Silos

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Lecture 20: 28/02/2014

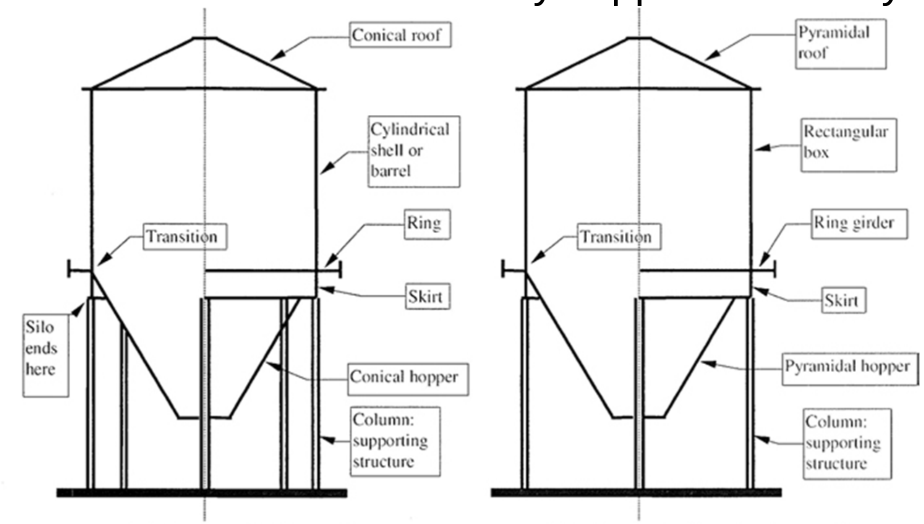
European Erasmus Mundus Master Course

Sustainable Constructions
under Natural Hazards and Catastrophic Events

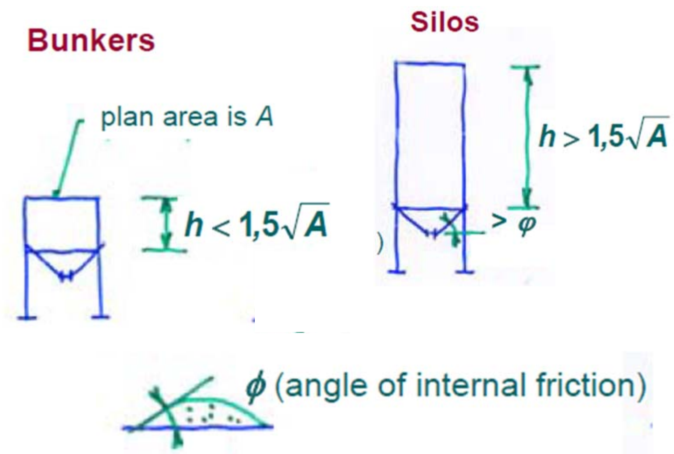
520121-1-2011-1-CZ-ERA MUNDUS-EMMC

Silos

- Silos are used by a wide range of industries to store bulk solids in quantities ranging from a few tones to hundreds or thousands of tones.
- The term silo includes all forms of particulate solids storage structure, that might otherwise be referred to as a bin, hopper, grain tank or bunker.
- 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.



a) Circular planform silo b) Rectangular planform silo



Terminology used in silo structures

Flat Bottom Silos

Used for long-term storage of large quantities of grain, seeds and granular products

Hopper Silos

Storage of grains (cereals, seeds, legumes, industrial products and other products) that require special storage conditions

Truck load silos

Are used for the storage and subsequent delivery of bulk products

Basis of design

Classification of two parameters, the size and the type of operation into consequence classes

Consequence classes depending on size and operation

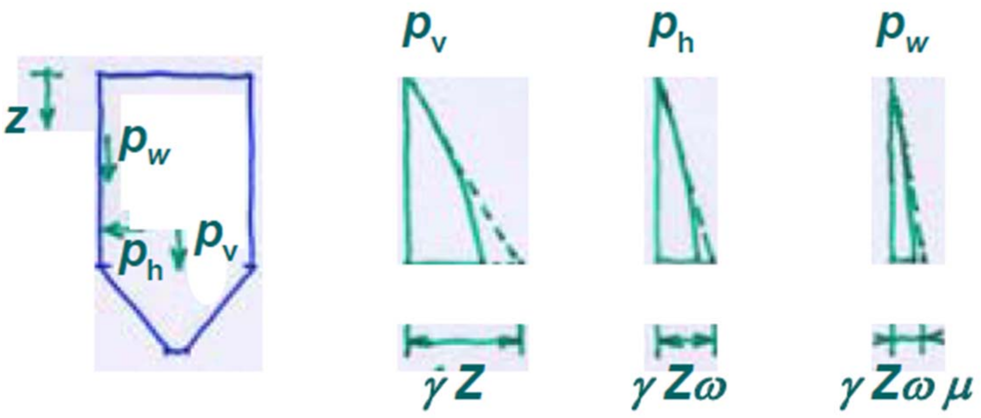
Consequence Class	Design situations
Consequence Class 3	Ground supported silos or silos supported on a complete skirt extending to the ground with capacity in excess of W_{3a} tonnes Discretely supported silos with capacity in excess of W_{3b} tonnes Silos with capacity in excess of W_{3c} tonnes in which any of the following design situations occur: a.eccentric discharge b.local patch loading c.unsymmetrical filling
Consequence Class 2	All silos covered by this Standard and not placed in another class
Consequence Class l	Silos with capacity between W_{1a} tonnes† and W_{1b} tonnes

† Silos with capacity less than W_{1a} tonnes are not covered by this standard.

Class boundary	Recommended value (tonnes)
W_{3a}	5000
W_{3b}	1000
W_{3c}	200
W_{1b}	100
W_{1a}	10

Recommended values for class boundaries

- <u>Actions on silos</u>



γ unit weight $\Rightarrow F_k$
ϕ angle of internal friction
μ internal friction factor
γ_F loading factor

Coefficient of active earth pressure:

$$\omega = \mathrm{tg}^2\left(45 - \frac{\phi}{2}\right)$$

Another actions:

Temperature variation

Thermal contraction of a bin wall is restrained by the stored material. The magnitude of the resulting increase in lateral pressure depends upon the temperature drop, the difference between the temperature coefficients of the wall and the stored material, the occurrence of temperature changes, the stiffness of the stored material and the stiffness of the bin wall.

Consolidation

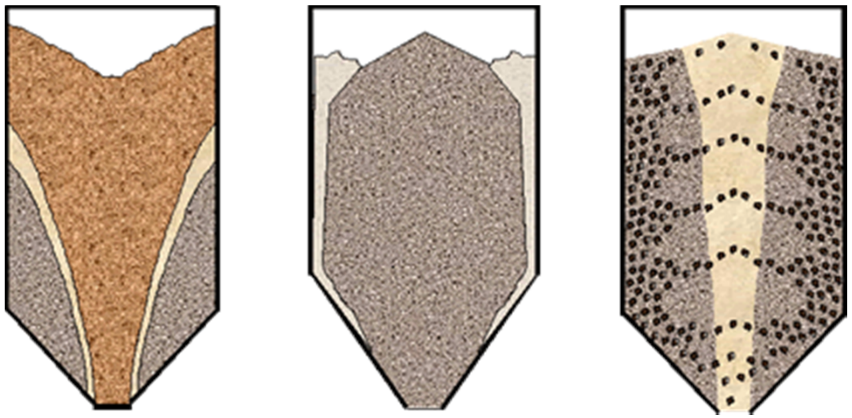
Consolidation of the stored material may occur due to release of air causing particles to compact (a particular problem with powders), physical instability caused by changes in surface moisture and temperature, chemical instability caused by chemical changes at the face of the particles, or vibration of the bin contents. The accurate determination of wall pressures requires a knowledge of the variation with depth of bulk density and the angle of internal friction.

Moisture Content

An increase in the moisture content of the stored material can increase cohesive forces or form links between the particles of water soluble substances. The angle of wall friction for pressure calculations should be determined using both the driest and wettest material likely to be encountered. Increased moisture can result in swelling of the stored solid and should be considered in design.

Segregation

For stored material with a wide range of density, size and shape, **the particles tend to segregate**. The greater the height of free fall on filling, the greater the segregation. Segregation may create areas of **dense material**. More seriously, **coarse particles** may flow to one side of the bin while **fine cohesive particles** remain on the opposite side. An **eccentric flow** channel may occur, leading to unsymmetrical loads on the wall. The concentration of fine particles may also lead to flow blockages.



Segregation patterns due to different mechanisms

Degradation

A solid may degrade on filling. Particles may be broken or reduced in size due to impact, agitation and attrition. This problem is particularly relevant in bins for the storage of silage where material degradation may result in a changing pressure field which tends to hydrostatic.

Corrosion

Stored material may attack the storage structure chemically, affecting the angle of wall friction and wall flexibility. Corrosion depends on the chemical characteristics of the stored material and also the moisture content. Typically, the design wall thickness may be increased to allow for corrosion and the increase depends upon the design life of the bin.

Abrasion

Large granular particles such as mineral ores can wear the wall surface resulting in problems similar to those described for corrosion. A lining may be provided to the structural wall, but care should be taken to ensure that wall deformation does not cause damage to the lining. The linings are usually manufactured from materials such as stainless steel or polypropylene.

Impact Pressures

The charging of large rocks can lead to high impact pressures. Unless there is sufficient material to cushion the impact, special protection must be given to the hopper walls. The collapse of natural arches which may form within the stored material and hold up flow, can also lead to severe impact pressures. In this case, a preventative solution is required at the geometric design stage.

Rapid Filling and Discharge

The rapid discharge of bulk solids having relatively low permeability to gasses can induce **negative air pressures** (internal suction) in the bin. Rapid filling can lead to greater consolidation, and the effects are discussed above.

Powders

The rapid filling of powders can aerate the material and lead to a temporary decrease in bulk density, cohesiveness, internal friction and wall friction. In an extreme case, the pressure from an aerated stored material can be hydrostatic.

Wind Loading

Design against wind loads is especially critical during bin construction.

Dust Explosions

Bins storing materials may explode should either be designed to resist the explosion or should have sufficient pressure relief area.

Differential Settlements

Large settlements often occur as bins are filled, particularly the first time. The effects of differential settlement of groups of bins should be considered. **Differential settlements may lead to buckling failure** of membrane steel bins.

Seismic Actions

Rules for seismic design are given in Eurocode 8, part 4.

Mechanical Discharge Equipment

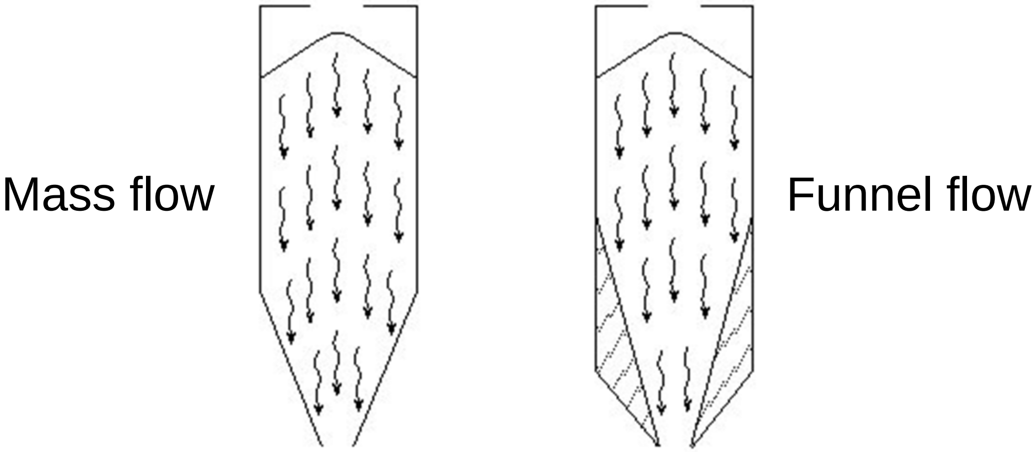
Mechanical discharge equipment can lead to unsymmetrical pressure distributions even when it is considered to withdraw the stored material uniformly.

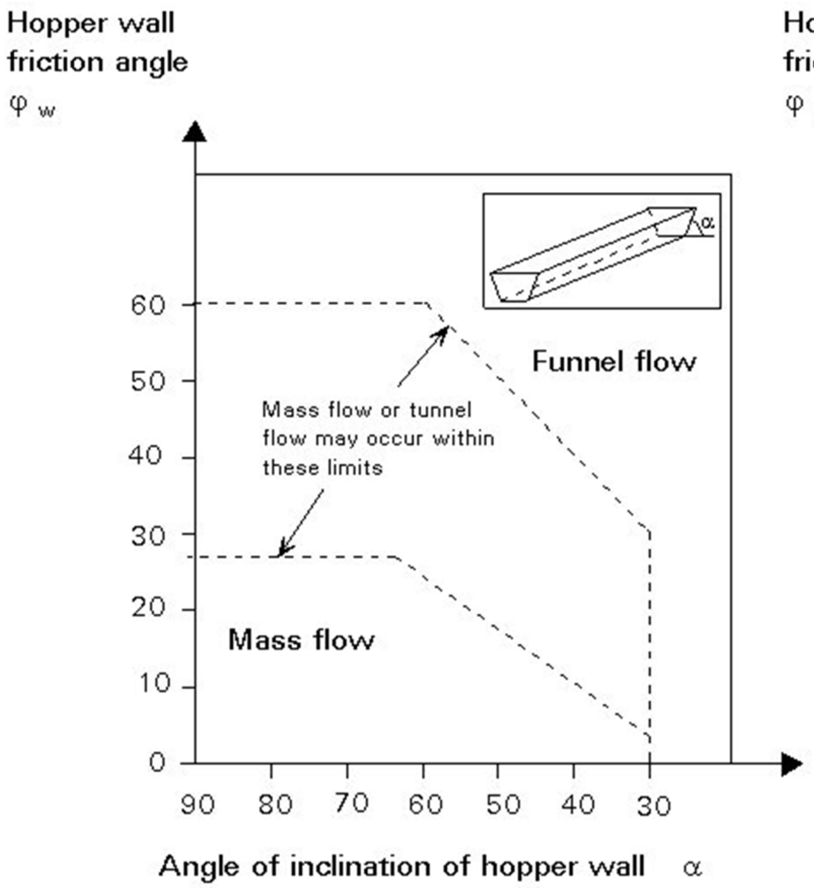
Roof Loads

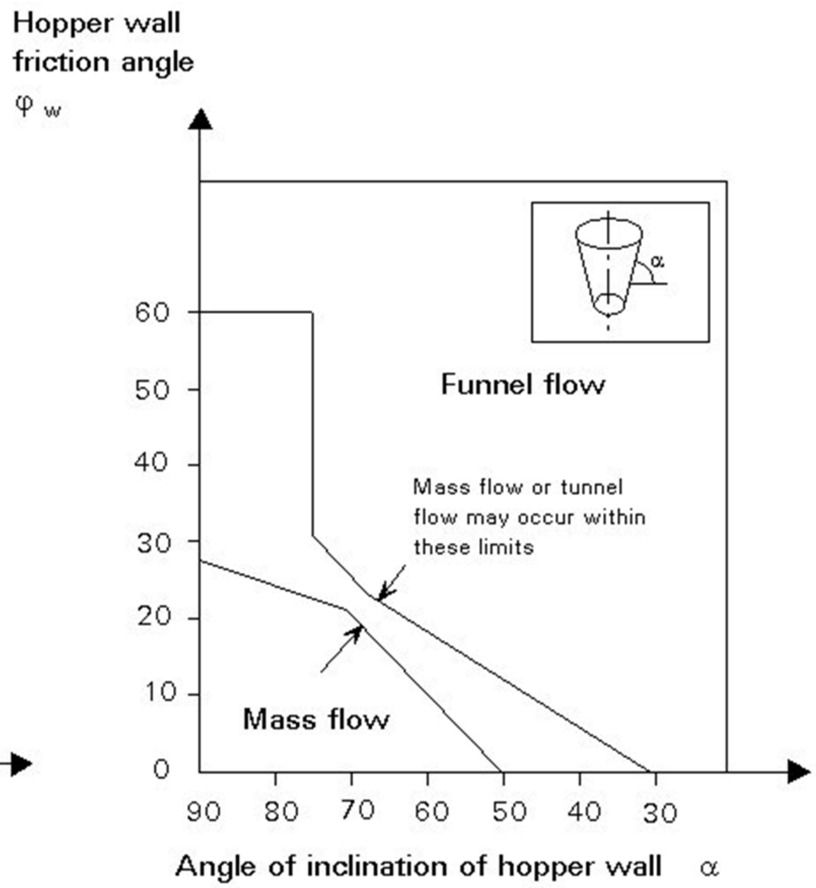
Bin roofs impose an outward thrust and axial compression on bin walls and should be considered during wall design. The design of bin roofs is beyond the scope of this lecture.

Silo design

- The design of bins and silos to store bulk solids involves bulk material, geometric, and structural considerations.
  - *Bulk material* considerations are important because the frictional and cohesive properties of bulk solids vary from one solid to another, and these properties affect material behavior considerably.
  - When considering the geometric design of a silo, potential problems include arching across an outlet, ratholing through the material, and the flow pattern during discharge.
  - Established design procedures include selection of the optimum hopper angles and minimum outlet dimensions. The ideal discharge mode is one where, at steady state, all material flows without obstruction. This is referred to as mass flow. The discharge mode where only some of the material flows is called funnel flow.







Graphical method for the determination of flow pattern

Analysis and design of silos (EN 1993-4-1)

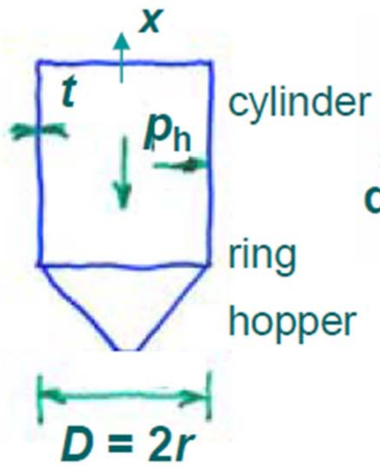
Design checks for:

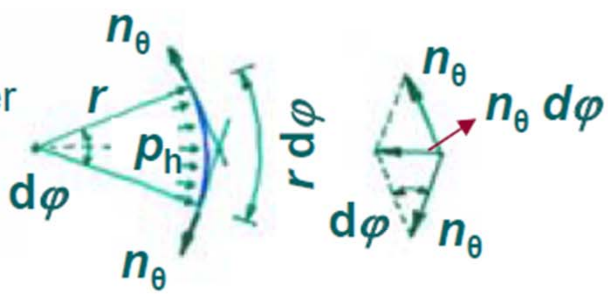
- global stability and static equilibrium,
- strength of the structure and joints,
- stability (global and local – formulas given in Eurocode),
- cyclic plasticity,
- fatigue,
- SLS (deflections and vibrations)

for Class 1 may be ignored

- Design allowance for corrosion and abrasion min. 2 mm is recommended!
- Simplified rules for circular silos in Consequence Class 1 can be used:
  - The following simplified action combinations may be considered for silos in Consequence Class 1:
    - Filling
    - Discharge
    - Wind when empty
    - Filling, combined with wind
    - A simplified treatment of wind loading is permitted.

Cylindrical silos (shell):





- **wall of unstiffened cylinder:**

from equilibrium (membrane theory)

$$p_h r\, d\varphi\, dx = n_\theta d\varphi\, dx$$

$\Rightarrow$ Membrane circumferential tension force in cylinder wall:

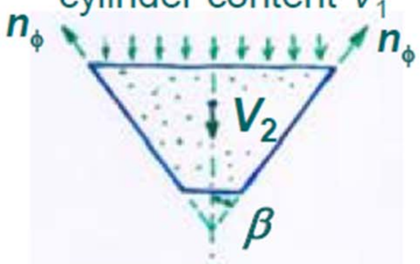
$$n_{\theta,Ed} = p_h r \le t\, f_{yd} \qquad \text{i.e.} \quad t = \frac{p_h\, r}{f_{yd}}$$

Meridian force (vertical, from weight and friction): $\boldsymbol{n_{x,Ed}}$

Strength check (Ilyushin yield criterion): $\sqrt{n_{x,Ed}^2 - n_{x,Ed}\,n_{\theta,Ed} + n_{\theta,Ed}^2} \le t\,f_{yd}$

- **wall of conical hopper:**

From equilibrium of vertical forces in ring the meridian force:



$$n_{\phi,Ed} = \frac{\sum V_{Ed}}{2\pi r \sin\beta}$$

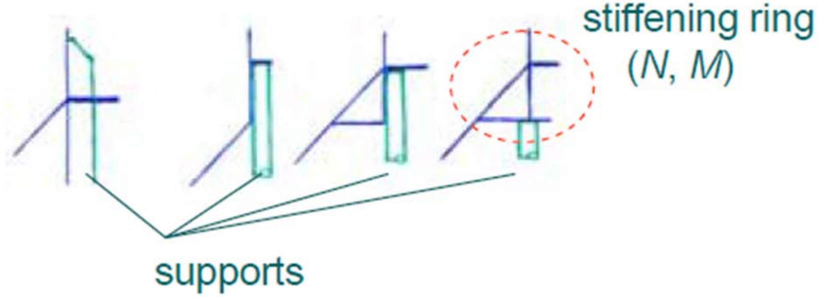
→ $V_1 + V_2$

Approximate check of hopper wall:

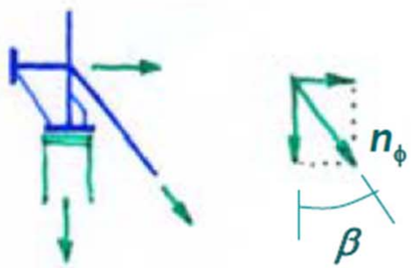
$1{,}2\; n_{\varphi,Ed} \le 0{,}90\; t\, f_{ud}$ (for $\gamma_{M2} = 1{,}25$)

→ recommended for asymmetrical loading

- **Transition junction**



loading of the ring:



Approximate circumferential compressive force in the junction (effective area of the ring A_{et} is given in Eurocode):

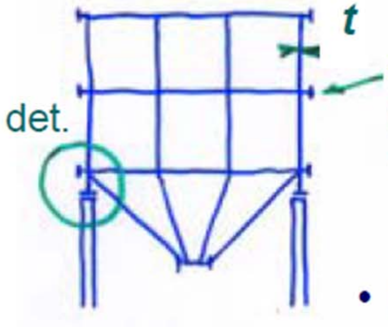
$$N_{Ed} = n_{\phi,Ed} r \sin\beta \quad \text{and} \quad \frac{N_{Ed}}{A_{et}} \leq f_{yd}$$

Except strength checks the stability (buckling) of the shell need to be assessed:

- **in vertical direction,**
- **in horizontal direction (due to wind and possible depression at discharge).**

Check formulas (critical values of internal forces, stresses) are given in Eurocode. Complex checks require FE analysis for all kinds of loadings.

Planar-sided silos



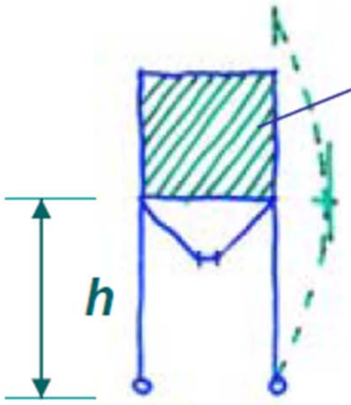
stiffeners (consider own cross-section + effective width of plate 30 t)

- **unstiffened web plates**
- **webs with stiffeners**

- **For Class 1 silos: 1st order analysis is possible.**
- **Resulting internal forces need to be checked for strength and stability.**

Analysis of supports

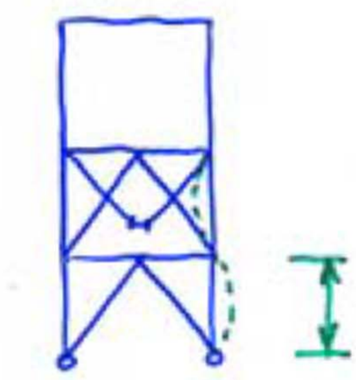
- frame support columns (needed for free passage):



can be considered with infinite (∞) rigidity.

$L_{cr} = 2h$

- truss structure:



1st order analysis may be used, no sway.

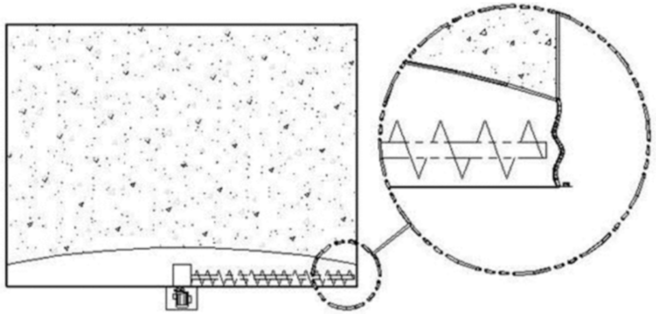
$L_{cr} = h$

Failure of silos

The major causes of silo failures are due to shortcomings in one or more of four categories:

- Failure due to design
- Failure due to construction
- Failure due to usage
- Failure due to maintenance.

Result of mass flow developing in a silo designed structurally for funnel flow



Buckling of unsupported wall above a sweep arm unloader

Failure of a grain silo

Failure due to design

- The designer must first establish the material's flow properties and design criteria, including load combinations, load paths, primary and secondary effects on structural elements, and the relative flexibility of the elements.

1999 Kocaeli, Turkey earthquake

Failure due to construction errors

- In the construction phase, there are two main problems that can cause potential failures:
    - The more common of these is poor workmanship. Faulty construction, such as using the wrong materials and uneven foundation settlement are two examples of such a problem. Uneven settlement is rare but when it does occur, the consequences can be catastrophic since usually the center of gravity of the mass is well above the ground.
    - The other cause of construction problems is the introduction of badly chosen, or even unauthorized, changes during construction in order to expedite the work or reduce costs.

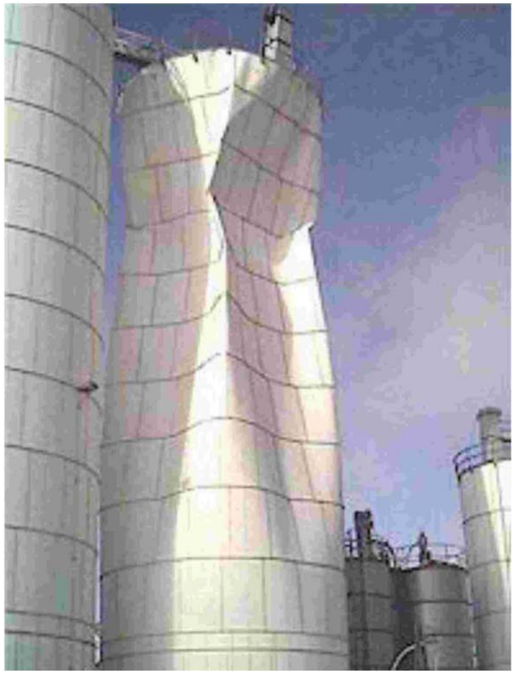
Failure due to usage

- Problems can arise when the flow properties of the material change, the structure changes because of wear, or an explosive condition arises. If a different bulk material is placed in a silo than the one for which the silo was designed, obstructions such as arches and ratholes may form, and the flow pattern and loads may be completely different than expected.

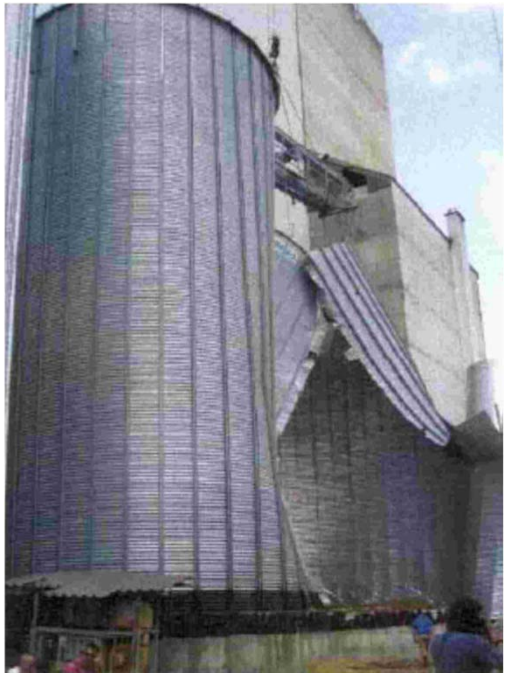
Arching

Ratholing

Flow problems experienced in an improperly designed



Damage to upper part of silo due to flow problems



Burst silo had fallen onto adjacent silo on left causing collateral damage (most probably due to improper emptying process)

Failure due to improper maintenance

- Maintenance of a silo comes in the owner's or user's domain, and must not be neglected. Two types of maintenance work are required:
  - The first is the regular preventative work, such as the periodic inspection and repair of the walls and/or liner used to promote flow, protect the structure, or both. Loss of a liner may be unavoidable with an abrasive or corrosive product, yet maintaining a liner in proper working condition is necessary if the silo is to operate as designed.
  - The second area of maintenance involves looking for signs of distress (e.g., cracks, wall distortion, tilting of the structure) and reacting to them. If evidence of a problem appears, expert help should be immediately asked.

This lecture was prepared for the 1st Edition of SUSCOS (2012/14) by Prof. Josef Macháček (CTU) and Michal Jandera, PhD. (CTU).

Adaptations brought by Florea Dinu, PhD (UPT) for 2nd Edition of SUSCOS

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