THE FLOW OF RAPE SEED IN A SILO EQUIPPED WITH A DISCHARGE DEVICE

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Abstract: The paper contains a review of experiments with rape seed in a model silo with a semicircular flat bottom equipped with a low-height discharge device. Observations of flow patterns were made during filling and discharging through the transparent front wall of the model silo. Measurement of wall normal pressures and discharge flow rate were also made. A properly designed discharging device can eliminate a pressure peak which is usual for the transition point (dynamic overpressure) in mass flow silos. Experiments have shown that a low-height discharge device can be applied to reduce the pressure increase during discharging damaged silos.

Keywords: silo, anti-dynamic tube, flow rate, pressure distribution, damaged silo

Nomenclature

d_T – diameter of discharge tube [m]
A_s – outlet area [m^2]
g – acceleration due to gravity [m/s^2]
ρ_i – bulk density [kN/m^3]
Q_s – mass flow rate [kg/s]

1. Introduction

Inside a standard (classic) discharge pipe, stresses are visibly smaller than in the bulk solid around the pipe. The maximum stress in a silo is proportional to its diameter. A discharging pipe may also be considered as a silo, but its diameter is smaller than that of a silo. Thus, the bulk solid flow on areas of low stresses. These areas are the top surface of the silo filled with material and the inside of the discharge pipe. The mass flow rate should rather be compared with that of a silo with the same outlet dimensions but without a discharge pipe. An important fact, which must be stressed here, is that only a well-designed discharging device has a positive influence on stresses in silo walls. The arrangement of perforations, geometry, shape and location of the orifice have the most influence on the flow pattern, wall stresses and mass flow rate.

The discharge device can be applied to reduce the increase in pressure occuring during discharge from damaged silos [1–7]. Many concrete silos in Poland have been used for a long time and are in majority damaged due to various external or internal factors. A combination of corrosive environmental pollution with poor lagging has caused advanced damage. Faulty design and errors in its execution (deviation from the vertical) combined with poor quality of concrete led to a critical state of many silo structures. Nowadays, various repair methods of reinforced concrete silos are available but applying a discharge device is clearly not as expensive as strengthening with the cables made of high-strength steel.

2. Experimental setup

Experiments were conducted with rape seed (mean particle size $d_{50} = 1.98$mm, bulk density $\rho_b = 8.5\text{kN/m}^3$) on a model silo with a semicircular flat bottom shown in Figure 1. The model silo height was 1.3m. The diameter of the semicircular bottom was 0.45m. The cylindrical wall and bottom were made of steel, while the 20mm thick front transparent wall was made of organic glass. Three steel columns supported the whole setup. The total capacity of the model silo was about 0.4m^3. Hence, half of the discharge pipe was installed near the transparent front wall. Due to this arrangement, it was possible to observe the flow pattern during discharging.

This model exemplifies a half of a cylindrical silo. The original discharging device shown in Figure 2 was designed to be applied in a food processing plant.

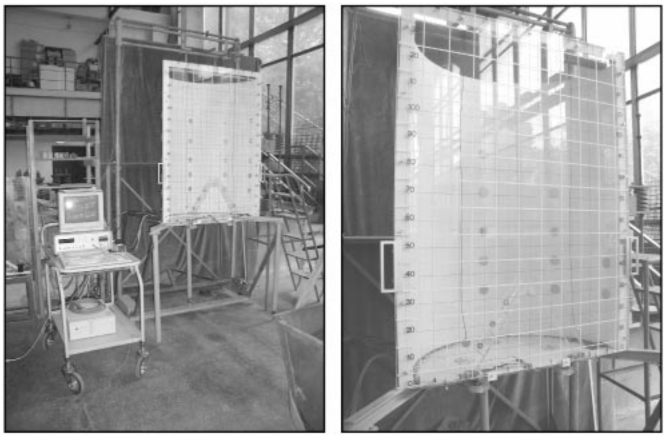

Figure 1. Experimental setup

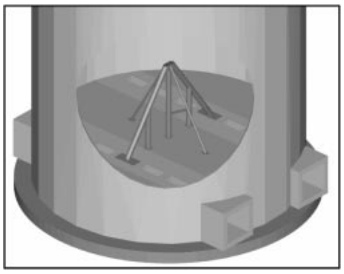

Figure 2. Discharge device designed for a full-sized silo

The purpose of the model silo experiments was to determine such geometrical parameters of the device that would help achieve the most favourable flow. Twenty normal (perpendicular) pressure sensors were installed in the cylindrical wall and three in the flat bottom. Additionally, some of the discharge devices were equipped with double-sided normal (perpendicular) pressure sensors which measured pressure inside and outside the pipe. Some of the discharge devices were equipped with a system of electric strain gauges. A series of observations was made for four basic types of discharge devices. Each type's geometrical parameters were changed during the experiments.

3. Mass flow rate through an orifice

Many investigations have been made to estimate the discharge mass flow rate through openings. Most investigations have been concerned with horizontally placed orifices. A number of correlations exist which can be used to estimate the mass flow rate, W, during discharge. Beverloo *et al.* [8] obtained a law from their experimental results in the following form:

$$W = C\rho_i\sqrt{g}(D_0 - kd)^{5/2}. \tag{1}$$

Because of the efficiency of this correlation, many authors have used it to estimate their experimental results. According to this law, the mass flow rate is dependent only on the diameter of the orifice, D_0, the mean bulk density, ρ_i, acceleration due to gravity, g, and the shape of particles, which is represented as k. C is constant for each group of experiments.

Four types of discharge devices were used to measure the mass flow rate (Figures 3–6).

In devices of the first type, a pair of discharge pipes of inner diameter $d_T = 56$mm were used. In type I, II and III a half of a discharge pipe were used of the inner diameter of 66, 92, 110mm, respectively. In general, all discharge pipes except for type I had only one side opening. The influence of tube thickness on the mass flow rate was eliminated by using thin (0.3mm) plastic plates, covering the relatively greater opening of the pipe.

The purpose of tests was to determine the orifice size and location to obtain a "dense-flow" regime. Nevertheless, "accelerated flow" occurred during emptying through large-diameter orifices. The transparent front wall allowed us to observe the flow regime. Figure 7 shows an example of flow with two layers of white mustard seed located over the orifice. The moment is shown, when a layer started to fall due to "accelerated flow". Figures 8 and 9 show the next two stages of emptying the silo, in the case of a 56mm pipe.

Results of measurements and mass flow rate values, Q_s, calculated from the Beverloo equation (Equation (1)) for discharge with a discharge device of type II, III and IV are shown in Figures 10–12. Adjustment of the calculated values in relation to the measured ones gives: $C = 0.13$. Previous studies, applying the Beverloo correlation for vertical tubes (silos) have found C in the range of 0.65–0.80 [9, 10]. It can be explained by the inclination of the tube and irregular flow crosswise the tube. For device types II, III and IV, a critical outlet area was obtained while flow velocity

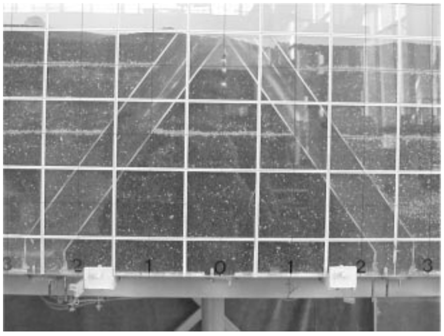

Figure 3. Discharge device – type I

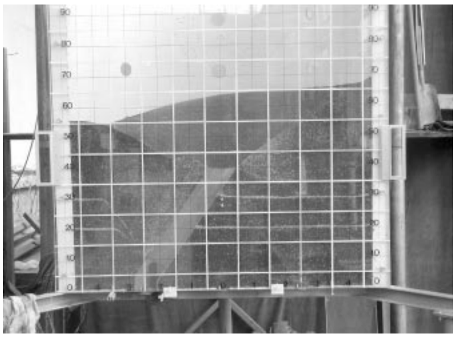

Figure 4. Discharge device – type II

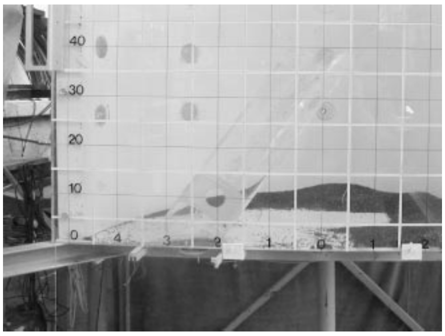

Figure 5. Discharge device – type III

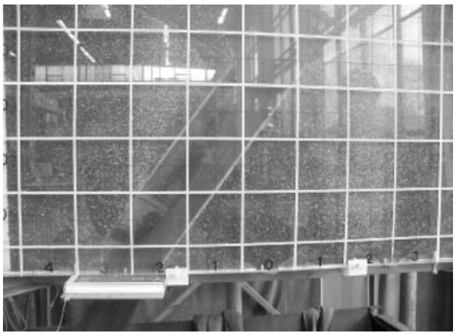

Figure 6. Discharge device – type IV

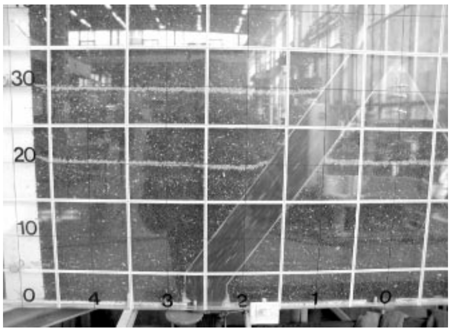

Figure 7. Layers of white mustard seed

Figure 8. Accelerated flow – the left arm of the device

Figure 9. Last stage of emptying – the right arm of the device

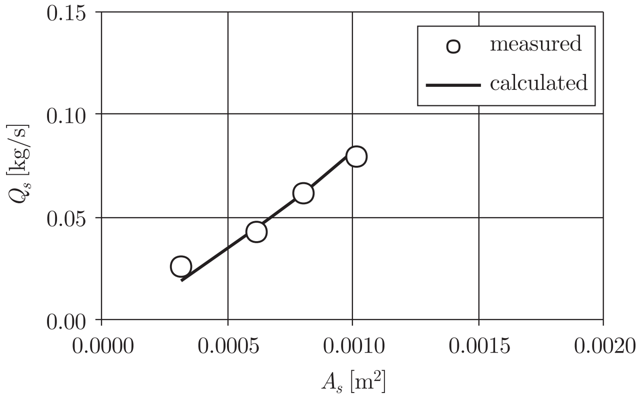

Figure 10. Mass flow rate, Q_s, as a function of outlet area, A_s, for a 66mm tube

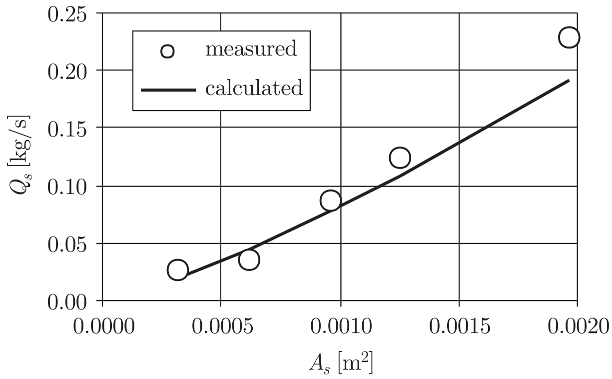

Figure 11. Mass flow rate, Q_s, as a function of outlet area, A_s, for a 92mm tube

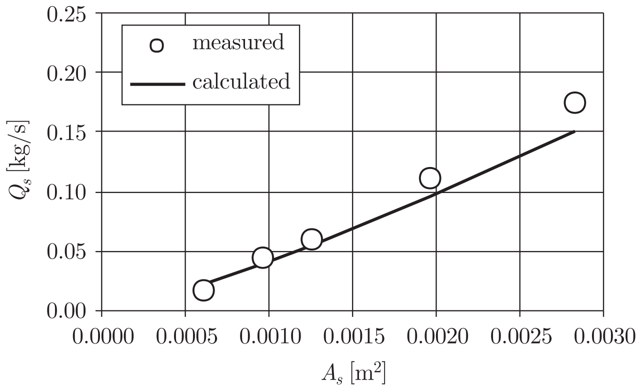

Figure 12. Mass flow rate, Q_s, as a function of outlet area, A_s, for a 110mm tube

increased to large values and a flow channel occurred in the tube. The mass flow rate during emptying through a large outlet also had a great value and the flow of the material through the uncovered side of the orifice occurred.

A number of tests was performed with rectangular and square orifices. A rectangular orifice was located parallel or perpendicular to the pipe's axis of symmetry. The tests have shown that a circular orifice to be the most effective. It allows the "dense flow" regime to occur with the maximum orifice area.

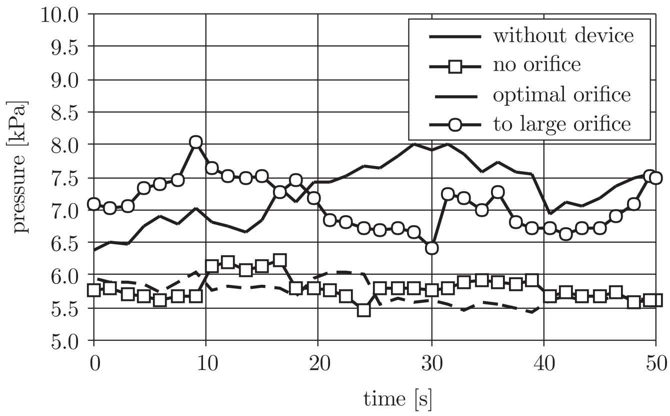

Figure 13. Pressure distribution during different kinds of discharging

4. Pressure distribution during discharge

Pressure measurements were performed on the model. Twelve strain gauge normal pressure cells were arranged in three generatrices. One (A) was placed on the axis of symmetry, the second (B) – at an angle of 45° from the first, and the third (C) – at 80°. There were five pressure cells in the first generatrix, three pressure cells in the second, and two pressure cells in the third. Results of the measurements were registered by an electrical device in kPa. Additionally, three pressure cells installed in the flat bottom measured vertical pressures in the model silo.

Figure 13 shows the pressure distribution plotted as a function of time for four different cases. Each curve shows the sum of pressure values in generatrix (A).

Grey curve shows pressure during emptying with the most favourable discharge device. Such a device allows to occur to the maximum flow rate and "dense flow" regime. Curve with square markers shows emptying with a device without an orifice. Curve with circular markers shows emptying with a device with too large orifice and continuous black line shows emptying without a discharge device. Pressure values are clearly greater in two last cases. It should be noted that the Figure 13 shows mean values of maximum discharge pressures. This figure shows clearly that a well-designed device allows to reduce pressure during emptying. On the other hand, discharging with not properly designed device may result in increase of pressure.

5. Flow patterns

A digital video camera was used to capture flow patterns. Four types of emptying mentioned in Section 4 was captured on video. To achieve the most visual effects thick white mustard layers were used. Some of typical digital solarized images are shown below. Figure 14 shows consecutive stages of emptying the silo with a device equipped with an optimal orifice. It was a side opening, parallel to the front transparent silo wall.

After opening the outlet, the first layer falls into the tube. This clearly shows that the velocity profile varies across the tube. During such emptying funnel flow occurred all over the discharge device. The flow channel was axi-symmetrical, with the maximum flow velocity in the middle of the flowing area. A narrow channel occured

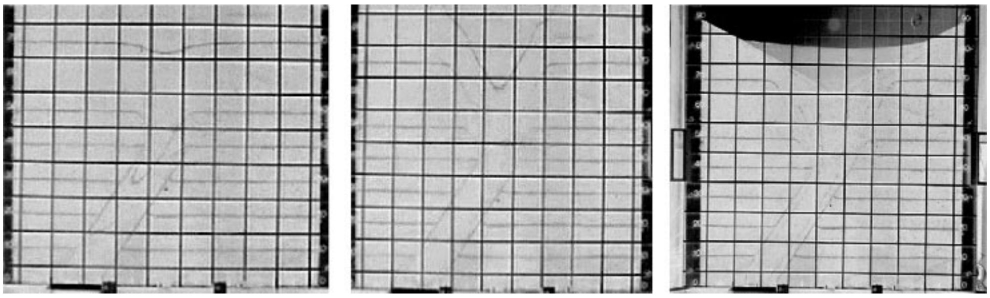

Figure 14. Stages of emptying the silo equipped with a discharge device

Figure 15. Front wall with worn traces

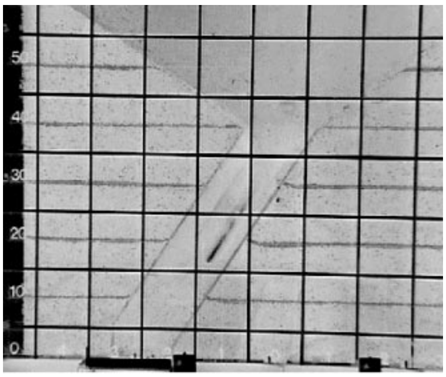

Figure 16. The rest of the upper mass is emptying

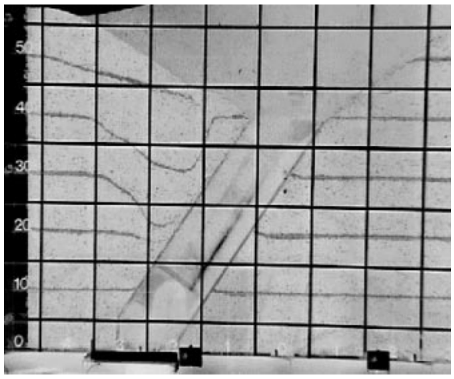

Figure 17. The tube is empty – the material flows through a side opening

in the higher part of the tube. The photo in Figure 15 was made after the experiments had been performed. This is the removed front wall with irregular, stripped traces of flowing. The upper part of the channel is less worn than the lower, as shearing forces were greater in the lower part. A worn strip also occurred all over the channel.

Figures 16 and 17 show photos made within a short time interval. It is the moment when the tube was emptying and material began to flow through a side opening (mustard layers were falling down).

Figures 18 and 19 show images captured during discharge from the model silo without a discharge device.

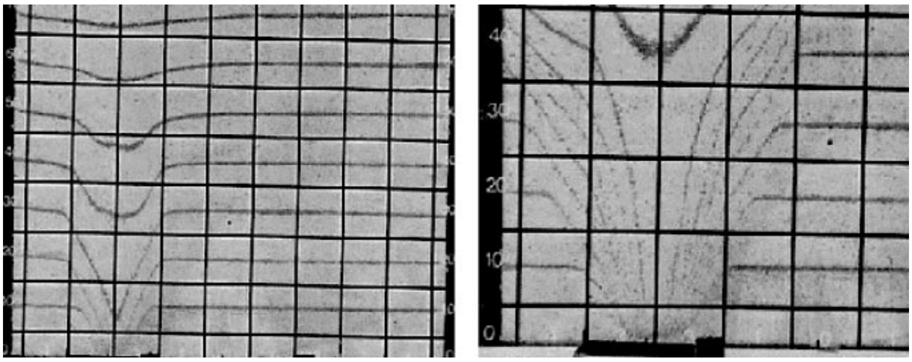

Figure 18. Mass flow in the model silo during eccentric discharge

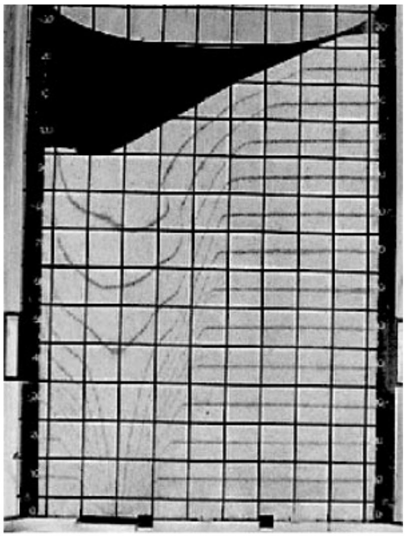

Figure 19. The hole model silo during eccentric discharge

During emptying through an eccentric outlet only the left-hand part of the material was moving, but – as already noted in Section 4 – such emptying caused deviations from the ideal symmetrical pressure distribution and increased the values. The material flowed along the left part of the model silo, forming a flow channel.

Figure 20 shows emptying with an improperly designed discharge device. The large area of the orifice allows material to flow simultaneously from the upper part of the silo and from the lower part close to the orifice.

Such flow patterns are comparable with the patterns mentioned above. This may suggest that such patterns are combinations of those previously mentioned. A flow channel occurs above the tube, and above the orifice the material is flowing in the direction of the orifice.

6. Conclusions

Our experiments with the model silo have shown that a discharge device can be used to reduce increases in pressure and mass flow rate, subject to proper design

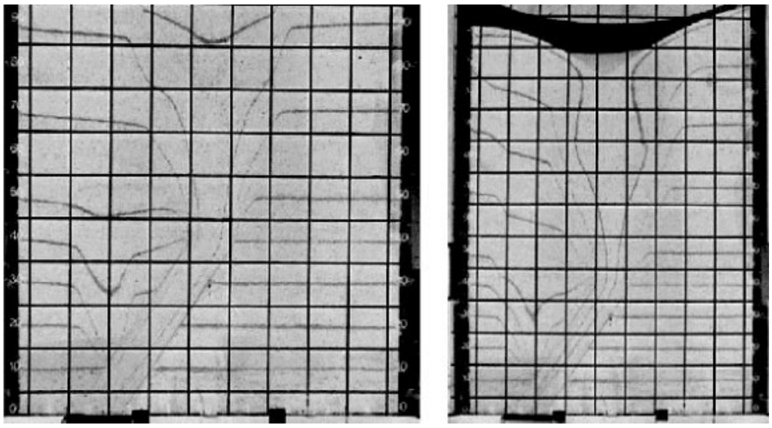

Figure 20. Emptying the silo through an improperly designed discharge device

of the device. The greatest influence on the flow is its geometry, *i.e.* the arrangement and size of the openings and the diameters of the main and side tubes.

Our observations have also confirmed that by using a discharge device it is possible to centre and control bulk solid flow. Besides, it has been observed that only a well-designed device can ensure a satisfactory discharge rate of bulk material.

The observed horizontal pressure on the walls does not increase during emptying with a well-designed device.

Further investigation of the effects accompanying and the loads acting during silo discharge are required.

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