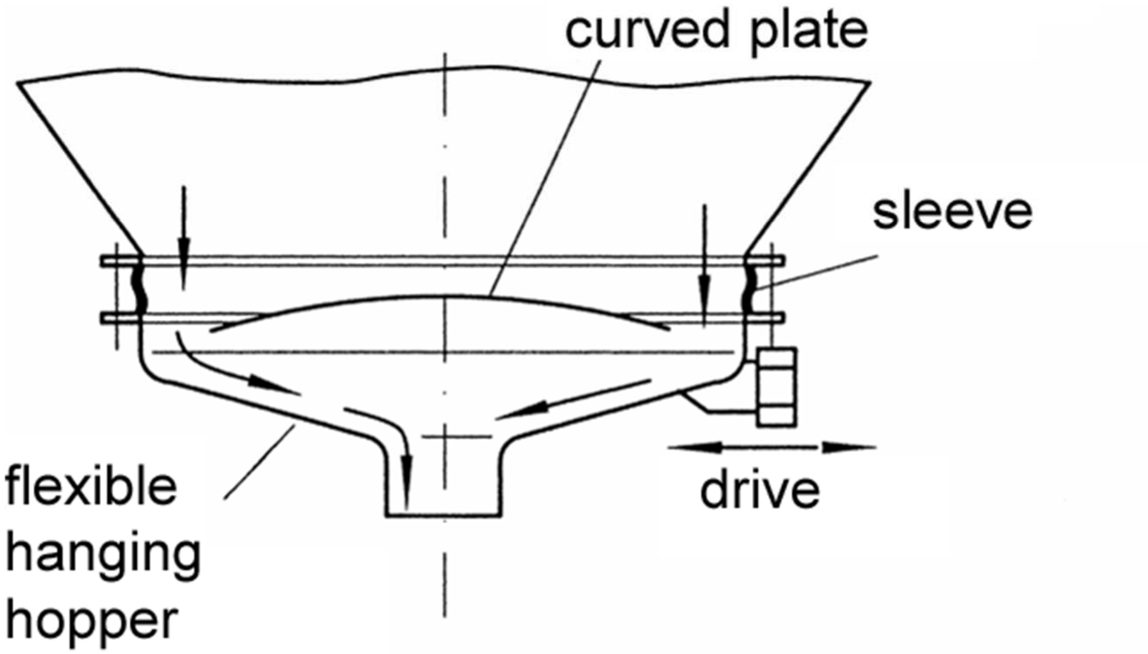


Rule No. 5
Discharge Over the Whole Outlet Diameter



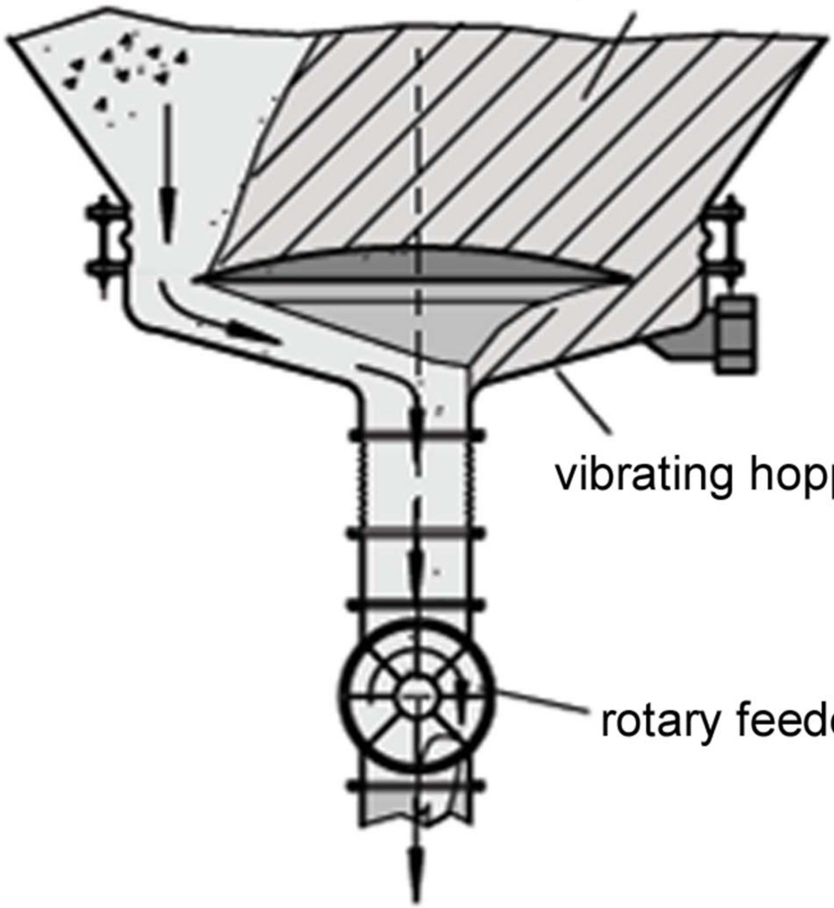
Caution:

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

Rule No. 5
Discharge Over the Whole Outlet Diameter



Pneumatic Discharge Aids