Exercises Powder Flow and Silo Design

1. General questions regarding behaviour of bulk solids

a) What are the two most common flow patterns observed in silos? Sketch and explain. Under what circumstances do these flow conditions occur?

b) Sketch the typical stress or pressure as function of the height inside a silo for both liquid and powder filling. What is the reason for the difference? Write down force-equilibrium for a layer of powder in a cylindrical silo. Discuss the terms and explain which term is responsible for the differences in stress (as function of height) in powder- and fluid containers.

c) Describe 2-3 devices used to discharge a silo. Explain advantages and disadvantages.

d) Assume you have a tall silo. Add a tracer on the surface of the bulk in the center of the silo. Under which flow condition (mass or core-flow) does the tracer exit first?

2. Silo design for flow

In a plant a new food product called "Granulate Super" with a median particle size of about 50 µm is produced by spray granulation. After granulation the particulate product should be stored in a silo which has to be designed. For the operation of the plant the following conditions for the silo arises:

- Storage capacity of the silo: 150 m^3
- Operation times: 24 h a day and 7 days a week, time between two discharges usually less than 8 h
- Longer interruptions: Once a year maximum of 10 days, a few times (at maximum 10 times) a year approximately 3 days
- Possible wall materials: Aluminium (80 \$ / m^2)
  Cold rolled stainless steel (100 \$ / m^2),
  Warm rolled stainless steel (70 \$ / m^2)

For the bulk solid "Granulate Super" shear tests were carried out. The results of the shear tests are given in the appendix. Moreover, the static angle of repose was determined to be 42° and the lateral stress ratio λ to be 0.5. The strength (stress in the moment of breakage) of the granulates at which extensive abrasion starts to take place was measured to be 120 kPa.

For the design of the silo the following steps should be carried out:

1. Determination of the characteristic values of the bulk solid "Granulate Super" based on the measurement data given in the appendix
2. Based on the characteristic values (e.g. unconfined yield strength of the bulk solid as function of consolidation stress) the geometric parameters of the silo to avoid flow problems should be determined (silo design for flow)

3. Based on the data achieved in 2. and the conditions given above possible designs of the silo in which breakage of the granulates can be avoided should be developed and discussed. Moreover, the costs for the silo should be as low as possible. For the silo designs (at least two alternatives should be developed) drawings should be constructed. The drawings should show the choice of discharge device and eventually the position of flow promoting devices. For the different alternatives among others it should be discussed
    - Choice of discharge device and eventually flow promoting devices
    - Choice of silo shape and dimensions to store the desired amount of product
    - Choice of wall material
4. Can you think of a silo design, if the abrasion strength due to flow in the silo is only 20 kPa?

Comment: The maximum horizontal stress at the switch in a mass flow silo can be estimated by $\sigma_{h,\max} = \overline{\sigma}_{v,\max} \cdot \frac{1+\sin\varphi_e}{1-\sin\varphi_e}$ where $\overline{\sigma}_{v,\max}$ is the mean vertical stress in the lower part of the cylindrical silo section.

Results of shear tests:

Shear tests without time consolidation:

Normal load 1:

Bulk density ρ_b	Preshear - normal stress	Preshear - shear stress	Shear to failure – Normal stress	Shear to failure – Shear stress
720 kg/m^3	2400 Pa	2000 Pa	800 Pa	1270 Pa
			1200 Pa	1450 Pa
			1600 Pa	1640 Pa

Normal load 2:

Bulk density ρ_b	Preshear - normal stress	Preshear - shear stress	Shear to failure – Normal stress	Shear to failure – Shear stress
755 kg/m^3	3900 Pa	3200 Pa	800 Pa	1550 Pa
			1600 Pa	2050 Pa
			2400 Pa	2540 Pa

Normal load 3:

Bulk density ρ_b	Preshear - normal stress	Preshear - shear stress	Shear to failure – Normal stress	Shear to failure – Shear stress
775 kg/m^3	5400 Pa	4100 Pa	800 Pa	1930 Pa
			2400 Pa	2970 Pa

			4000 Pa	3700 Pa

Shear tests with time consolidation:

Time consolidation tests were run at Normal load 2

Bulk density ρ_b	Time at rest	Shear to failure - Normal stress	Shear to failure – Shear stress
755 kg/m^3	8 h	1600 Pa	2380 Pa
	24 h	1600 Pa	2670 Pa
	3 days	1600 Pa	2950 Pa
	10 days	1600 Pa	3240 Pa

Wall friction tests:

Aluminium

Normal stress	Shear stress
900 Pa	560 Pa
2400 Pa	1500 Pa
3900 Pa	2435 Pa
5400 Pa	3378 Pa

Cold rolled stainless steel

Normal stress	Shear stress
900 Pa	440 Pa
2400 Pa	1170 Pa
3900 Pa	1905 Pa
5400 Pa	2635 Pa

Warm rolled stainless steel

Normal stress	Shear stress
900 Pa	705 Pa
2400 Pa	1876 Pa
3900 Pa	3047 Pa
5400 Pa	4218 Pa