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Anisotropic behaviour of bulk solids and its effect on silo design

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ABSTRACT

The anisotropic material behaviour is a characteristic property of bulk solids. Prior research work proved that the measured unconfined yield strength of cohesive bulk solids is lower when the direction of the collapsing stress and the consolidation stress does not coincide. A new powder tester has been developed to measure both the unconfined yield strength in the uniaxial direction, which provides consolidation and collapse stresses in the same direction, as well as the anisotropic unconfined yield strength, which means consolidation and collapse stresses are in orthogonal directions. The friction between the walls and the bulk solid is minimised by the use of rubber membranes which deform uniformly with the bulk sample. The uniaxial and the anisotropic unconfined yield strengths have been measured for a limestone powder at different consolidation stresses. Experimental results as well as their application on the design for funnel flow silos are discussed. To avoid piping two design criteria exist for the design of a funnel flow silo: Jenike assumes a passive state of stress to prevail close to the silo outlet (Jenike, 1961 [1]); Johanson assumes an active state of stress (Johanson, 1969 [2]). While the approach of Jenike leads to good results, the estimation of the critical outlet diameter in a silo with an active state of stress is not satisfying. The pipe dimensions for an active state of stress were measured using a silo centrifuge. The application of the design criteria gives reasonable and safe design value only if the anisotropic behaviour of the bulk solid is considered which was measured by the new powder tester.

1. Introduction

The handling of bulk solids results in a compaction of the material, whether desired or not. In many industrial applications, the compaction of the bulk solid is discussed as an isotropic procedure. But the resulting strength of the bulk solid can be very different depending on the way the compaction takes place. Only when all three principal stresses are identical, an isotropic behaviour might be expected. But an isostatic consolidation is a very rare event in technical applications. In the majority of cases the minimal strength of the bulk solid is important and the minimal strength can only be found when the anisotropic behaviour of the material is considered.

2. Experimental setup

2.1. Powder tester

Bulk solids exhibit an anisotropic behaviour. This was shown by different measurements in literature like those of Molerus [3], Saraber et al. [4], Puri et al. [5], Feise [6], Schwedes [7] and Schwedes et al. [8]. Anisotropy means that bulk solids get a direction dependent strength when they are consolidated in a non-isotropic way. A new Anisotropy-Tester was developed and built to measure the anisotropic compressive strength $\sigma_{c,\perp}$ (major principal stress σ_1 perpendicular to the measured strength σ_c) as well as the uniaxial compressive strength $\sigma_{c,}$ (σ_1 parallel to σ_c). The measured stresses are assumed as principal stresses, as the friction between powder and walls is minimised by the use of highly flexible rubber membranes. To apply the force on the bulk solid sample, a material-testing machine was combined with a system of hydraulic cylinders. This experimental setup and the design of the Anisotropy-Tester make it possible to reach a maximal stress of $\sigma_{max} = 300$ kPa in the horizontal direction and vertical direction.

As shown in Fig. 1 the Anisotropy-Tester is a box with detachable walls. The consolidation stress σ_1 is applied through two movable side walls in a horizontal direction. With a special latex-membrane construction the friction between the walls and the bulk solid is minimised. After the consolidation, all the side walls and the membranes are removed. Thereafter, the free-standing sample can be destroyed with the unconfined failure stress σ_c applied through a plunger in vertical direction.

The testing procedure has to be divided into two steps. The first step is the compaction of the bulk solid. The compaction can be done in two different ways, i.e. parallel or perpendicular to the subsequent stress applied to the sample in vertical direction. After reaching a target compaction stress, the movement of the cylinders stops and the hydraulic system is opened. By using a hydraulic pump the cylinders are moved to their starting positions and the top cover and all sidewalls can be removed. After removing all walls the sample is free-standing and the second step of the testing procedure can start,

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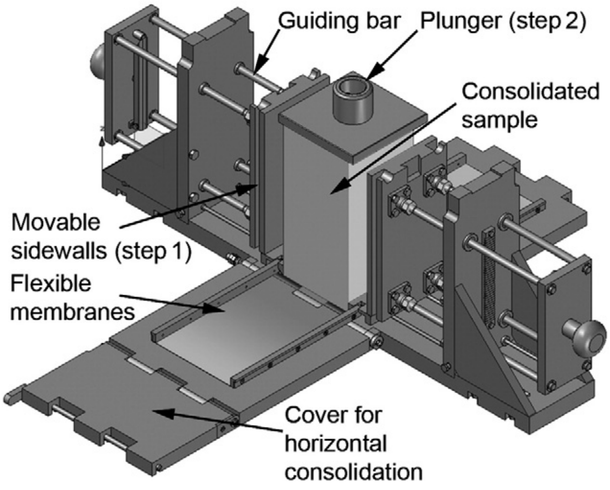

Fig. 1. Three dimensional drawing of the Anisotropy-Tester for horizontal compaction.

i.e. the sample is stressed with the unconfined failure stress σ_c in the vertical direction. Therefore the plunger is moving downwards and the vertical stress on the sample increases till the unconfined failure stress σ_c is reached. With the beginning of cracking the vertical stress decreases, see also Ittershagen and Kwade [9].

The strength $\sigma_{c,\perp}$ after horizontal consolidation is smaller than the strength $\sigma_{c,\parallel}$ after vertical consolidation. The ratio between the measured strengths $\sigma_{c,\perp}$ and $\sigma_{c,\parallel}$ leads to the intensity of the anisotropic consolidation behaviour. The anisotropy is defined as the difference between 1 and the strengths ratio of $\sigma_{c,\perp}$ and $\sigma_{c,\parallel}$, see also Ittershagen and Kwade [9]:

$$k = 1 - \frac{\sigma_{c,\perp}}{\sigma_{c,||}}. \tag{1}$$

2.2. Silo centrifuge

In order to perform silo tests with cohesive bulk solids in smaller scale a change from gravity to centrifugal forces is necessary. For this purpose a silo centrifuge was developed and built at the Institute for Particle Technology in which acceleration factors z of about 100 can be achieved. The length of the rotating arm is 2.6 m and the radius between the axis of rotation and the outlet of the model silo is 1.0 m. The silo centrifuge is shown schematically in Fig. 2. The model silo can be turned vertical for filling purposes. When the bulk solid is moving it flows from the model silo in horizontal direction into a collecting bin. This bin is connected to a load cell on the other side of the rotation arm by four tension-rods. To transmit the signals of the measurement system from the rotating system to the control room a slip ring transducer is used. During the rotation a CCD-camera placed at the top of the model silo shows the behaviour of the bulk material inside the silo.

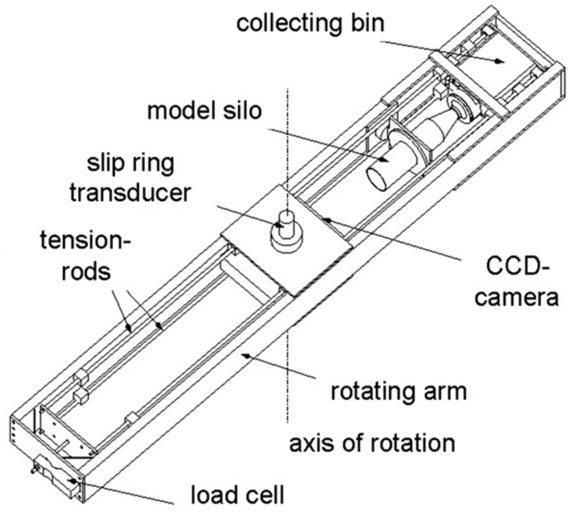

Fig. 2. Silo centrifuge.

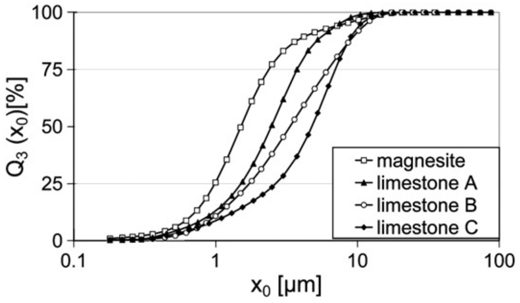

Fig. 3. Particle size distributions of the test materials.

In order to calculate the outlet dimension D_{sc} of a full size silo the multiple of the acceleration of gravity z reached in the centrifuge has to be multiplied with the outlet dimension D_{ms} of the model silo:

$$D_{sc} = z \cdot D_{ms}. \tag{2}$$

2.3. Material

The test material was a cohesive limestone with a median particle size of $x_{50} = 2.5$ µm (fraction A), $x_{50} = 3.3$ µm (fraction B) and $x_{50} =$ 4.8 µm (fraction C) measured by laser diffraction (HELOS, Sympatec, Germany). Additionally the anisotropic consolidation behaviour of a magnesium carbonate powder with a median particle size of $x_{50} =$ 1.5 µm was determined. The partical size distributions are shown in Fig. 3.

The flowfactor ff_c of all four test materials (see Fig. 4) is measured in a Ring Shear Tester (RST, Schulze, Germany). The magnesite powder shows with a ff_c between 2 and 3 the worst flowability. For the three limestone fractions the flowfactor increases with rising median particle size. The flow functions are shown in Fig. 4. The dotted lines illustrate lines of constant flowfactor ff_c which separates the category groups defined by Jenike to characterise the flow properties of powders [1,10].

Table 1 exemplarily shows the angle of the linearised yield locus, φ_{lin}, the bulk density, ρ_b, and the unconfined failure stress, σ_c, of the limestone fraction A as function of the major principal stress, σ_1 (measured in the Ring Shear Tester, Schulze, Germany). The angle of the linearised yield locus, φ_{lin}, is a good approximation for the angle of internal friction, φ_i [7]. The angle of the linearised yield locus, φ_{lin}, shows only little variation with increasing the major principal stress, σ_1, while the flowfactor ff_c increases.

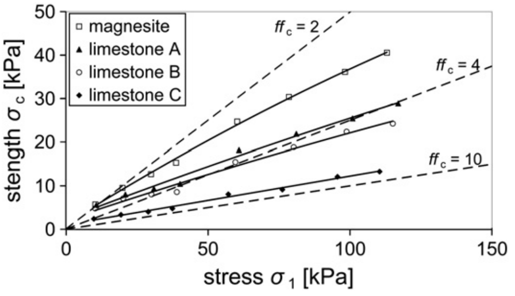

Fig. 4. Flowabilities of the test materials.

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