PROGETTO DI STRUTTURE IN ACCIAIO

Corso di aggiornamento per ingegneri organizzato da APICE srl e prof. Aurelio Ghersi

col patrocinio di:

Ordine degli ingegneri della provincia di Perugia e Fondazione Promozione Acciaio

Problematiche costruttive, strutturali e funzionali di serbatoi e sili in acciaio

Parte 3: Tipologie e comportamento dei silos

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INTRODUCTION

Bins are used by a wide range of industries throughout Europe to store bulk solids in quantities ranging from a few tonnes to over one hundred thousand tonnes. Bins are also called **bunkers** and **silos**. They can be constructed of **steel** or **reinforced concrete** and may discharge by gravity flow or by mechanical means. **Steel bins** range from heavily **stiffened flat plate** structures to efficient **unstiffened shell** structures. They can be supported on **columns**, load bearing **skirts**, or they may be **hung from floors**. **Flat bottom bins** are usually supported directly on foundations.

For structural design, bins can be classified according to the **British Material Handling Board** system into the following four categories:

Class 1 Small bins holding less than 100 tonnes, are simply and robustly constructed often with substantial reserves of strength.

Class 2 Intermediate bins, between 100 and 1000 tonnes, can be designed using simple hand calculations. Care is required to ensure reliable flow and predictable wall pressures.

Class 3 Large bins, over 1000 tonnes. Specialist knowledge of bins is required to prevent problems due to uncertainties of flow, pressure and structural behaviour. Sophisticated finite element analyses of the structure may be justified.

Class 4 Eccentrically discharging bins where the eccentricity of the outlet e_o is greater than 0,25 times the silo diameter, d_c.

Main source ESDEP

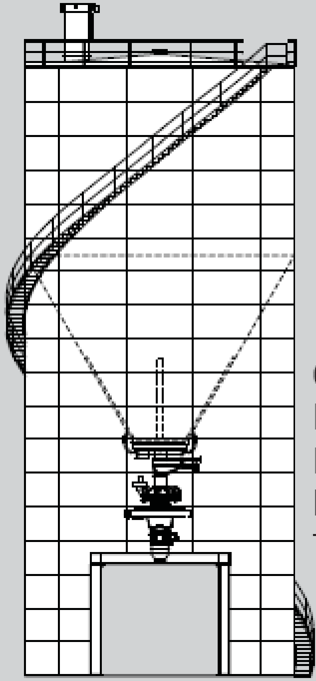
Storage Silo Selection – Dry Bulk Applications

The process of silo selection starts with a series of questions that require **answers before proceeding**. This is one of the main problems witnessed in today's dry bulk storage market. Tank and silo selection many times is based on a preferred "**construction type**" in lieu of "**stored material**" performance requirements. Silo manufacturers tend to process **customer information** relative to their standard storage products and design parameters, which leaves the client responsible for the outcome. This is an **archaic approach** which is **safe for the vendor**, but many times misses the mark in achieving a functional and efficient storage system that performs per your requirements.

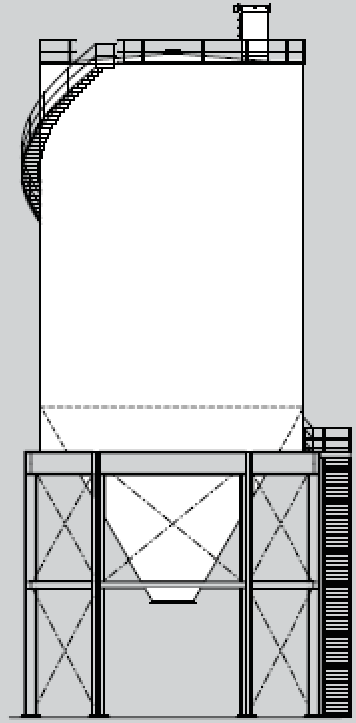
"Top 10" basic considerations for storage applications

1. How much material will be stored….(tons / cubic feet)?
2. Are there any unique characteristics of the stored material to consider?
3. What materials of construction should be used?
4. What product density should be used for volume and design calculation?
5. Is material degradation a concern?
6. Is material segregation a concern?
7. What type of material discharge pattern is preferred or required for the application? (i.e., funnel flow, mass flow, expanded flow, etc.)
8. Is a hopper flow aid device required for reliable discharge?
9. Should my material be tested by a "flow specialist"?
10. Do I need a reliable performance guarantee from the silo supplier?

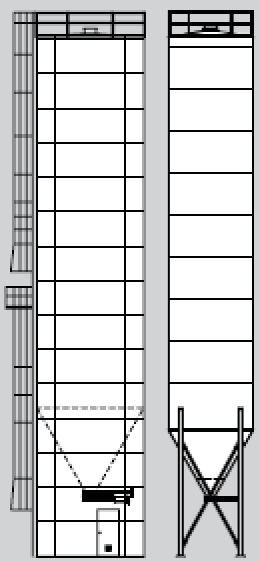
If the basics are covered in storage silo selection, years of trouble free containment and reliable discharge can be expected. In all cases, a reliable integrated storage system starts with a properly designed and configured silo. In today's industrial market, a storage specialist is advisable.



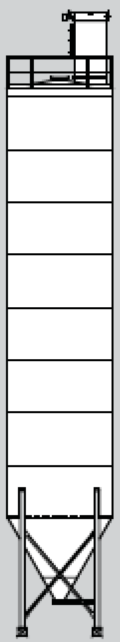
Cement Storage
Fly Ash Storage
Fluidized
Dustless Unloading
Truck & Rail Loadout



Mineral Storage
Field-Welded
6 & 8 Legs



Plastics
Gravity Blender
Skirted Bolted
Shop-Welded
Design Gravity Feed



Weighing on
Load Cells

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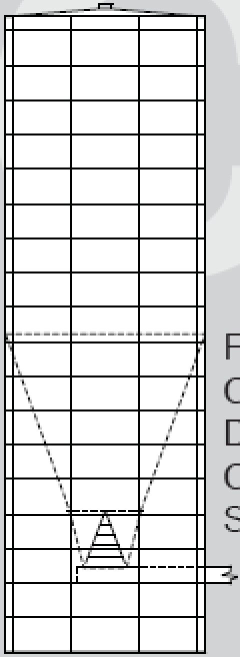
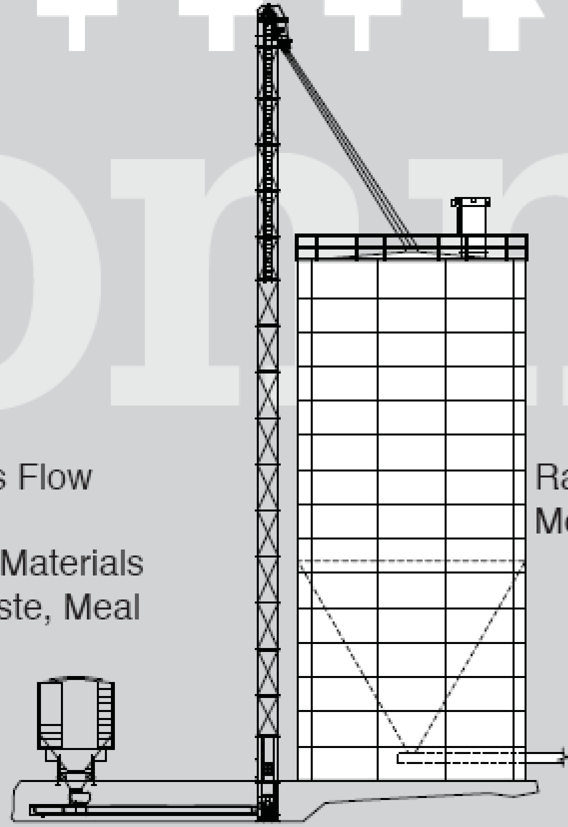
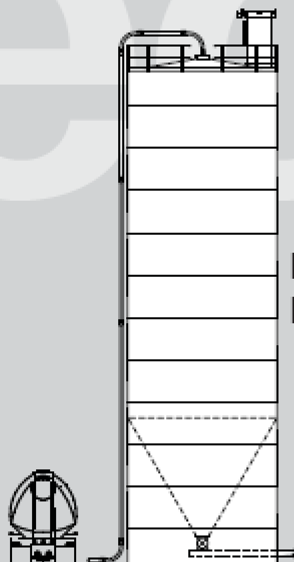


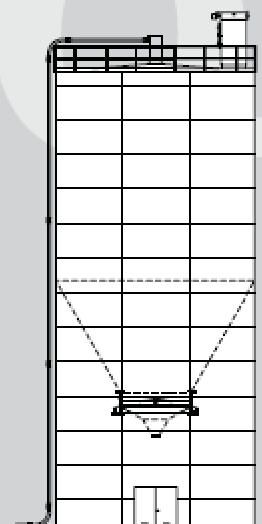
Functional Mass Flow
Chisel Bottom
Difficult to Flow Materials
Coal, Wood Waste, Meal
Storage



Rail Unload
Mechanical Fill



Pneumatic Fill
Pneumatic Discharge



Lime Storage
Pneumatic Fill
Active Discharge

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Silo categories

Shop-Weld Construction

The silo of choice for the storage of dry bulk materials up to capacities of 300 m^3. Also, the typical approach required for food grade storage, when bolted panel connections are not allowed.

Applications: Plastic resins, food products, dry chemicals, minerals, wood waste & misc. dry other

- Hopper capacities under 300 m^3
- Shop-controlled quality
- One piece tank construction
- Factory applied coating systems
- Increased freight cost to the jobsite
- Less field installation requirements

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Shop-Weld Construction

Shop-Weld Construction

Bolted Smoothwall Flat Panel (FP) Construction

Available in precision FP (flat panel) construction, the industrial "smoothwall" bolted silo remains the economical product of choice for dry bulk materials, when storage requirements exceed shop-welded tank requirements (i.e., greater than 250-300 m^3 of storage). Hopper gravity discharge is available in a variety of designs including skirted silos, drive-through skirted silos, silos on structures, tanks on load cells and tanks elevated on structural legs. Hopper capacities range from 25 m^3 up to 2.000 m^3. Flat bottom capacities range up to 55000 m^3 of storage.

Applications: Cement, fly ash, coal, limestone, lime, aggregates, minerals, chemicals, plastics, select foods, wood waste & misc. dry other

- Hopper capacities from 25 – 2500 m^3
- Shop-controlled quality
- Modular construction requires bolted field assembly
- Decreased field installation timeframe
- Factory applied powder coating systems


TANK
14/04/2002

Different types of bolted panel silos

API 12B bolted silo

Archaic / outdated design originally adapted from crude oil storage.
Chime lap (bent flange) connection leaks and is difficult to seal in the field.
Light gauge material design up to 6mm plate.
Horizontal chime creates ledge for material hang-up.
Silos are built using the same erection process used 50 years ago. This includes elevating people in the air on scaffold brackets and using a gin pole and air tugger.

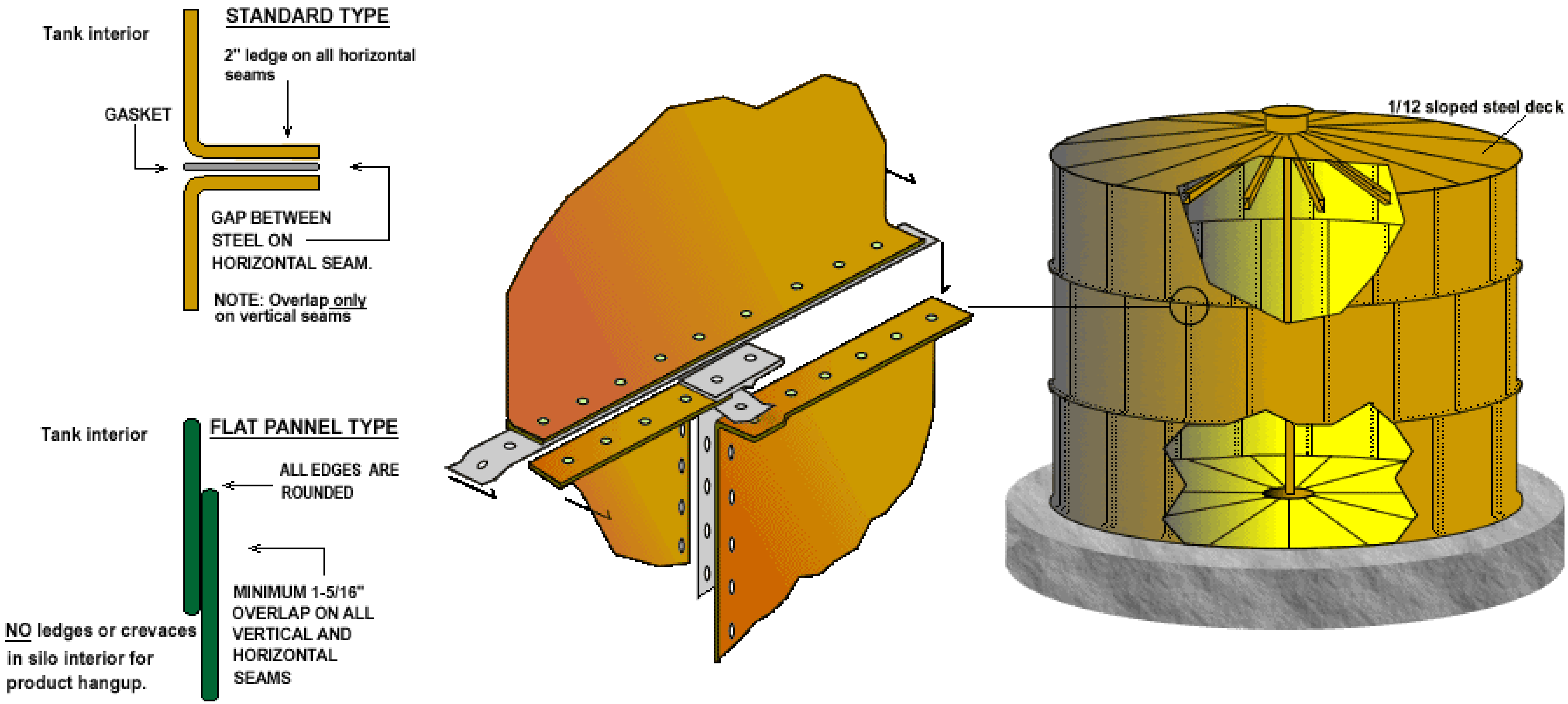
Vertical notched panel silo

Panels are vertical (ca. 2.5 x 1.5m wide) and conceived to remove the problematic (chime) flange connection on the API 12B tank.
When scaffold built, the tall & narrow panels tend to fold over in very low wind conditions. The panels have no arc rigidity, which enforces crews have to tie the scaffold boards and brackets together with “C” clamps, simulating a make-shift girder for stability. Sometimes this type of construction does not meet field safety requirements.

Smoothwall Bolted Design

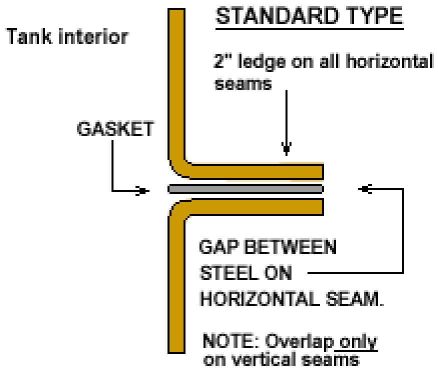
Designed for dry bulk & liquid storage applications.
Exact tolerance fabricated panels, which do not leak or develop future leaks
Heavy design up to 12mm plate.
No interior or exterior ledges for product hang-up.
Lap-joint connection allows pressure design use.
Silos are jacked from ground, which means safe tank construction.

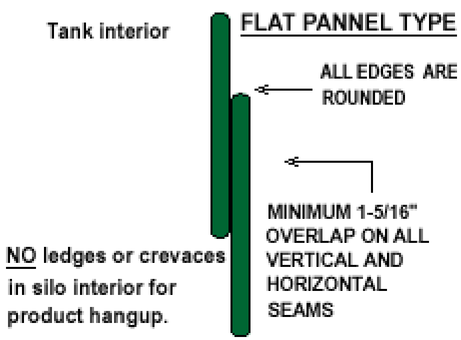
API 12B flanged bolted tank

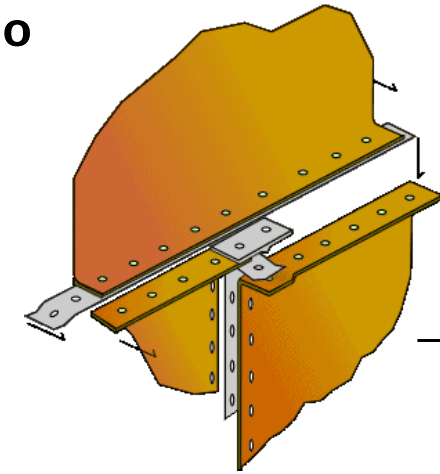


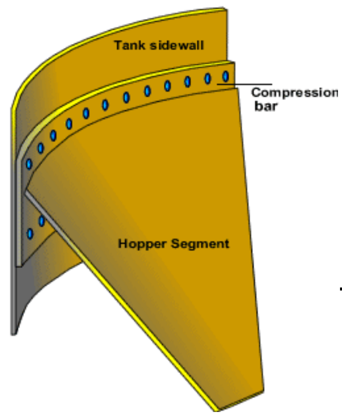
Panels are vertical (ca. 2.5 x 1.5m wide) and utilize an exterior horizontal flange connection called a chime. The API 12B flanged panel tank is a quite outdated bolted tank design that originated in the oil patch territories in the early 1900's. The big problem with this design is the exterior horizontal flange (chime) connection, which has a history of continuous leaks. Additionally, the exterior flange connection creates a ledge that holds material, moisture and debris, which removes the paint quickly. Typically, this product can be seen in the field with rusty horizontal connections from top to bottom of tank.

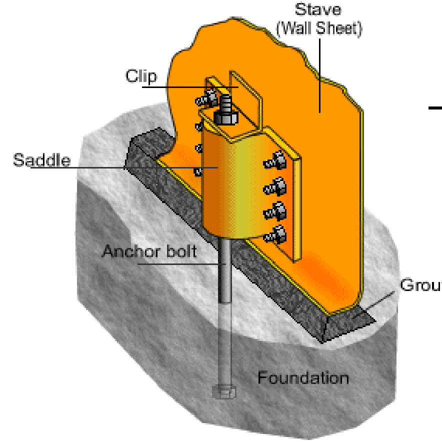
API 12B flanged bolted silo

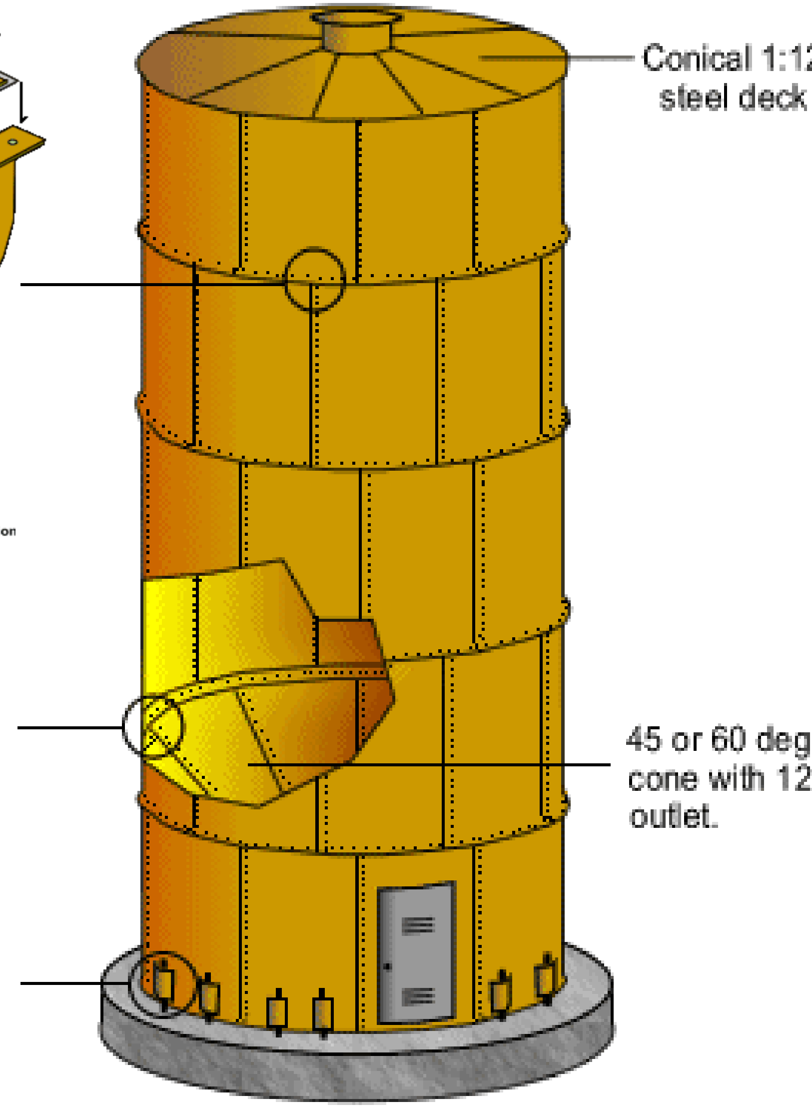




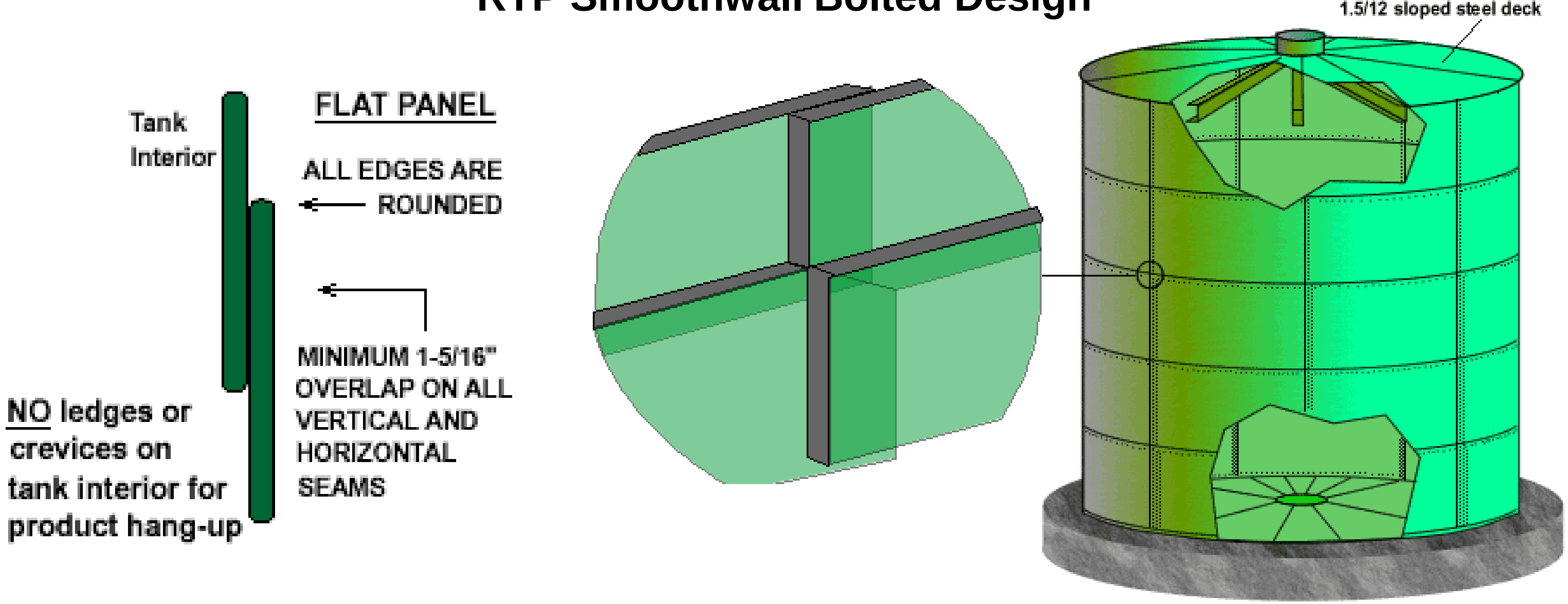






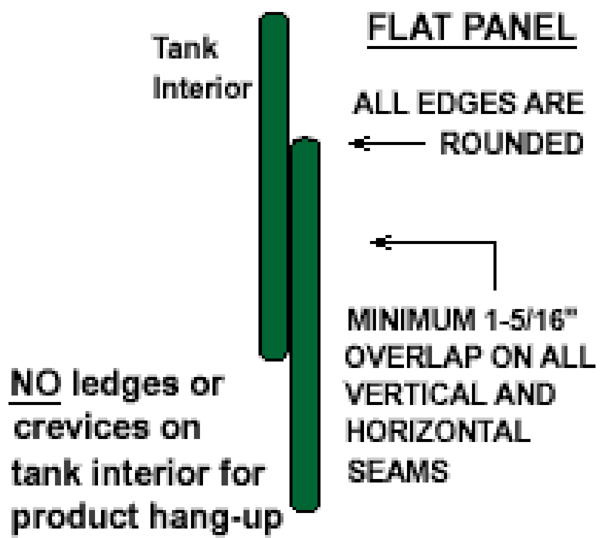


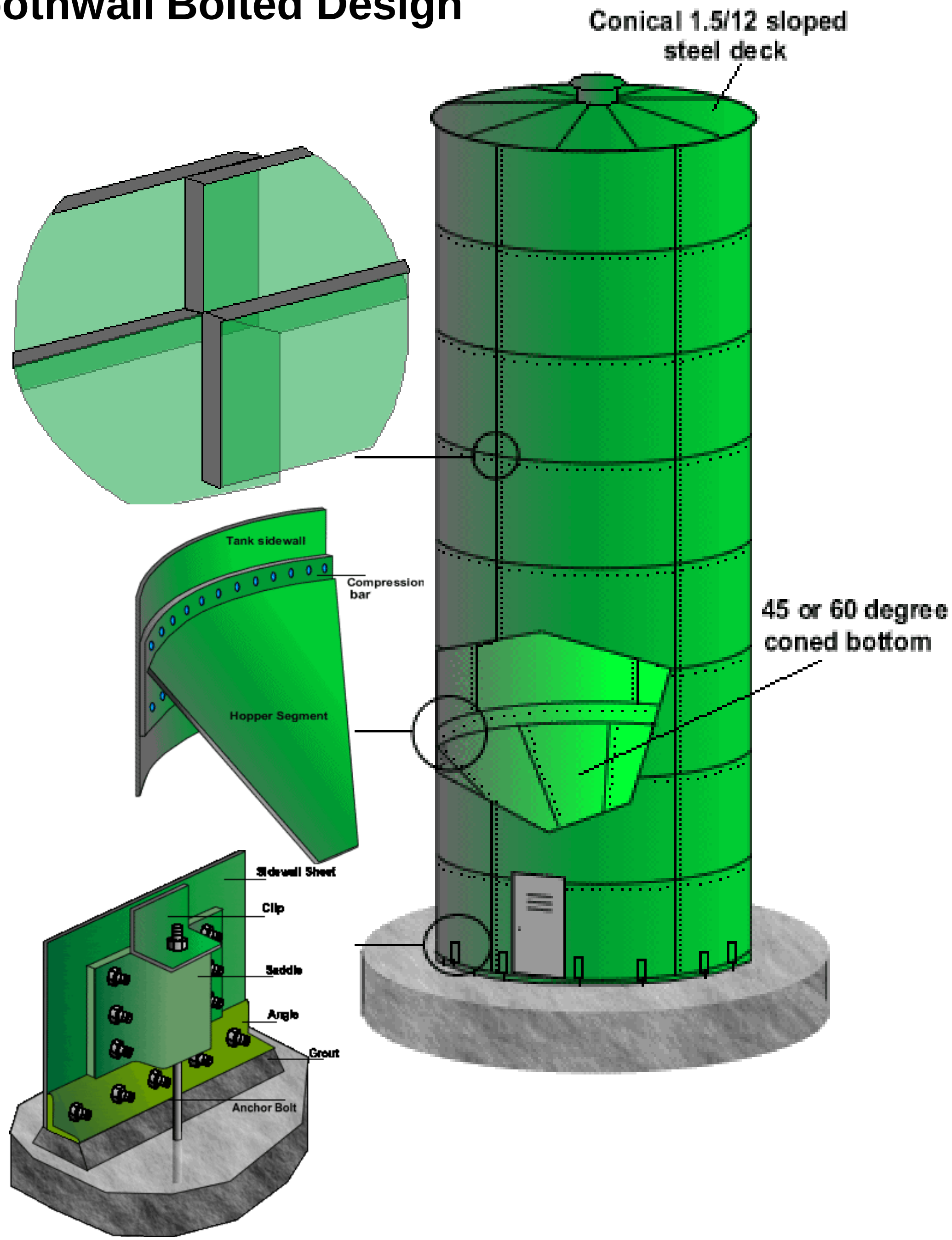
RTP Smoothwall Bolted Design

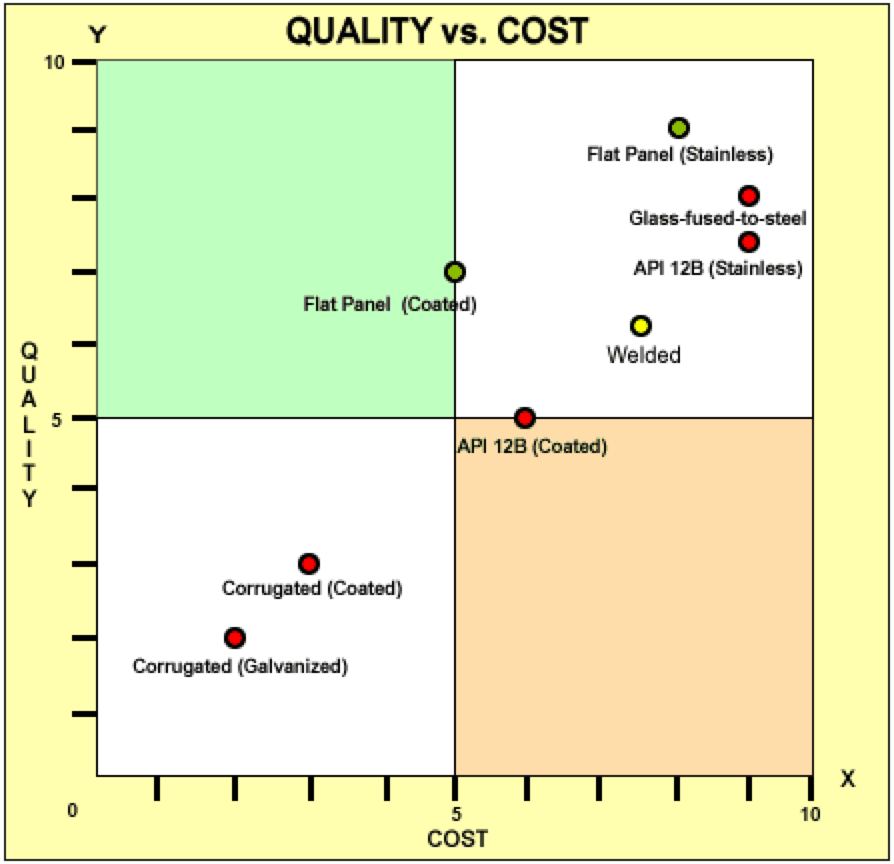


Because of design, flat panel tanks seal better. Flat Panel Tanks have only 2 exposed external edges vs. the 3 of the API 12B type bolted tank. The Flat Panel Tank has steel to steel overlap on both vertical and horizontal seams. There are no internal edges or crevices for product hangup, nor any external ledges for standing water. All parts of a flat panel tank are standardized which leads to consistency from one tank to another. Because of standardized parts on flat panel tanks, erection time can more easily be determined. With the time savings of eliminating skilled welders and eliminating field painting, the end user has realized cost savings on labor and materials because of lighter gauges on flat panel tanks. Because of standardized parts on a flat panel tank, the pricing of a flat panel tank is significantly more accurate. If tanks ever have to be expanded or relocated, it is a relatively simple proposition. Tanks can be dismantled, moved to another location and re-erected again easily and less expensively because all parts are standardized and interchangeable.

RTP Smoothwall Bolted Design







NOTE: THE VALUES DEFINING QUALITY ARE DESIGN, COATINGS OR FINISH, AND SERVICE. COSTS AND QUALITY ARE RELATIVE. ● = International Tank

Field-Weld Construction

The field-welded silo and tank remains the product of choice in select dry bulk storage applications. Typical applications include: storage requirements that require heavier shell designs than bolted smoothwall constructions offer, storage capacities in excess of 2000 m^3 when hopper bottom discharge is required, power market, heavy and abrasive bulk material applications. Quality field-weld fabrication is evidenced by following code requirements including radiograph examination, etc.

Applications: Minerals, aggregates, dry chemicals & misc. dry other

- Hopper capacities from 500 – 7000 m^3
- Shop-controlled quality – minimize large piece count
- Modular construction requires field welded assembly
- Increased field installation timeframe
- Field applied coating systems

Field-Weld Construction


2007.05.15


2007.06.06

2007.07.09

Drive-through Skirt silos are the most economical choice for truck load-out applications. Capacities range up to 4.000 m^3. Bolted FP silo construction is the new industry standard for industrial process applications.

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Hybrid Silo Construction

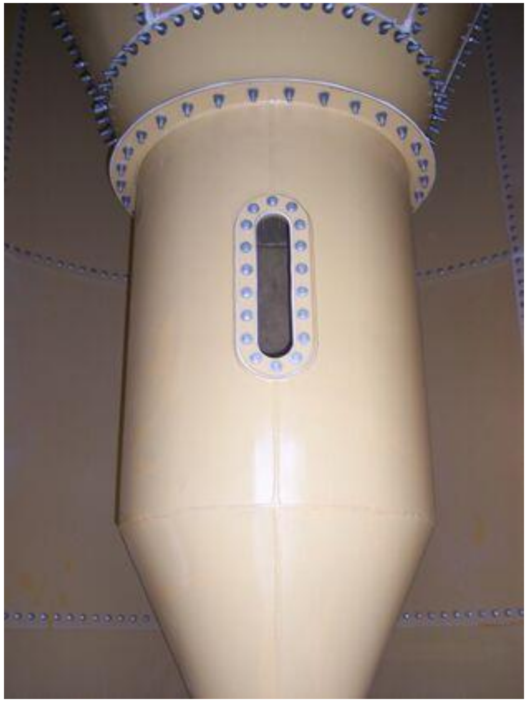
Combines the best qualities of **bolted FP**, **field-weld** and **concrete construction** together in one product. The hybrid silo has become a preferred storage tank design when storage volume requirements exceed bolted FP designs. Hybrid construction can utilize a bolted FP sidewall with a field-weld deck or hopper. Other hybrid designs utilize concrete floors elevated on structural steel and field-weld designs with bolted tank components. The hybrid silo is uniquely tailored for the application. Many large volume applications designed for functional mass flow discharge utilize a hybrid tank design.

Applications: Cement, fly ash, coal, limestone, lime, aggregates, minerals, chemicals & misc. dry other

- Hopper capacities from 500 – 4000 m^3
- Shop-controlled quality
- Modular construction requires field assembly
- Decreased field installation timeframe
- Factory applied powder coating systems

Stainless Steel Storage Silos – Tank construction is available in materials with various polished surface profiles. SS construction should be evaluated when product purity, flow inducement and/or chemical attack issues exists with the stored material. Stainless construction is the high price storage approach.

Aluminum Storage Silos – Quality containment (fabrication satisfies ASME Section VIII requirements) required in select food, chemical and petrochem applications. A variety of alloy designations are available with 5052 H32 material being the most common and versatile in dry bulk storage applications. Shop welded aluminum tanks are available up to 300 m^3 capacity in one-piece construction. Quality welded aluminum silos are an economical alternative to coated carbon steel tanks.



Gravity Blend Silos – Blend silos are utilized in the plastics market by producers, compounders and processors to reduce variables in the process stream. Blend tanks smooth out plastic resin variables associated with melt index, color variation and particle size.

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Silos supporting structures





General design considerations

In general, dry bulk applications that require a storage volume of **less than 300 m^3** will utilize a **shop-welded** or **smoothwall bolted** silo. Both products are used interchangeably in the industry. Shop-weld and bolted construction maintain advantages as listed above. Under review, the total installed **costs** (material + freight + field installation) are **comparable** between both products.

Bolted FP (flat panel), field-weld, concrete and **hybrid** silos are typically utilized in **large volume** storage applications. All four designs are routinely specified in the **power industry**. In the industrial market, **bolted FP and hybrid** construction are the **most cost efficient** silo designs. Field-weld and concrete construction require **extended field installation timeframes**, which equates to **higher installation cost**.

Relative to steel and alloy "**materials of construction**" selection, bolted, shop-weld and field-weld silos are available in **coated carbon steel**, **stainless steel** and **aluminum** construction. All tanks/silos can be customized for the application and are available with full **skirt** support, **leg** supports, **structure** supports or **lug** supports. Typical silo **accessories** include a **filter flange** connection for dust control, **level control nozzles**, **manway access** into silo deck and hopper areas, maintenance access **platforms**, caged **ladders**, spiral **stairways**, perimeter **guardrails**, pressure vacuum **relief devices** and custom requirements for system integration.

Some of stored products…

Dry Foods
Flour, Pearl Starch, Starch, Sugar, Rice, Salt, Soybean Meal, Cornmeal, Bonemeal, Meat Meal, Dried Distillers Grain, Beet Pellets, Buttermilk Solids, Corn Gluten, Dextrose, Farina, Feather Meal,
Fish - Whole/Meal, Flour Premix, Milk Solids, Mids/Middlings, Oyster Meal, Blood, Peanuts, Malt

Grain & Seed
Corn, Wheat, Milo, Soybeans, Grain Dust, Guar Beans, Rice Hulls, Coffee Beans, Corn Hull, Cotton Seed, Cocoa Beans, Mustard Seed, Misc. Grains, Barley

Plastics
ABS Pellets, Nylon Pellets, Polycarbonate Pellets, Polyethylene Pellets, Polyester Pellets, Polypropylene Pellets, Polystyrene Pellets, PVA Pellets, Virgin PVC Pellets, Other Plastic Pellets, PVC Compound, PET, Rim Regrind, Other Regrind, Other Powders, Linear Low Polyethylene, PVC Powder, PVC Flexible Pellets, Starch, Thermo Plastic Granules

Dry Chemicals
Carbon Black, Sodium Carbonate (Soda), Soda Ash, Fly Ash, Bottom Ash, Miscellaneous Ash, Cement, Sodium Hydroxide, Urea Prills, Sodium Nitrate, Petroleum Coke, Coal Coke, Magnesium Oxide, Rubber, Soap, Detergent, Glass, Gullet, Stucco, Miscellaneous Acid, Potassium Carbonate K2C03, Potassium Nitrate KN03, Aluminum Trihydroxide

Wood Products
Wood Chips, Sawdust, Hogged Fuel Bark, Wood Flour, Charcoal, Sanders Dust, Other Wood Fuel, Dry Wood Waste, Starch

Dry - Other
Kiln/Furnace/Smelter Dust, Crushed Rock Dust, Roofing Granules, Dewatered Sludge, Product Testing,
Geometry Recommendations/Consulting, Blend Tanks, Enclosure-No Product

Minerals
Other Lime, Pebbled Lime, Quick Lime, Hydrated Lime, Diatomaceous Earth, Barite, Perlite, Bentonite, Calcium Carbonate, Alumina, Gypsum, Talc, Sand, Coal, Kaolin Clay, Other Clay, Phosphates, Mineral Salt, Vermiculite, Zeolite, Ore, Feldspar

Blenders - Plastic
ABS Pellets, Nylon Pellets, Polycarbonate Pellets, Polyethylene, Polyester Pellets, Polypropylene, Polystyrene, PVA Pellets, Virgin PVC Pellets, Other Plastic Pellets, PVC Compound, P.E.T., Regrind, Film, Regrind, Other, Powders, Other, Polyethylene Linear Low, PVC Powder, PVC Flexible Pellets, San Resin, K-Resin

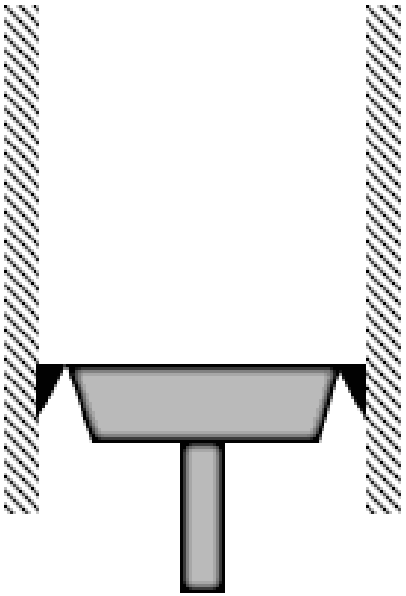
Properties of stored products

Bulk solids
Powder, solids, dry matter, granular material, bulk material...

Bulk solids do not have an unambiguous name; it is not an unambiguous material. Bulk solids do neither behave as a solid, nor a liquid, nor a gas.

A definition of this matter could be: a number of particles that in principal can move freely, but that definitely show interaction and are also influenced by gases and/or liquids that are present between these particles.

List of equipment that can be used to determine experimentally the properties of bulk solids



Jenike Shear Cell

Determination of characteristic bulk properties such as internal friction and flow function.

** determination of flow pattern;*
** calculation mass flow angle of hopper;*
** avoiding arching and bridging;*
** calculation of stress reduction in silos;*
** comparison of bulk properties;*
** consideration of storage conditions;*

Shear Cell and Time Consolidation Bench

Determination of the influence of time on the mechanical properties.

** bridging properties after long periods of storage.*

Shear Cell and Wall Materials

Determination of the wall friction.

** obtaining mass flow, through coating or lining;*
** avoiding build-ups caused by adhesion;*
** testing of wear-resistant materials.*

Fluidisation Column
Determination of aeration properties.
** application of aeration-pads, air injection, etc.*

Permeability Tester
Determination of bulk solid permeability.
** deaeration rate in a silo;*
** application of air slides, etc.*

Indicizer Test
Comparison of bridging properties
** applicable to product comparison*

Moisture Content Tester
Determination of the moisture percentage.

Data Logger
Accurate digital registration of process signals and loads on structures.
** registration of nature, extent, regularity and cause of malfunctions;*
** optimisation of process settings;*

Solid Density Tester
Determination of the solid density of bulk material.
** used for pneumatic transport.*

Dynamic Wall Friction Tester
Determination of the wall friction at higher speed and long periods of time.
* *wear of wall material, lining, coating;*
* *start-up-effect.*

Tap Density Tester
Determination of the settling rate.
* *classification of products.*

Chute Angle Tester
Determination of flow angle, possible for different wall materials.
* *required flow angle for chutes, etc.*

Angle of Repose Tester
Determination of the angle of repose.
* *belt conveyors;*
* *flat bottom bins;*

Model Silos
round and rectangular model silos with adjustable hopper angles.
* *small quantity applications.*
* *determination of flow pattern.*

Structural Material of the Bin Wall

Most bins are constructed from **steel** or **reinforced concrete**. The economic choice depends upon the material costs as well as the costs of fabrication and erection. Other factors such as available space also influence the selection. The **main advantages** of **steel** bins over cost in-situ **concrete** bins are that small and medium sized steel bins and bunkers can be **prefabricated** and, therefore, their **erection time** is considerably **shorter**; in addition, bolted bins are relatively easy to **disassemble**, move, and **rebuild** in another location;

The main **disadvantages** of steel bins are the necessity of **maintenance** to prevent **corrosion**, the steel walls may require lining to prevent excessive **wear**, and the steel walls are prone to **condensation** which may damage stored products such as grain and sugar, etc. which are **moisture sensitive**.

The selection of structural material for the wall may depend upon the bin geometry. A bin wall is subject to both **vertical** and **horizontal** forces. The **vertical** forces are due to **friction** between the wall and stored materials, while the **horizontal** forces are due to **lateral thrust** from the stored materials. **Reinforced concrete** bins carry vertical compressive forces with ease and so tend to fail in **tension** due to the high lateral thrusts. **Steel** bins, circular in plan, usually carry the lateral forces by hoop tension. They are more prone to failure by **buckling** under excessive vertical forces.

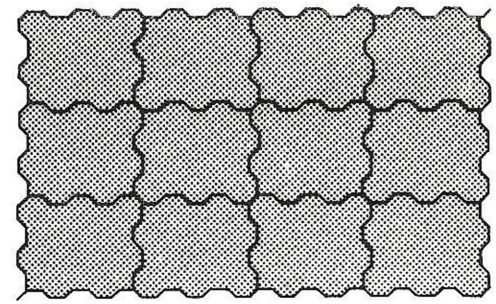
Main source: ESDEP

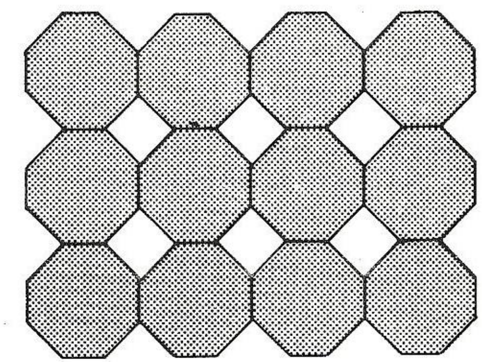
BIN CLASSIFICATION

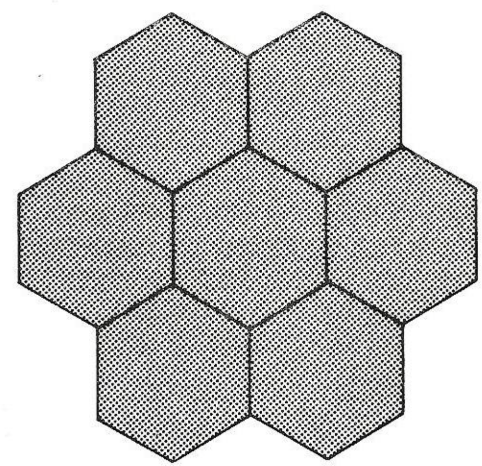
As said above, for design purposes, bins are classified by their size, geometry, the type of flow during discharge of the contents, and the structural material of the wall. The bin size and geometry depend on the functional requirements such as the storage volume and the method and rate of discharge, the properties of the stored material, available space and economic considerations. Bins usually consist of a **vertical sided section** with a **flat bottom** or a bottom with inclined sides, known as the **hopper**. They are usually circular, square or rectangular in cross-section and may be arranged singly or in groups.

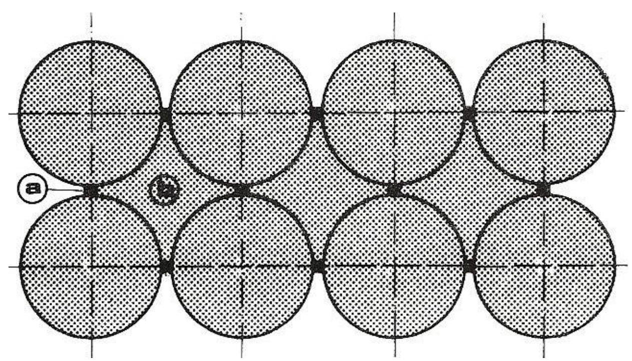
Circular bins are more efficient structures than square or **rectangular** bins, leading to lower material costs. For the same height, a square bin provides 27% more storage than a circular bin whose diameter equals the length of the side of the square bin. Flat-bottom bins require less height for a given volume of stored material.

The bin size is determined by feeding and discharge rates and the maximum quantity of material to be stored. **High discharge rates** require **deep hoppers** with steep walls. **Flat bottomed** bins usually have **low discharge rates** and are used when the storage time is long, the discharge is infrequent and the storage volume is high.

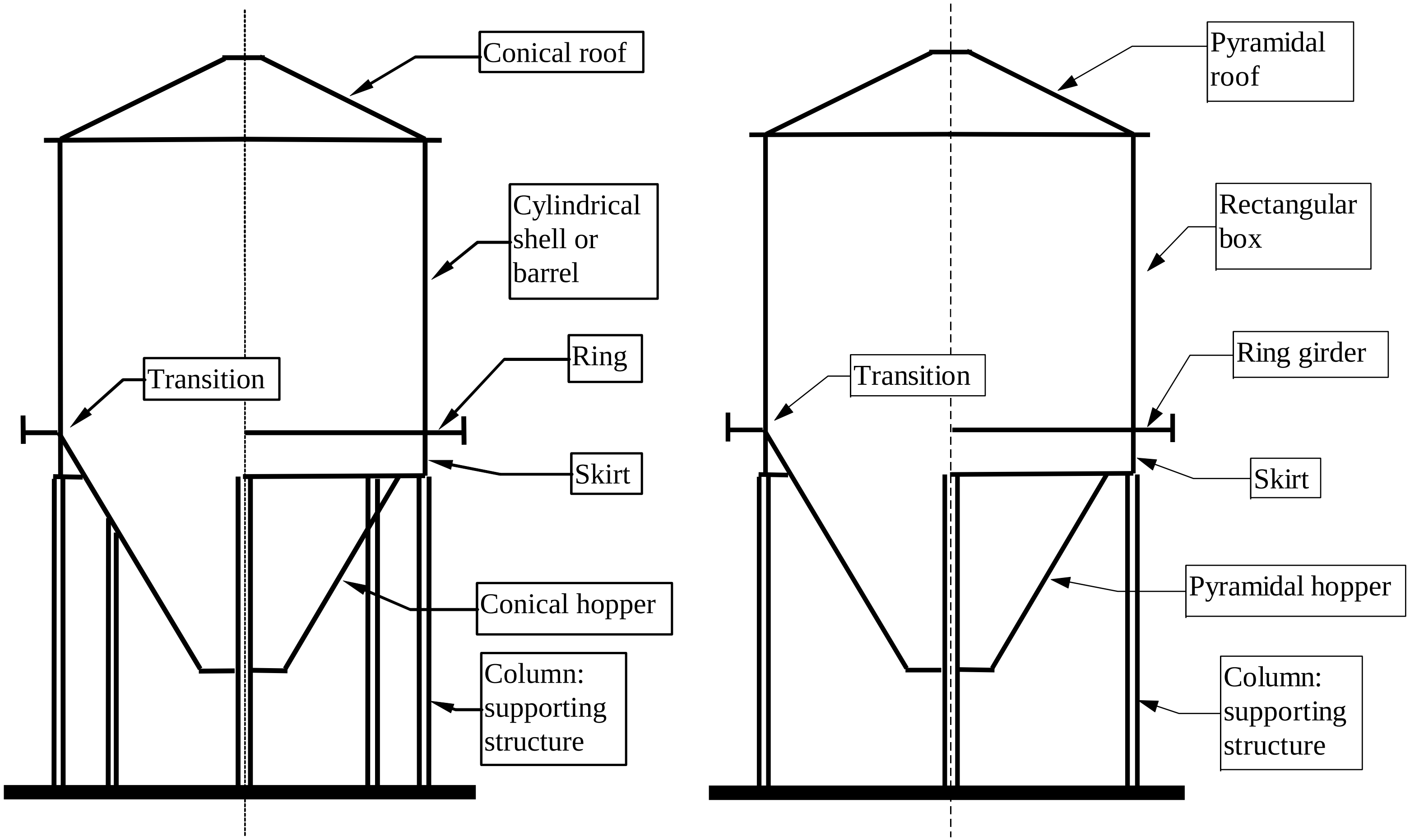








Main source: ESDEP



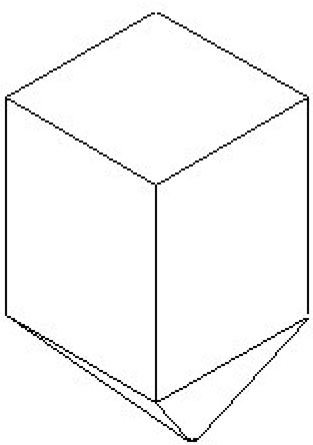
a) Circular planform silo

b) Rectangular planform silo

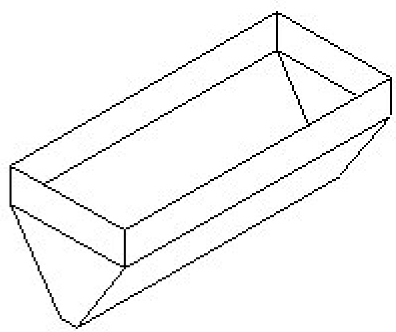
EC3 Terminology used in steel silo structures

The **ratio of bin height to diameter** influences the loads from the stored material and hence the structural design. Eurocode 1 classifies bins as either **squat** or **slender**. Squat bins are defined as those where the height does not exceed 1,5 times the diameter or smallest side length. Slender bins have a height to diameter ratio greater than 1,5.

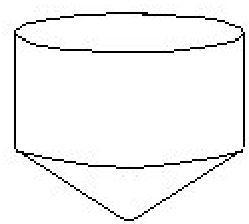
Hoppers are usually **conical**, **pyramidal** or **wedge shaped**. Pyramidal hoppers have the advantage of being simple to manufacture although they may lead to flow problems due to the building up of stored material in the corners. **Outlets** may be either **concentric** or **eccentric** to the centre of the bin. Eccentric outlets should be avoided because the pressure distribution is difficult to predict and there may be problems due to segregation of the stored material. The **angle of inclination** of the **hopper** sides is selected to ensure continuous discharge with the required **flow pattern.**



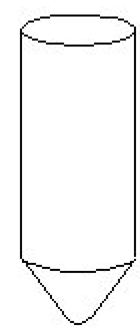
(a) Square with pyramidal hopper



(b) Trough bunker



(c) Shallow funnel flow cylindrical bin with conical hopper



(d) Deep mass flow bin

Main source: ESDEP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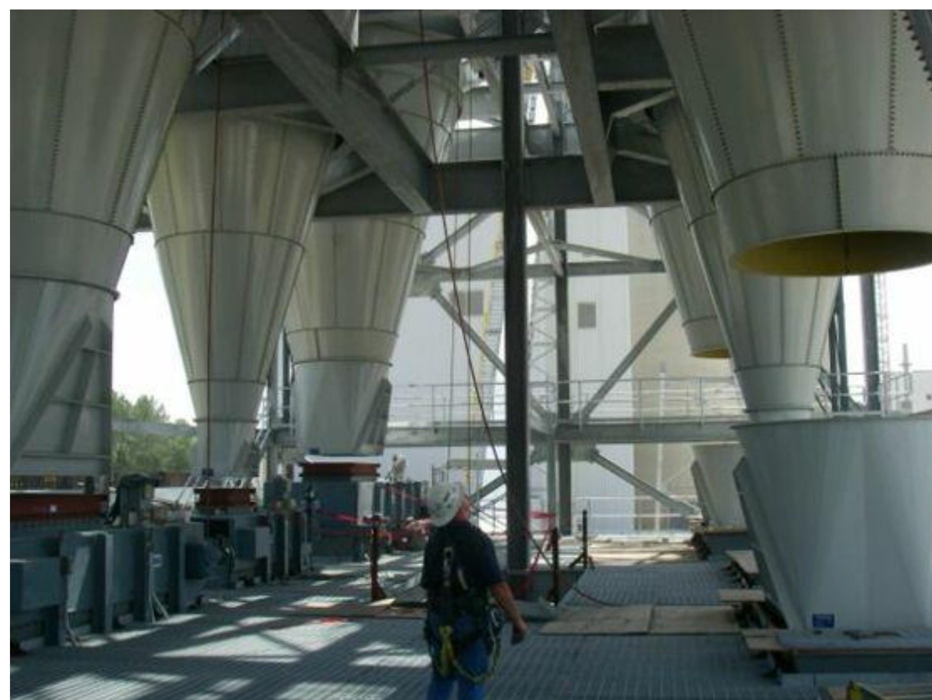
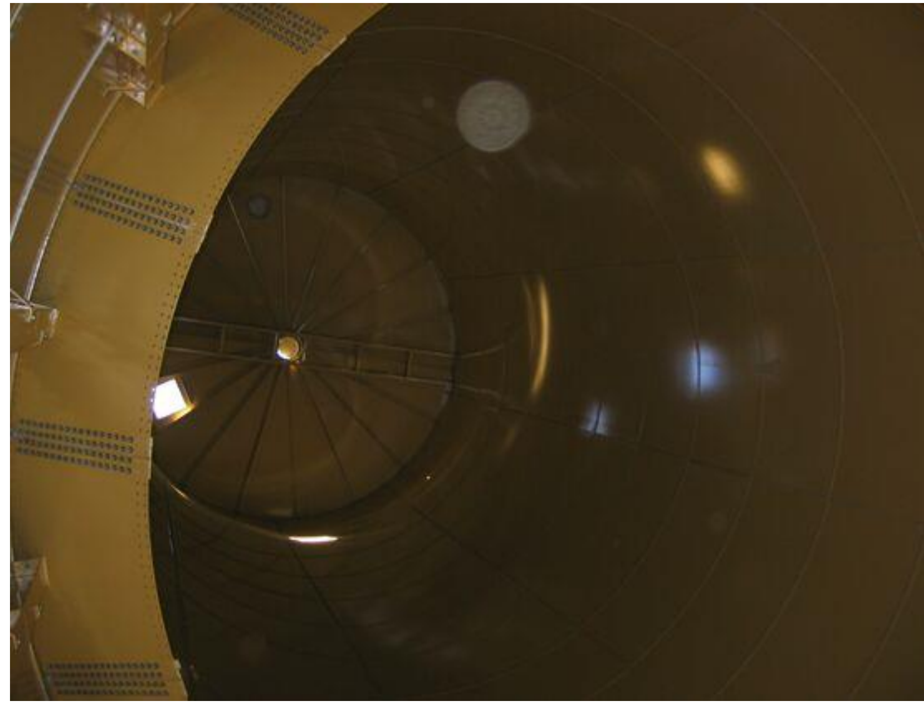
ARROW



MERRICK



Yale

INTRODUCTION TO SILO DESIGN

The design of silos in order to obtain **reliable flow** is possible on the basis of measured material properties and calculation methods. Because badly designed silos can yield **operational problems** and a decrease of the product quality, the geometry of silos should be determined always on the basis of the material properties. The expenses for testing and silo design are small compared to the costs of loss of production, quality problems and retrofits. To prevent flow problems in a silo, proper silo design is necessary.

The most obvious (and the most economical) way of storing bulk solids is in a silo with **gravity flow**. In this case the silo consists of a **cylindrical** or **rectangular** part with a **hopper**. The hopper lets the product converge to the opening. This simple fact is the direct cause of most **problems**, such as: **unsteady flow, segregation, remaining product, ageing or decay of the product, shaking or quaking of the silo, flooding, or flow does not occur at all.** For a lot of these problems equipment is available, or a solution can be found through "trial and error".

Of course it is better to prevent these problems. This is possible when design is based on the measured properties of the product. **The flow properties of the product must determine the geometry that is used.**

In the design of a silo the major issues are: ***flow***, ***bridging*** and ***feeder***.

Main source: ESDEP

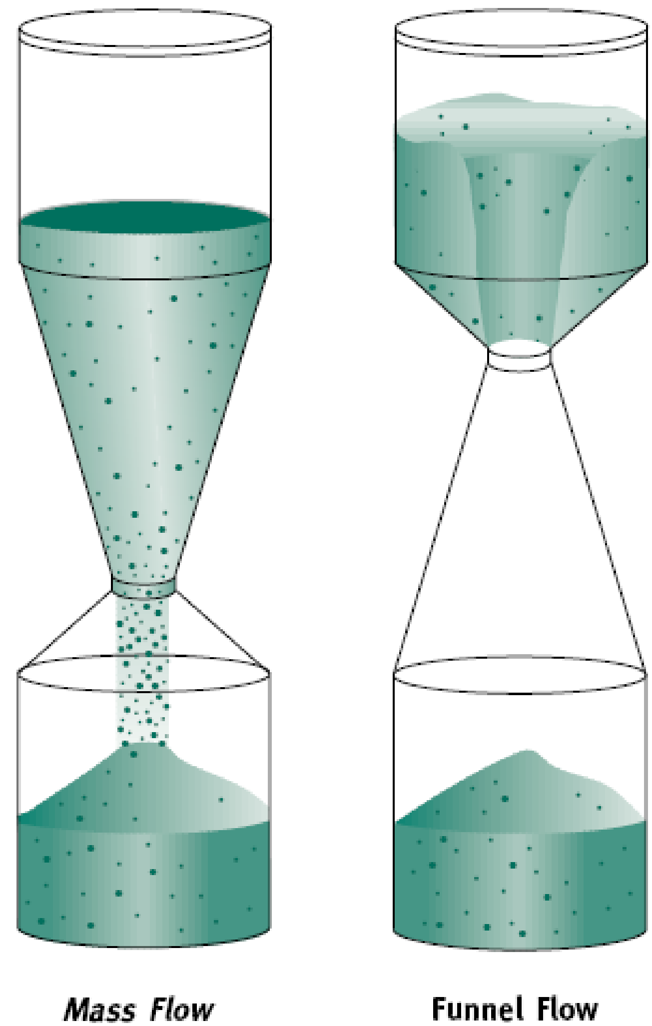
FLOW

Problems with flow are connected to the occurring flow pattern. In a silo two important flow types can be distinguished:

*** mass flow;**

*** funnel flow (ratholing, or core flow).**

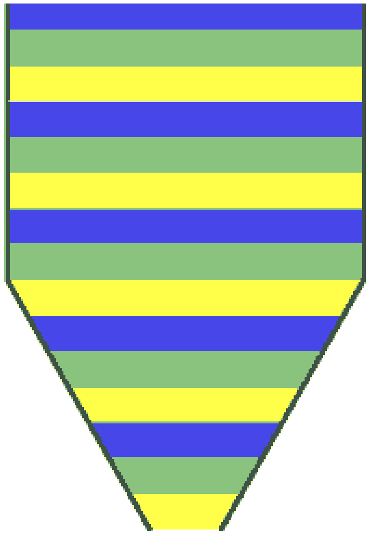
In case of mass flow, the whole contents of the silo are in motion at discharge. Mass flow is only possible, if the hopper walls are sufficiently steep and/or smooth, and the bulk solid is discharged across the whole outlet opening. If a hopper wall is too flat or too rough, funnel flow will appear. In case of funnel flow, only that bulk solid is in motion first, which is placed in the area more or less above the outlet. The bulk solid adjacent to the hopper walls remains at rest and is called „dead" or „stagnant" zone. This bulk solid can be discharged only when the silo is emptied completely. The dead zones can reach the surface of the bulk solid filling so that funnel flow becomes obviously when observing the surface. It is possible as well that the dead zones are located only in the lower part of the silo so that funnel flow cannot be recognised by observing the surface of the silo filling.



Mass flow
With mass flow the whole contents of the silo is moving, as soon as product is distracted from the silo. This type of flow is characterised by:

* *first in - first out;*
* *little segregation;*
* *steady flow and a well controllable discharge-capacity;*
* *no risk of ageing, decay, or contamination;*
* *possibility of 'following' product batches with a specific composition.*

Disadvantage of mass flow can be that in certain cases silo **quaking** can occur. When dealing with abrasive products, the silo wall will **wear** quicker. In general this will not be problem, because of the low flow velocities in a silo.



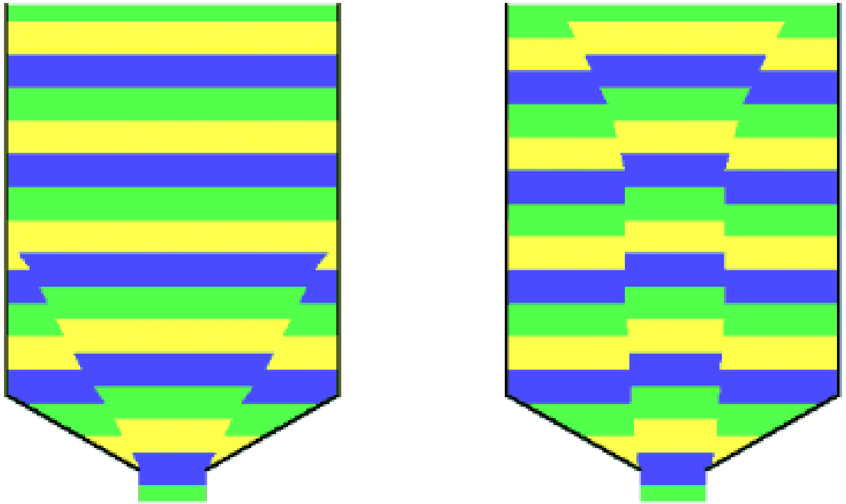
Funnel flow

In case of funnel flow the product flows **through the core**. Owing to this areas exist where the product is at rest (**stagnant zones**).

This can result in the following problems:

* *When the silo is filled again before it is completely empty, ageing and decay of the product will occur.*
* *If the silo is used for several products, contamination will occur.*
* *In some case the stagnant zones grow, so that at a certain moment the product only flows from a channel (rat hole) above the opening. Then the risk is great, that flow will stop altogether.*
* *The collapse of stagnant zones can lead to uncontrollable flow of product (flooding).*

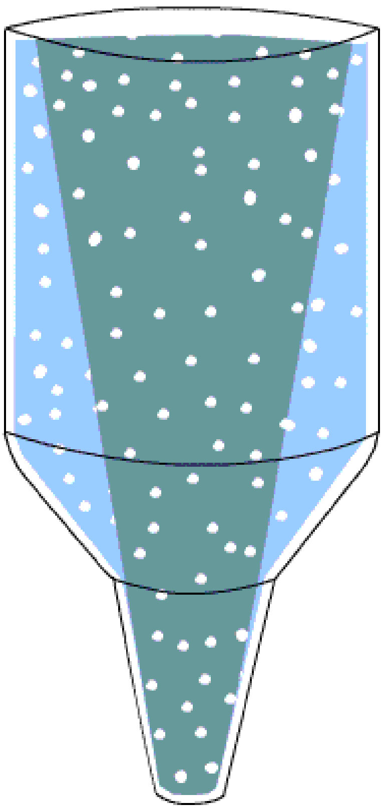
Stagnant product remains in the silo. For these reasons funnel flow is only applicable for coarse, free flowing products, where ageing or decay is not important.



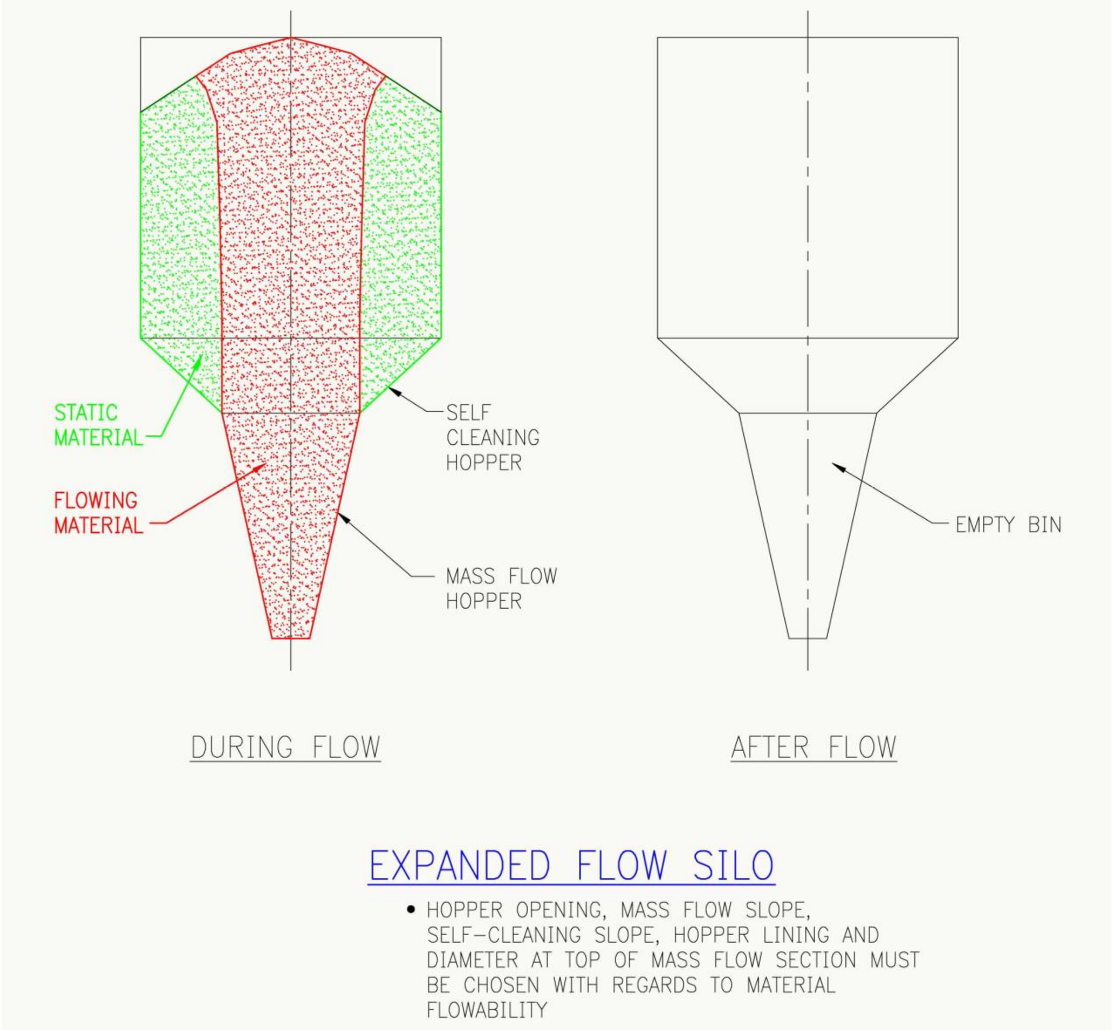
Expanded flow

Expanded flow silos offer the same benefits as the mass flow pattern, but for less cost. These are good for materials that don't need to be stored very long. They feature a 45-60 degree angle tapering into a 68-72 degree cone angle.

These silos have a similar effect as the mass flow except they may require that dead material captured within the silo be fully emptied periodically.

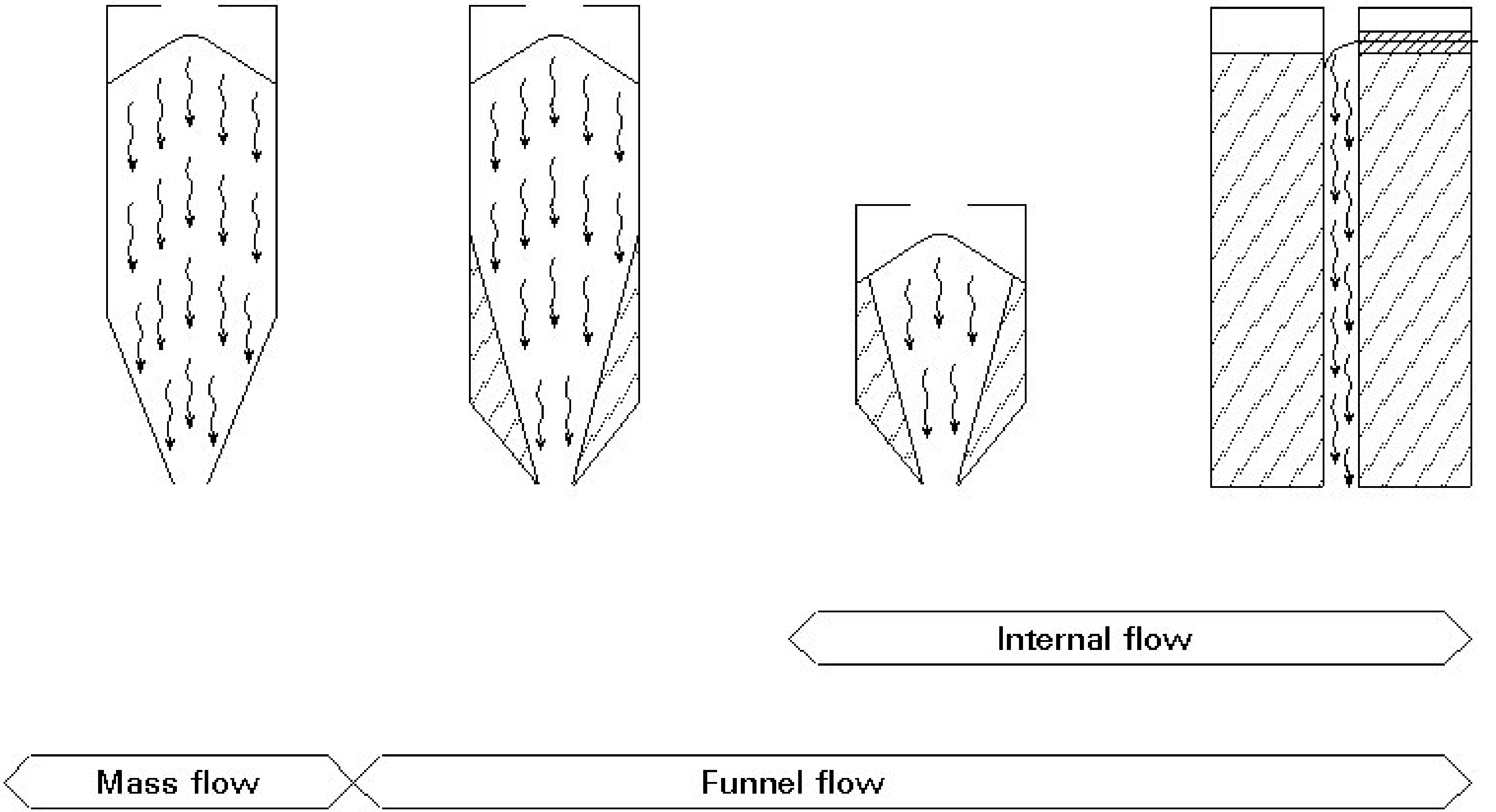


Mariettasilos.com



Flow patterns allowed for in EC1

Two types of flow are described in Eurocode 1 and shown in Figure. They are **mass flow** and **funnel flow**. Discharge pressure is influenced by the flow pattern and so the flow assessment must be made before the calculation of loads from the stored material. In mass flow bins, all the contents of the bin flow as a single mass and flow is on a first-in first-out basis. The stored material in funnel flow bins flows down a central core of stationary stored material and flow is on a last-in, first-out basis.



Desired flow pattern

It may be clear, that in by far the most cases **mass flow is desired**. Design of the silo must be such, that this type of flow is guaranteed for the product handled.

The flow pattern in a silo depends on:

* *the slope angle of the hopper;*
* *the friction between product and wall;*
* *the shape of the hopper;*
* *the internal friction of the product.*

In general can be stated that **mass flow** is sooner achieved by a **steeper and smoother hopper**. The finish of walls and corners must be smooth. Furthermore a hopper with a **slot shaped opening** is better than a rectangular or round hopper.

Mass flow design

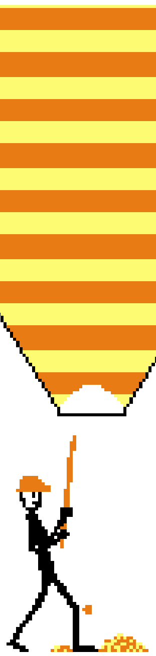
The procedure for the design of a mass flow hopper is as follows:

1) *Measure of the internal friction of the product.*
2) *Measure of the wall friction of the product on the proposed wall material.*
3) *Determination, on the basis of these data, of the appropriate hopper shape, and calculation of the mass flow angle.*
4) *When in step 3) no practical solution is found, a coating, lining or other wall material with a lower wall friction might be an option.*
5) *If this is not feasible, vibration of aeration can be a solution.*
6) *If this does not work, then application of a hopper must be abandoned.*

Flow Problems

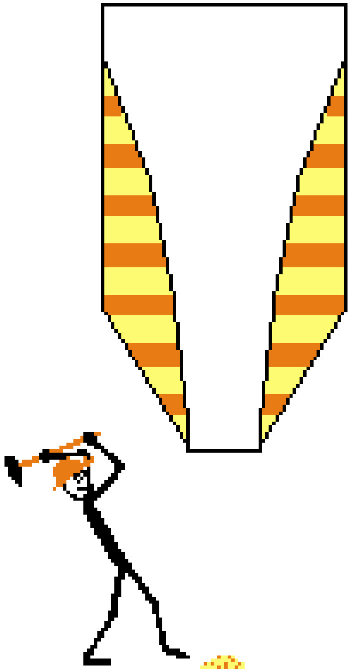
Typical problems which occur at the storage of bulk solids are:

Arching: If a stable arch is formed above the outlet so that the flow of the bulk solid is stopped, then this situation is called arching (figure 3a). In case of fine grained, cohesive bulk solid, the reason of arching is the strength (unconfined yield strength) of the bulk solid which is caused by the adhesion forces acting between the particles. In case of coarse grained bulk solid, arching is caused by blocking of single particles. Arching can be prevented by sufficiently large outlets.



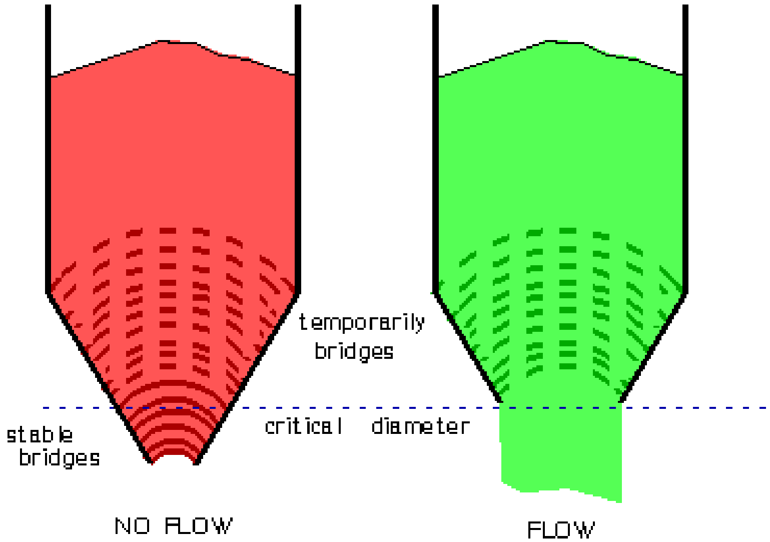
Ratholing occurs in case of funnel flow if only the bulk solid above the outlet is flowing out, and the remaining bulk solid - the dead zones - keeps on its place and forms the rathole. The reason for this is the strength (unconfined yield strength) of the bulk solid. If the bulk solid consolidates increasingly with increasing period of storage at rest, the risk of ratholing increases. If a funnel flow silo is not emptied completely in sufficiently small regular time intervals, the period of storage at rest can become very large thus causing a strong time consolidation.

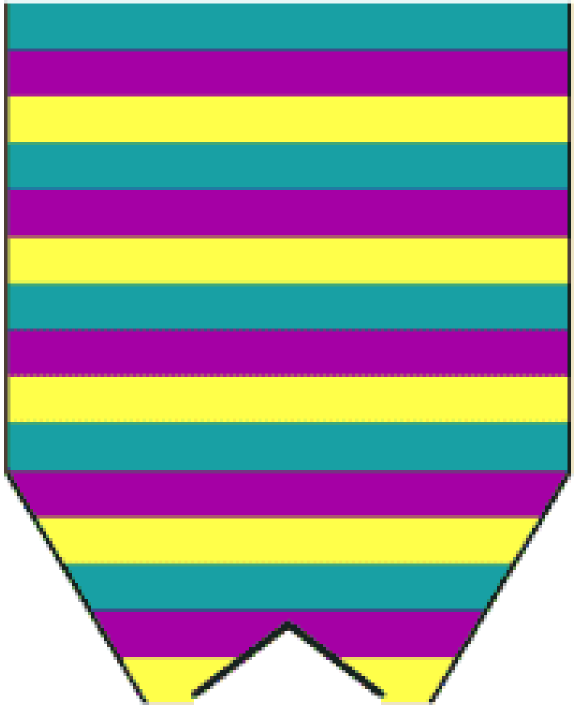
Wide permanence time distribution: If dead zones are formed (funnel flow), the bulk solid in this zones is discharged only at the complete emptying of the silo, whereas bulk solid, which is filled in later, but located closer to the axis of the silo, is discharged earlier. Because of that, a wide distribution of permanence time appears which is disadvantageous in some cases (e.g. in case of storage of food or other products changing their properties with time).



D. Schulze

Bridging: Bridging is one of the most apparent and troublesome problems with silos. It can occur because product particles jam over the opening. The opening must be approx. 7 times the size of the biggest particle to avoid this kind of bridging.
But a lot of bridging problems occur with powders. Generally it is the **cohesion**, the sticking of particles, that makes the product hang up. Dependent on the circumstances (for example storage time) a stable bridge of a powder can reach span of 3 metres! When a product is withdrawn from a silo, it must converge in the hopper. This causes stress arches in the product, supported by the hopper wall. Flow in a silo is the continuous yield (collapse) of these arches (temporary bridges). Bridging occurs when an arch does not yield.





Design for bridging

At this part of the silo design the minimum diameter of the opening is determined. The procedure is as follows:

1. When different products or conditions are concerned, first the most critical product or condition is determined. This is done with a qualitative tester, with which bridging behaviour can be compared.
2. The wall friction and internal friction are measured, and the occurring silo stresses are calculated.
3. The bridging properties, i.e. the strength of the product, is measured with the Jenike shear cell, under the applicable conditions, and for different stress levels.
4. If applicable the time consolidation is measured, for the period that the product can be at rest in the silo.
5. The critical diameter, the diameter where stable bridges can be formed, is calculated.
6. If a greater critical diameter is found than an opening that can be used in practice, a solution must be found in the form of bridge breakers, vibrating bottoms, grate bottoms, aeration, etc.

Step 6

Application of solutions that can avoid or break bridges, can be selected based on data available from the design procedure and if necessary from additional tests. For example:

> ** When applying a bridge breaker it is important to place it at the position where bridging will occur. From the design this diameter is known.*
> ** Recirculation of the product will cancel time consolidation. For a given opening the maximum period of storage can be determined.*
> ** If an aerated bottom is considered, the influence of aeration on the flow properties can be investigated.*

With the design method and supporting tests, one can find an optimum solution for each situation.

Irregular flow occurs if arches (bridges) and ratholes are formed and collapse alternately. Thereby fine grained bulk solids can become fluidized when falling downwards to the outlet opening, so that they flow out of the silo like a fluid. This behaviour is called **flooding**. Flooding can cause a lot of dust, a continuous discharge becomes impossible.

If a product is "**free flowing**" problems with bridging will not occur. An example is sand, provided that the particles are reasonably round and approximately the same size, and that the sand is not moist.
From this it becomes clear that the name of a product is not enough to know what the flow properties will be. Also the conditions play an important role.
Most products are cohesive, particles stick together. This makes that the product is not free flowing, so that bridging can occur in a silo.
Flow in a silo is in fact the continuous yielding of bridges. Bridging is only then a problem if a bridge does not collapse when flow is required. Here two factors are of concern:

- *the strength of a bridge;*
- *the force acting on that bridge.*

Strength of the bridge

The product in a silo will experience pressure from the above lying product. Through this silo pressure the product gets a certain strength (**the unconfined yield strength**).

Compare this to forming a snow ball and a "sand ball" with dry sand, the latter is not possible.

The strength of a product depends on:

- *the composition;*
- *the particle size (distribution);*
- *the pressure that it has undergone;*
- *the moisture content;*
- *the temperature;*
- *the storage duration.*

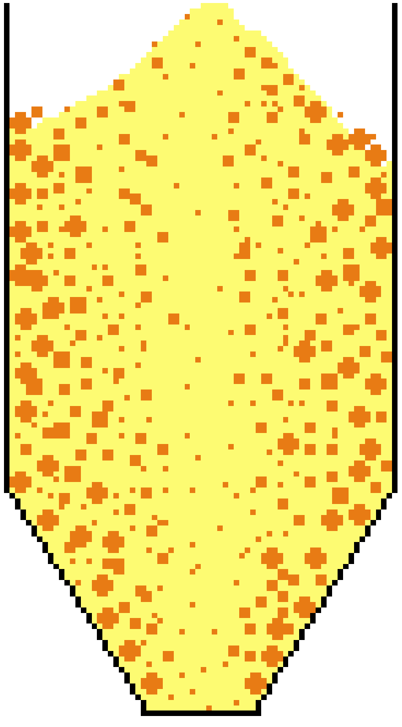
Especially the last factor is important in practice, as appears from starting-up problems after a weekend.

To calculate the strength of a bridge, the strength of the product must be measured as a function of the stress. From the above may be clear that it is important to measure the properties under the applicable conditions.

Force on the bridge
To let the product flow out of a silo, the binding strength of the product must be broken. Stable bridging will not occur as long as bridges that are formed in a closed silo, yield when the opening is free.
Bridges will collapse if the gravitational force is **greater** than the **strength** of the product. Products with a low bulk density are therefore more likely to give bridging problems.

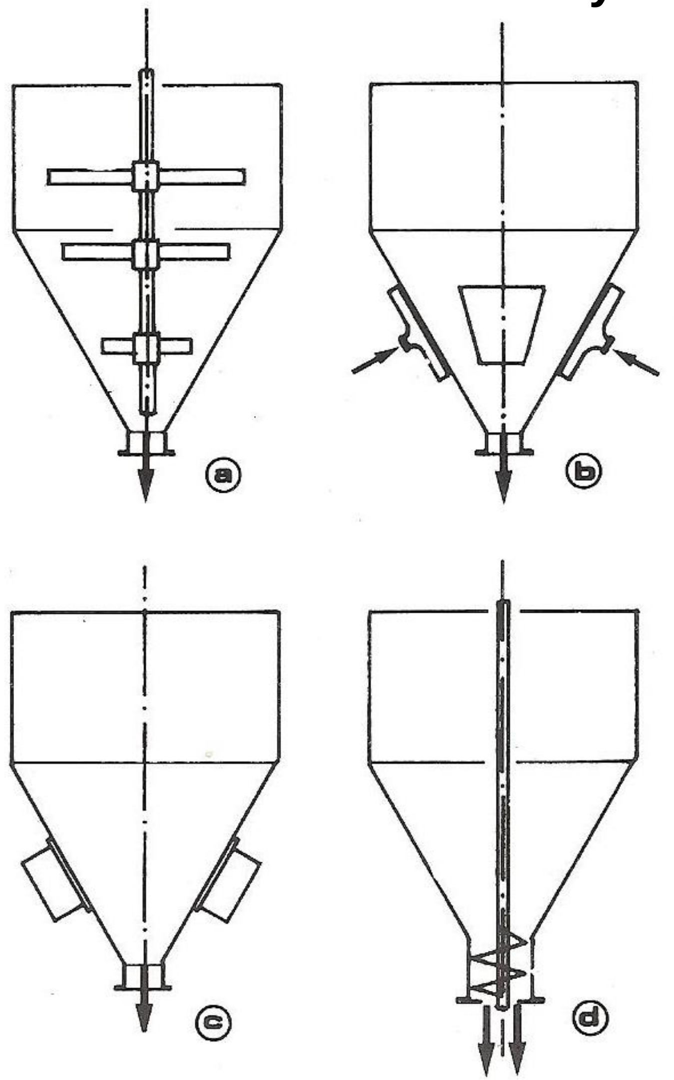
Whether **stable bridges** occur is dependant on the bulk density, the shape of the silo, the wall friction, the internal friction and of course the cohesion of the product. If these parameters are known (measured), then the **critical diameter** can be calculated. The **opening** to apply must be greater than this critical diameter to prevent bridging.

Segregation: If a heap is formed on the bulk solids' surface at filling of the silo, segregation is possible according to particle size or particle density. In case of centric filling as shown in figure, the larger particles accumulate close to the silo walls, while the smaller particles collect in the centre. In case of funnel flow, the finer particles, which are placed close to the centre, are discharged first while the coarser particles are discharged at the end. If such a silo is used, for example, as a buffer for a packing machine, this behaviour will yield to different particle size distributions in each packing. In case of a mass flow, the bulk solid will segregate at filling in the same manner, but it will become "remixed" when flowing downwards in the hopper. Therewith, at mass flow the segregation effect described above is reduced significantly.



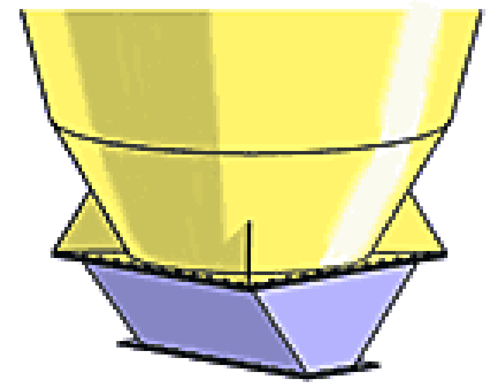
D. Schulze

Systems for improving flow



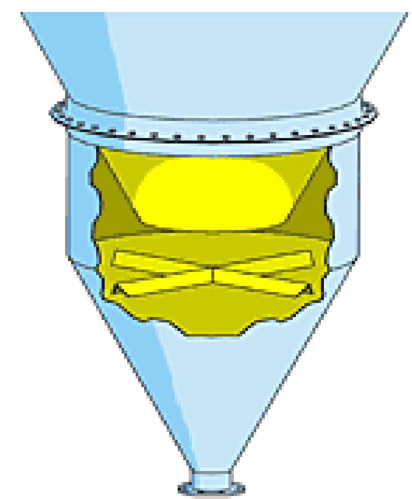
a) **Rotating blades**
b) **Fluidificator**
c) **Vibrator**
d) **Screw feeder**

Special Transition/Hopper Systems



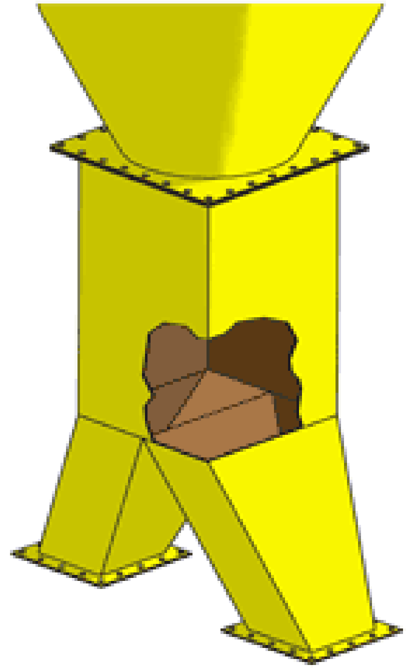
Opposed wedge sections reduce the consolidating pressure of the product
Promotes mass flow
Ideal for products with less than desirable flowability characteristics
Easily adaptable for retrofit applications

ExpandaFlow™ Reverse Hoppers

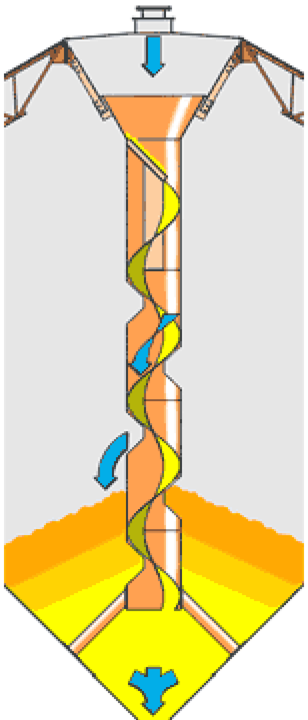


Can incorporate consolidation pressure breaker beams
Ideal for products with less than desirable flowability characteristics
Easily adaptable for retrofit applications

Outlet Splitter Chutes Approximately one-fourth the cost of a dual outlet transition
Design minimizes flow channel propagation
Allows the discharge of the silo into two separate process lines
Easily adaptable for retrofit applications



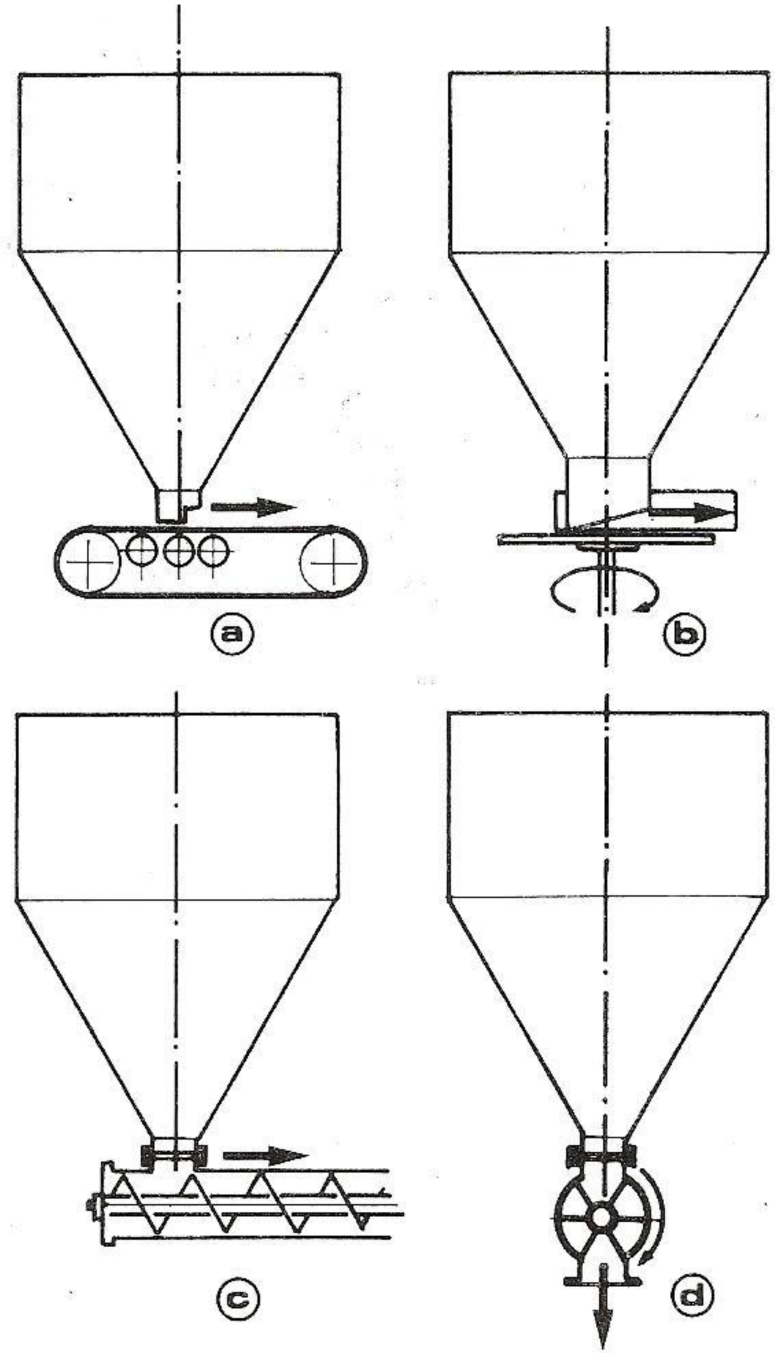
SoftFlow™ - Product Let Down Spirals
Minimizes degradation of friable products during filling of tank
Minimizes segregation
Food applications
Industrial applications



FEEDERS

Not only the silo geometry, also the choice and design of the feeder is of importance in the functioning of a silo. In the above is mentioned that a slot shaped opening helps to create mass flow. This will pose additional demands on the feeder.

A feeder must provide an equal discharge over the area of the opening. If this is not the case then the feeder will cause funnel flow, even if the silo has build for mass flow.



a) Belt feeder
b) Rotating dish feeder
c) Screw feeder
d) … feeder

Guidelines for feeder design

There is no overall theory for the design of feeders. There are however a few points of attention, that must be taken into account when designing feeders. The feeder must:

* *be able to yield all demanded capacities;*
* *be adequate for all products handled;*
* *supply a flow as constant as possible, at every capacity;*
* *be well controllable over the whole range;*
* *discharge product evenly over the whole area of the opening;*
* *when using a screw feeder, the pitch must tuned to the product characteristics, so equal drawdown is ensured*.

When vibratory feeders are used in combination with other feeders or transport devices, the vibratory unit must determine the capacity. For example in the combination of vibrating bottom and transport screw, the latter must have a significantly greater capacity, to prevent the bottom from blocking.

General considerations on silo design

In a funnel flow silo, all problems mentioned above can occur generally, while in case of mass flow only arching has to be considered: **segregation, ratholing, irregular flow and flooding of the bulk solid do not appear in a well designed mass flow silo.** The permanence time distribution of a mass flow silo is narrow, because it acts as a „first in - first out" system.

Two steps are necessary for the design of mass flow silos:

The calculation of the required hopper slope which ensures mass flow, and the determination of the minimum outlet size to prevent arching.

For every situation a so-called **critical outlet** diameter can be determined. When the outlet of the silo is bigger than this critical diameter, the product will flow from the silo. If the existing diameter is smaller, bridging will occur.

The critical diameter depends on the shape of the hopper and on the silo pressures, but mainly on the unconfined yield stress of the product. As already seen, this unconfined yield stress is the cohesion at a certain pressure, and is highly dependent on the material conditions, such as:

* *the composition*
* *the particle size distribution*
* *the exerted silo pressure*
* *the moisture content*
* *the temperature*
* *the storage time*

To calculate the critical diameter, measurements are therefore performed under the applicable conditions.

Bin **design procedures** consists of **four parts** as follows:

1) Determine the **strength** and **flow properties** of the **bulk solid**.
2) Determine the **bin geometry** to give the desired capacity, to provide a **flow pattern** with acceptable flow characteristics and to ensure that **discharge** is **reliable** and **predictable**. Specialised mechanical feeder design may be required.
3) Estimate the bin **wall loads** from the stored material and other loads such as wind, ancillary equipment, thermal, etc.
4) **Design** and **detail** the bin **structure**.

Before the structural design can be carried out, the **loads** on the bin must be evaluated. Loads from the stored material are **dependent**, amongst other things, on the **flow pattern**, the **properties** of the **stored material** and the bin **geometry** while the methods of structural analysis and design depend upon the bin geometry and the flow pattern. The importance of Stages 1) and 2) of the design should not be underestimated. Simplified rules for the functional design of bins and for estimating wall loads are given in EC1 Part 4 (1991-4). Detailed rules for the structural design of steel bins will be given in EC3 Part 4-1 (1993-4-1).

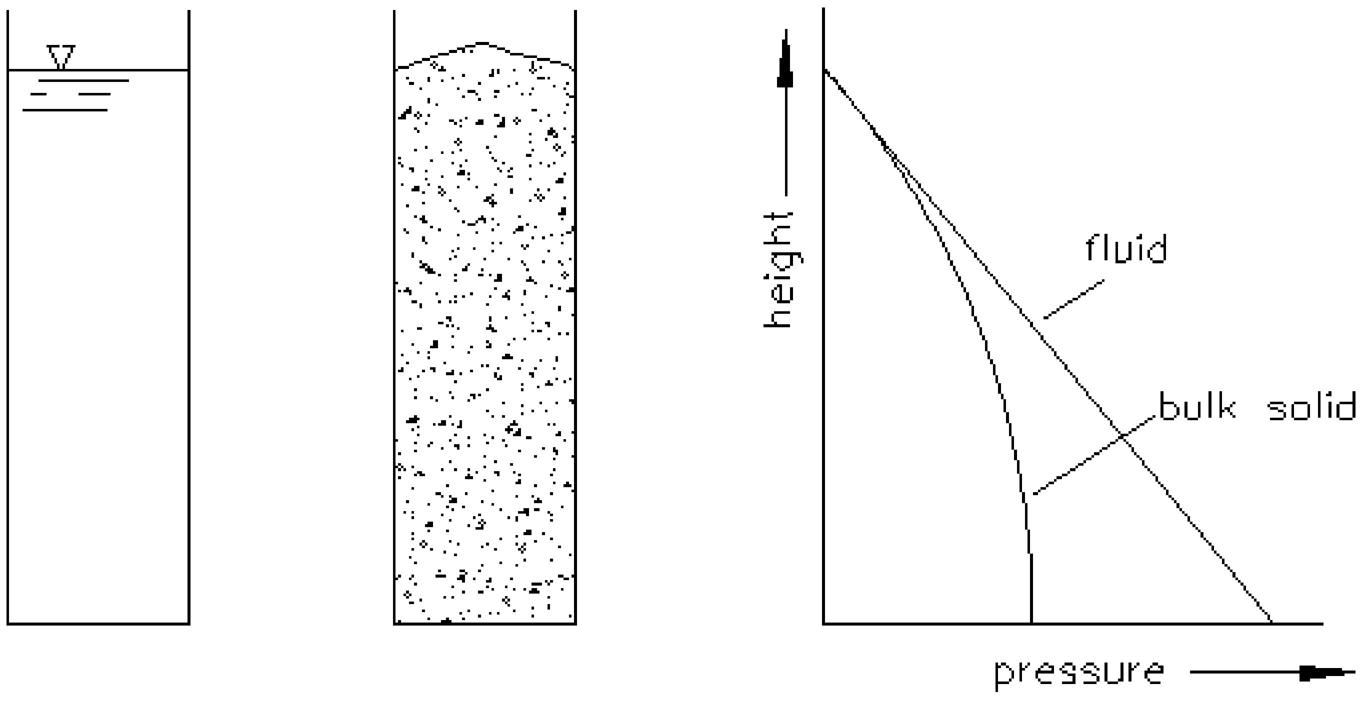
Introduction to structural design of silos

Knowledge of the **stresses** acting in silos is important for many applications:

Silo design for strength
Silo design for flow
Loads on feeders and inserts
Driving torque of feeders
Design of silos in which a specific maximum stress is not exceeded (e.g. to avoid vibrations, particle attrition or extreme time consolidation)

The calculation methods used by an engineer who is interested in avoiding flow problems and in feeder design differ from the calculation methods of a civil engineer who is interested in the stability of the silo structure. The civil engineer would choose the parameters for calculating silo stresses so that the major part of the load from the bulk solid is carried by the silo walls, whereas the engineer who has to calculate the feeder load and the required driving power would assume that the silo walls carry only a minor part of the load of the bulk solid. The stress distribution across the periphery of the silo is another example of the different points of view: whereas a strong irregular distribution of the stresses on the silo wall is quite unimportant for the design of a feeder, these different stresses cannot be neglected for the structural design of the silo walls.

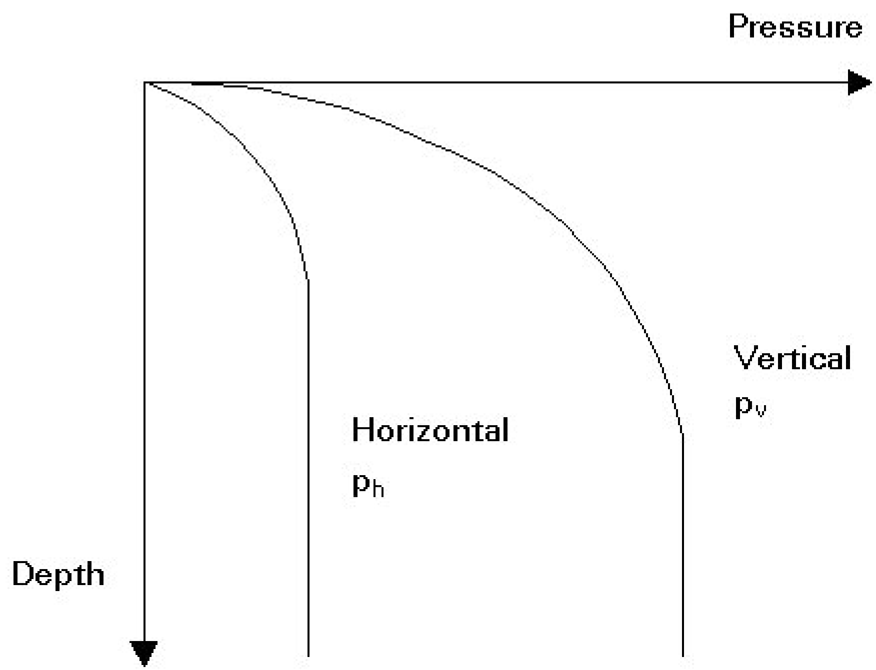
In contrast to a fluid, a bulk solid at rest can transmit shear stresses. While the pressure in a container filled with a fluid increases linearly with the depth, the weight of the bulk solid in a silo is carried partly by the silo walls because of the shear stresses (friction at the silo wall) so that the stress does not increase linearly with the depth like the pressure of a fluid.



Pressures in fluids and stresses in bulk solids (in principle)

Stresses in silos

The increase of **horizontal** and **vertical pressure** with depth is shown in the Figure. Increases in horizontal pressure are negligible beyond a certain depth and therefore **concrete** bins are more efficient if they are **tall**, whereas **steel** bins tend to be **shallower** structures.

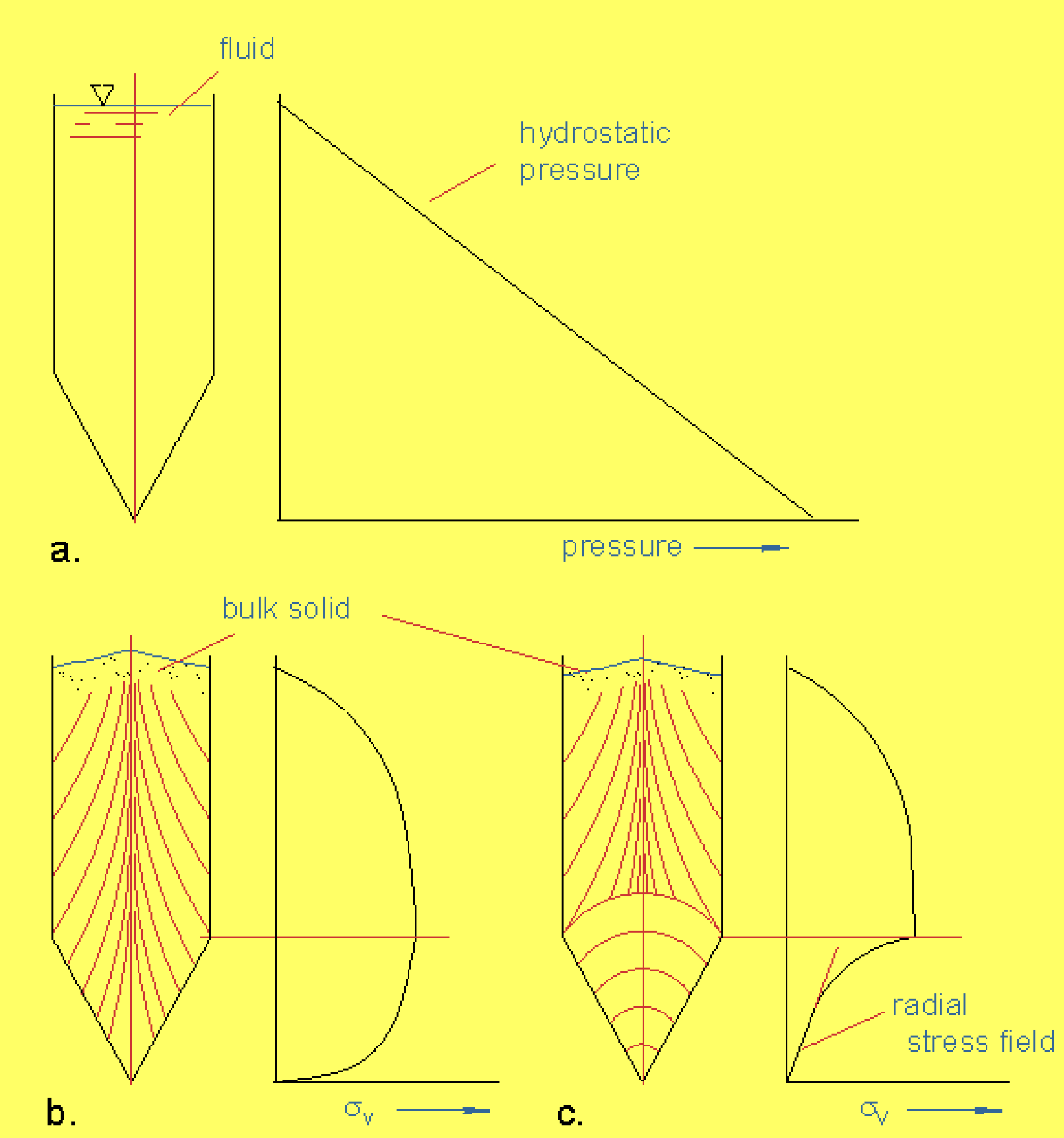


Distribution of horizontal and vertical pressure against depth of stored material

Main source: ESDEP

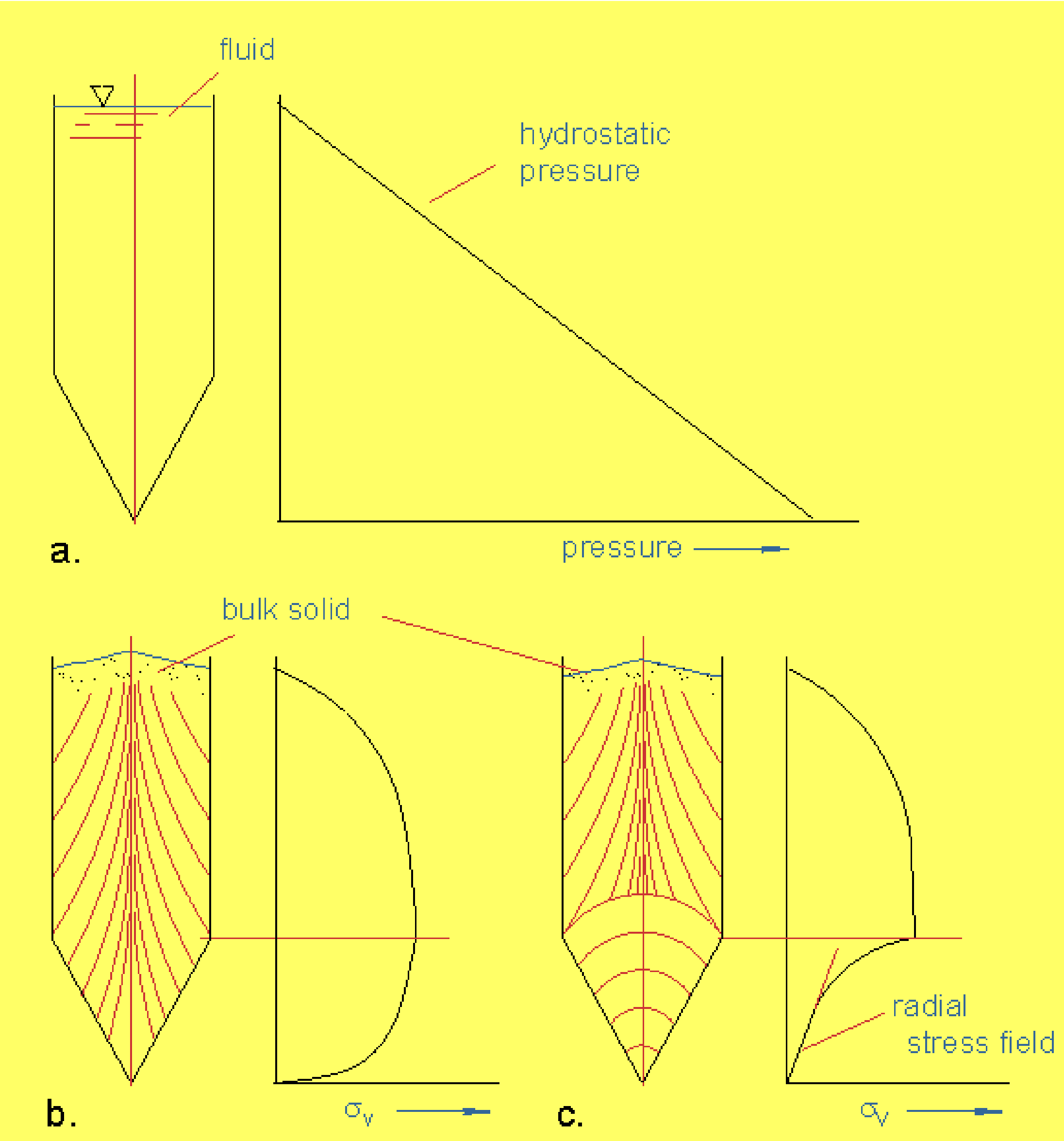
Stresses in silos

While the pressure (**for fluids it is commonly used the word "pressure"**) would increase linearly downwards if the silo would have been filled with a fluid (a), the course of the vertical stress (**for bulk solids we will use the word "stress"**) in a silo filled with a bulk solid is rather different (b,c): In the latter case in the vertical (cylindrical) section of the silo the vertical stress increases in a degressive way. If the height to diameter ratio of the silo is sufficiently large (usually: > 3), a **constant vertical stress** is attained. This means that the vertical stress will not increase further even if the filling height is much larger. The reason for this course are the **shear stresses** acting between the **bulk solid and the silo walls** even if the bulk solid is at rest. Due to the shear stresses, the silo walls carry a part of the weight of the bulk solid.



a. pressure in a silo filled with a fluid (imaginary); b. vertical stress after **filling** the silo with a bulk solid; c. vertical stress after the **discharge** of some bulk solid

D. Schulze



a. pressure in a silo filled with a fluid (imaginary); b. vertical stress after **filling** the silo with a bulk solid; c. vertical stress after the **discharge** of some bulk solid

The stresses acting in a hopper are different from those in the vertical section. Just after filling an empty silo, the so called **filling stress state** (also: **active stress state** (b) prevails, where the vertical stress in the hopper decreases less in the upper part of the hopper and then more near the imaginary hopper apex. As soon as some bulk solid is discharged for the first time after filling, the stresses in the hopper change and the so-called **emptying stress state** (also : **passive stress state,** c) prevails.

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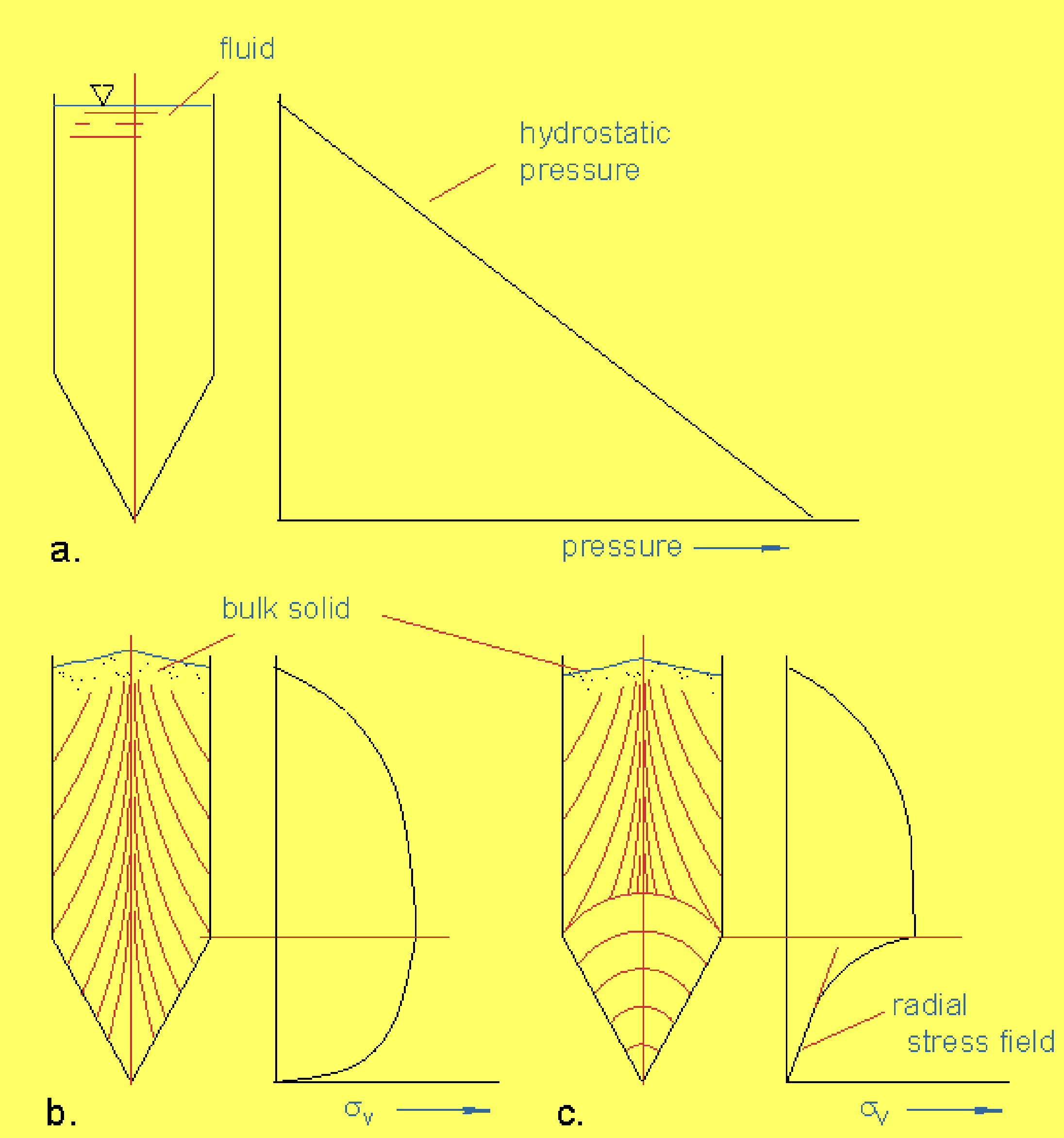

a. pressure in a silo filled with a fluid (imaginary); b. vertical stress after **filling** the silo with a bulk solid; c. vertical stress after the **discharge** of some bulk solid

When flowing downwards in the hopper, the bulk solid is **compressed in the horizontal direction** so that the walls of the hopper carry a larger part of the weight of the bulk solid and, hence, the vertical stress in the lower part of the hopper is clearly smaller than after filling. In the emptying stress state the vertical stresses in the lower part of the hopper are nearly proportional to the distance to the imaginary hopper tip or, in other words, the stresses are proportional to the local hopper diameter. This linear course of stress is called the **radial stress field**. In principle, in the **vertical section** of the silo the stresses remain **unchanged** at discharge.

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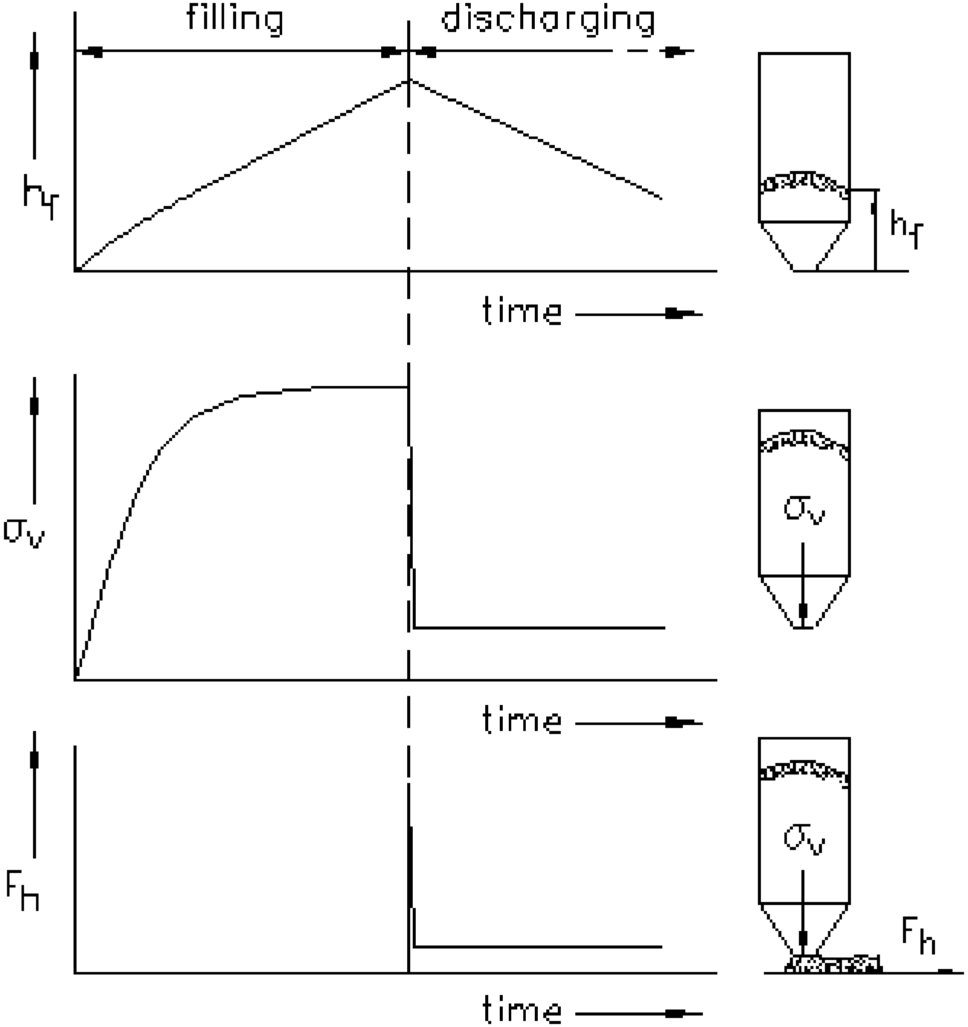
Loading history



Filling height h_f, vertical stress at the outlet σ_v, and feeder force F_h vs. time

Just after the filling of an empty silo (**filling state, active stress state**) the vertical stress at the outlet is larger than in the case of the **passive stress state** (**discharging**). In experiments stresses up to 10 times higher than in the case of the passive stress field have been measured for the active stress state. The figure shows what happens during the filling and discharging of a silo. During filling the filling height h_f and the vertical stress at the outlet, σ_v , increase with time. As soon as bulk solid is discharged the first time the passive stress field develops and the vertical stress at the outlet, σ_v, decreases suddenly. Thus it can be shown that at the beginning of the discharge a feeder has to be able to move the bulk solid under a huge vertical stress σ_v. Therefore the feeder has to exert a large horizontal force F_h on the bulk solid. As soon as the bulk solid is in motion the passive stress field with its low vertical stresses prevails thus reducing the feeder force F_h sharply.

D. Schulze

CALCULATION OF PRESSURES ON BIN WALLS

General

Most existing theories for the calculation of loads from the stored material in bins assume that the **pressure distribution around the perimeter of a bin is uniform at any given depth**. In reality, there is always a non-uniformity of loading. This may arise from imperfections in the bin walls, non-concentric filling techniques, or discharge outlets positioned eccentrically to the centre of a bin.

The pressure exerted on the bin wall by the stored material is **different when the material is flowing and when it is stationary**. The stress state within a stored material **changes as flow commences and the bin walls are subjected to high localised pressures of short duration**. Research studies have identified **two types of high pressure during discharge**. The **first** is known as the **kick load** which occurs at the start of flow and is only significant in the hopper. The **second** high pressure is attributed to a **local stress re-distribution** within the flowing material as it passes the **imperfections of the bin walls**. **The neglect of the non-uniform loading in design results in more bin failures than any other causes.** It leads to particular problems with circular bins which are designed to resist membrane forces only. Pressures due to eccentric discharge are erratic and may be higher or lower than the uniform pressure predicted using most existing theories.

Although high discharge pressures and their fundamental causes have been identified, they are **difficult to quantify**. It is common practice therefore for designers to multiply the calculated static pressure by a constant derived from experimental data. The **empirical factor** has traditionally been applied to the static pressure without any regard to the structural response of the bin. Since the high discharge pressures only affect local areas, variation of the pressure may result in a worse stress state in the bin wall than a high uniform pressure. Therefore the assumption of a high but constant pressure at any level is not necessarily safe.

Stress calculation

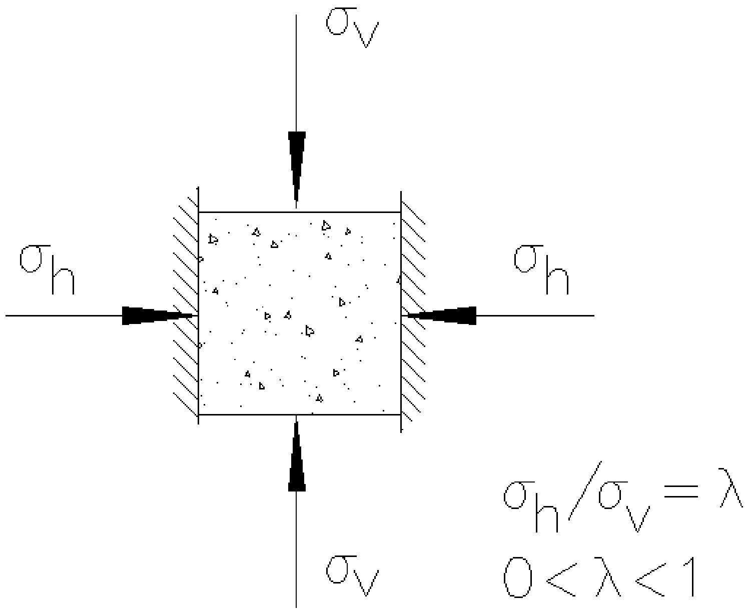
The behaviour of bulk solids in silos

The Figure shows an element of bulk solid in a cylinder which is filled with bulk solid (frictionless walls). The element of bulk solid is affected by the vertical stress σ_v. As a result of the vertical stress, the horizontal stress σ_h acts in the horizontal direction. The stress ratio λ which is well-known from soil mechanics is used for the description of the ratio of σ_h to σ_v:

$\lambda = \sigma_h / \sigma_v$ (1)

Every bulk solid has a specific stress ratio λ. While an ideal, non-elastic solid has a stress ratio of 0, a fluid would have a stress ratio of 1. That of bulk solids stored at rest is mostly in the **range from 0.3 to 0.6**.

For the stress calculation, a bulk solid is considered as continuum instead of single particles. Because of this the methods of continuum mechanics can be applied. If different sloped cuts through an element of bulk solid are considered it can be seen that different shear and normal stresses are acting at different cutting planes. This is shown in a simplified way in the figure where the stresses σ_h and σ_v which act in different directions differ from each other. In a bulk solid there is one direction where the maximum normal stress is acting. This maximum normal stress is called major principal stress σ_1. The minimum normal stress which acts perpendicular to σ_1 is called minor principal stress σ_2.



Element of bulk solid

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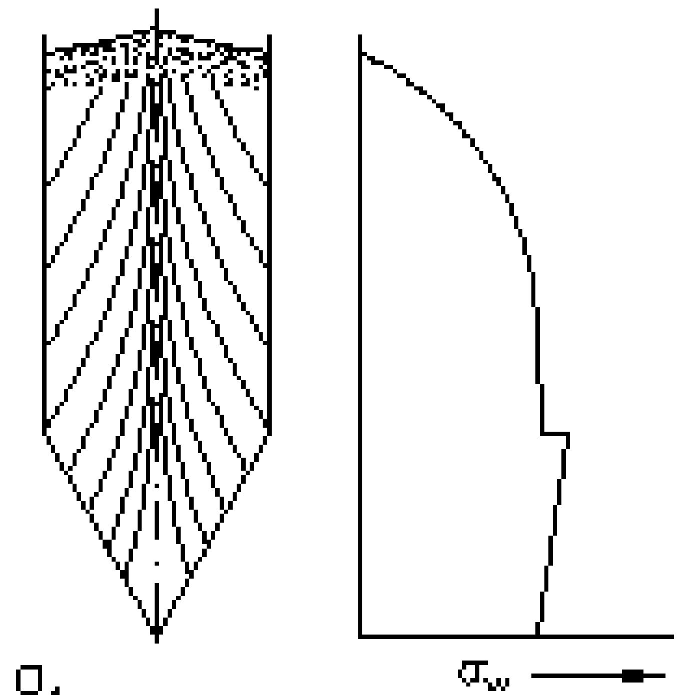
If an empty silo is filled, the plot of wall normal stress σ_w looks like in the figure. The **wall normal stress σ_w** in the vertical part of the silo increases with depth, but with a decreasing gradient, tending asymptotically towards a maximum. In the vertical section of the silo the vertical stresses are the larger stresses while the horizontal stresses appear according to the stress ratio λ, equation (1). **The major principal stress σ_1 acts downwards along the silo axis.** As the silo walls are approached, the direction of the major principal stress **diverges more and more from the vertical direction** as it can be seen from the trajectories of the major principal stress, σ_1.



Qualitative courses of wall normal stresses, σ_w, and assumed trajectories of the major principal stress, σ_1.

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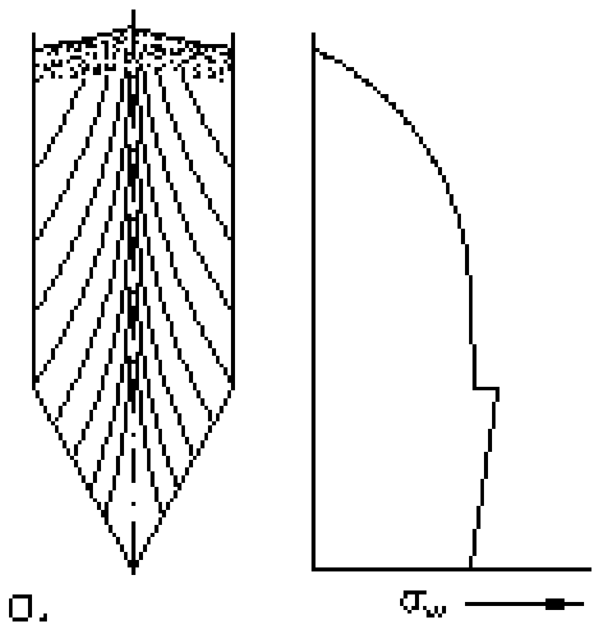
A point of **discontinuity** is present at the transition from the vertical section to the hopper. In the hopper the stress can decrease or first increase and then decrease on the way down through the hopper. This depends on the geometry of the hopper and the bulk solids properties. This stress state after the filling of the silo is called **active stress state** or **filling state**. As with the vertical section, in the active stress state **the larger stresses in the hopper are also acting downwards** (major principal stress acts vertically along the hopper axis).



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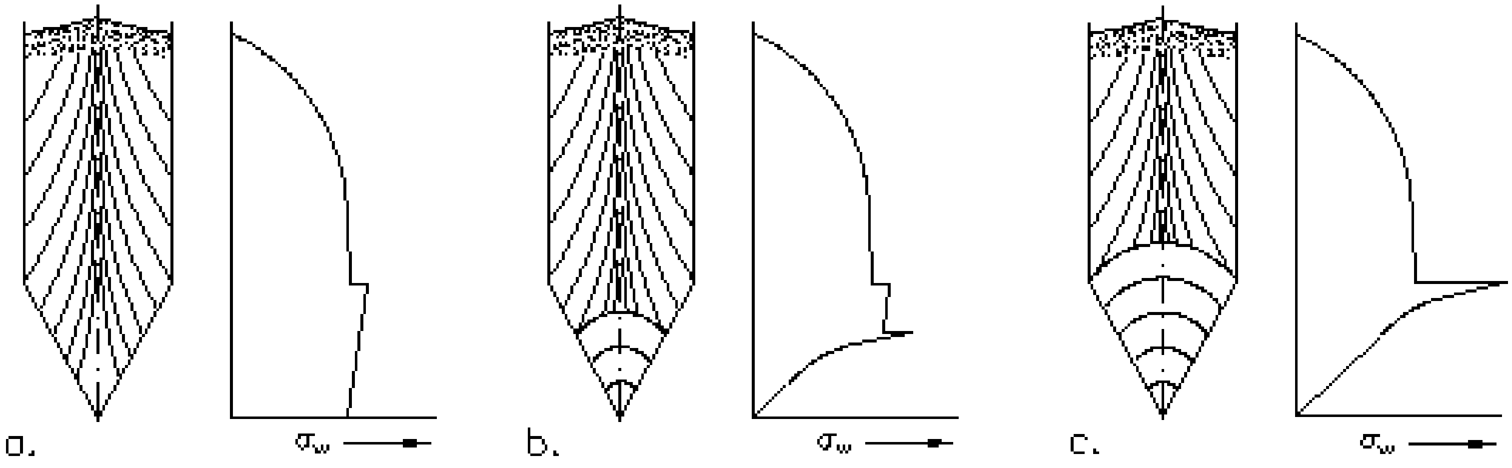
At the beginning of discharge of a **mass flow** hopper all of the silos contents are set in motion and the stress conditions in the hopper change. Starting at the (theoretical) hopper apex the passive stress field (**passive state of stress**) prevails. When the bulk solid flows downwards through the converging hopper section, **the bulk solid is compressed horizontally whereas the vertical stress is reduced due to the flow being directed downwards**. Therefore, the stresses acting in the horizontal direction become the larger stresses (major principal stress acts horizontally in the hopper axis). In the case shown in figure b, which shows the stresses just after the start of the discharge, the passive state of stress is only present in the lower part of the hopper whereas in case of figure c (shortly after b) the passive stress field has developed in the whole hopper. In the vertical part of the silo the active state of stress remains unchanged if no local convergences (local convergences caused by inserts, dents, etc.) are present. At the transition from the active to the passive stress field (in case of mass flow silos the transition from the vertical section to the hopper) a **local stress peak** occurs which is called the **switch**. The passive state of stress remains even if the discharge is stopped.



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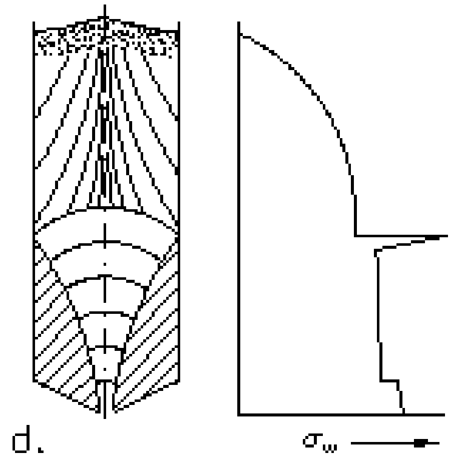
In the case of a **funnel flow** silo, the bulk solid flows downwards inside the dead zones. If the borderline between the flow zone and the dead zone intersects the silo wall as it is shown in figure d, a **stress peak** (**switch**) is formed at that point. The position of the stress peak cannot be predicted so that the whole vertical section of the silo has to be designed to resist the stress peak.



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Methods of stress calculation (overview)

From the considerations above it can be seen that **three different cases** have to be taken into account when calculating stresses in silos:

Stresses in the vertical part of silo
Stresses in the hopper (active state of stress, filling state)
Stresses in the hopper (passive state of stress, emptying state)

Stresses in silos have been investigated both experimentally and theoretically for approximately 100 years. At first the stresses in the **vertical part** of a silo were considered (Janssen, Koenen). The **hopper stresses** were examined later. The best known investigations are those of Jenike, Walker and Walters. The first approaches are based on **slice element methods** where the **equilibrium of forces** on slice elements of infinitesimal thickness is considered.

The calculation method which was developed by **Jenike** describes the **hopper stresses for the passive stress state**. Jenike's approach can also be used when designing silos for flow by determining the maximum hopper slope for mass flow and the minimum outlet size to prevent arching and ratholing. Jenike presented the results of his calculations in the form of diagrams to simplify the application of his method.

Calculation of the stresses in the vertical section of a silo

The stresses in the vertical section of a silo (**active state of stress**) have been calculated by Janssen, who used a so-called **slice element method**. He considered a slice-shaped volume element of infinitesimal height *dz* (see figure) which has the same cross-sectional area *A* as the vertical section of the silo. Assuming uniform vertical stress σ_v and constant bulk density ρ_b across the whole cross-section, the **equilibrium of forces** in z-direction yields:

$$A\sigma_v + g\rho_b A dz = A(\sigma_v + d\sigma_v) + \tau_w U dz \qquad (2)$$

After the introduction of the wall friction angle

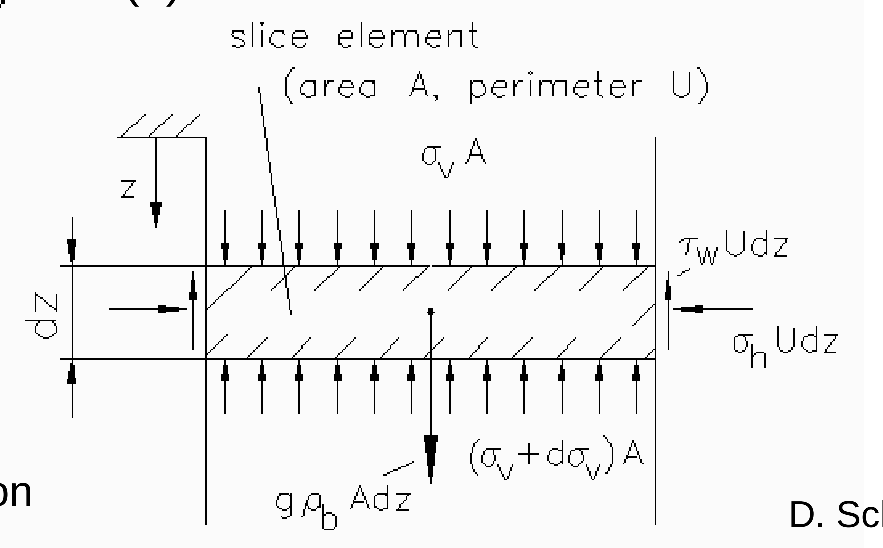
$$\tan\varphi_x = \tau_w / \sigma_w \qquad (3)$$

and the stress ratio

$$\lambda = \sigma_h / \sigma_v \qquad (4)$$

an ordinary differential equation for the vertical stress σ_v is obtained.

$$\frac{d\sigma_v}{dz} + \sigma_v \lambda \frac{U}{A} \tan\varphi_x = g\rho_b \qquad (5)$$



Slice element in the vertical section

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From the integration of the differential equation (5) whilst considering the boundary condition that the vertical stress is equal to σ_{v0} at z = 0 it follows that:

$$\sigma_v = \frac{g\rho_b A}{\lambda \tan(\varphi_x) U}\left\{1 - e^{-\frac{\lambda \tan(\varphi_x) U z}{A}}\right\} + \sigma_{v0}\, e^{-\frac{\lambda \tan(\varphi_x) U z}{A}} \qquad (6)$$

For σ_{v0} = 0 it follows from eq. (6) that:

$$\sigma_v = \frac{g\rho_b A}{\lambda \tan(\varphi_x) U}\left\{1 - e^{-\frac{\lambda \tan(\varphi_x) U z}{A}}\right\} \qquad (6.a)$$

Horizontal stress σ_h and wall shear stress τ_w can be calculated by combining eqs. (3), (4), and (6):

$$\sigma_h = \frac{g\rho_b A}{\tan(\varphi_x) U}\left\{1 - e^{-\frac{\lambda \tan(\varphi_x) U z}{A}}\right\} + \lambda\, \sigma_{v0}\, e^{-\frac{\lambda \tan(\varphi_x) U z}{A}} \qquad (6.b)$$

$$\tau_w = \frac{g\rho_b A}{U}\left\{1 - e^{-\frac{\lambda \tan(\varphi_x) U z}{A}}\right\} + \lambda\, \tan(\varphi_x)\, \sigma_{v0}\, e^{-\frac{\lambda \tan(\varphi_x) U z}{A}} \qquad (6.c)$$

The *e*-function in eqs. (6) to (6.c) approaches zero for large values of z. Therefore, the expression in front of the term in brackets is the stress which is approached for large values of *z*, i.e. in case of a silo with sufficiently large height/diameter ratio.

Considerations on the use of Janssen approach (1)

The expression in front of the brackets depends on the bulk solid properties and the silo geometry represented by the ratio *A/U* (cross-sectional area *A* divided by perimeter *U*). In case of a cylindrical silo, the ratio A/U is equal to d/4 (d = silo diameter). Therefore, the **maximum stress** which is possible is **proportional to the diameter** of the vertical section of the silo (see eqs. (6.a) to (6.c)). **For this reason, silos are usually slender (small d) and high. In contrast to this, fluid containers (e.g. oil tanks) are usually flat and have a large diameter because of the hydrostatic pressure.**

The validity of the Janssen equation (6.a) has been checked in several experimental tests over the last 100 years. For example, the influence of the wall friction angle φ_x is as follows: A rough wall (= large wall friction angle) carries a larger part of the weight of the bulk solid than a smooth wall (= small wall friction angle) . Therefore, the maximum horizontal stress is greater in a silo with a smoother wall (if all other parameters and dimensions are identical). This can be seen clearly in eq.(6.b) where the wall friction angle φ_x is placed in the denominator of the first term.

The Janssen equation is the basis of several standards for the calculation of stresses in silos because of its principle validity. Janssen determined the value of the stress ratio λ by adapting equation (6) to the stresses measured in a model silo.

Considerations on the use of Janssen approach (2)

Often the equation of Kézdi is used for the estimation of the stress ratio λ:

$$\lambda = 1 - \sin\varphi \qquad (7)$$

Where φ is the bulk solids angle of internal friction. Usually, the effective angle of internal friction, φ_e , measured in a shear tester is often used in its place. Some codes recommend the following equation which is based on eq. (7):

$$\lambda = 1.2\,(1 - \sin\varphi) \qquad (8)$$

The use of eq. (8) results in higher wall loads in the upper area of the silo, i.e. wall normal stresses σ_w and shear stresses τ_w are greater than those calculated on the basis of eq. (7). Therefore, the load assumptions for the structural design are on the safe side with eq.(8). To be on the safe side for applications where the maximum vertical stress is important (e.g. for the calculation of the feeder load or the maximum vertical stress) the smaller λ (eq.(7)) should be used because it yields higher vertical stresses.

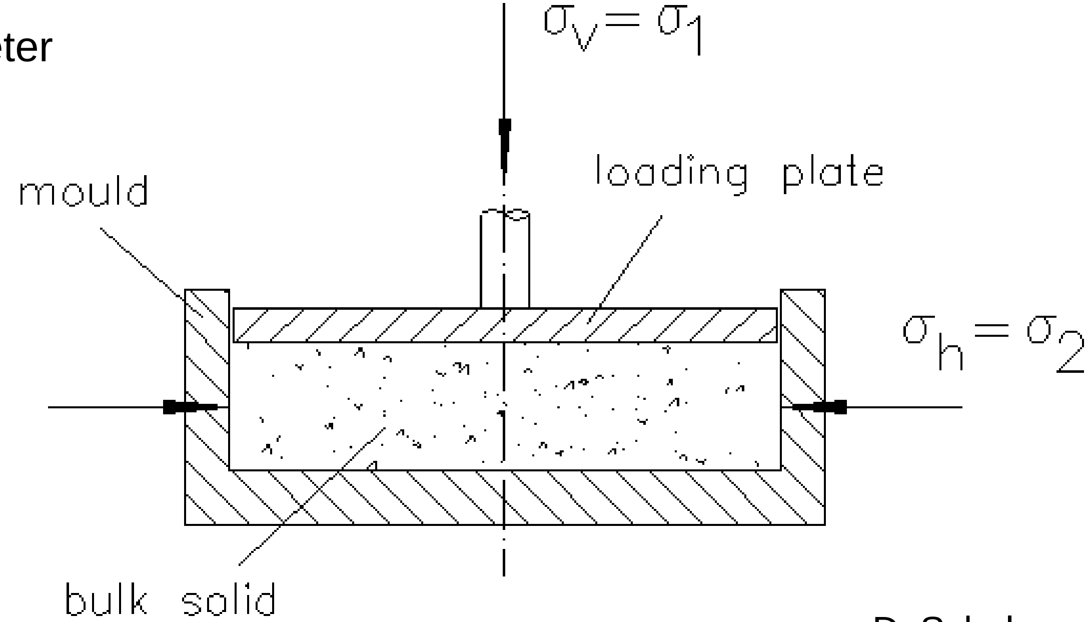
For rough estimations of the stresses in the vertical section the following value of λ can be used.

$$\lambda = 0.4 \qquad (9)$$

Considerations on the use of Janssen approach (3)

The values of the stress ratio which are calculated according to either eq. (8) or codes, are not correct in any case because the stress ratio depends on a lot of parameters which are not taken into account in eq.(8). A step towards improving safety is the recommendation in the new ISO-guideline [ISO TC98/SC3/WG5] to determine the stress ratio directly from a uniaxial compression test with a modified oedometer (see figure). The test is performed in the following way: A cylindrical mould is filled with the bulk solid to be tested. Then a vertical stress is applied on the sample and the resulting horizontal stress is measured. This test does not take into account all influencing parameters, but all which depend on the properties of the bulk solid. Measurements show that it is possible to use a modified oedometer - called a lambdameter - to determine the stress ratio λ.

Uniaxial compression in the lambdameter



D. Schulze

Calculation of the hopper stresses

The stresses in the hopper can be assessed also using a **slice element method**. An equilibrium of forces on a slice element in the hopper (see figure) yields:

$$d\{A\sigma_v\} + g\rho_b A dz = \sin(\Theta)\,\sigma_w dA_M + \cos(\Theta)\,\tau_w dA_M \qquad (10)$$

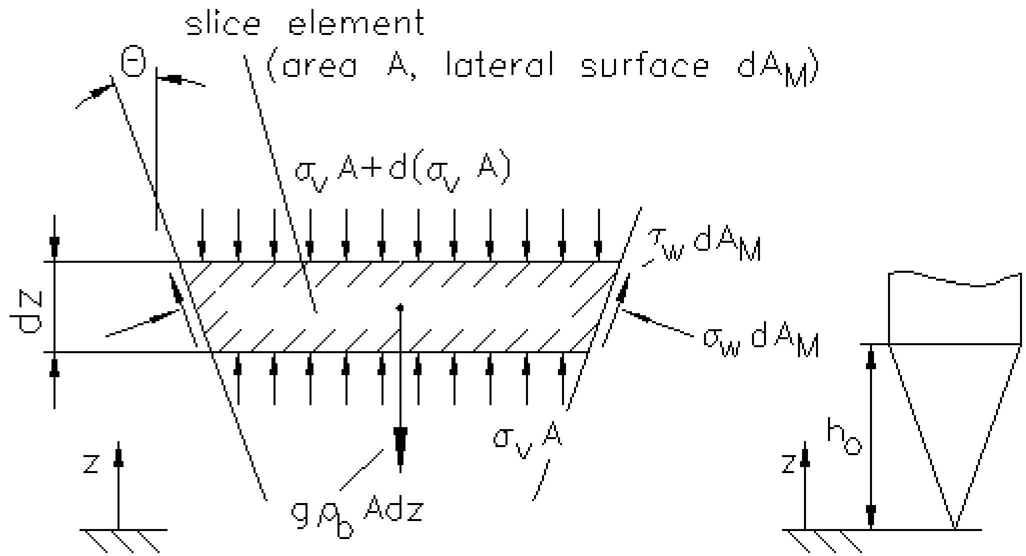
Please note the different direction of co-ordinate *z* compared to the vertical section.
If fully mobilized wall friction is assumed (see eq.(3)), it follows:

$$\frac{d\sigma_v}{dz} - n\frac{\sigma_v}{z} = -g\rho_b \qquad (11)$$

with:

$$n = (m+1)\left\{K\left[1+\frac{\tan(\varphi_x)}{\tan(\Theta)}\right]-1\right\} \qquad K = \sigma_w / \sigma_v \qquad (12)$$

With the parameter *m* the shape of the hopper is taken into account: *m* = 0 for wedge-shaped hoppers, *m* = 1 for conical hoppers.



Slice element in the hopper

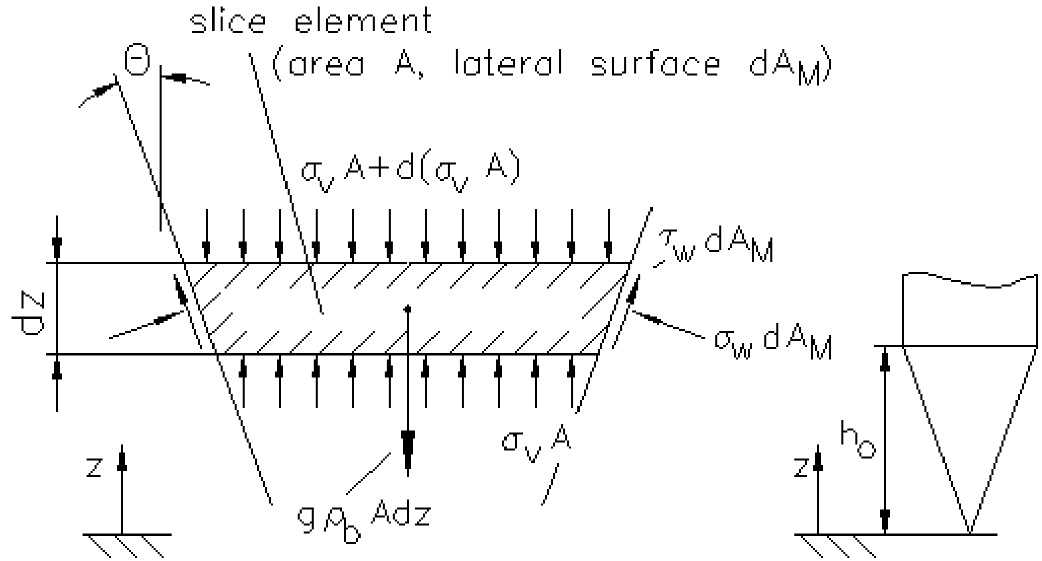
At wedge-shaped hoppers with a small length to width ratio also the end walls play a role. If the **friction at the end walls** is taken into account, the differential equation (11) has to be extended by one additional term:

$$\frac{d\sigma_v}{dz} - n\frac{\sigma_v}{z} - (1-m)\,\lambda_s\,\sigma_v\,\frac{2\tan(\varphi_x)}{l_s} = -g\rho_b \qquad (11.a)$$

Here λ_s is the ratio of the normal stress acting on the end walls to the mean vertical stress. As an approximation, the stress ratio λ_s is assumed to be equal to the stress ratio λ (eq.(4)). l_s is the length of the wedge-shaped hopper.

The values of *K* and *n*, respectively, are dependent on the flow properties, the hopper geometry, and the mode of operation (filling, discharging). Thus the problem in the application of the equations presented above is the **calculation of *K* and *n***. It has been shown that the method of Motzkus (filling) and Arnold and McLean (discharging) make possible a fairly realistic assessment of the stresses in the hopper.

Slice element in the hopper



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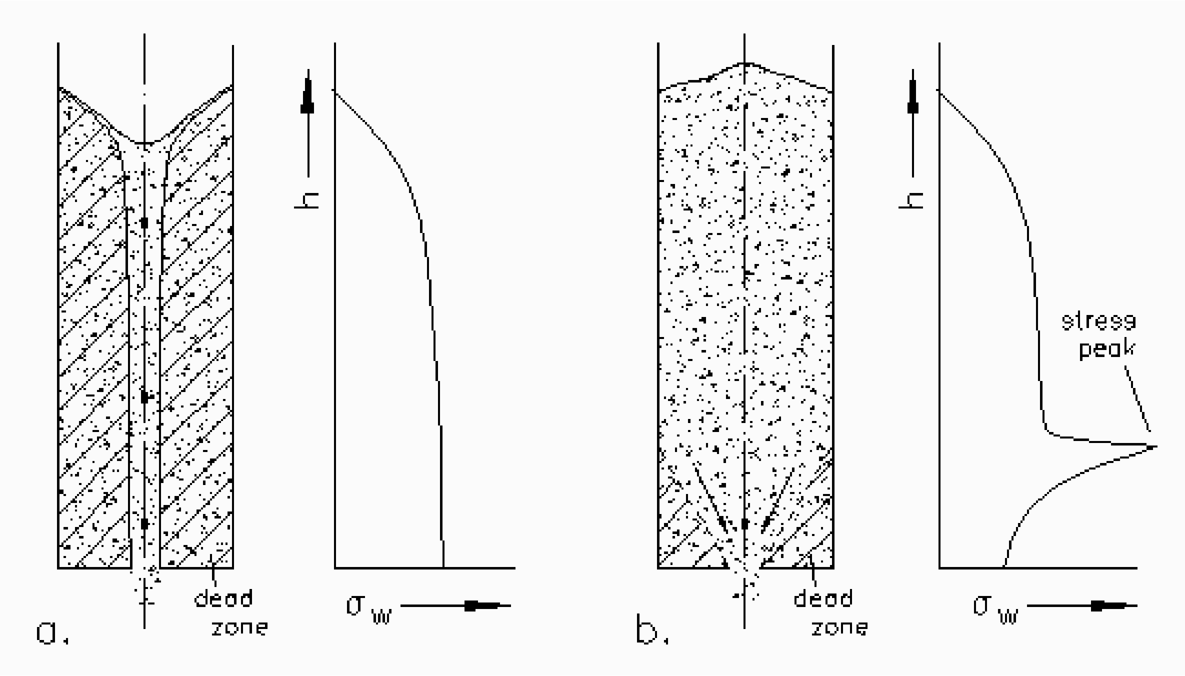
Irregularities
Switch

The stresses acting on the silo walls have to be known for the structural design of a silo. On the other hand additional loads on the silo walls which result from, for example, non-uniform stresses across the perimeter or local stress peaks have to be taken into account.

The stress peak which appears at the transition from the vertical section to the hopper in the passive stress field in mass flow silos are also termed "**switch**“ stresses. The reason for the switch can be clarified with a consideration of plausibility. A relatively large vertical stress σ_v acts on the bulk solid in the hopper because in the vertical part of the silo the major principal stress acts downwards. In the hopper the bulk solid is compressed horizontally as it flows downwards. Therefore, in the hopper the horizontal stress is larger than the vertical stress. Due to the equilibrium of forces, **the vertical stress σ_v at the upper end of the hopper is equal to the vertical stress σ_{v0}** at the lower end of the vertical section. Then in the hopper axis **σ_h is larger than σ_{v0}**. However, at the lower end of the vertical section the horizontal stress **$\sigma_h = \lambda\sigma_{v0}$ is obviously smaller than σ_{v0}**. This situation explains the abrupt increase of the horizontal stress at the transition from the vertical section to the hopper. Only the stresses in the axis of the silo are included in this consideration of plausibility because the horizontal and the vertical stresses are principal stresses only at that position. With decreasing distance to the silo walls the directions of the principal stresses are more and more sloped against the horizontal and the vertical line.

The calculation of the switch stresses is possible in principle, e.g. using Enstad's method. There are other approaches as well, e.g. from Walters and Jenike. New investigations apply the finite element method to calculate the temporary courses of the stresses.
In the case of **mass flow** silos, the switch generally appears at the transition from the vertical section to the hopper. This has to be considered for the structural design. In the case of **funnel flow** silos, however, the switch appears where the borderline between dead zones and the flowing bulk solid intersects the silo wall (figure b). Because of this, the stress peak is located in the sensitive area of the vertical section on the one hand, and on the other hand the vertical position of the switch can vary along the perimeter and can also vary with time. This has to be taken account for the structural design. Some bulk solids (e.g. different types of sugar), if stored in a funnel flow silo, form flow zones with nearly vertical borderlines which do not intersect the silo wall at any point. Hence, they cannot generate stress peaks on the silo wall (figure a).



Wall normal stress in funnel flow silos
a. steep border line b. flat border line

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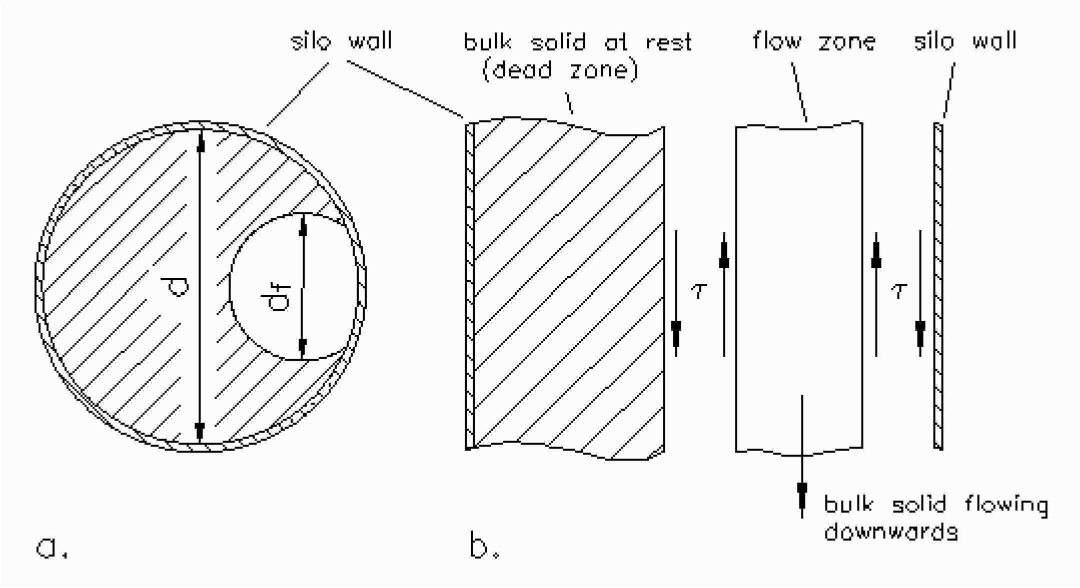
Imperfections

Even in **mass flow** silos local stress peaks in the vertical section are possible. The stress peaks are caused by irregularities (imperfections) in the silo wall, i.e. the vertical section is converging locally due to a local reduction in the cross-sectional area. Measurements taken by van Zanten and Mooij on a silo with artificial imperfections in the vertical section have shown that locally the passive state of stress prevails. The wall normal stress can increase significantly in the vicinity of the imperfections (up to four times of the horizontal stress measured without imperfections). This effect is comparable to the switch.

Eccentric flow

If the bulk solid in a silo does not flow downwards uniformly across the cross-section but in an eccentric flow zone, then this behaviour is called eccentric flow. Typical **reasons for eccentric flow** are:

- **Funnel flow** silo with an **asymmetrically** formed flow zone, especially in the case of an **eccentric outlet** opening.
- Silo with a feeder which withdraws the bulk solid only from a part of the outlet opening.
- **Asymmetric** hopper.
- Silo with more than one outlet opening of which not all are in use.



Eccentric flow in the vertical section of a silo (schematic)
a. top view   b. longitudinal section

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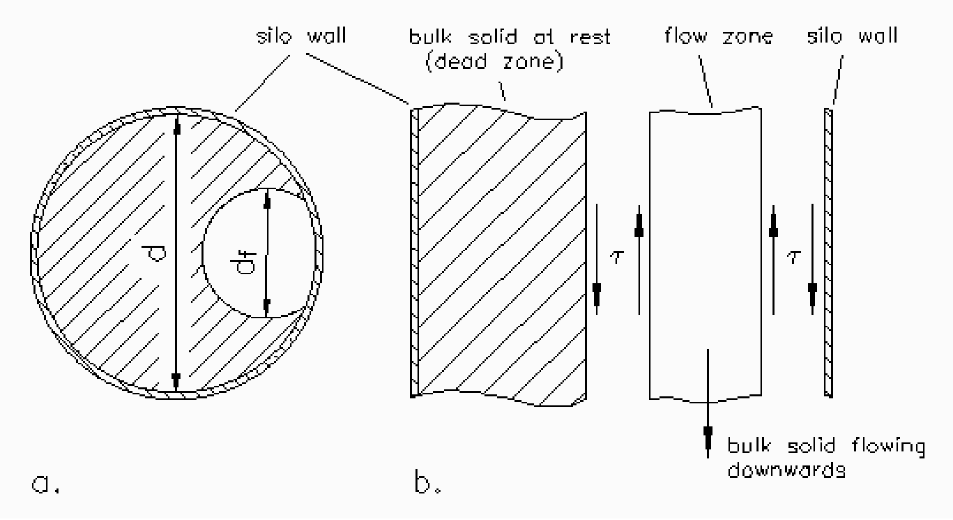
The **problems of eccentric flow** are, in addition to the known problems of funnel flow, the **non-uniform stress distribution over the perimeter** which has to be considered in structural design. Because of the non-uniform load on the silo walls, bending moments and normal forces are caused which would not occur during a regular loading.

The non-uniform stress distribution can be explained as follows. Figure a shows schematically a vertical section of a silo (diameter d) from above with an assumed flow zone (diameter d_f). A longitudinal section of the silo is drawn in figure b. The bulk solid in the flow zone which flows downwards affects not only the silo wall but also the bulk solid at rest (dead zone) with downwards directed shear stresses τ, i.e. the bulk solid in the flow zone transmits a part of its weight to the silo walls and to the bulk solid at rest (the shear stresses are drawn in their direction of action). Therefore, the stress in the flow zone decreases whereas the stress in the dead zone increases. In reality the situation is more complicated.



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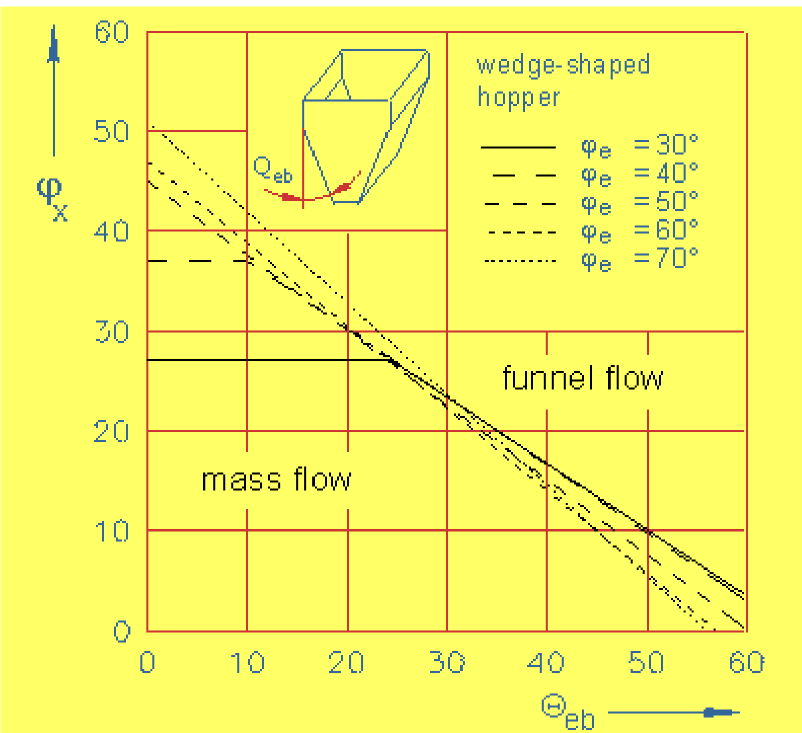
Hopper design

The flow behaviour of a bulk solid is defined by several well-defined parameters. In general, these are the bulk density ρ_b, the effective angle of internal friction φ_e (a measure for the internal friction of the bulk solid at stationary flow), the unconfined yield strength σ_c, and the wall friction angle φ_x. **For mass flow design, the wall friction angle φ_x is the most important parameter, whereby the unconfined yield strength σ_c is the most important parameter regarding arching.** The wall friction angle φ_x is defined as the friction angle between the surface of the silo wall and the corresponding bulk solid. The unconfined yield strength σ_c is the compressive strength of a bulk solid. **It has to be taken into account that all these parameters are dependent on the stress level, represented by the consolidation stress σ_1.**

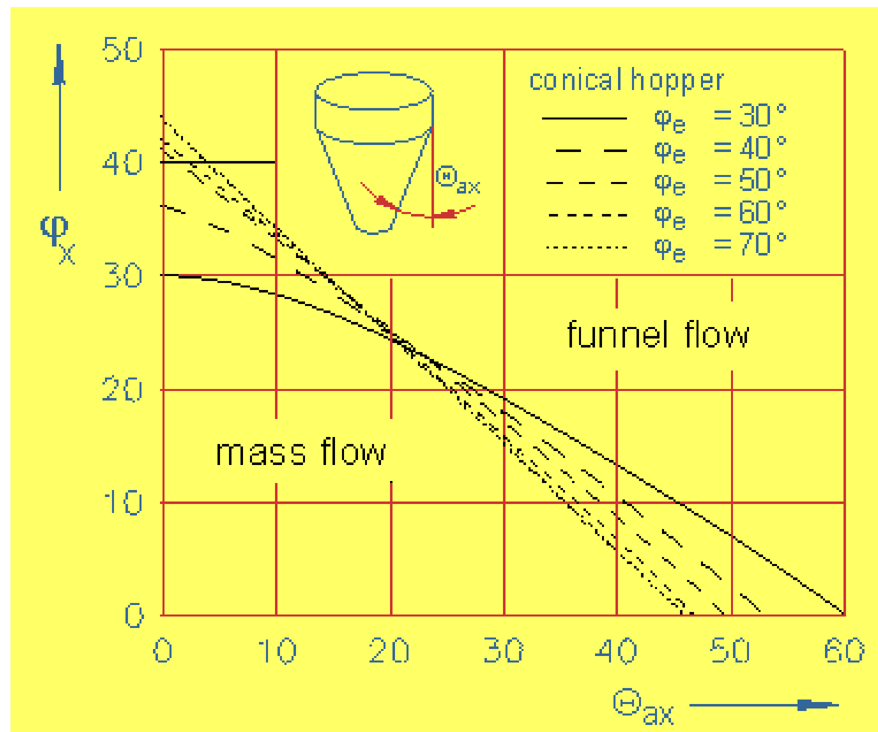
The parameters mentioned are measured in dependency on the consolidation stress with shear testers, e.g. with the Jenike shear tester or a ring shear tester. The **hopper slope required for mass flow and the minimum outlet size to prevent arching** can be calculated with the measured values using Jenikes' theory. This method showed its validity in many cases in more than 35 years.

Hopper design

The borders between funnel and mass flow, which result from the calculations of Jenike, are shown in figure a for the wedge shaped hopper and in figure b for the conical hopper. In the diagrams the **wall friction angle φ_x** is drawn over the **hopper slope angle Θ** measured against the vertical. The **effective angle of internal friction φ_e**, which is a measure of the internal friction of the bulk solid, is the parameter of the mass flow/funnel flow borderlines. The borderlines separate all pairs of values leading to mass flow from those leading to funnel flow.



a: Design diagram for mass flow (wedge-shaped hopper) (Jenike)



b: Design diagram for mass flow (conical hopper) (Jenike)

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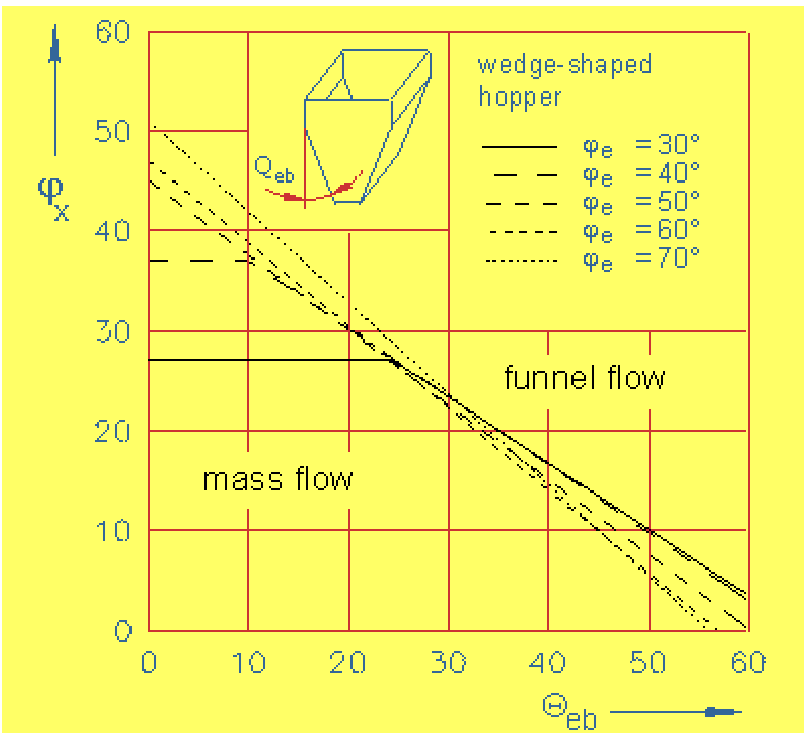
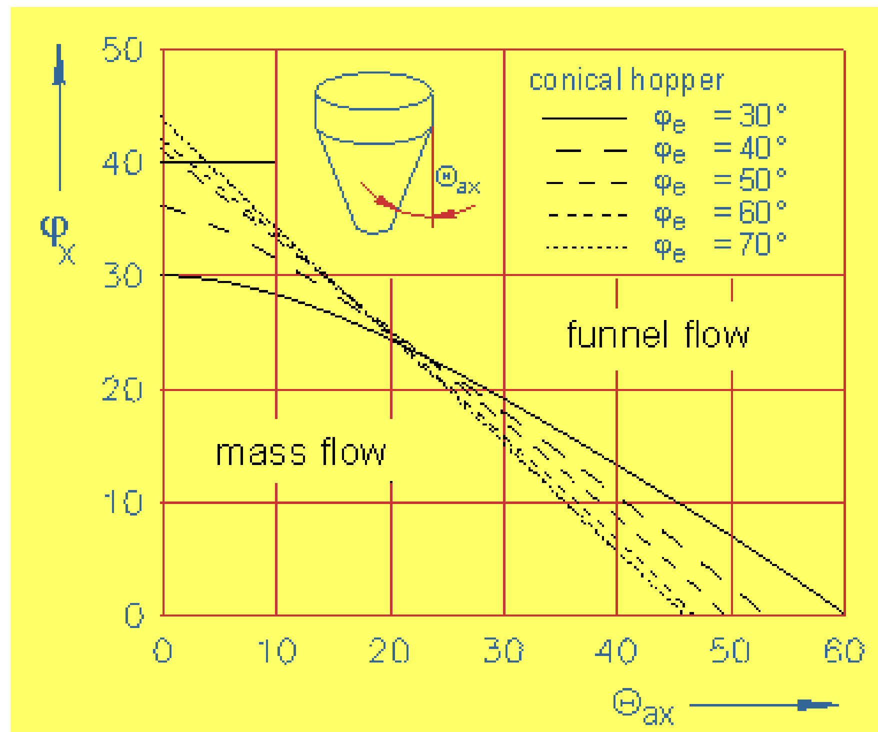
Hopper design

Conditions which lie within the borderline yield mass flow whereas funnel flow is present in case of conditions outside of the borderline. If the wall friction angle φ_x and the effective angle of internal friction φ_e are known (measured with a shear tester, e.g. with the ring shear tester), the maximum slope angle Θ of the hopper wall against the vertical which ensures mass flow can be determined with this diagram. The courses of the borderlines indicate, that **the larger the wall friction angle φ_x is, the steeper (smaller Θ) the hopper has to be for mass flow**. The wedge shaped hopper allows a somewhat (often 8° to 10°) larger slope angle Θ against the vertical with the same material properties. That means that the walls of a wedge shaped mass flow hopper can be flatter than the walls of a conical mass flow hopper.



a: Design diagram for mass flow (wedge-shaped hopper) (Jenike)



b: Design diagram for mass flow (conical hopper) (Jenike)

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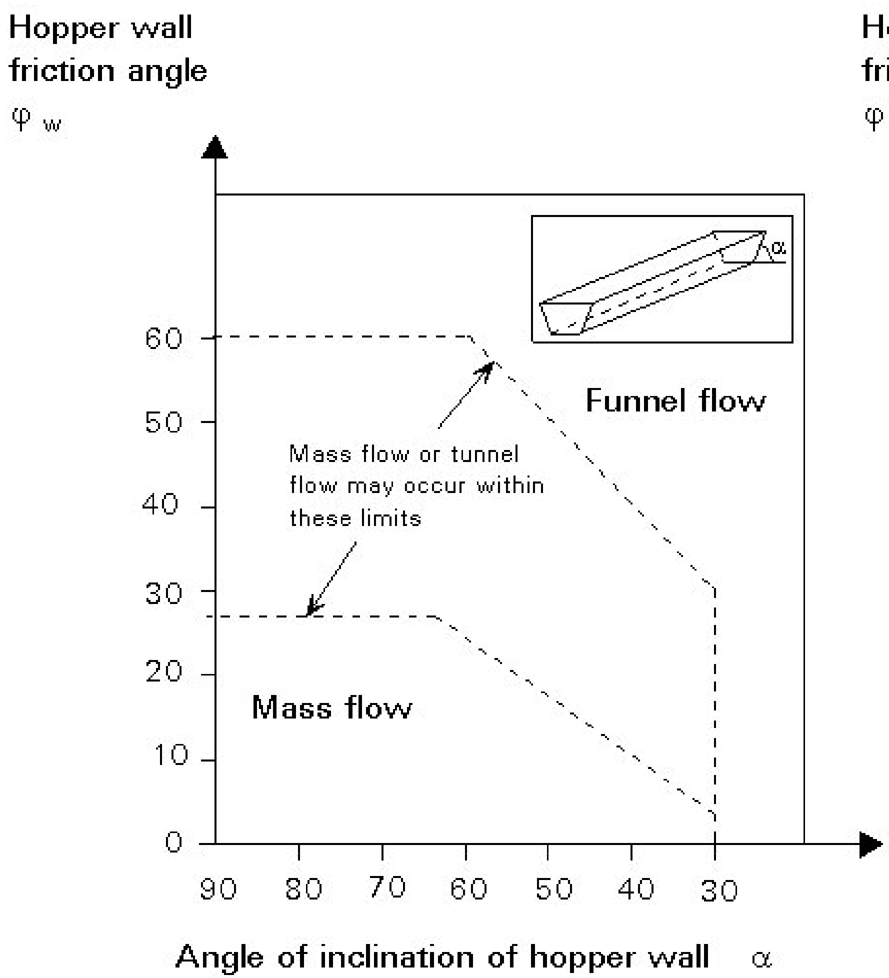
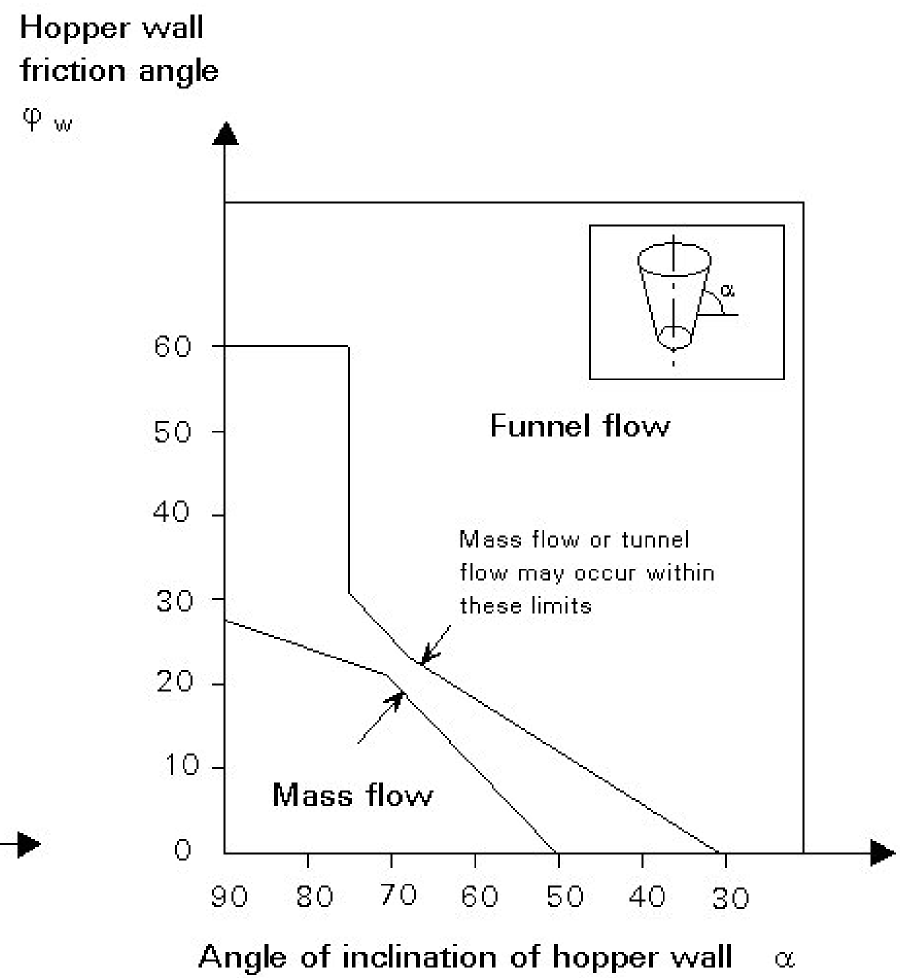
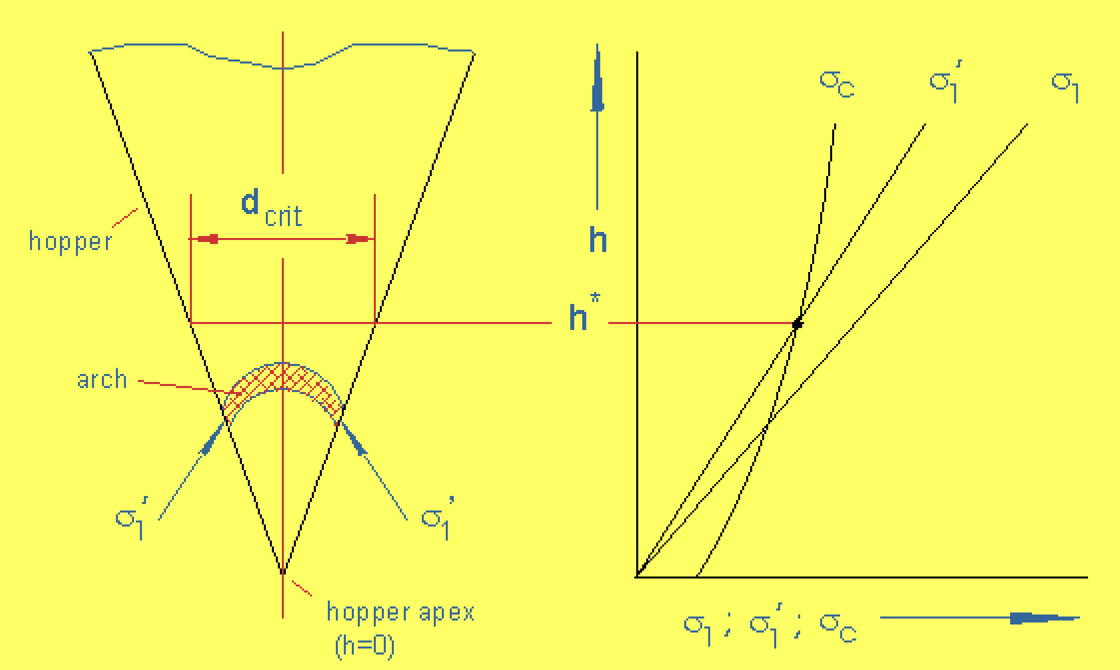
EC1 method for hopper design

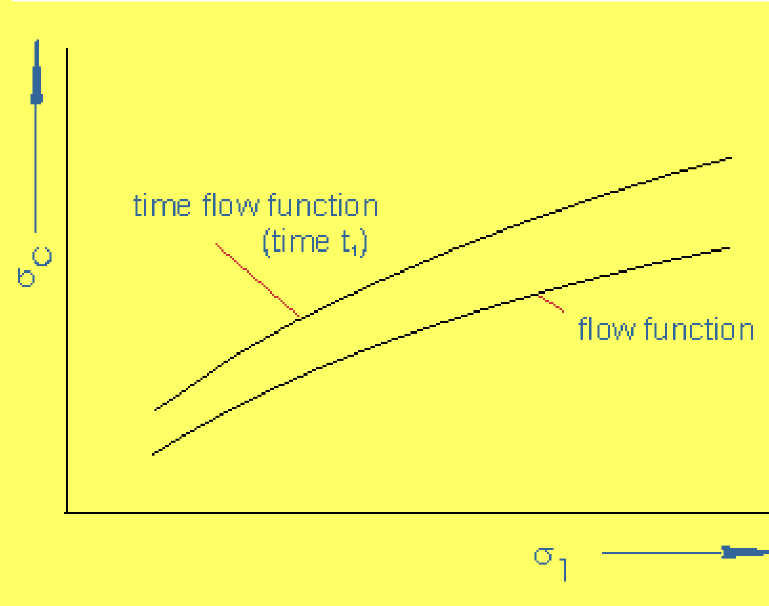
EC1 gives a graphical method (see Figure) for determining the flow pattern in conical and wedge shaped hoppers for the purpose of structural design only. Bins with hoppers between the boundaries of both the mass and the funnel flows should be designed for both situations.







a: Stress conditions in the hopper (emptying)



b: Flow function and time flow function

Evaluation of outlet diameter

When bulk solid is **discharged** from a mass flow silo, the **radial stress field prevails** in the hopper. In the hopper (at least beneath a sufficiently large distance from the vertical section) the major principal stress σ_1 is proportional to the local hopper diameter (figure a). It decreases to zero towards the imaginary hopper apex. The stress σ_1 acts as a **consolidation stress** thus determining the properties of the bulk solid, e.g. the bulk density ρ_b and the unconfined yield strength σ_c. **The unconfined yield strength σ_c of a bulk solid can be measured for each major principal stress (consolidation stress) σ_1.** The function $\sigma_c = f(\sigma_1)$ (figure b) is called the **flow function.** Usually, the unconfined yield strength increases with the consolidation stress. If the flow function has been measured, the unconfined yield strength σ_c can be drawn in figure a at each position of the hopper.

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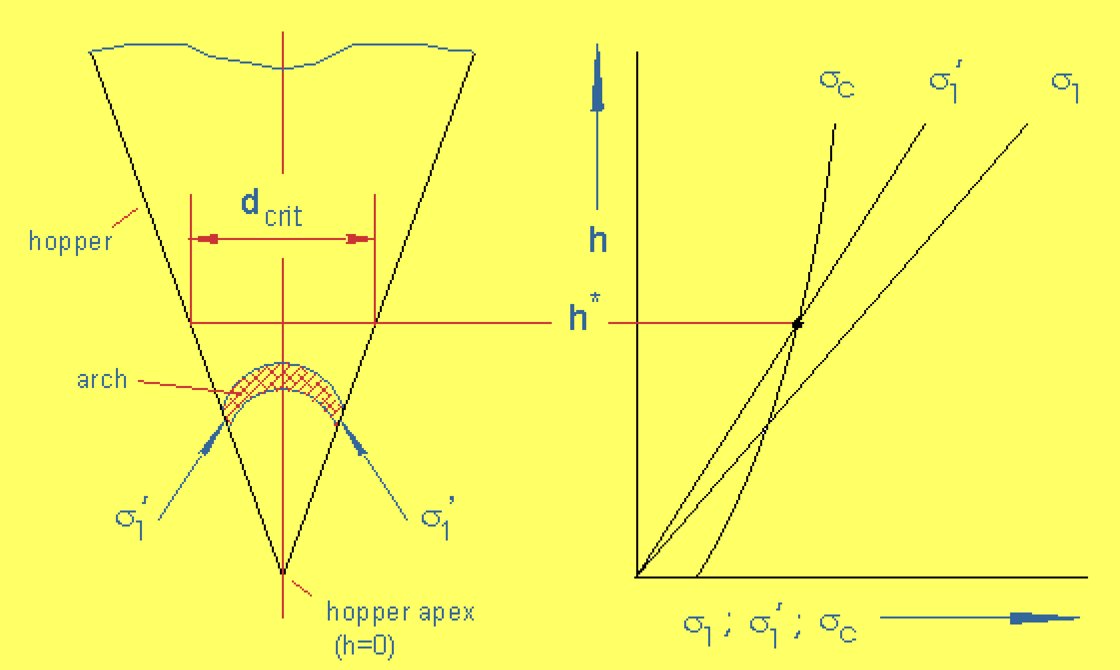

Figure a: Stress conditions in the hopper (emptying)

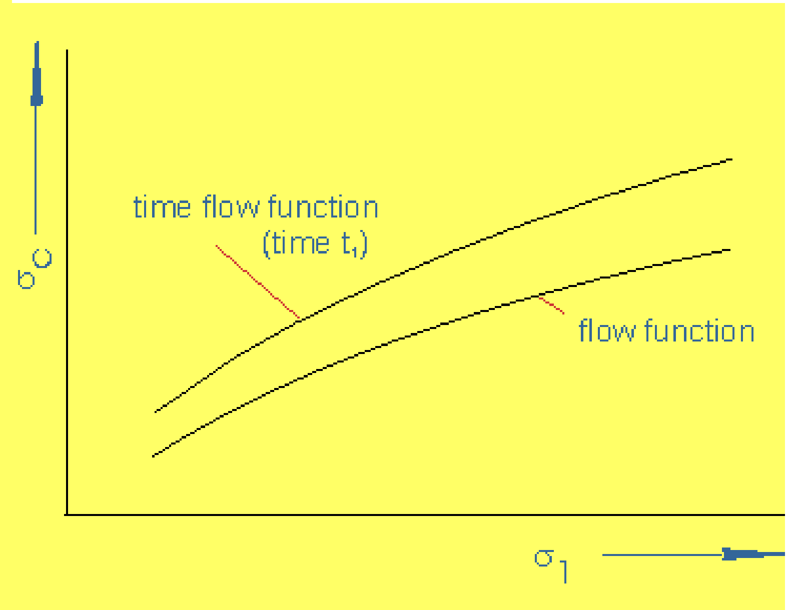

Figure b: Flow function and time flow function

Evaluation of outlet diameter

σ_1' is the **bearing stress** acting where an imaginary stable arch of bulk solid is carried by the hopper walls. σ_1' is proportional to the local hopper diameter such as σ_1. An arch can only be stable in that area of the hopper where **the unconfined yield strength σ_c is larger than the bearing stress σ_1'** . This is the case beneath the point of intersection of the σ_c curve with the σ_1' curve. Above that intersection the unconfined yield strength is smaller than the bearing stress of the arch. In this case, the unconfined yield strength is not large enough to support an arch, i.e. an arch would not be stable at this position. **The point of intersection indicates the lowest possible position in the hopper (height h*, figure a) for an outlet opening large enough to avoid arching.** The diameter of this minimum outlet opening is called **d_{crit}.** If a smaller outlet opening would be chosen, h* indicates up to where flow promoting devices have to be installed beginning at the outlet.

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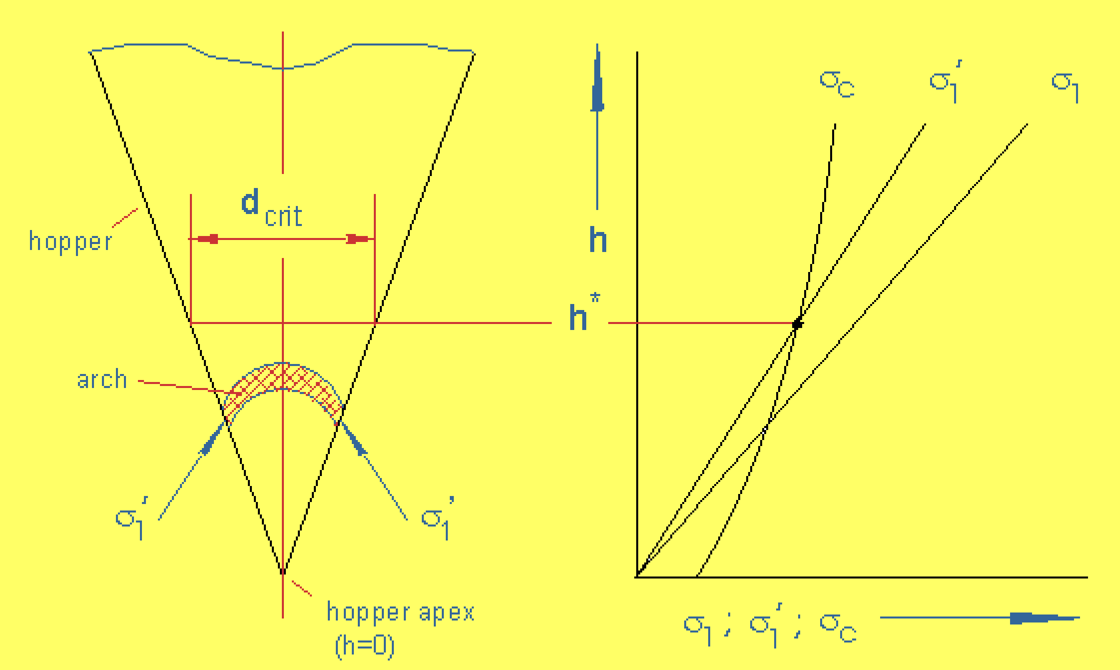

Figure a: Stress conditions in the hopper (emptying)

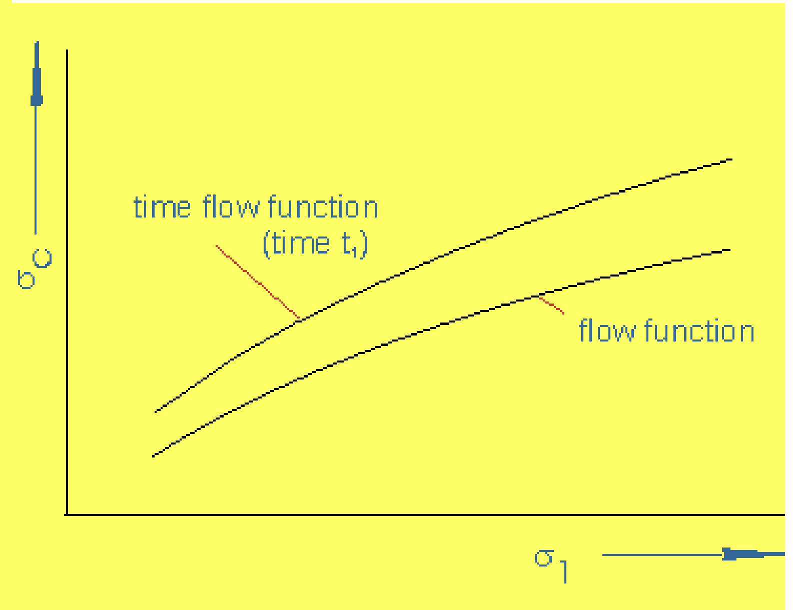

Figure b: Flow function and time flow function

Evaluation of outlet diameter

Some bulk solids tend to **consolidate increasingly with the period of storage at rest** (time consolidation). It can be found a time flow function $\sigma_{ct} = f(\sigma_1)$ (figure b) for each storage time analogously to the flow function. If the time flow function would be drawn in figure a then this would yield to a point of intersection of the σ_1'-curve and the σ_{ct}-curve, which would be above the already determined point of intersection of the σ_{1c}- and σ_1'-curves. This means that **larger outlets** are required to prevent arching with increasing storage time at rest.

For practical silo design, equations or diagrams derived by Jenike are used to determine the stresses σ_1 and σ_1' in dependence on the flow properties measured (φ_e, φ_x, ρ_b) and the silo geometry (Θ). With this means the minimum outlet sizes of conical as well as wedge-shaped hoppers can be calculated. Furthermore, the minimum outlet sizes for avoiding ratholing at funnel flow can be determined.

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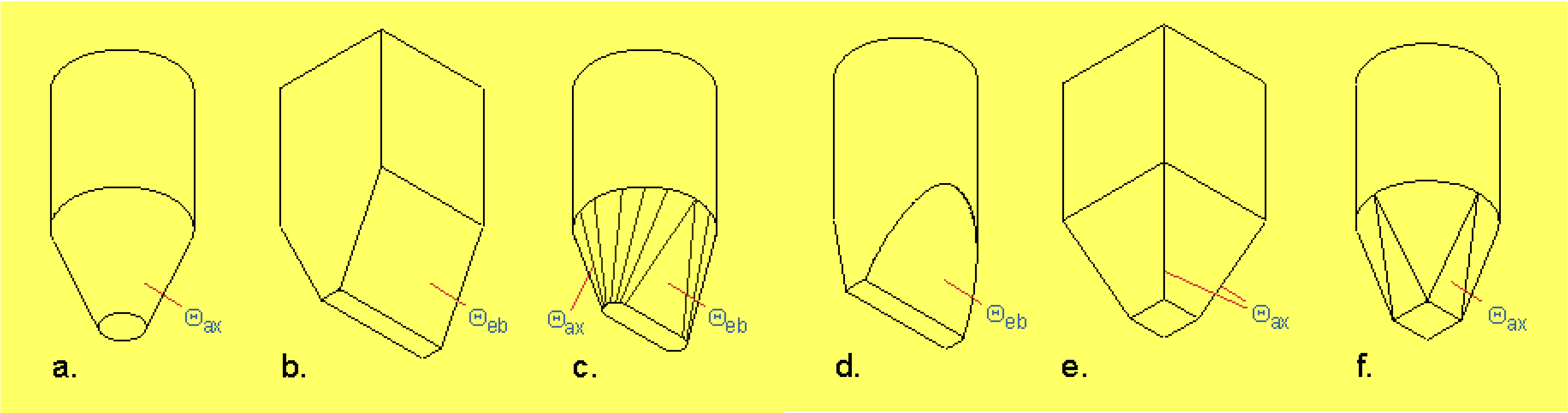
Choice of the hopper geometry

The figure shows some opportunities to design **mass flow silos**. The calculations of Jenike (see design diagrams, previous slide) refer to conical hoppers (a) and wedge shaped hoppers (b). In case of these basic hopper forms, the maximum slope angles of the walls to achieve mass flow (Θ_{ax} in case of a conical, Θ_{eb} in case of a wedge-shaped hopper) and the outlet dimensions (d, b) to prevent arching can be determined. In case of the wedge shaped hopper it is assumed, that the influence of the vertical end walls can be neglected if the length of the outlet L is at least three times the width b. The variants c and d are advantageous as well to ensure mass flow if the maximum slope angles as indicated in the figure are not exceeded. The pyramidal hopper geometry (e) is disadvantageous because the bulk solid has to flow from the top in the edges of the hopper and in the edges to the outlet. Thus, the bulk solid has to overcome wall friction at two sides what supports the formation of dead zones. If mass flow has to be achieved with such a hopper geometry, the edges have to be rounded on the inside, and the maximum slope angle against the vertical of the edges must not exceed Θ_{ax}.



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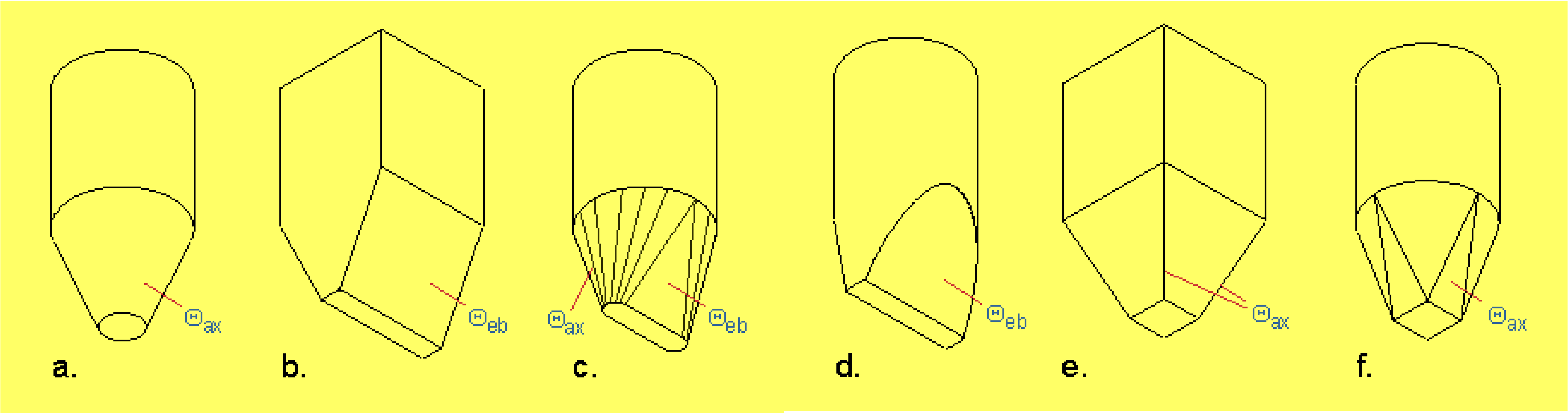
Hopper forms

Because the walls of a pyramidal hopper are always steeper than the adjacent edges, a pyramidal mass flow hopper is steeper than a conical hopper for a specific bulk solid. Variant f is just a transition from a cylindrical section to a square outlet. In this case, the slope of the hopper walls against the vertical must not exceed Θ_{ax} at any position.
In order to achieve mass flow, variants e and f must have the steepest walls. The conical hopper (a) can be designed more shallow, and the largest slope angles measured against the vertical can be achieved with geometry b,c or d (wedge-shaped hoppers).
In some industries non-symmetrical silos are preferred (e.g. pyramidal hoppers with differently sloped walls). From the view of mass flow design, there is no reason to build such silos. If mass flow has to be achieved, symmetrical hoppers usually require the lowest height for the transition from the silo cross-section to the outlet cross-section to achieve mass flow .



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Hopper forms

Silo collapse

Failures due to Design Errors

Bending of circular walls caused by eccentric withdrawal
Large and/or non-symmetric pressures caused by inserts
Ignoring flow patterns and material properties
Special considerations with bolted tanks and r.c. construction
Special considerations concerning temperature and moisture

Failures due to Construction Errors

Incorrect material
Uneven foundation settlement
Design changes during construction

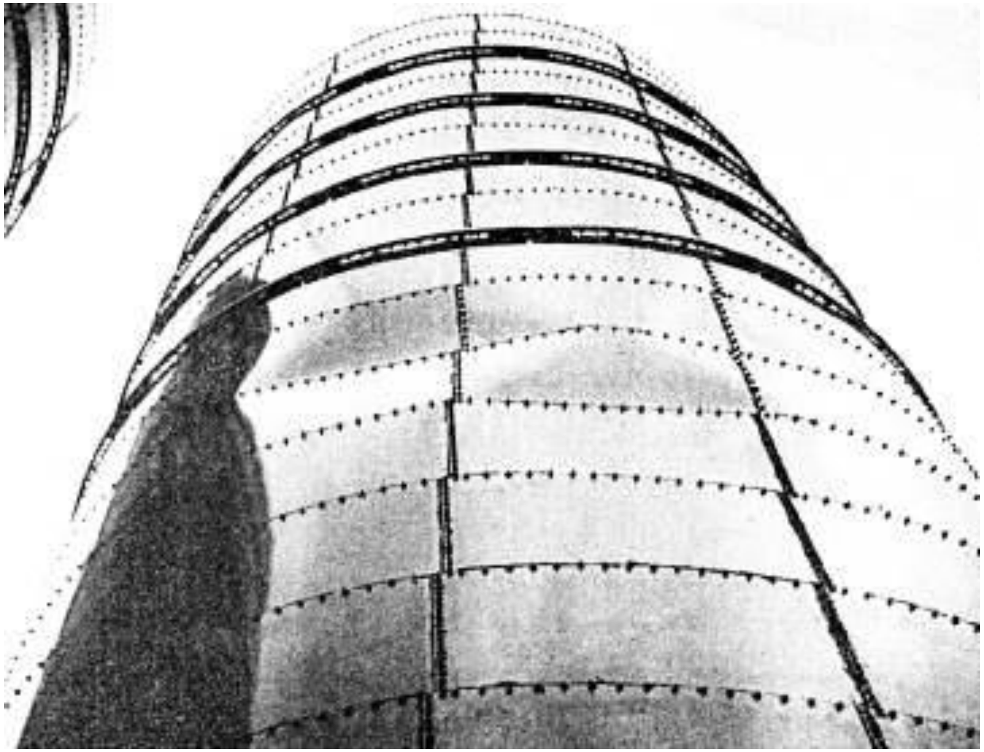
Failures Resulting from Silo Usage

Dinamic loads due to collapsing arches or ratholes, self-induced vibrations or explosions
Changes in flow patterns
Improper sequence of silo emptying
Lack of ventilation during emptying
Buckling of unsupported walls

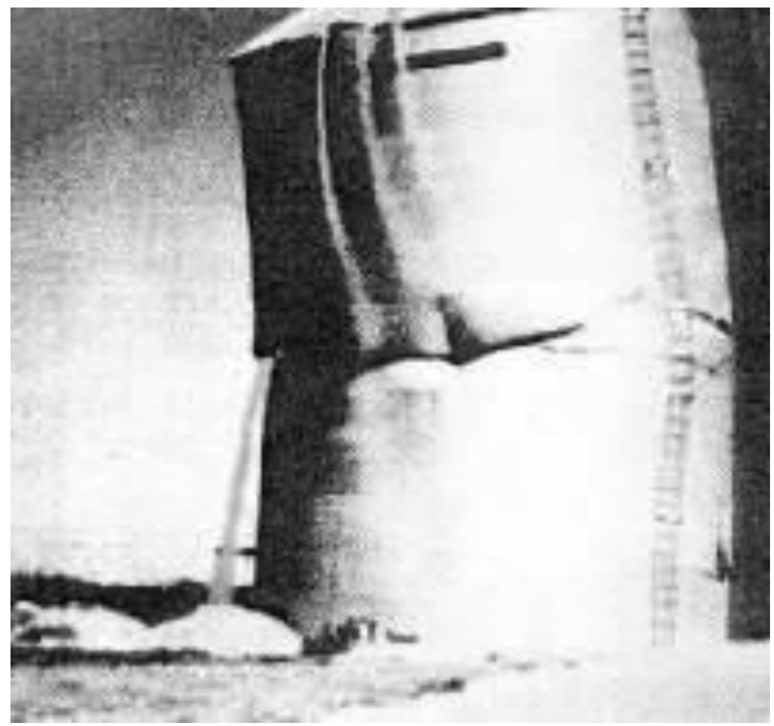
Failures Due to Improper Maintenance

Corrosion and erosion
Lack of routine inspection
Improper reaction to signs of distress

Silo collapse



Silo collapse due to buckling



Silo collapse due to buckling

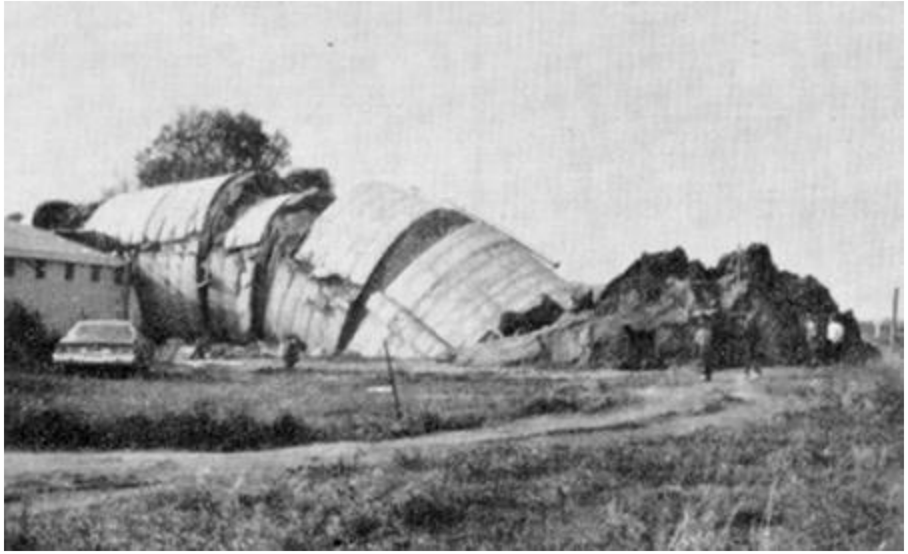
A grain silo had collapsed unexpectedly during filling. An examination revealed that the support structure of the silo had failed in **buckling**. The collapse was due to a combination of non-uniform loading caused by uneven filling of the storage compartment and the extremely poor quality of welding of the main support member pipes to the base plate.
The fillet weld shown in the photograph below illustrates a lack of significant fusion between the weld deposit and the base plate.

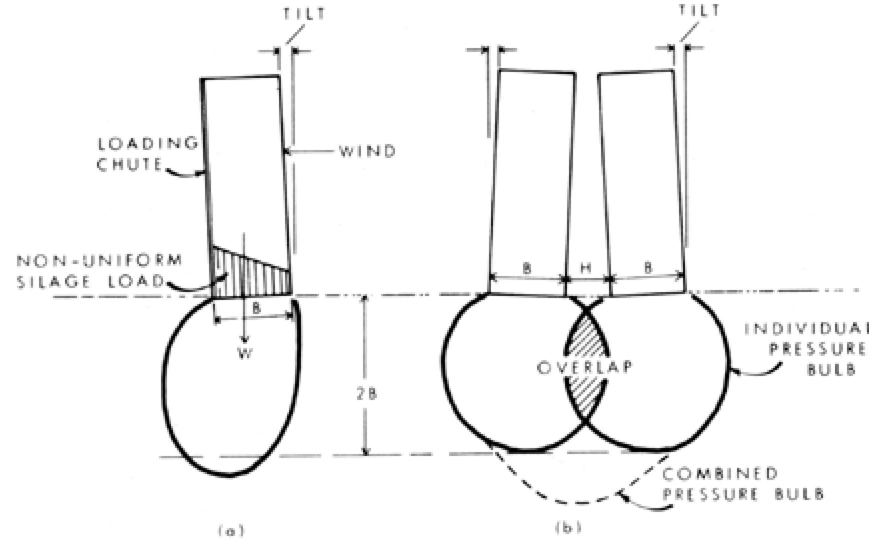
Silo collapse due to buckling

Silo collapse due to buckling

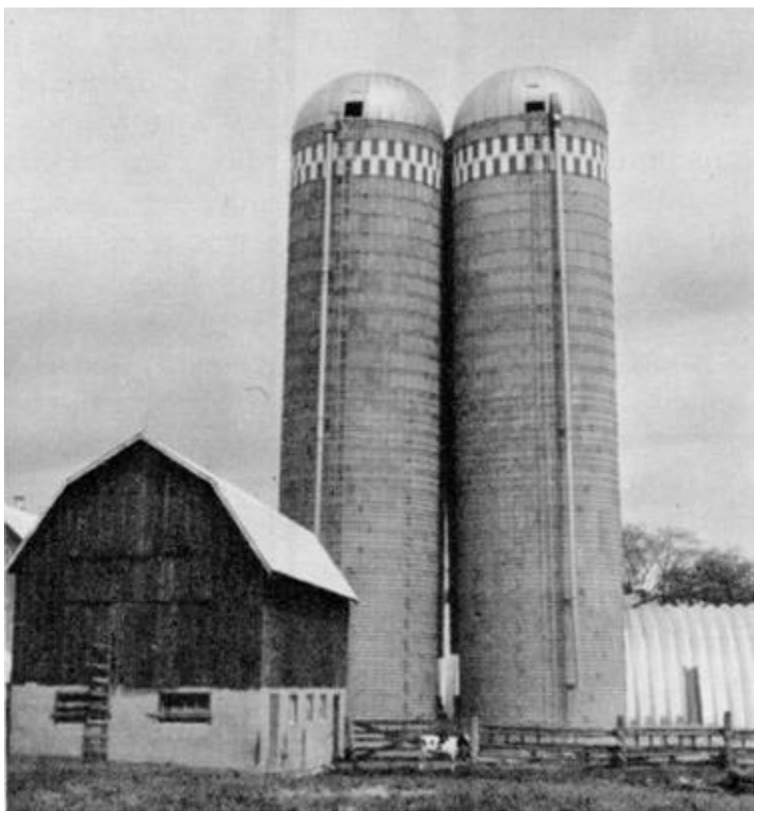
Silo collapse due to earthquake

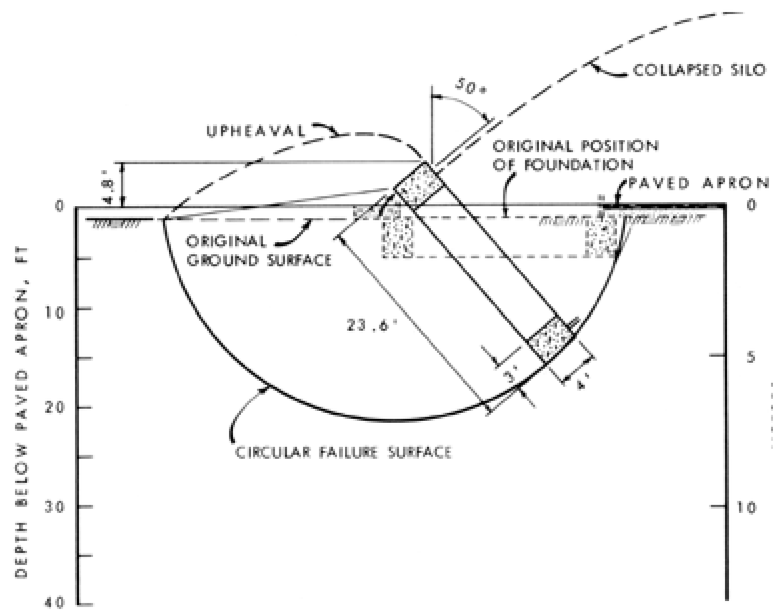
Guatemala Earthquake 1976. Collapse of a
corrugated steel grain silo in Villalobos



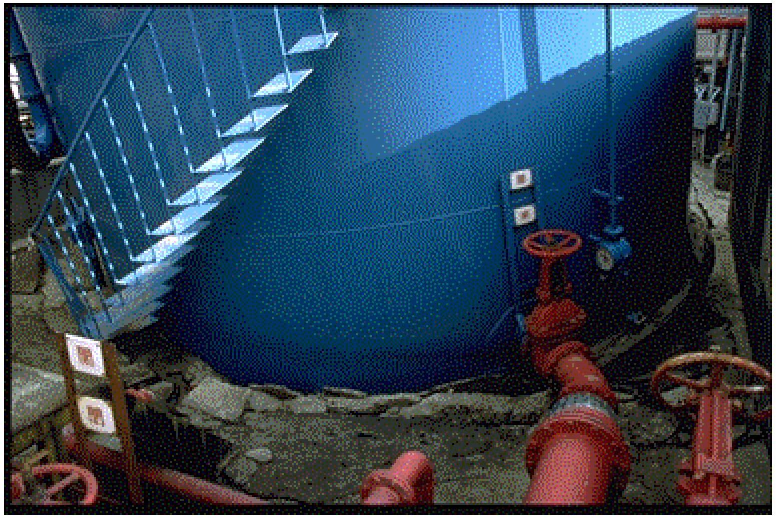


Silo collapse due to uneven settlement

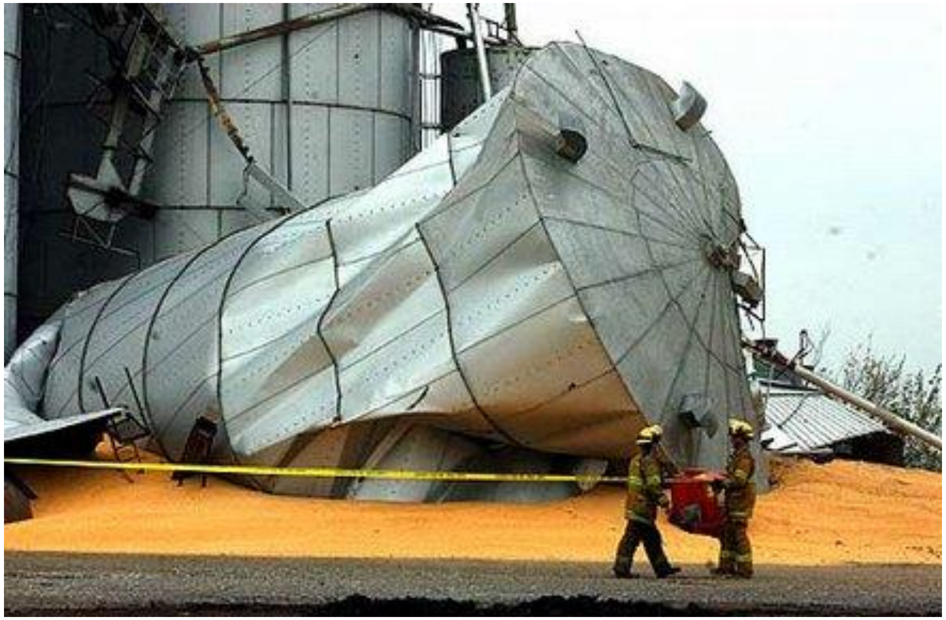




Silo collapse due to uneven settlement



Silo collapse due to failure of the supporting structure



Silo collapse due to vacuum

Silo demolition