SOLID STORAGE
(SILO DESIGN AND WAREHOUSE)

FE 467 FOOD PLANT DESIGN

PROF. DR. MUSTAFA BAYRAM
UNIVERSITY OF GAZIANTEP
FACULTY OF ENGINEERING
DEPARTMENT OF FOOD ENGINEERING
GAZIANTEP-TURKEY
PROFDRMUSBAY

REV: 2017 SEPTEMBER
NOTE:
FROM FE 366 DON’T FORGET

This semester you have to prepare PID drawing

P&ID Diagram *(YOU WILL DRAW THIS FOR YOUR PROJECT* (Fe 467 Design II) The details of PID will be learned at FE 403 Food Process Control
Some benefits of grain storage

In most countries grains are among the most important staple foods. However they are produced on a seasonal basis, and in many places there is only one harvest a year, which itself may be subject to failure.

This means that in order to feed the world’s population, most of the global production of cereals (maize, wheat, rice, sorghum, millet) must be held in storage for periods varying from one month up to more than a year.

Grain storage therefore occupies a vital place in the economies of developed and developing countries alike.
Some benefits of grain storage

When there are significant inter-seasonal price variations, small farmers often store their grain in silos for speculative gain.

Even when sourcing supplies from local producers, traders and millers must hold stocks to cover the needs of their urban clientele.

The Government may become involved in storage for the purpose of stabilising prices and revenues to farmers.

Governments' overriding concern for national food security includes:

- a food security reserve
- a price stabilisation stock
- national storage reserves designed to supply most or all consumer needs in urban areas, and in rural deficit areas.
Some benefits of grain storage

Grain has to be handled in large volumes and at great speed, for example at port facilities, railway & truck terminals or at mills. This is only possible with silo storage and corresponding handling equipment.

From the tank of the harvester the grain can be transferred mechanically to a bulk truck, from there to a bulk store or silo, and from there to a mill.

This completely eliminates the use of the bags in the system, and overcomes problems of labour shortage and congestion which sometimes occur with a bag handling system as well as avoiding rodents, insects and other spoils, due to humidity or long term storage.
Some benefits of grain storage

Early harvest also avoids what are often substantial losses from shredding and lodging that can occur should harvest be delayed. In some circumstances being able to achieve a quick early harvest allows necessary time to prepare the ground for a subsequent crop, an opportunity that may have been lost without drying and storage capacity.

Silo storage capacity also provides growers with the facilities for better post harvest management of grain. Blending grain can substantially reduce downgrading losses due to screenings and protein levels.

With storage and drying capacity growers have the option to harvest grain earlier at higher moisture content, thus avoiding harvest delays and severe weather damage to grain whilst it is left in the field.
TYPES OF SOLID STORAGE

Open area

- Over soil/ground
- Under soil/ground

By using PP, PE sheet
By using pool, hill

Closed area

- Warehouse (concrete, steel, wood)
- Silo (concrete, steel, wood)
TYPES OF SOLID STORAGE

BULK

- Horizontal warehouse as bulk and packaged
- Vertical silo (concrete, steel)
  - Cylindrical
  - Cubic
  - Hexagonal

PACKAGED

- In bag (25, 50 kg bags, box, bigbag «1 ton, 2 tons») with palette or not
HORIZONTAL WAREHOUSE/STORAGE

FE 467
Dr. Mustafa BAYRAM
BULK / WAREHOUSE

FE 467
Dr. Mustafa BAYRAM
PACKAGED TYPE-WAREHOUSE

FE 467
Dr. Mustafa BAYRAM
Bag-Bigbag-Palette
BULK SILO/HOPPER/BUNKER

- Concrete
- Wood
- Steel/Iron/Galvanized (smooth surface or corrugated/hadveli)
  - Cylindrical
    - Conical bottom
    - Flat bottom
- Square
- Hexagonal
**TYPES OF SILOS**

- Steel/Iron/Galvanized (smooth surface or corrugated/hadveli)
  - Cylindrical
  - Conical bottom

### Farm silos

<table>
<thead>
<tr>
<th>MODELO</th>
<th>CAPACIDAD</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>ALTURA TOTAL</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>M³</td>
<td>TONS (100 KG/M³)</td>
<td>MM.</td>
<td>MM.</td>
<td>MM.</td>
<td>MM.</td>
</tr>
<tr>
<td>GC231/T67P4</td>
<td>9.6</td>
<td>6.25</td>
<td>726</td>
<td>1.140</td>
<td>2.245</td>
<td>1.125</td>
</tr>
<tr>
<td>GC233/T67P4</td>
<td>19.07</td>
<td>12.59</td>
<td>726</td>
<td>3.240</td>
<td>2.245</td>
<td>1.125</td>
</tr>
<tr>
<td>GC234/T67P4</td>
<td>23.80</td>
<td>15.47</td>
<td>726</td>
<td>4.560</td>
<td>2.245</td>
<td>1.125</td>
</tr>
<tr>
<td>GC235/T67P4</td>
<td>28.60</td>
<td>18.45</td>
<td>726</td>
<td>5.880</td>
<td>2.245</td>
<td>1.125</td>
</tr>
</tbody>
</table>

- Storage Volume from 9.61 m³ to 35.23 m³
- Diameters 2.3 m and 2.5 m
- pre-lacquered POLIESTER sheets or galvanized sheets
- All parts galvanisation 450 gr/m²
SPECIAL SOLUTIONS

Trailer unloading with flexible auger (aprox. 2 Ton/h, auxiliary nozzle)

Optional SYMAGA supply
Poultry and farm installations
Hopper Silos, without structure

Small Hopper Silos

Diameters
3.0 m up to 6.10 m

Capacities
30 m³ up to 266 m³

Without compression ring

Hopper slopes
45° / 60° / 66°
Hopper Silos, with structure

Hopper Silos

Diameters
4.6 m up to 12.23 m

Capacities
153 m³ up to 2,600 m³

With compression ring

Hopper slopes
45° & 60°
Flat Bottom Silos

Diameters
4.6 m up to 32.08 m

Capacities
81 m³ up to 26,000 m³

Conical concrete bottom

Diameters
4.6 m up to 12.23 m

Capacities
88 m³ up to 2,642 m³
Unloading of silo with free flowing grain/flat silo

**UNLOADING STEPS**

- **Main slide**
  - Electrical driven

- **Auxiliary slide gate**
  - Manually operated
Flat bottom-Mass discharge

“Non free flowing materials”: Soja cake, Rape cake, DDGS, etc

Special reinforced silos and MASS DISCHARGE SYSTEMS
Sweep Augers

Sweep augers of HEAVY DUTY INDUSTRIAL design, explosion proof and accomplish with ATEX norm.

“S” types: Vertical drive by electric motor and gear-angle placed inside the silo. Electric feeding by rotary collector. Equipment certified Ex II 2 D T=125°C 94/9/EC directive (compatible zone 21 inside the silo).

“SCD” types: Horizontal drive by electric motor and belt transmission under closed casing, placed under the silo. Equipment certified Ex II 1/2 D T=125°C 94/9/EC directive (compatible zone 20 inside the silo and zone 21 outside)

Clearing screw for sweep augers:

- REQUIRED
  - For oil seeds (soya, sunflower)
  - For wood pellets, paddy rice, peas

- ADVISED
  - For barley, oat, rye, rape seeds
CONSTRUCTION OF SILO

FULL RAW MATERIAL TRACEABILITY IMPLEMENTED FOR ROOFS, BODY SHEETS AND STIFFENERS
First roof,
From top to bottom
Top sheet thickness is less than the bottom

**OIL EXTRACTION PLANT**
Soybean and sunflower

MHP, Ukraine, Katerinopol - 3 silos 32.08/19 with a capacity of 20,000 m³ each
1 silo 9.20/18 T45 for dryer

**STEEL SILO STORAGE PROVIDES:**
Compared to concrete silos, more economical, easy and fast to build,
to install and maintain (almost inexistent maintenance in steel silos).
CACAO BEANS
Ghana / Africa

1 silo 350/6T66 for structure
COMPARISON OF WAREHOUSE AND SILO
COMPARISON FLAT STORAGE – ROUND STEEL SILO

Storage of 5000 tons wheat (6600 m3) requires 1 building of approx:

25 m (width) x 55 m (length) x 4 m (usefull wall height)

Ground surface = 1.375 m²

aprox. 181.000 € (sep. 2010)

Storage of 5000 tons wheat (6600 m3) requires 1 SILO of approx:

Diameter 22,15 m x wall height 14,9 m x total height 21,3 m.

Ground Surface = 386 m² (-72%)

aprox 75.000 € (sep. 2010) (-58%)
COMPARISON CEMENT SILO AND STEEL SILO

Thickness of wall
Hygiene
Cleaning
Aeration
Fast construction
Price
Service life
Contamination and breaking of wall
Thickness of wall

Concrete silo

- Diam 22 Meters
- Concrete Volumen
- Wall thickness: 250 mm
- Wall thickness: 350 mm

Corrugated Steel silo

- Wall thickness: 2-3 mm
- Wall thickness: 4-5 mm
ADVANTAGES OF STEEL SILO

STEEL SILO STORAGE PROVIDES:

Easy handling

Possibilities of great charge and discharge capacities (e.g. a 100 ton/hour elevator will give the possibility to unload 4 to 5 trucks/hour)

Truck discharge unit

(Tireme-Pitting hole)
STEEL SILO STORAGE PROVIDES:

Steel grain silos, provides effective protection to rodents and insects.
STEEL SILO STORAGE PROVIDES:

Long term storage is possible, reduction of spoil, with aeration and temperature control systems and in combination e.g with dryers.
STEEL SILO STORAGE PROVIDES:

- Reduction of labour costs and resources
- Low maintenance,
- Low resources for filling / emptying
- High automation potential
STEEL SILO STORAGE PROVIDES:

- No losses due to pilferage, rodents, rats etc.
- No chance of damage due to rains.
- Automatic loading & Unloading.
- Facility of moisture control and thereby preventing the damage to grain due to excessive moisture level.
- More quantity could be stored in less space.
COMPARISON OF CONICAL AND FLAT BOTTOM SILOS

Benefits of steel hopper bottom silos

• Easier foundations, no tunnels for the handling equipment below silos needed, no aeration channels in the foundations needed.
• Due the above no problems with ground water
• Better maintenance & accessibility of handling equipment, as it is completely over ground
• No problems with humidity for the conveyors as these are over ground
  • No problems with incoming humidity into silos through silo foundations (no problems of sealing concrete foundation to silo bottom of the flat bottom silos)
  • 100% emptying of silo per gravity,
  • No need of sweep augers, so no maintenance for these, less electrical consumption.
  • No need on manual sweeping silo after discharge (the sweep never cleans 100% of the silo, there is always a rest remaining on the ground)
  • Technical optimum solution of continuous grain movement is expected
IMPORTANCE OF GALZANIZATION

Galvanization:

SYMAGA silos are manufactured with steel of corresponding to European UNE-EN-10326

SIMILAR but ABOVE
American Standard ASTM 525 A G-140, with

Other Manufacturers provide

American Standard G-115
similar to Z350 according EN-10326

American Standard G-90,
(similar to Z270 according EN-10326)

450 gr/m² galvanization
Z 450

427 gr/m²

350 gr/m²

270 gr./m²
Loss of Zink

<table>
<thead>
<tr>
<th>CATEGORY</th>
<th>Corrosivity</th>
<th>Average loss of Zink per year in ym</th>
</tr>
</thead>
<tbody>
<tr>
<td>C1</td>
<td>Very Low</td>
<td>0.1</td>
</tr>
<tr>
<td>C2</td>
<td>Low</td>
<td>0.1 to 0.7</td>
</tr>
<tr>
<td>C3</td>
<td>Medium</td>
<td>0.7 to 2.1</td>
</tr>
<tr>
<td>C4</td>
<td>High</td>
<td>2.1 to 4.2</td>
</tr>
<tr>
<td>C5</td>
<td>Very High</td>
<td>4.2 to 8.4</td>
</tr>
</tbody>
</table>

ISO – 9223: categories of corrosivity of the atmosphere

*Service life is defined as the time to 5% rusting of the steel surface. 1mil = 25.4 μm = 0.56 cz/ft²*
STANDARDS OF SILO DESIGN

Calculation Norms...

- **E.E.U.U.**
  - ACI 313-77 (1997)
  - >90%

- **GERMANY**
  - DIN 1055 / 6 (2000)

- **FRANCE**
  - SNBATTI (1986)
  - P22-630 (1992)

- **CANADA**
  - CFBC (1990)

- **RUSSIA**
  - GOST 25627 - 83 (1983)

- **EUROPE (IN SHORT)**
  - EUROCODE for LOADS and STRUCTURES
  - ≤3%
Loads in silos

Flow of Bulk Solids in Silos
Liquid vs. Bulk Solid

Tank with liquid
Silo with bulk solid
Vertical stress

ANSI LOAD-DIN (EUROCODE SIMILAR) LOAD COMPARISON

Fh
Fv

ANSI LOADS
DIN/EUROCODE LOADS

TYPICAL DIN LOAD-ANSI LOAD COMPARISON, ON SILO Ø 12,23 m.

Silo Weight

Comparación ANSI-DIN

Peso DIN
Peso ANSI

Silo height

FE 467
Dr. Mustafa BAYRAM
External factors for silo calculation

Snow

Seismic actions

Wind
SNOW LOADS

SNOW LOAD INFLUENCE ON SILO ROOF WEIGHT

Weight of silo roof with snow load silo 840

RESULT OF POOR SILO ROOF DESIGN
SPECIAL ROOF STRUCTURES

Roof WAVE with special geometry and LONGITUDINAL bending during manufacturing:

- great resistance and stiffness to roof sectors
- Easy to reinforce
- Watertight
- Fully overlapping
- Self supporting roof up to 12.23 m. of diameter
SEISMIC INFLUENCE ON SILOS

Factors for silo calculation

Seismic actions
Anchorbolts for different seismic factors

“0”

“+”

“++”

Silicone around silo: last body sheet is difficult to apply, and to seal against water to avoid water.

Inside silo elevated, water penetration avoided

Outside and inside of silo at same level

Foundations solution
Wind rings

- Wind increases its speed between silos, and its pressure

DRAG FORCE

- **WIND RINGS** avoid bending of empty silos and increase its rigidity
WALL SHEETS AND STIFFNERS IMPORTANCE

Short distance between horizontal joint bolting & 2 or 3 narrow stiffener rows per body sheet

Improve silo wall resistance to avoid...
SPECIAL EQUIPMENTS IN SILO
ATEX-EXPROOF ELECTRICITY

DUST EXPLOSION: Due to increase dust pressure and ignition from electrical equipment

ATEX Solution on silos

- EC Declaration of conformity of Bursting panels
- ID Plate
- Panels mounted on frame on silo roof
- Easy erection and maintenance / easy exchangeability
- Panels with rupture sensors switch

Explosion gate at silo and elevators:

Every thin sheet (when dust exploded → thin sheet thrown.)
Temperature control system

Our standard temperature control system is explosion proof and accomplish with ATEX norm:

Zone 20 ATEX.

Certificate: EX II (1)GD [EEx ia] IIA LOM 04ATEX2069X.

- Cables are installed from outside of the roof, so easy accessible for installation, inspection, and maintenance.

- Cable can be pulled out of the silo even full of grain for maintenance & inspection.
CATWALKS & SUPPORTS DESIGNED, CALCULATED AND MANUFACTURED BY symaga

➢ Tubular Handrail system

➢ Single
➢ Double
➢ Column with overhang
➢ Double with overhang

DESIGN ACCORDING CONVEYOR LOAD, SNOW LOAD, SILO DIAMETER, ETC
SPEED REDUCER FOR FRAGILE PRODUCTS

Conical flowing down of free flowing material (CONICAL speed reducer)

HELEZONIC (SCREW) type system for free flowing material (SCREW speed reducer)

Wall sliding speed reducer:

Photo for screw system used in nut industry for filling silo to prevent breaking kernel (screw type speed reducer)

Dr. Mustafa BAYRAM
Wrong discharge and silo damage

Correct working of side discharge system is only possible by defined inner buckets on inner silo wall.

Excenter unloading causes uneven loads and is detrimental to silo stability.

Unloading by gravity is only allowed through center outlet.

Fig. 5, End-result of mass flow developing in a silo designed structurally for funnel flow.
SIDE DISCHARGE SYSTEMS

➢ Allows to discharge up to 70% of the silo capacity (depending on model) to truck or floor conveyor, without the use of energy.
If you prefer only two pipe for side discharging from wall; You can use the following procedures:
Silo Protection

Isolation to protect grain from environmental temperature

SILO CLADDING / SILO PROTECTION

➢ Thermal protection

➢ Additional corrosion protection to the silo, based on GALVANIZED & POLYESTER coated steel sheets.

Insulating material local supply
FLAT BOTTOM SILO CONSTRUCTION
General view for flat bottom silo

Diagram:
- Insulated elevated
- Vent
- Corrugated / ondula
- Metal sheet
- Earthquake join
- Concrete part

Dr. Mustafa BAYRAM
BASIC INFORMATION ABOUT SILO SYSTEMS

Distribution of product:

- height of elevator is higher.
- angle of repose for pipe is important.
Discharging of flat bottom silo /tunnel
Experience in......

Sunflower

Maize

Kork and wood chips

Animal Feed

Malt and Barley
Experience in......

Malt and Barley

Wood Pellets

Rape Seeds

Paddy Rice

Wheat

Cacao beans
Truck discharge unit
(Tereme-Pitting hole)
BIOETHANOL PLANT,
La Coruña, Spain
6 Silos Ø 24.44
Maize
MALTING PLANT
ABA / Nigeria

8 Silos 1680/10
4 Silos 920/13T45
1 Silo 840/12T60
4 Silos 830/13T45
1 Silo 687/12T45
Germany, Tangermünde Silos

Wood Pellet Hopper silos
6 silos Ø 610/14T45
Slovakia, SOKOLCE

6 silos Ø 14,51/14

Delivery Silo on structure
Color difference on the wall sheet is due to galvanization difference.
SILO DESIGN
TYPES OF BINS

- Conical
- Pyramidal
- Wedge/Plane Flow

Watch for inflowing valleys in these bins!
THE FOUR BIG QUESTIONS

1- What is the appropriate flow mode?
2- What is the hopper angle?
3- How large is the outlet for reliable flow?
4- What type of discharger is required and what is the discharge rate?
MATERIAL/PRODUCT CONSIDERATIONS FOR HOPPER DESIGN

• Is it a fine powder (< 200 microns)?
• Is the material abrasive?
• Is the material elastic?
• Does the material deform under pressure?
FLOW MODES

Mass Flow - all the material in the hopper is in motion, but not necessarily at the same velocity

Funnel Flow - centrally moving core, dead or non-moving annular region

Expanded Flow - mass flow cone with funnel flow above it

Fig. 6: Mass flow (on the left), funnel flow (on the right)
MASS FLOW

Material in motion along the walls

Typically need 0.75 D to 1D to enforce mass flow

Does not imply plug flow with equal velocity
Funnel flow can result from:

- too rough and/or too shallow hopper walls,
- a feeder which discharges the bulk material only from a part of the outlet opening,
- a valve or gate which is not totally open,
- or from edges or welds protruding into the bulk solid.
EXPANDED FLOW

Funnel Flow upper section

Mass Flow bottom section
MASS FLOW (+/-)

Advantages:
+ flow is more consistent
+ reduces effects of radial segregation
+ stress field is more predictable
+ full bin capacity is utilized
+ first in/first out

Disadvantages:
- wall wear is higher (esp. for abrasives)
- higher stresses on walls
- more height is required
FUNNEL FLOW (+/-)

Advantages:
+ less height required

Disadvantages:
- ratholing
- a problem for segregating solids
- first in/last out
- time consolidation effects can be severe
- silo collapse
- flooding
- reduction of effective storage capacity
HOW TO INVESTIGATE THE FLOW PROFILE:

• Check the top of the silo.
• If homogen falling occurs (flat shape) \( \rightarrow \) mass flow, or not \( \rightarrow \) funnel flow
• Use thin rod (short and long at different silo position, near or far position on the center of silo)
• Use different colored particles by controlling their discharge orders
PROBLEMS WITH HOPPERS

• Ratholing/Piping
• Funnel Flow
• Arching/Doming
• Insufficient Flow
• Flushing
• Inadequate Emptying
• Mechanical Arching
• **Time Consolidation - Caking**
PROBLEMS WITH HOPPERS

Ratholing/Piping
RATHOLING/PIPING

• If only the bulk solid above the outlet is flowing out, and the remaining bulk solid - the dead zones -.
• The reason: 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.
PROBLEMS WITH HOPPERS

Ratholing/Piping

Funnel Flow
FUNNEL FLOW

- Segregation
- Inadequate Emptying
- Structural Issues
PROBLEMS WITH HOPPERS

Ratholing/Piping
Funnel Flow
Arching/Doming
**ARCHING/DOMING**

- If a stable arch is formed above the outlet so that the flow of the bulk solid is stopped.
- 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.

Cohesive Arch preventing material from exiting hopper
PROBLEMS WITH HOPPERS

Ratholing/Piping
Funnel Flow
Arching/Doming
Insufficient Flow
INSUFFICIENT FLOW

- Outlet size too small
- Material not sufficiently permeable to permit dilation in conical section -> “plop-plop” flow

Material under compression in the cylinder section

Material needs to dilate here
PROBLEMS WITH HOPPERS

Ratholing/Piping
Funnel Flow
Arching/Doming
Insufficient Flow
Flushing
FLUSHING

Uncontrolled flow from a hopper due to powder being in an aerated state
- occurs only in fine powders (rough rule of thumb - Geldart group A and smaller)
- causes --> improper use of aeration devices, collapse of a rathole
PROBLEMS WITH HOPPERS

Ratholing/Piping
Funnel Flow
Arching/Doming
Insufficient Flow
Flushing
Inadequate Emptying
INADEQUATE EMPTYING

Usually occurs in funnel flow silos where the cone angle is insufficient to allow self draining of the bulk solid.
PROBLEMS WITH HOPPERS

Ratholing/Piping
Funnel Flow
Arching/Doming
Insufficient Flow
Flushing
Inadequate Emptying
Mechanical Arching
MECHANICAL ARCHING

a “traffic jam” at the outlet of bin - too many large particle competing for the small outlet

$6 \times d_{p,\text{large}}$ is the minimum outlet size to prevent mechanical arching, 8-12 $x$ is preferred
PROBLEMS WITH HOPPERS

- Ratholing/Piping
- Funnel Flow
- Arching/Doming
- Insufficient Flow
- Flushing
- Inadequate Emptying
- Mechanical Arching
- **Time Consolidation - Caking**
TIME CONSOLIDATION
- CAKING

Many powders will tend to cake as a function of time, humidity, pressure, temperature

Particularly a problem for funnel flow silos which are infrequently emptied completely
• In case of centric filling, 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.
HOW IS A HOPPER DESIGNED?

Measure
- powder cohesion/interparticle friction
- wall friction
- compressibility/permeability

Calculate
- outlet size
- hopper angle for mass flow
- discharge rates
Two steps are necessary for the design of mass flow silos:

1-The calculation of the required hopper slope which ensures mass flow, and

2-the determination of the minimum outlet size (orifice) to prevent arching.
WHAT ABOUT ANGLE?

\[ \alpha: \text{angle of repose} \]

\[ \beta: \text{Sliding angle} \]
ANGLE OF REPOSE

Angle of repose is not an adequate indicator of bin design parameters

“… In fact, it (the angle of repose) is only useful in the determination of the contour of a pile, and its popularity among engineers and investigators is due not to its usefulness but to the ease with which it is measured.” - Andrew W. Jenike

Do not use angle of repose to design the angle on a hopper! (if you have data).

Use Sliding angle
Table 7.2  Densities and angles of repose of some cereal grains and oilseeds (Muir and Sinha 1988, Irvine et al. 1992, Rameshbabu et al. 1996)

<table>
<thead>
<tr>
<th>Crop</th>
<th>Cultivar</th>
<th>Bulk density (kg/m$^3$)</th>
<th>Kernel density (kg/m$^3$)</th>
<th>Porosity$^b$ (%)</th>
<th>Filling</th>
<th>Emptying</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Stand$^a$</td>
<td>Compact$^a$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bread</td>
<td>Columbus</td>
<td>780</td>
<td>856</td>
<td>1379</td>
<td>38</td>
<td>26</td>
</tr>
<tr>
<td>wheat</td>
<td>Neepawa$^c$</td>
<td>763</td>
<td>846</td>
<td>1384</td>
<td>39</td>
<td>26</td>
</tr>
<tr>
<td></td>
<td>Neepawa$^d$</td>
<td>725</td>
<td>821</td>
<td>1370</td>
<td>40</td>
<td>31</td>
</tr>
<tr>
<td>Durum</td>
<td>Coulter$^e$</td>
<td>744</td>
<td>816</td>
<td>1377</td>
<td>41</td>
<td>23</td>
</tr>
<tr>
<td></td>
<td>Coulter$^f$</td>
<td>709</td>
<td>790</td>
<td>1372</td>
<td>42</td>
<td>29</td>
</tr>
<tr>
<td>Barley</td>
<td>Bedford$^c$</td>
<td>664</td>
<td>750</td>
<td>1346</td>
<td>44</td>
<td>24</td>
</tr>
<tr>
<td></td>
<td>Bedford$^d$</td>
<td>649</td>
<td>621</td>
<td>1372</td>
<td>47</td>
<td>26</td>
</tr>
<tr>
<td></td>
<td>Condor$^e$</td>
<td>770</td>
<td>802</td>
<td>1416</td>
<td>43</td>
<td>23</td>
</tr>
<tr>
<td>Oats</td>
<td>Fidler$^c$</td>
<td>555</td>
<td>631</td>
<td>1315</td>
<td>52</td>
<td>27</td>
</tr>
<tr>
<td></td>
<td>Fidler$^d$</td>
<td>537</td>
<td>617</td>
<td>1329</td>
<td>54</td>
<td>36</td>
</tr>
<tr>
<td>Triticale</td>
<td>Carman$^c$</td>
<td>669</td>
<td>733</td>
<td>1385</td>
<td>47</td>
<td>23</td>
</tr>
<tr>
<td>Rye</td>
<td>Gazelle$^e$</td>
<td>760</td>
<td>834</td>
<td>1406</td>
<td>41</td>
<td>25</td>
</tr>
<tr>
<td>Canola</td>
<td>Candle$^f$</td>
<td>677</td>
<td>743</td>
<td>1122</td>
<td>34</td>
<td>24</td>
</tr>
<tr>
<td></td>
<td>Torch$^f$</td>
<td>664</td>
<td>746</td>
<td>1118</td>
<td>33</td>
<td>27</td>
</tr>
<tr>
<td>Mustard</td>
<td>Lethbridge$^f$</td>
<td>703</td>
<td>775</td>
<td>1153</td>
<td>33</td>
<td>26</td>
</tr>
<tr>
<td>Flax</td>
<td>Culbert$^f$</td>
<td>669</td>
<td>743</td>
<td>1152</td>
<td>36</td>
<td>27</td>
</tr>
<tr>
<td>Sunflower</td>
<td>Saturn$^f$</td>
<td>427</td>
<td>468</td>
<td>1077</td>
<td>56</td>
<td></td>
</tr>
<tr>
<td>Soybean</td>
<td>McCall$^f$</td>
<td>721</td>
<td>775</td>
<td>1250</td>
<td>38</td>
<td></td>
</tr>
<tr>
<td>Lentils</td>
<td>Eston$^g$</td>
<td>825</td>
<td>850</td>
<td>1410</td>
<td>40</td>
<td>27</td>
</tr>
</tbody>
</table>

$^a$ Standard bulk density was measured using the Canadian Grain Commission method (CGC 1991).
$^b$ Compacted bulk density was measured by slowly dropping the grain 1.6 m into a 0.5 L cup.
$^c$ Moisture content was 12.7% wet basis.
$^d$ Moisture content was 16.4%.
$^e$ Moisture content was 14%, Condor is 95% hulless, slight differences in test methods (Rameshbabu et al. 1996).
$^f$ Moisture content was 8.1%.
$^g$ Moisture content 11.6%, slight differences in test methods (Irvine et al. 1992).
(1) Cylindrical section - Janssen equation

(2) Conical section - radial stress field

Stresses = Pressures

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 Flow Function

The unconfined yield strength $\sigma_c$ increases with increasing consolidation stress $\sigma_1$. Curve A shows a typical function of the unconfined yield strength $\sigma_c$ in dependence on the consolidation stress $\sigma_1$ (figure 3). The flowability is the ratio $f_f c$ of the consolidation stress $\sigma_1$ to the unconfined yield strength $\sigma_c$:

$$f_f c = \frac{\sigma_1}{\sigma_c}$$  \hspace{1cm} (1)

The larger $f_f c$ is, the better a bulk solid flows. Often the following ranking is used:

- $f_f c < 1$: non-flowing
- $1 < f_f c < 2$: very cohesive (to non-flowing)
- $2 < f_f c < 4$: cohesive
- $4 < f_f c < 10$: easy flowing
- $10 < f_f c$: free flowing

![Graph showing unconfined yield strength in dependence on the consolidation stress; lines of constant flowability](image)

Fig. 3: Unconfined yield strength in dependence on the consolidation stress; lines of constant flowability
DETERMINATION OF Outlet/Orifice Size (Diameter (B or D))
1) EXPERIMENTAL SILO OUTLET SIZE DETERMINATION

Generally, the rate of discharge (Q) is related to the orifice diameter (D) by an equation of the form:

$$Q = k \cdot D^n$$

Log Q = log k + n . Log D

where k is proportionality constant and n is a power of about 2.5 - 3.0. It is generally found that the head of material over the orifice has no detectable effect on the rate of discharge.

Plot the calculated discharge rates against the orifice diameter on a log-log basis:

A straight line should result from which the values of k and n may be determined and hence the equation relating Q and D evaluated.
2) DISCHARGE RATES AND DISCHARGE DIAMETER (B)

Numerous methods to predict discharge rates from silos or hopper

For coarse particles (>500 microns)
  
  Beverloo equation - funnel flow
  
  Johanson equation - mass flow

For fine particles - one must consider influence of air upon discharge rate
BEVERLOO EQUATION

\[ W = 0.58 \, \rho_b \, g^{0.5} \, (B - kd_p)^{2.5} \]

where \( W \) is the discharge rate (kg/sec)

\( \rho_b \) is the bulk density (kg/m\(^3\))

\( g \) is the gravitational constant

\( B \) is the outlet size (m)

\( k \) is a constant (typically 1.4)

\( d_p \) is the particle size (m)

Note: Units must be SI
JOHANSON EQUATION

Equation is derived from fundamental principles - not empirical

\[ w = \rho_b \left( \frac{\pi}{4} \right) B^2 \left( gB/4 \tan \theta_c \right)^{0.5} \]

where \( \theta_c \) is the angle of hopper from vertical

This equation applies to circular outlets

Units can be any dimensionally consistent set

Note that both Beverloo and Johanson show that \( W \propto B^{2.5} \)!
An engineer wants to know how fast a compartment on a railcar will fill with polyethylene pellets if the hopper is designed with a 6” Sch. 10 outlet. The car has 4 compartments and can carry 180000 lbs. The bulk solid is being discharged from mass flow silo and has a 65° angle from horizontal. Polyethylene has a bulk density of 35 lb/cu ft.
One compartment = $180000/4 = 45000$ lbs.

Since silo is mass flow, use Johanson equation.

6” Sch. 10 pipe is 6.36 inch diameter = B

$$W = (35 \text{ lb/ft}^3)(\pi/4)(6.36/12)^2 \left(32.2 \times (6.36/12)/4 \tan 25\right)^{0.5}$$

$W= 23.35 \text{ lb/sec}$

Time required is $45000/23.35 = 1926$ secs or ~32 min.

In practice, this is too long – 8inch or 10inch would be a better choice.
DESIGN AND DIMENSION OF SILO

- Determine required equipment

- Determine properties of material (void, bulk density, angle of repose, sliding angle, temperature, RH%, aeration etc.)

- Determine required storage capacity and flow capacity

- Then, calculate required volume of silo (weight of product/bulk density of product)

- Then, From volume \( \rightarrow \) Calculate \( \rightarrow \) Diameter (Ds) and Height (H) of silo:

\[
\frac{Ds}{H} = \frac{2}{1} \text{ or } 1/1 \text{ or } \frac{1}{2} \text{ or } \frac{3}{4} \text{ ratios}
\]

(Use 10% head space, Don’t forget, angle of repose and sliding angle)

- Then, calculate orifice/outlet D of silo.
SILO DISCHARGING DEVICES

- Rotary valve
- Screw
- Slide valve/Slide gate/Gate valve
- Vibrating Bin Bottoms/Vibrating Grates
- others
ROTARY VALVES

Quite commonly used to discharge materials from bins.
Dead Region

Better Solution
VIBRATIONAL DISCHARGE EQUIPMENTS

- Air cannons
- Pneumatic Hammers
- Vibrators

These devices should not be used in place of a properly designed hopper!

They can be used to break up the effects of time consolidation.
AERATION OF SILO

(To control temperature, moisture content and RH%, aeration is used)
AERATION OF SILO

a) PLAN VIEW

UPWARD AIRFLOW

Figure 7. Aeration Ducts for Grain Bins

Dr. Mustafa BAYRAM
REMEMBER FE 222 FLUID MECHANICS COURSE:

CHAPTER «PACKED BED». AERATION OF SILO IS SAME.
Sol’n:
Calculate the motor requirement for this example;

First; calculate ΔP from Ergun’s Equation then

SHAFT WORK(Ws) (Watt of kW) = (ΔP/ρ) * Mair

MOTOR POWER (Watt or kW) = -Ws/n

n = efficiency of motor, fan, blower, %
ΔP = total pressure drop in system
ρ = density of air
Mair: mass flow rate of air
AERATION

(To find required fan/aspirator, we must calculated Pressure Drop (ΔP):

Correlation equations for airflow resistances through grain

1) The equation for the low velocity range of 0.004 to 0.05 m/s is:

\[
\frac{\Delta \rho}{L} = (5178 \times C_1)v^{1.11}
\]

where:

\[\Delta \rho = \text{pressure drop (Pa)},\]
\[L = \text{bed depth (m)},\]
\[v = \text{apparent or superficial air velocity (m/s), and}\]
\[C = \text{coefficients}.\]
2) The equations for the high velocity range of 0.05 to 0.35 m/s are:

\[ \frac{\Delta \rho}{L} = (8404 \times C_2) \nu^{1.28} \]

\[ \frac{\Delta \rho}{L} = (6368 \times C_3) \nu^{1.67} \]
3) Alternative formula:

Their equation is:

\[ \frac{\Delta P}{L} = C_4 (v)^{C_5} \]
<table>
<thead>
<tr>
<th>Crop</th>
<th>$C_1$</th>
<th>$C_2$</th>
<th>$C_3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soybeans</td>
<td>0.22</td>
<td></td>
<td>0.66</td>
</tr>
<tr>
<td>Corn, shelled</td>
<td>0.29</td>
<td></td>
<td>1.00</td>
</tr>
<tr>
<td>Barley</td>
<td>0.56</td>
<td>0.63</td>
<td></td>
</tr>
<tr>
<td>Oats</td>
<td>0.61</td>
<td>0.69</td>
<td></td>
</tr>
<tr>
<td>Rice, rough</td>
<td>0.67</td>
<td>0.72</td>
<td></td>
</tr>
<tr>
<td>Lentil, Eston</td>
<td>0.75</td>
<td></td>
<td>2.14</td>
</tr>
<tr>
<td>Sorghum</td>
<td>0.83</td>
<td>0.83</td>
<td></td>
</tr>
<tr>
<td>Wheat</td>
<td>1.00</td>
<td>1.00</td>
<td></td>
</tr>
<tr>
<td>Canola, Westar</td>
<td>1.60</td>
<td>1.61</td>
<td></td>
</tr>
<tr>
<td>Canola, Tobin</td>
<td>2.29</td>
<td>2.21</td>
<td></td>
</tr>
<tr>
<td>Flax</td>
<td>3.25</td>
<td>3.36</td>
<td></td>
</tr>
<tr>
<td>Clover, alsike</td>
<td>7.73</td>
<td>7.23</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Crop</th>
<th>Velocity range, m/s</th>
<th>$C_4$</th>
<th>$C_5$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Corn, shelled</td>
<td>0.014 - 0.055</td>
<td>6283</td>
<td>1.35</td>
</tr>
<tr>
<td>Sunflowers</td>
<td>0.027 - 0.115</td>
<td>7784</td>
<td>1.29</td>
</tr>
<tr>
<td>Barley</td>
<td>0.018 - 0.050</td>
<td>5387</td>
<td>1.10</td>
</tr>
<tr>
<td>Barley</td>
<td>0.050 - 0.091</td>
<td>11204</td>
<td>1.34</td>
</tr>
<tr>
<td>Wheat</td>
<td>0.013 - 0.088</td>
<td>8413</td>
<td>1.17</td>
</tr>
<tr>
<td>Canola, Argentine</td>
<td>0.012 - 0.077</td>
<td>11300</td>
<td>1.05</td>
</tr>
<tr>
<td>Flax</td>
<td>0.009 - 0.037</td>
<td>25731</td>
<td>1.06</td>
</tr>
</tbody>
</table>
INSTEAD OF CALCULATION,

READY-TO-USE GRAPHS CAN BE USED
Fig. 7.2 Airflow resistance of wheat and barley measured in farm bins with completely perforated floors in Manitoba (Friesen and Huminicki 1987)
Fig. 7.3 Airflow resistance of corn (maize) and canola (rapeseed) measured in farm bins with completely perforated floors in Manitoba (Friesen and Huminicki 1987)
Fig. 7.4 Airflow resistance of flax and sunflowers measured in farm bins with completely perforated floors in Manitoba (Friesen and Huminicki 1987)
DESIGN DATA
TEMPERATURE IN SILO FOR SAFE STORAGE

Table 1: Storage periods for cooled grain in relation to climate zones and moisture content

<table>
<thead>
<tr>
<th>Moisture content [%]</th>
<th>temperate* [months]</th>
<th>tropics** [months]</th>
</tr>
</thead>
<tbody>
<tr>
<td>12 - 15</td>
<td>8 - 12</td>
<td>6 - 8</td>
</tr>
<tr>
<td>15 - 17</td>
<td>6 - 10</td>
<td>3 - 5</td>
</tr>
<tr>
<td>17 - 19</td>
<td>4 - 6</td>
<td>1 - 2</td>
</tr>
<tr>
<td>19 - 21</td>
<td>1 - 4</td>
<td>0.5 - 1</td>
</tr>
</tbody>
</table>

* Primary cooling to 10 °C for Europe
** Primary cooling to 15 °C e.g. for Latin America and Asia
MOISTURE CONTENT IN SILO FOR SAFE STORAGE

Figure 1. Effect of Temperature and Moisture Content on Allowable Storage Time of Wheat, Oats and Barley.

Figure 2. Effect of Temperature and Moisture Content on Allowable Storage Time and Continuously Ventilated Rapeseed.

Figure 3. Effect of Temperature and Moisture Content on Allowable Storage Time of Corn.
Figure 4. Moisture Migration in Fall & Winter.

Figure 5. Moisture Migration in Spring & Summer
DETAILS ABOUT OTHER ISSUE
DEAL WITH SILO SYSTEM

CONVEYING SYSTEM
FOR SILO
## Table 26.2 Applications of materials-handling equipment

<table>
<thead>
<tr>
<th>Direction</th>
<th>Conveyors</th>
<th>Elevators</th>
<th>Cranes and hoists</th>
<th>Trucks</th>
<th>Pneumatic equipment</th>
<th>Water flumes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vertical up</td>
<td>*</td>
<td></td>
<td>*</td>
<td>*</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vertical down</td>
<td></td>
<td>*</td>
<td>*</td>
<td>*</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Incline up</td>
<td>*</td>
<td></td>
<td>*</td>
<td>*</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Incline down</td>
<td></td>
<td>*</td>
<td>*</td>
<td>*</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Horizontal</td>
<td></td>
<td></td>
<td>*</td>
<td>*</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Frequency</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th>*</th>
<th>*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Continuous</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>*</td>
</tr>
<tr>
<td>Intermittent</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>*</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Location served</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th>*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Point</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>*</td>
</tr>
<tr>
<td>Path</td>
<td>*</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>*</td>
</tr>
<tr>
<td>Limited area</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>*</td>
</tr>
<tr>
<td>Unlimited area</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>*</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Height</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th>*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overhead</td>
<td>*</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>*</td>
</tr>
<tr>
<td>Working height</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>*</td>
</tr>
<tr>
<td>Floor level</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>*</td>
</tr>
<tr>
<td>Underfloor</td>
<td>*</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>*</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Materials</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th>*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Packed</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>*</td>
</tr>
<tr>
<td>Bulk</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>*</td>
</tr>
<tr>
<td>Solid</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>*</td>
</tr>
<tr>
<td>Liquid</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>*</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Service</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th>*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Permanent</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>*</td>
</tr>
<tr>
<td>Temporary</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>*</td>
</tr>
</tbody>
</table>

*From Brennan et al. (1990).*
FIG. 21-1 Typical feed arrangements for screw conveyors. (a) Fixed plate or chute. (b) Rotary cutoff valve. (c) Rotary-vane feeder. (d) Bi- gate. (e) Side inlet gate. (FMC Corporation, Material Handling Systems Division.)
CHAIN CONVEYOR

CHAINS for distribution systems

Chain boots

Distribution Components

Chains
Up to 2000 kg/hour

Drive Stations

FE 467
Dr. Mustafa BAYRAM
SCREW CONVEYOR

\[ M_s = A' \times U_s \times \rho_b \times E_f \]

- \( A' \): cross sectional area, available for flow (not occupied by screw and shaft)
- \( E_f \): filling efficiency (within conveyor) (area occupied by the bed of solids) (compared to the cross-sectional area)
- \( U_s \): solids velocity inside a screw conveyor (\( U_s \) is the product of the blade pitch and revolutions per second)

\[ U_s = \text{Rev/s} \times \text{pitch} \]
Work (ton/h) = 3600 \( f \times v \times \rho \times \phi \)

Power (PS) = \( (W \times l \times k) / 305 \) (except belt power)

\( f \) = cross sectional area of product along width of belt, m²
\( v \) = belt velocity, m/s
\( \rho \) = density of product ton/m³
\( \phi \) = distribution coefficient of product (for dense: 1, loose: 0.9, 0.8 ..)
\( l \) = length of belt, m
\( k \) = constant (frictional), 0.15-0.30
L: length of leg of elevator (~belt)
X: distance between two dishes
Ubelt: velocity of belt
V = volume of each dish
D: Diameter of pulley
M = weight of material in a dish
Number of dish = L/X
Ubelt = motor drive (rev/sec) * 3.14 D/rev
L = Ubelt * t
Number of dish * X = Ubelt * t
M = \( \rho_b \) * A * V = kg/m\(^3\) * m\(^2\) * m/s = kg/m * m/s

U belt = <0.5 m/s
Width of dish = <0.5 m
VIBRO CONVEYOR

Vs < 0.4 m/s conveyor velocity

Figure 10. This vibratory conveyor can handle two streams of material.
PNEUMATIC CONVEYOR

(a) Pressure

(b) Vacuum

(c) Pressure-vacuum

(d) Pressure-vacuum unloading and transfer

(e) Fluidizing system

(f) Blow tank
FIG. 31.60c Tractor hoppers used for plastics (Baker Ltd., Co.). To convert data to the SI system, change the dimensions shown to inches and multiply by 2.54. To convert volumes to cubic meters, multiply cubic feet by 0.02832.

Dr. Mustafa BAYRAM
SOME EXAM QUESTIONS
EXAMPLES
(HOME STUDY-EXAM QUESTIONS)

1) a) Find h, L and volume of silo. (Bulk angle of repose: 35°. Sliding angle of repose: 45°. Diameter of silo: 2 m. Weight of product in silo: 7000 kg. Head space: 10%. Bulk density of product: 700 kg/m³. Volume of conical part: 1/3 *(3.14*r²*height)

b) We want to discharge this silo within 30 mins. Calculate required discharge diameter) (Hint: Q=k.Dⁿ). Given;

<table>
<thead>
<tr>
<th>Diameter of discharger (m)</th>
<th>0.1</th>
<th>0.3</th>
<th>0.5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass flow rate (kg/sec)</td>
<td>1.80</td>
<td>1.88</td>
<td>1.97</td>
</tr>
</tbody>
</table>
b) Find $h$, $L$ and volume of silo. (Bulk angle of repose: 35°, Sliding angle of repose: 45°, Diameter of silo: 2 m, Weight of product in silo: 7000 kg. Head space: 10%, Bulk density of product: 700 kg/m$^3$. Volume of conical part: $\frac{1}{3}$ *$\pi$(1.14)^2 *height)

b) We want to discharge this silo within 30 mins. Calculate required discharge diameter (Hint: $Q = k \cdot D^3$). Given:

<table>
<thead>
<tr>
<th>Diameter of Discharger (m)</th>
<th>0.1</th>
<th>0.3</th>
<th>0.5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass flow rate (kg/sec)</td>
<td>1.80</td>
<td>1.88</td>
<td>1.97</td>
</tr>
</tbody>
</table>

$V = \frac{3 \cdot \pi \cdot r^2 \cdot height}{3}$

Volume of product = 7000 kg = $\frac{\pi}{3}$

Total volume of silo = $V + \frac{1}{3} \pi (1.14)^2 - \frac{1}{3} \cdot h^3$

$V_T = (\pi r^2 h) + (k \cdot h) \cdot \frac{\pi r^2 h}{3}$

$h = \frac{1}{3}$

$\tan 25 = \frac{h}{r} \Rightarrow 25 \cdot \tan 25 = 1 \Rightarrow h = 0.76 m$

b) $D (m)$

<table>
<thead>
<tr>
<th>$D$ (m)</th>
<th>0.1</th>
<th>0.3</th>
<th>0.5</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Q$ (kg/sec)</td>
<td>1.8</td>
<td>4.88</td>
<td>1.97</td>
</tr>
</tbody>
</table>

$\ln Q = 0.588 + 0.63 + 0.073$

$\ln Q = 0.0520$

$\ln Q = 0.906 + 202$

$Q = 7000 kg / 30 min = 233.33 kg/min \times 1 min = 8.389 kg/sec$

$Q = 0.0520 + 0.906 + 202$

$Q = 202.906$ kg/sec

$Q = 3.889 = \ln 202 + 0.0520 \times \ln b + 0.63$

$\ln b = 0.144 + \Delta = 0.187 + 0.28$
SILO CAPACITY AND SIZE DESIGN

100 tons of wheat is stored in a cylindrical silo. Angle of repose and bulk density of wheat are 30° and 750 kg/m³, respectively. Head space of the silo is 10% of the wheat volume. The top of the wheat bulk in the silo is triangular.

a) Calculate all dimensions of the silo (take the bottom conical part as triangle). \((h_1, h_2, h_3, h_4, V_{silo}, V_{wheat})\)
b) At different diameters of the opening, the following values are measured. We want to discharge the silo which containing 100 ton of wheat within 3 hrs. Calculate the required the opening diameter \((D_1)\).

<table>
<thead>
<tr>
<th>D (cm)</th>
<th>20</th>
<th>30</th>
<th>40</th>
</tr>
</thead>
<tbody>
<tr>
<td>Q (kg/hr)</td>
<td>25000</td>
<td>42000</td>
<td>53000</td>
</tr>
</tbody>
</table>

Note: In this example: Sliding slope angle is same with angle of repose.
Solid handling & mixing. Unknown 1 Answer Key 2011/2012.

\[ V_{\text{sil}} = V_{\text{wh}} + V_{\text{w}} \times 0.1 \]

\[ V_{\text{sil}} = 133.3 + 13.3 \]

\[ V_{\text{sil}} = 146.6 \text{ m}^3 \]

\[ V_{\text{sil}} = V_{1} + V_{2} = 146.6 = 3.14 \times 1^2 \times h_4 + 3.14 \times 1^2 \times h_1 \]

\[ h_4 = 46.5 \text{ m} \]

\[ h_1 = 0.577 \]

\[ h_2 = 42.6 \text{ m} \]

\[ h_3 = 0.577 \]

\[ h_4 = 46.5 \]
b) \( Q = aD^n \)

\[ \ln Q = \ln a + n \ln D \]

\[ y = n + m \times \]

\( (r^2 = 0.985) \)

Required capacity \( = \frac{1000000 \text{ kg}}{3 \text{ hrs}} = 33333.3 \text{ kg/hr} \)

\[ \ln Q = \ln (33333.3) = 10.42 \]

\[ 10.42 = 6.91 + 1.085 \times x \quad (\text{lnD}) \]

\[ x = 3.235 \]

\[ \ln D = 3.235 \]

\[ D = 25.41 \text{ cm} \quad \text{for} \quad 1000000 \text{ kg in 3 hrs} \]
EXAMPLE: CALCULATION OF A HOPPER GEOMETRY FOR MASS FLOW

An organic solid powder has a bulk density of 22 lb/cu ft. Jenike shear testing has determined the following characteristics given below. The hopper to be designed is conical.

Wall friction angle (against SS plate) = $\varphi' = 25^\circ$

Bulk density = $\gamma = 22 \text{ lb/cu ft}$

Angle of internal friction = $\delta = 50^\circ$

Flow function $\sigma_c = 0.3 \sigma_1 + 4.3$

Using the design chart for conical hoppers, at $\varphi' = 25^\circ$

$\theta_c = 17^\circ$ with $3^\circ$ safety factor

& $ff = 1.27$
EXAMPLE: CALCULATION OF A HOPPER GEOMETRY FOR MASS FLOW

\[ ff = \sigma / \sigma_a \quad \text{or} \quad \sigma_a = (1/ff) \sigma \]

Condition for no arching \( \Rightarrow \quad \sigma_a > \sigma_c \)

\[
(1/ff) \sigma = 0.3 \sigma_1 + 4.3 \quad (1/1.27) \sigma = 0.3 \sigma_1 + 4.3
\]

\[
\sigma_1 = 8.82 \quad \sigma_c = 8.82/1.27 = 6.95
\]

\[
B = 2.2 \times 6.95/22 = 0.69 \text{ ft} = 8.33 \text{ in}
\]
- (20 pts.) In a food plant, we want to transfer semolina from a machine at 2nd floor (upstair) to another machine at 1st floor (downstair) using a pipe. The bulk density of semolina is 700 kg/m$^3$. The diameter of pipe is 10 cm. The height between the floors is 5 m. 30% of pipe is only full at cross-section with semolina during transportation (see figure). The velocity of product is 2 m/s in the pipe. The angle of repose of semolina is 45°. The product is out from the bottom of the machine found on 2nd floor and then inlet at the bottom of the machine found on 1st floor.

a) (10 pts.) Calculate possible minimum horizontal distance between the machines and show the positions of both machines by drawing.

b) (7 pts.) Calculate the mass flow rate of semolina in the pipe.

c) (3 pts.) What is the capacity of the machine (Machine 2) under this condition at steady-state (no by-product, in=out)?
a) (7 pts.) Calculate the mass flow rate of semolina in the pipe.

\[ m = (\text{bulk density}) \times (\text{Cross sectional area of filled portion}) \times (\text{velocity}) \]

Cross section of whole pipe: \[ 3.14 \times (r^2) = 3.14 \times (0.05^2) = 0.00785 \text{ m}^2 \]

Cross sectional area of filled portion “%30” = \[ 0.00785 \times 0.30 = 0.002355 \text{ m}^2 \]

\[ m = 700 \times 0.002355 \times 2 = 3.297 \text{ kg/s} \]

b) (3 pts.) What is the capacity of the machine (Machine 2) under this condition at steady-state (no by-product, in-out)?

It is same with the mass flow rate. The produced product flows in the pipe: \[ 3.297 \text{ kg/s} \]
In a food plant, the capacity is 30 tons/hr. You have a silo of 100 tons to feed the plant. The product found in the silo is soybean and its particle size is 5 mm. Its bulk density is 800 kg/m$^3$. The flow in silo is funnel flow. The angle of hopper from vertical is 45$^\circ$. Gravitational constant=9.8.

a) What is the silo discharge orifice diameter?, b) How long will it take to feed the plant by using this silo?

**Hints:**

<table>
<thead>
<tr>
<th>Beverloo Equation;</th>
<th>Johanson Equation;</th>
</tr>
</thead>
<tbody>
<tr>
<td>$W = 0.58 \rho_b g^{0.5} (B - k d_p)^{2.5}$</td>
<td>$W = \rho_b (\pi/4) B^2 (g B/4 \tan \theta_c)^{0.5}$</td>
</tr>
</tbody>
</table>

Units must be in SI unit

- $W$ is the discharge rate, $\rho_b$ is the bulk density, $g$ is the gravitational constant, $B$ is the outlet size, $k$ is a constant (typically 1.4), $d_p$ is the particle size, $\theta_c$ is the angle of hopper from vertical.
b) \( \frac{100 \text{ t}}{30 \text{ t/h}} = 3.33 \text{ hr} \)
Draw the flow-diagram of full silo system
1. (10 pts) Design a silo to store 1000 kg of bread wheat (h=6D). Use given table. (Compact, Columbus). Silo is cylindrical. 
Volume of conical part: $\frac{1}{3} * (3.14*r^2*h)$

Table 7.2 Densities and angles of repose of some cereal grains and oilseeds (Muir and Sinha 1988, Irvine et al. 1992, Rameshbabu et al. 1996)

<table>
<thead>
<tr>
<th>Crop</th>
<th>Cultivar</th>
<th>Bulk density (kg/m³)</th>
<th>Kernel density (kg/m³)</th>
<th>Porosity (%)</th>
<th>Filling</th>
<th>Emptying</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bread wheat</td>
<td>Columbus</td>
<td>780</td>
<td>1379</td>
<td>38</td>
<td>26</td>
<td>23</td>
</tr>
<tr>
<td></td>
<td>Neepawa</td>
<td>763</td>
<td>1384</td>
<td>39</td>
<td>26</td>
<td>27</td>
</tr>
<tr>
<td></td>
<td>Neepawa</td>
<td>725</td>
<td>1370</td>
<td>40</td>
<td>31</td>
<td>34</td>
</tr>
<tr>
<td>Durum</td>
<td>Coulter</td>
<td>744</td>
<td>1377</td>
<td>41</td>
<td>23</td>
<td>21</td>
</tr>
<tr>
<td></td>
<td>Coulter</td>
<td>709</td>
<td>1372</td>
<td>42</td>
<td>29</td>
<td>30</td>
</tr>
</tbody>
</table>
1. (10 pts) Calculate time to fill a truck with lentils if the hopper is designed with a 6” Sch. 10 outlet (6.36 inch). The truck carries 45000 lbs. The bulk solid is being discharged from mass flow silo and has a 65° angle from horizontal. Lentil has a bulk density of 35 lb/cu ft. Use given Hint.

Hints:

<table>
<thead>
<tr>
<th>Beverloo Equation;</th>
<th>Johanson Equation;</th>
</tr>
</thead>
<tbody>
<tr>
<td>$W = 0.58 \rho_b g^{0.5} (B - k d_p)^{2.5}$</td>
<td>$W = \rho_b (\pi/4) B^2 (g B/4 \tan \theta_c)^{0.5}$</td>
</tr>
<tr>
<td>Units must be in SI unit</td>
<td></td>
</tr>
</tbody>
</table>

$W$ is the discharge rate, $\rho_b$ is the bulk density, $g$ is the gravitational constant, $B$ is the outlet size, $k$ is a constant (typically 1.4), $d_p$ is the particle size, $\theta_c$ is the angle of hopper from vertical.