THE APPLICATION OF SILO CENTRIFUGE TESTING

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Abstract: Common problems of industrial silo design can be solved with calculations based on the Jenike method. However in some cases, especially when a silo design is calculated for highly dispersed bulk solids in the nano-range or when the bulk solid contains moisture, experiments in model scale under centrifuge forces may yield better understanding of silo problems. In this work, the results from scale-up experiments in a silo centrifuge are presented. The experiments have been performed to investigate critical outlet dimensions for a silo filled with very fine and moist bulk solids.

Keywords: silo design, silo, moist bulk solids, silo-centrifuge, scale-up, model tests

1. Introduction

Common problems of industrial silo design can be solved with the use of the Jenike method. The Jenike method is an established procedure to investigate the critical outlet dimensions of a silo and the flow profile. However, in some cases the Jenike method is assumed to lead to overdesign, especially when silo design is calculated for highly dispersed bulk solids in the nano range or if the bulk solid contains moisture. Another way to determine the critical outlet dimension of a silo is a model test. We then have to consider the boundary conditions, *i.e.* the particle size, and a possible size reduction of the model silo, which is only possible in a centrifugal field using cohesive bulk solids. In this work, results of experiments in a silo centrifuge regarding scale-up are presented. The experiments have been performed to investigate the critical outlet dimension for a silo for very fine and moist bulk solids.

2. Theoretical background

2.1. Standard silo design

The objective of silo design is to predict a proper flow profile and determine the minimum outlet dimension for trouble-free flow. In most cases this can be done by using results from experiments in shear testers (for example a ring shear tester or a translation shear tester) and applying the Jenike method to design a silo geometry

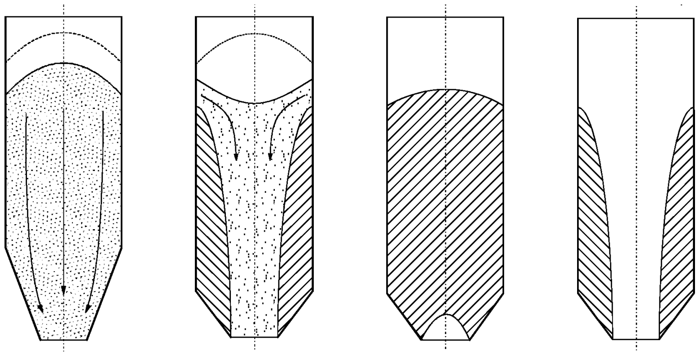

Figure 1. Flow profiles and flow problems

for trouble-free flow [1–3]. The basis of the Jenike method is a theory of the flow in silos, especially in the lower convergent area in the hopper. The Jenike method is based on the radial stress field, which is valid for the passive state of stress or discharge state of stress which soon develops after the first discharge of a small amount of the stored bulk solid. The most relevant bulk solid properties which can be measured with shear testers are the angle of wall friction (φ_x) between wall and bulk solid, two angles of inner friction (φ_i, φ_e), and the correlation between bulk solid strength (σ_c) and consolidation stress (σ_1) called the flow function ($\sigma_c = f(\sigma_1)$). If storage time at rest is of influence, the strength is increasing and time flow functions ($\sigma_{c,t} = f(\sigma_1, t)$) can be gained and used in the calculation.

Figure 1 shows possible flow profiles in a silo and the most relevant flow problems. Mass flow is a state of flow with the whole content moving. However, in a funnel flow profile the bulk solid is moving only in an area above the outlet and dead zones develop in the periphery, which come into motion only towards the end of the emptying process. This often leads to irregular flow. Silos with a mass flow profile have a lot of further advantages compared with funnel flow silos (no segregation, very narrow residence time distribution).

Arching occurs in silos with insufficient outlet dimensions. With increasing outlet dimensions, the stresses of the bulk solid at the wall are increasing. If these stresses exceed the bulk solid strength, arching is not possible, and a critical outlet dimension can be predicted beyond which arching will not occur. Stable arches are possible in a mass flow silo as well as in a funnel flow silo. A stable funnel, often called a “pipe” or a “rathole”, can only be found in a funnel flow silo. Critical outlet dimensions for piping not to occur can be predicted as well. The most relevant geometric parameters for trouble-free flow in silos are outlet diameter and the angle of inclination of the hopper. The angle of inclination is responsible for the flow profile (mass flow, funnel flow). Dimensions the outlet must be large enough to prevent arching and piping.

2.2. Model tests for silo design

Model tests in the gravity field can be used to investigate the flow behaviour of bulk solids by performing experiments in a silo reduced in scale. This is only possible for free-flowing bulk solids. For fine cohesive bulk solids, their strength depends on the consolidation stresses. Therefore no prediction of outlet dimension is possible when using only small-sized model silos in gravity, due to the reduced stress level in the scale model. However, using a centrifugal field the stresses on the bulk solid can be increased and the outlet dimensions for trouble-free flow can be decreased. The scale of model silos can be reduced in a centrifugal field by the ratio between the centrifugal forces at the outlet of the silo and the forces caused by gravity. Model tests with a silo centrifuge had been carried out by Molerus and Egerer [4, 5] and Nielsen [6–8], with several coarse and fine powders, and by Lepert [9], to analyse the discharge behaviour in grain silos. Molerus and Egerer compared the results obtained from a silo centrifuge with a full-scale silo and the Jenike method [4, 5].

To calculate the outlet dimension of a full-size silo (d_G) the ratio between the centrifugal and gravity forces, z, can be used with the outlet dimension of the model silo (d_M) [4]:

$$d_G = z \cdot d_M, \tag{1}$$

$$z = \frac{b}{g}, \tag{2}$$

with centrifugal acceleration:

$$b = r \cdot \omega^2 = 4 \cdot r \cdot \pi^2 \left(\frac{n}{60}\right)^2. \tag{3}$$

The centrifugal forces depend on the radius of the centrifugal fields. Therefore, the critical outlet dimension for trouble-free flow must be calculated with the effective radius of the centrifuge. In tests with model silos it is the distance between the rotation axis of the centrifuge and the outlet of the model silo. The aim of research has been to investigate the critical outlet dimension caused by arching and piping with very fine cohesive and moist bulk solids. Therefore, the dependence of stresses on the radius can be neglected. The main interest is the beginning of flow, *i.e.* the breaking of a stable arch or pipe by the increasing centrifugal forces. Therefore the Coriolis effect has little effect here.

3. Set-up of the silo centrifuge

In Figure 2 the silo centrifuge is shown schematically (left, with the model silo on the right part of the rotating arm) and in photography (right, with the rotating arm turned 180°). The diameter of the rotating arm is 2.6m, and the distance between the axis of rotation and the outlet of the model silo is 1.0m. The model silo placed on one side of the rotating arm can be turned vertical for filling. At the bottom of the model silo a slide valve is positioned which can be opened by two pneumatic pistons. The operation of the slide valve during rotation of the centrifuge is possible thanks to a pressure tank and radio-controlled magnetic valves on the rotating arm. A damper guarantees constant and slow opening of the slide valve to minimise the influence of the opening action on the arch above the outlet. The bulk solid flows out of the silo into a collecting bin. Due to the fineness of the particles, a flexible funnel is placed between the outlet of the slider valve and the collecting bin to avoid dusting. The collecting bin is connected to a load cell on the other side of the rotating arm with four tension rods (as shown in Figure 2, on the left). A part of the net weight of

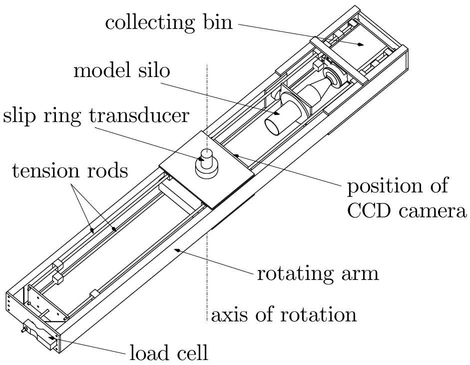

Figure 2. The silo centrifuge: left – a scheme with the model silo; right – a picture with the rotating arm turned 180°

the collecting bin and mounting equipment can be balanced by this set-up and the forces on the load cell can be decreased. A maximum allowed force on the load cell of 10kN guarantees a maximum load of 10kg in the collecting bin up to a multiple of centrifugal acceleration of 100 (300rpm).

Two types of model silos have been used. The circular model silos (scheme; left) are made of stainless steel with a height of 500mm and can be equipped with various cone elements for changing the outlet diameter (5, 10, 15mm). Three model silos with various wall inclinations have been investigated (10, 15, 25° hopper angle to the axis of symmetry). The diameter of the silo (100mm) is the same for all circular silos. Furthermore, a rectangular model silo has been developed (photography, right). The height is also 500mm, and the outlet width can be changed from 5 to 15mm by the use of different wall elements. PVC had been used as wall material for the hopper and the shaft. The high rotational speed requires a cap of acrylic glass for protection against dust and for infra-red lighting for the CCD Camera on top of the model silo. Experiments have shown that the critical outlet dimensions measured with the silo centrifuge are not affected by this cap. The set-up of the silo centrifuge makes possible experiments with the silo filled in gravity and, therefore, requires pre-consolidation to adjust the stresses to those of the centrifugal field.

Electric power and data are transferred with a slip ring transducer into and out of the rotating system. A process computer with a data acquisition card is set up in the control room and controls the centrifuge. An operator supervises the centrifuge. The CCD Camera is mounted on the centrifuge to allow an axial view into the silo and to help characterise the flow profile of the bulk solid. The onset of flow can be determined on-line from the data of the load cell. Outflowing bulk solids increase the load on the load cell at a constant rotational speed. In Figure 2, the drive assembly is shown in the photography. The drive of the centrifuge is provided by an electric engine with a belt drive. A maximum rotational speed of 350rpm can be reached, which gives a ratio of centrifugal forces to gravity of 130 at the outlet of the silo. The power of the electric engine is 11kW, and the rotational speed can be adjusted with a frequency converter.

4. Experimental tests

The first experimental test series was performed to establish an optimum test procedure with respect to precision and expenditure. The experiments were verified by investigating the stress state, as well as by comparing the critical outlet dimension with the Jenike method by performing shear tests. In the second part of the work, moist bulk solids were used to investigate the influence of creeping on the critical outlet dimension.

4.1. Experiments with different test methods

Due to the set-up of the silo centrifuge, tests have to be carried out with pre-consolidation after filling in gravity. To compare the results with the Jenike method a discharge state is required. Due to high compression during the pre-consolidation the bulk solid in the hopper moves convergently to achieve the higher bulk densities due to the higher stress in the centrifugal field. This convergent movement is sufficient to change the stress state from the filling state to the discharge state. Thus, it can be assumed that the discharge state is fully developed. The stress state is investigated in the next Section. Two test procedures after filling are possible:

- method 1: pre-consolidation, stopping, opening the outlet, acceleration until the arch collapses;
- method 2: pre-consolidation, opening the silo outlet, checking if the arch is stable or collapses.

Rotational speed and force on the load cell is plotted in Figure 3 for both of these methods. After filling in gravity the model silo is turned horizontally and the silo centrifuge is accelerated for pre-consolidation. Its rotational speed increases and is then kept constant for further pre-consolidation. The duration of pre-consolidation must be long enough to ensure that the bulk solid has settled down sufficiently and is in a steady state. For fine limestone, a pre-consolidation time of 300s was sufficient. Due to the partial mass balance of the collecting bin, a force is measured on the load cell even with an empty collecting bin.

In the case of method 1, the centrifuge is stopped after pre-consolidation and the outlet of the model silo is opened. Afterwards, the centrifuge is started again and the rotational speed is increased at a constant rate until the stable arch above the outlet breaks. As a result, the force on the load cell increases at a higher rate. With the onset of flow, the rotational speed is kept constant until the model silo is emptied. Finally, the centrifuge is stopped. This procedure had to be carried out for different levels of pre-consolidation until a level of rotational speed is found where pre-consolidation and the onset of flow are at the same rotational speed. Only this point is suitable for scale-up because of the same stresses during pre-consolidation and flow.

The first step of method 2 is identical to the fist step of method 1. After consolidation the outlet of the model silo is opened without stopping the centrifuge and it is observed wheter discharge of the bulk solid starts or not. After performing numerous experiments, the lowest rotational speed for trouble-free flow is determined. Due to the performance of the experiment, an identical stress state during pre-consolidation and flow is guaranteed by method 2. Experiments have been carried out

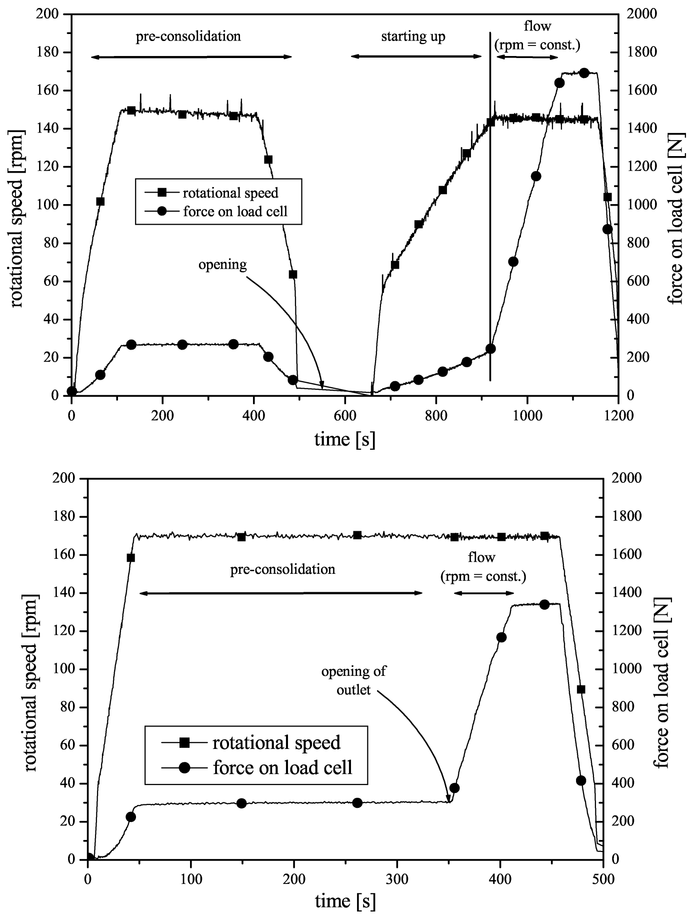

Figure 3. The test methods: top – method 1; bottom – method 2

with the same silo geometry, using fine limestone ($x_{50} = 20\mu$m). The critical outlet dimension for trouble free flow has been determined. The results for both methods are plotted in Figure 4. The rotational speed has been converted with Equation (3) into multiples of the gravitational acceleration. The multiple of gravitational acceleration at the onset of trouble-free flow is plotted versus the multiple of gravitational acceleration during pre-consolidation.

The multiples of gravitational acceleration for method 1 (open triangles) have an asymptotic trend. The critical multiple of gravitational acceleration for scale-up can only be determined after interpolation and is imprecise, even though a large number of tests have been performed. A series of tests is also necessary with method 2 (filled triangles), but the number of tests is lower than for method 1. Only the results of tests leading to the critical multiple of gravitational acceleration are plotted for method 2. Both methods lead to the same critical multiple of gravitational acceleration and, therefore, to the same critical outlet dimension. Earlier tests with the silo centrifuge have shown a very low critical multiple of gravitational acceleration, which was due to a suction effect. Therefore, the cone design depicted in Figure 5 was examined.

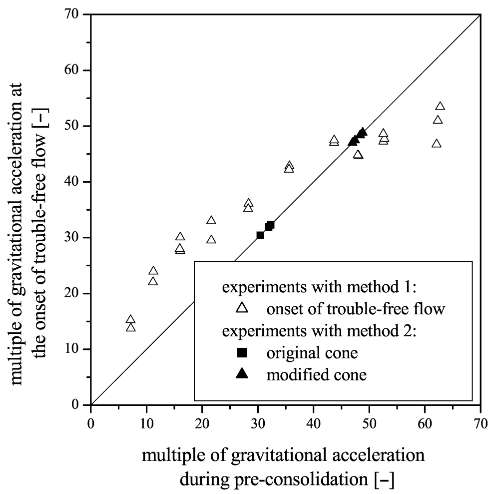

Figure 4. Multiple of gravitational acceleration using different test methods

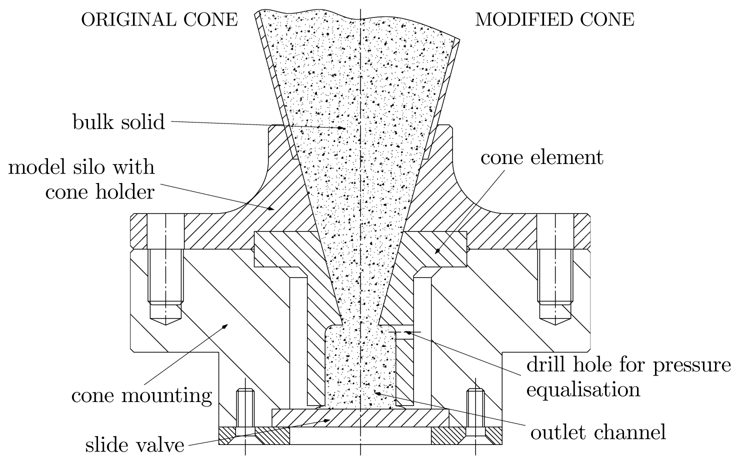

Figure 5. Cone design: left – original; right – modified

Figure 5 shows the design of the cone of the circular model silo and the assembly of the slider valve. Due to the use of different cone elements in the model silo, an outlet channel had to be placed between the critical outlet of the model silo and the slider valve. The channel was larger in diameter than the outlet to prevent the bulk solid from arching therein. Upon opening the slide valve, the bulk solid in the channel (of larger diameter) starts to flow immediately and initiates a suction effect on the arch above (at the lower diameter), which may be sufficient to break the arch earlier. As a result, the flow of bulk solids is possible at a lower rotational speed than without the suction effect. A lower critical outlet dimension has been predicted (filled squares in Figure 5). Due to drill holes for pressure equalisation (a modified cone), air can flow into the outlet channel after opening the slider valve. Thus, the suction effect is eliminated and a correct measurement of the critical outlet is possible (filled triangles in Figure 4).

4.2. Experiments to verify the discharge state

It is known that the stresses in the hopper are greater for the filling state than for the discharge state and, therefore, a smaller critical outlet dimension is required for the discharge state. The Jenike method is based on the discharge state in the hopper of a silo. The pre-consolidation in the silo centrifuge causes high compression of the bulk solid, which may lead to a fully developed discharge state, as already explained. To verify this assumption, tests have been performed with several bulk solid removals and freezing the stress state by quickly closing the slider valve. In these tests, two bulk solids with different particle sizes have been used.

The rotational speed for the tests was the critical rotational speed for trouble-free flow. The slider valve was opened after pre-consolidation and the flow started. Subsequently, the flow was interrupted by closing the slider valve again, thus freezing the discharge state. If a filling state or a not fully developed discharge state would exist after pre-consolidation, flow through smaller outlets must be possible after the second opening, because after the fist opening a discharge state was definitely reached. This discharge state leads to smaller stresses at the outlet and, therefore, to smaller outlet dimensions for flow. A smaller outlet means a lower rotational speed in silo centrifuge testing with an identical outlet. In Figure 6, results of two equivalent tests are presented. The shown result is from a test where the rotational speed at the opening was the critical rotational speed. With the critical rotational speed at the first opening, the flow of bulk solids is only possible after the second opening at the same rotational speed (open symbols). If the rotational speed was decreased before the second opening, the second opening did not lead to flow (filled symbols). Therefore, the stress state after pre-consolidation must be the discharge state. To start the flow after the second opening, the rotational speed must be increased to the former level.

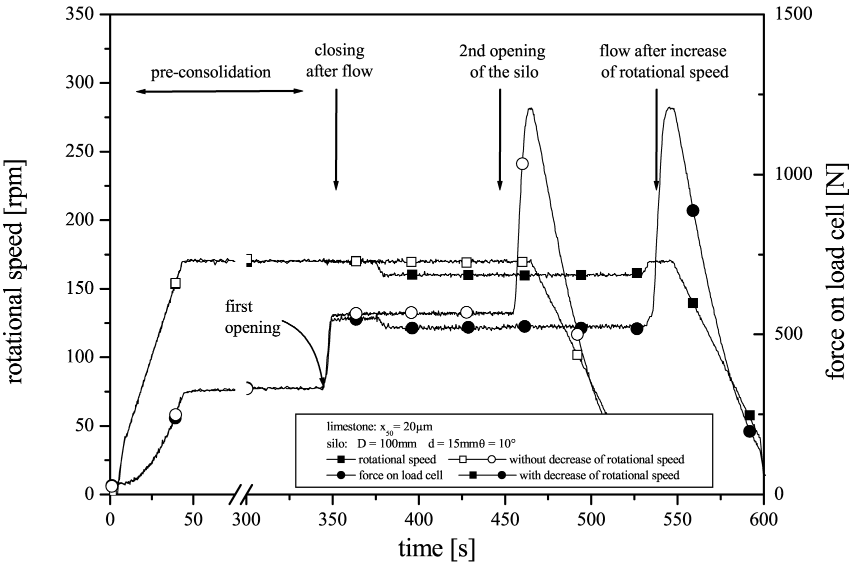

Figure 6. Test procedure to investigate the stress state after pre-consolidation (coarse limestone)

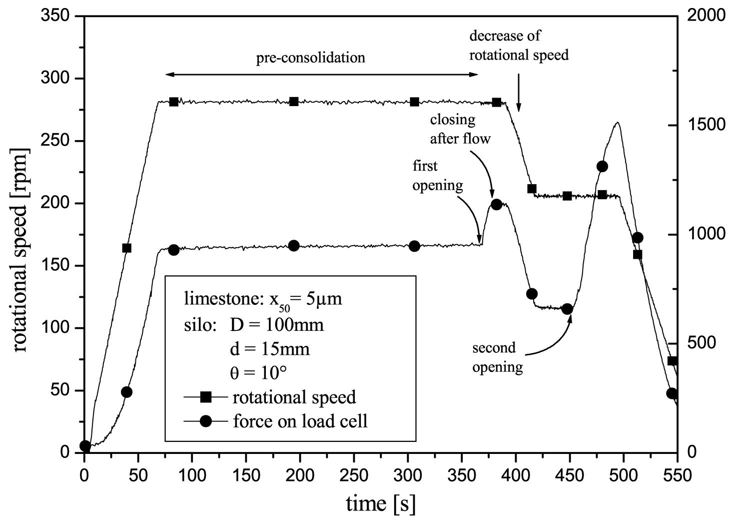

Figure 7. Test procedure to investigate the stress state after pre-consolidation (fine limestone)

This test was repeated under similar conditions with finer limestone. First the critical rotational speed was investigated and then the rotational speed for the second opening was decreased (Figure 7).

In contrast to the behaviour of the coarser limestone (Figure 6), the finer limestone started to flow after the second opening at a reduced rotational speed. In a series of experiments with rotational speed decreasing from experiment to experiment, the lowest rotational speed for flow was determined for the second opening. The lowest rotational speed is characteristic for the fully developed discharge state. Since this rotational speed is lower than the critical one after pre-consolidation, the state of stress after pre-consolidation is somewhere between the filling state and the discharge state. Only with the help of wall stress measurements in the cone the precise state of stress can be given for the situation immediately after pre-consolidation. Therefore, the state of stress after pre-consolidation must be investigated for each new bulk solid to make sure that the discharge state of stress prevails. A scale-up compared with the Jenike method is only possible having the discharge state of stress in the model and in full scale.

4.3. Experiments with moist gypsum

Moist bulk solids like the gypsum of flue gas desulfurization plants are often difficult to handle and the prediction of the critical outlet dimension by the Jenike method may lead to overdesign in spite of proper results from shear tests and accurate calculations. Overdesign can amount to 100% for the moist gypsum of flue gas desulfurization plants. Experience has shown that the flow of bulk solid occurs some time after opening the model silo. The causes of this overdesign are yet to be fully understood. It is assumed that this time-dependent behaviour is caused by creeping (decreasing strains at constant stresses) and relaxation (decreasing stresses at constant strains). Silo centrifuge testing is a way to reduce overdesign by predicting the influence of creeping and to understand this creeping effect.

The testing procedure to investigate creeping effects in moist gypsum is similar to the procedure described in Section 4.2. After filling in the gravity field, the silo centrifuge is accelerated for pre-consolidation. After pre-consolidation the outlet of the model silo is opened. If the rotational speed is set above the critical value, flow occurs and the force on the load cell, is increased by the increasing amount of bulk solid in the collecting bin. The creeping experiment with moist gypsum plotted in Figure 8 (top) has been performed at a rotational speed below the critical value. After opening the outlet of the model silo no flow occurs. The rotational speed of the silo centrifuge is kept constant for the whole test. Due to creeping effects, the bulk solid starts to flow after a while without any external influence. The time interval between the opening of the silo and the onset of flow is called the creeping period. The model silo has a mass-flow profile design. Therefore, discharge is not interrupted by piping. The flow rate of moist gypsum is extremely high due to unengaged discharge from the model silo. A duration of flow of only 4 seconds has been found at the rotational speed of 280 rpm, starting from the onset of flow until the silo is empty. Therefore, no freezing of the stress state by closing the slider valve is possible, as was done in the experiments with fine limestone described in Section 4.2. This experiment was repeated in a series of tests, decreasing the rotational speed from experiment to experiment and measuring the creeping period for each experiment.

The results of the creeping experiments are plotted in Figure 8 (bottom). The creeping period for each experiment is plotted versus an outlet dimension of a full scale silo. The outlet dimension for full scale can be calculated with Equation (1). Each dot marks a single experiment regarding the creeping time until the onset of flow. The creeping period increases with decreasing rotational speed, equivalent to a smaller outlet dimension of a full scale silo. Even at an outlet dimension the size of nearly half the size of the maximum critical outlet diameter, flow still occurs, but up to half an hour creeping time is necessary before the flow starts. A minimum value for the required outlet dimension could be found at 1130 mm for the full size scale. The creeping time for a fixed scale varies over a wide range. At a high rotational speed – equivalent to outlet dimensions from 1560 mm to 1970 mm – flow starts immediately or there is only a short creeping time after opening the outlet. If the rotational speed is decreased further, longer creeping time is essential for the onset of flow. This area extends from the outlet dimension of 1130 mm to 1560 mm in full scale. Below the outlet dimension of 1130 mm no flow occurs, even for very long creeping times. At longer times, the superposition of time consolidation with the creeping effect can lead to larger required outlet dimensions.

To compare the results of silo centrifuge tests with the results of silo design by Jenike, critical outlet dimensions have been calculated using shear tests. These tests were performed with a ring shear tester. The test results were used to calculate the critical outlet dimensions according to the Jenike method [1, 2]. As a result, an outlet dimension of 1940 mm had been calculated according to [1]. The results for the critical outlet dimension according the Jenike method and those found by silo centrifuge testing show good agreement regarding the maximum value of immediate flow and the value calculated according to the Jenike method. Nevertheless, the flow of moist gypsum can be found at smaller outlet dimensions if significant creeping time is allowed.

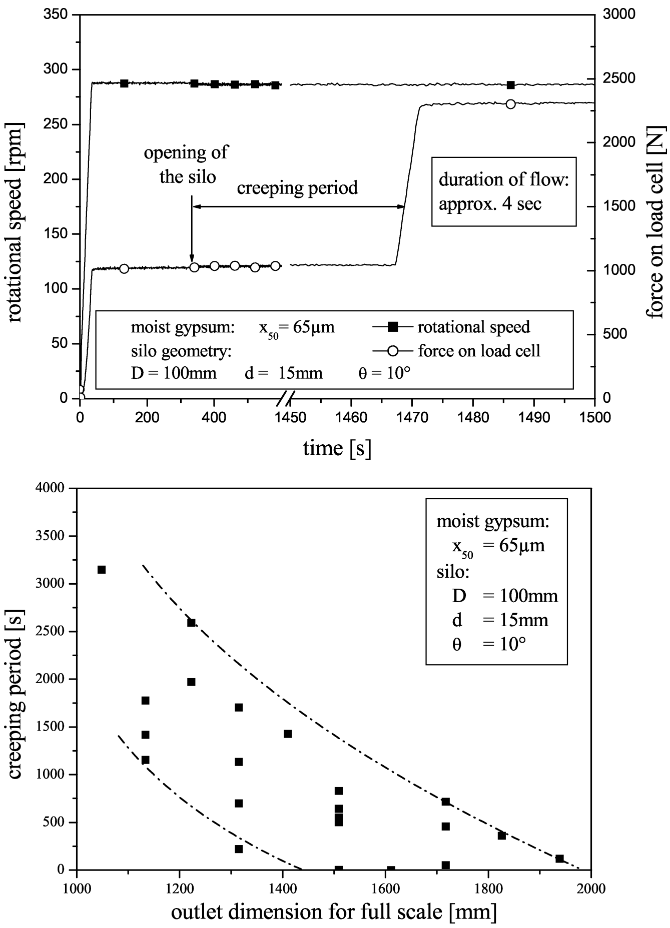

Figure 8. Top – testing procedure to investigate creeping of moist gypsum; bottom – creeping period versus the outlet dimension for full scale

5. Conclusions

Experiments with various test methods have shown that the procedure of silo centrifuge testing can be simplified if, after pre-consolidation, the silo is opened directly in the centrifugal field without an intermediate stop. A special sequence of one opening, closure and another opening at various rotational speeds allows one to verify and guarantee the discharge state of stress, a prerequisite for scale-up. The application of silo centrifuge testing for silo design has been shown for various dry and moist bulk solids. For moist gypsum, creeping influence effects have been detected. It has been found that the critical outlet diameter for arching not to occur could be reduced by a factor of about two if the creeping effect be taken into account.

Acknowledgements

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References

[1] Jenike A W 1964 *Storage and Flow of Solids, Bulletin* (123), Utah Engng. Station, University of Utah, Salt Lake City

[2] Schwedes J 1968 *Fließverhalten von Schüttgütern in Bunkern*, Verlag Chemie, Weinheim

[3] Wilms H and Schwedes J 1988 *Siloausläufe. Silo-Handbuch*, Verlag Ernst u. Sohn, pp. 85–110

[4] Egerer B 1982 *Kritische Auslaufdurchmesser bei Massenflußbunkem für kohäsive Schüttgüter*, Dissertation, Universität Erlangen

[5] Schöneborn P-R and Molerus O 1976 *Aufbereitungstechnik* **5** 217

[6] Nielsen J and Askegaard V 1977 *Powder Technology* **16** 123

[7] Kristiansen N O, Munch-Andersen J and Nielsen J 1989 *Centrifuge* **88** 593

[8] Munch-Andersen J and Nielsen J 1986 *Bulk solids handling* **6** (5) 885

[9] Lepert P, Ranaivoson D and Gourdon J L 1989 *Powders and Grains* (Biarez J and Gourves R, Eds), A.A.Balkema, Rotterdam, pp. 385–392