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Filling and Emptying State of Silos Above Discharge Devices

Drive power is an essential design criterion for most machines,as well as for different discharge devices, such as conveyor belts or screw conveyors, which can be found below silos. However, in order to be able to determine the required driving power, the knowledge of the load transferred from the silo to the discharge device is necessary first. In this paper, the effects of the interaction of these two components on the basis of investigations on a model bin with a discharge belt will be discussed. Subsequently, the possibilities and problems of an analytical calculation are examined and compared with simulation results using the discrete element method.

Keywords: *silo and discharge belt interaction, filling and emptying state, measurement, DEM-Simulation.*

1. INTRODUCTION

The discharge behavior of silos as well as the occurring stress states have already been extensively studied since the end of the 19th century beginning with Janssen [3]. Also for the hopper, which is usually located at the lower end of a silo, Motzkus [4] and others [1] already gave early analytical approaches for the calculation of the vertical stresses and wall stresses.

If the silo – consisting of a cylindrical section and a hopper – is considered on its own, the described calculation methods, which are for example also implemented in Schulze's Silo-Stress-Tool [6], lead to qualitative and quantitative good results. The requirement for this is compliance with the respective prerequisites, simplifications and assumptions. One of the most important influences is, for example, the correct assignment of mass flow or core flow silo as well as the differentiation in filling and emptying conditions.

However, in combination with a discharge device, many of the assumptions made for the silo in the calculation approaches may become invalid, which is why the correct determination of the required discharge force is considerably more complex. Schulze dealt In his dissertation [7] extensively with this interaction between the silo and the discharge device and carried out some measurements. A similar approach is pursued by this paper, with a particular focus on the causes of the occurring phenomena, which should be underpinned by the DEM simulation.

2. Experimental setup

The experiments are carried out using the bunker with the discharge belt shown in Figure 1.

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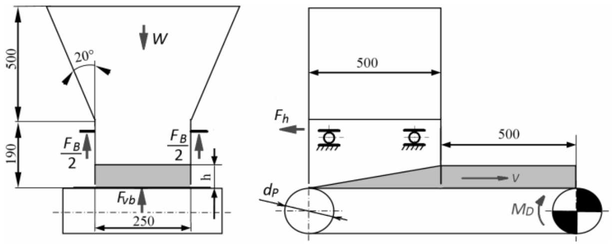

Figure 1. Model bunker

The Bunker and the discharge belt are supported independently from each other to enable the investigation of the load distribution between bunker and discharge belt. A dynamometer for measuring the belt speed v is attached to the drive drum. The drive torque M_D is measured by a torque support on the motor.

The bunker itself is mounted on four rollers with load cells which measure the vertical force of the bunker F_B, position (a) in Figure 2. In the horizontal direction, the bunker is also fastened via a load cell (b), so that a comparison can be made between the discharge force $F_h$on the bunker and the required drive torque M_D.

$$M_D = \frac{\left(F_h + F_{NL}\right) \cdot d_P}{2} \tag{1}$$

Equation (1) computes the drive torque M_D whereF_{NL} is the no-load drive force to overcome the friction resistances in the bearings and the belt.

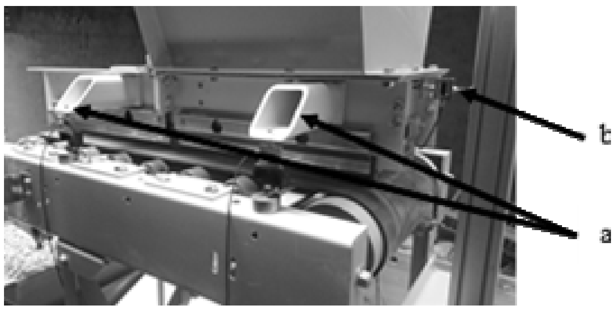

Figure 2. Test facility with load cells

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Since, during the filling process, the bulk material mass in the bunker is recorded via a load cell too, the vertical force on the conveyor belt F_{vb} can be determined by means of the difference between the weight W of the bulk material and the measured vertical force of the bunker F_B.

$$F_{vb} = W - F_B \tag{2}$$

By means of a measurement of the bulk material height h on the conveyor belt after the slide opening and the aforementioned measurement of the belt speed v, it is also possible to calculate the occuring mass flow. The bulk material weight$W(t)$, which is located in the bunker at any given time, can then be calculated based on an initial bulk material weight W_0.

$$W(t) = W_0 - 2,45 \frac{m^2}{s^2} \cdot h \cdot v \cdot \rho \cdot t \tag{3}$$

The weak point of this measurement setup is the indirect measurement of the vertical force acting on the belt, which should be the main subject of the measurements. Due to the necessary gap between the hopper and the discharge belt, an unintended and unrecordable force transmission between the bunker and the frame can occur when individual particles of the bulk material enter this gap. This was particularly noticeable at very small slide openings with large vertical and horizontal forces. However, the occurrence of this effect can easily be detected in the results of the measurements and thus the validity of the individual measurements can be checked.

A typical indirect measurement result for a para–meter combination during emptying the bunker is plotted in Figure 3 over time. The diagram shows the measuredhorizontal force F_h and vertical force $F_B$on the bunker. Also belt speed v and discharge force of the motor ($F_h + F_{NL}$) is drawn as well as the vertical force F_{vb} determined by the expression in equation (2)..

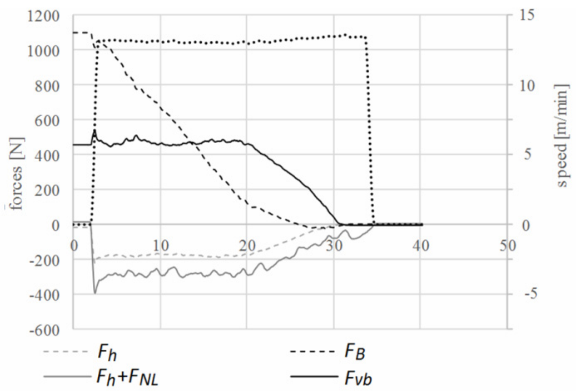

Figure 3. Horizontal and vertical forces acting on belt and hopper at emptying

However, this is only one of three partial measurements. An entire measurement to a parameter set is made up of the following sections:

- Filling: Measurement of the weight distribution on hopper and belt
- First start: Measurement of the transition from active filling stress state to passive emptying stress state
- Emptying: check if the passive stress state is preserved when the machine is stopped and started again.

Independently from the setup for indirect measurement of the vertical force acting on the belt by measuring the vertical force of the bunker F_B described above, direct vertical stress measurements are applied. For this purpose a pressure sensor has been developed which is depicted in Figure 4.

The pressure sensor is placed on the belt underneath the bunker centered on the bunker's axis. It measures directly the mean of vertical stress acting on it.

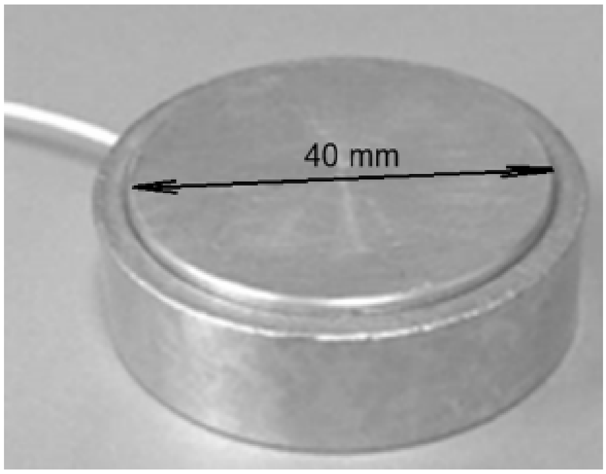

Figure 4. Pressure sensor for direct measurement of the vertical stress acting on the belt

As the sensor moves with the belt, the time plot of its measurement results can be divided into three stages:

I – Filling
II – Emptying
III – Leaving the bunker

A typical measurement of the vertical stress σ_v over time is shown in Figure 5. In the filling stage *I* the vertical stress onto the belt is relatively high. At the end of stage *I* the belt drive is taken into service and the belt starts to discharge the bunker. Due to the mass flow, the vertical stress σ_v onto the belt decreases suddenly and reaches a constant level while the sensor passes through the slide opening (Emptying stage *II*). Outside the bunker the pressure sensor is covered by a thin layer of bulk material, hence the vertical stress onto the sensor decreases again.

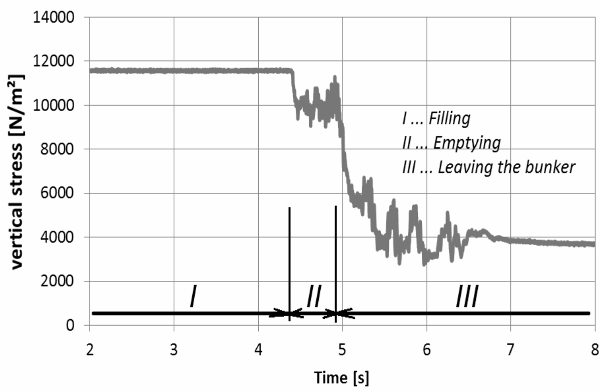

Figure 5. Typical vertical stress versus time curve $\sigma_v(t)$ measured by the pressure sensor for direct measurement

The bulk material used in this paper and also in earlier works [2] is crushed rock with a particle size of 4-8 mm and the properties in Table 1:

Table 1. Material data of the bulk material

Bulk material: Crushed rock (grain size 4/8 mm)	
Bulk density (ρ)	1320 kg/m³
Effective angle of internal friction (δ)	45°
Angle of wall friction between steel and bulk material (φ_x)	23.5°
Stress ratio ($K_v=\sigma_h/\sigma_v=1.2\cdot[1-\sin(\delta)]$)	0.35

The following parameters are investigated at the different measurements:

- The slide opening is varied in several steps between 15mm and 120mm.
- The speed of the conveyor is varied between 0.2 m/s and 0.6 m/s.
- The outlet cross-section of the hopper is to be varied by means of appropriate internals.

3. Measurements Results

3.1 Filling

No significant differences could be seen in all measu–rements during filling. In each case, about 172.8 kg of the bulk material were charged into the hopper. The weight forceW_0 of 1695 N is distributed with a deviation of +/- 15 N to about 900 N acting on the bunker and about 795 N on the belt, independently of the chosen slide opening.This corresponds to a vertical stress of 6360 N/m², see Figure 6.

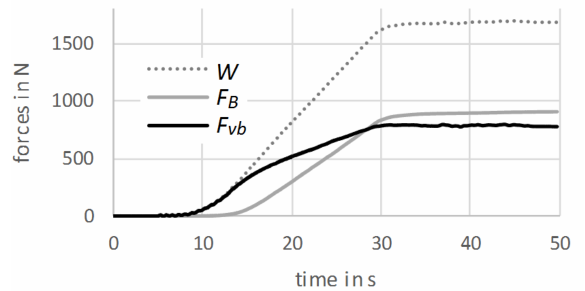

Figure 6. Distribution of the bulk weight on bunker and belt

During the time between the filling process and the first batching, it is possible to prove subsiding effects of the bulk material, which have a positive effect on the vertical force on the belt. In the time span between the measurements of approximately 260 s, a reduction of the vertical force on the belt by approximately 5% to 755 N and 6040 N/m² respectively, can be seen at all measurements. The hopper has to take up this difference.

When using a 25% smaller outlet cross-section of the hopper, like in Figure 7, the vertical force on the belt is with 660 N about 17% less than without the downsizing internals. Due to the bigger difference in the cross-section and the smaller difference in the acting force, the vertical pressure is about 11% higher than before.

The result of the direct measurement of the vertical stress $\sigma_v(t)$ on the belt is shown in Figure 8. The pressure sensor is placed underneath the bunker directly on the belt. During filling the vertical stress increases to its maximum value of about 12250 N/m² which is much more than the maximum of 7040 N/m² obtained from the indirect measurement. The experience shows, that this kind of direct pressure measurement results in too high readings. The reason for theseincreased measurement results has not yet been completely explained. Probably the positioning of the pressure sensor influences the local stress condition within the bulk material.

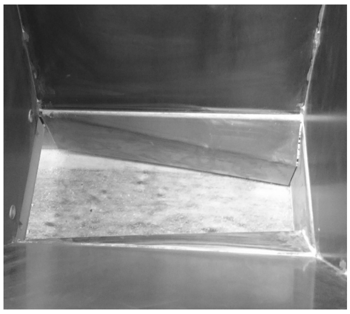

Figure 7. Geometry of the used bunker internals

In the same manner, as already mentioned before, subsiding effects can be observed too. Within 260 s the measured vertical stress reduces from 12250 N/m² to 11610 N/m², which corresponds to the 5% obtained from the indirect measurements. Also, this effect can not be completely explained yet.

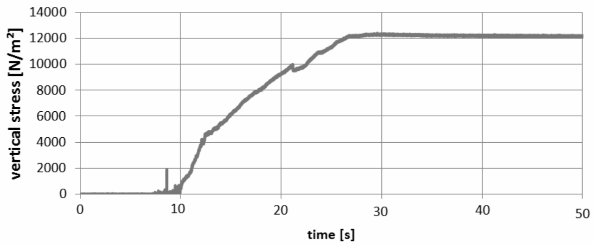

Figure 8. Vertical stress on the belt during filling, measured by use of the pressure sensor for direct measurement with a reduced cross-section of the hopper due to internals

3.2 First start

When the belt is switched on, it is possible to measure clear differences as a result of the adjusted slide opening, see Figure 9. In the case of small slide openings, a significant increase in the vertical force on the belt occurs before a quasi-steady state is established. This is due to the formation of a shear band of reduced density. As the volume in this area expands, the vertical force on the belt increases. This effect counteracts the actual reduction in the vertical force due to the transition to the passive emptying state.

In the case of a large slide opening, the effect of the pressure reduction due to the setting passive stress state predominates, and the vertical force is always smaller than in the filling state before. However, on closer examination of the qualitative course of the vertical force at the moment of starting the belt, an increase can be seen at all slide openings after a steep drop. The development of a shear band can thus be measured at all slide openings.

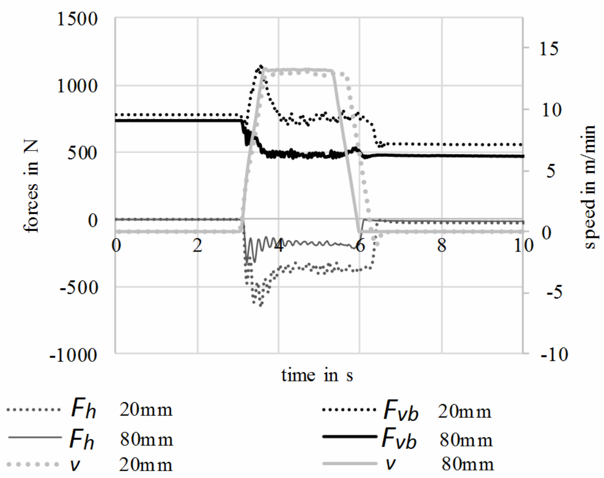

Figure 9. Comparison of a small and a large slide opening

After this, a quasi-steady state is established in a very short period of time, as it can be seen in Figure 9. As known from the literature [5], the vertical stress on the belt in the emptying state should be substantially smaller than in the filling state. However, in the case of small slide openings, the pressure level in the emptying state is much higher than in the case of large slide openings, which can be seen in Figure 10.

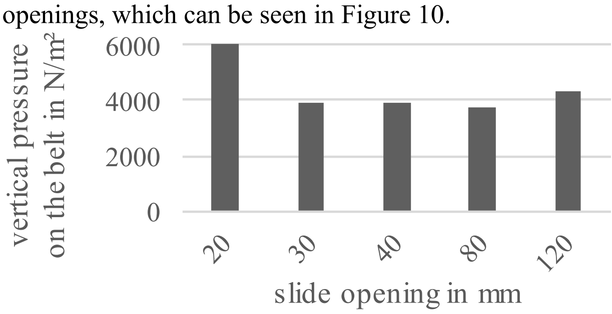

Figure 10. Vertical pressure on the belt in emptying state

When the belt is stopped, another very interesting effect can be seen: the vertical force drops again as compared to the quasi-steady emptying state. This effect is significantly more dominant in the case of smaller slide openings.The result is that the vertical forces at the different slide openings approach one another at a stop of the belt. It is assumed that the following two effects are responsible for this:

On the one hand, the generated shear band collapses, which reduces the required volume.

On the other hand, the small slide openings lead to an upward movement of the bulk material in front of the slide since the conveyed material picked up by the belt can not be transported through the small slide openings. This effect counteracts the setting of the actual emptying state of the designed mass flow hopper, which is why the quasi-steady emptying pressures on the belt are larger for small slide openings. This effect is confirmed in section four by simulations. As soon as the belt is stopped, the force required for the upward movement is no longer necessary and the vertical force drops off in a sudden manner.

The acting vertical forces are more or less the same for both belt speeds and thus independent of them. The influence of the outlet cross-section of the hopper should be discussed in the next section.

3.1 Emptying

When the moving of the belt starts again, the vertical belt force is again increased, depending on the slide opening.This is analogous to the observed drop when stopping the belt and is illustrated for an outlet height of 80mm in Figure3.It can be seen that the vertical force on the belt remains constant over a long period of time, while the force on the bunker decreases continuously. As a result, the discharge force remains almost constant until shortly before the bunker is emptied completely.

The influence of the 25% smaller outlet cross-section of the hopper is shown in Figure 11 for a slide opening of 30 mm. Just as in the filling state, the internals also result in a significant reduction of the vertical force on the belt in the emptying state and thus a lower required discharge force.

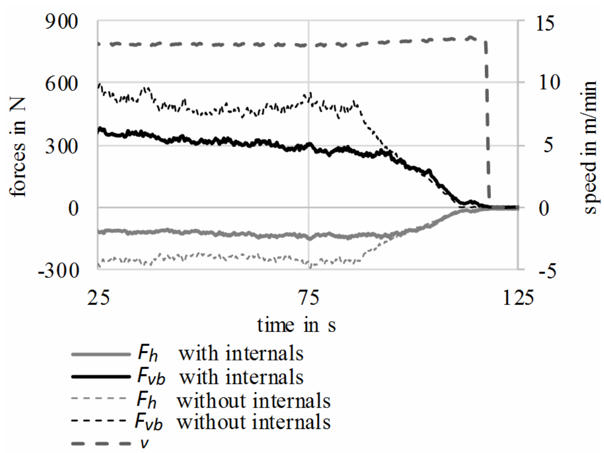

Figure 11. Emptying forces with and without internals at a outlet height of 30 mm

4. SIMULATION

The basically good accordance between the simulation and the measurements was already shown in [2]. The simulation results at this point should be examined again for a comparison with the effects occurring during the measurements.

In Figure 12, the simulation results at different slide openings are compared. It should be noted that the time horizon was kept as low as possible for the lowest possible computation time. Thus, some effects, such as the subsiding process, are not so dominant as at the longer lasting measurements. The belt starts moving one second after the beginning of the simulation run. Depending on the slide opening, the vertical force then changes from an almost equal value in the filling state to a value, specific to each slide opening in the emptying state.

Until the quasi-steady emptying state is reached, the effects known from the measurements can be confirmed: At the beginning, the subsiding behavior can be clearly seen. However, due to the rapid generation of particles, the drop in the vertical force up to the start of the belt is significantly faster than during the slow filling of the measurements. After that, the formation of the shear band can be observed. Due to the lower belt acceleration of only 0.2 m/s² instead of the acceleration of 0.35 m/s² set in the measurements, the increase in the vertical force is slightly less than in the measurements. However, particularly for a slide opening of 30 mm the formation of the shear band is very good to recognize in Figure 12.

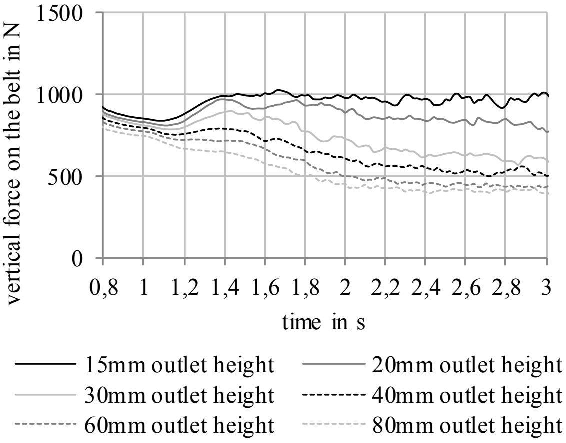

Figure 12. Simulation results for the vertical force on the belt at different slide openings

Figure 13 shows the flow behavior at a small slide opening. With the help of the simulation, a view into the inside of the bunker can be carried out and the particle motions can be examined. As already described above, an upward movement of the particles in front of the slide opening occurs and the vertical force on the belt is significantly increased thereby. It can also be shown that the vertical force does not increase over the entire bunker length, but mainly in the front area right before the slide opening.

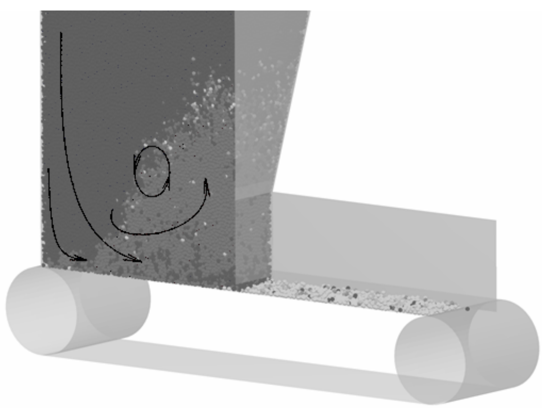

Figure 13. Particle flow inside the hopper at 15mm outlet height

5. COMPARISON

At this point, the obtained quantitative results should be compared. Particular attention is paid to the applicability of analytical methods of calculation. Figure 14 shows a comparison of the calculation, measurement and simulation for the vertical pressure in the filling state. It can be seen that the analytical calculation for the filling state without internals provides good results. The simulation provides an even more accurate result, but the time required to obtain the simulation result is in no relation to that in the analytical result. However, the analytical calculation is not suitable for more complex hopper outlet cross sections with internals.

For the emptying state, as shown in Figure 15, the analytical calculation can only be used for appropriate large slide openings. Whether a slide opening in this sense is large or small depends less on the particle size but on the size of the outlet cross-section of the silo.

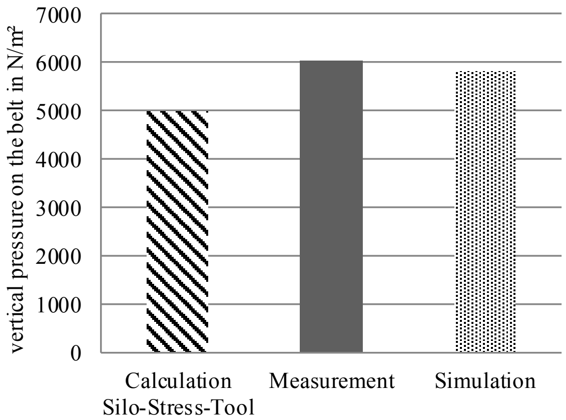

Figure 14. Comparison of vertical pressures on the belt in filling state without internals

The applicability of the analytical methods for the emptying state of a silo with a discharge device located underneath is therefore of utmost care. In general, but particularly for small slide openings and any installed internalsin the bunker, it is recommended to determine the occurring pressures and forces in the vertical and horizontal direction using the DEM simulation.

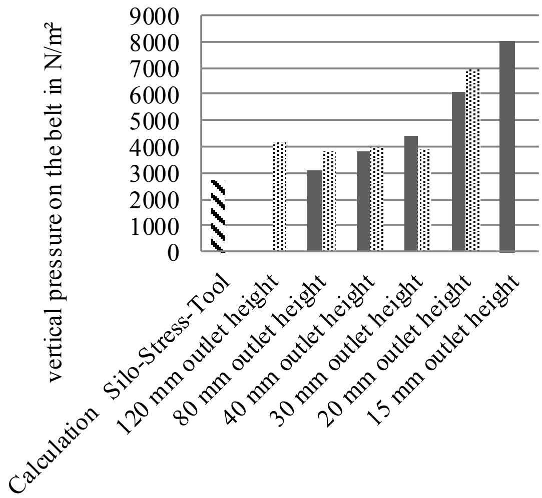

Figure 15. . Comparison of vertical pressures on the belt in emptying state without internals

6. CONCLUSION

The analytical calculation of the actual pressure on a discharge device under a silo and the required discharge force is almost impossible in the emptying state. Since on one hand, the assumptions for mass flow are no longer fulfilled and, on the other hand, additional effects such as internals and accumulation of bulk material can hardly be taken into account.

The DEM simulation provides here a workaround and delivers very reliable results for the dimensioning of the machines if the bulk material calibration is suitable. Also the implementation of complicated geometries is not a problem.

The pressure sensor for the direct measurement is currently of limited suitability to measure autonomously local pressures, since the installation of the load cell presumably influences the local stress state too much. However, since such a measurement would in principle be very advantageous, the cause for the stress increase should be investigated further. It is potentially possible to carry out an appropriate calibration on the basis of the examinations so being able to identify the actual pressures. In addition to bunker pressures, applications for such measurements would, for example, also be soil pressures.

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NOMENCLATURE

F_B	vertical force of the bunker
F_h	discharge force on the bunker
F_{NL}	no-load drive force
F_{vb}	vertical force acting in the belt
h	height of outlet
M_D	drive torque
t	time
v	velocity of the belt
W	bulk material weight force

GREEK SYMBOLS

σ_v	vertical pressure on the belt

ПУЊЕЊЕ И ПРАЖЊЕЊЕ СИЛОСА КАДА ЈЕ УРЕЂАЈ ЗА ПРАЖЊЕЊЕ У ГОРЊЕМ ПОЛОЖАЈУ

А. Хабер, С. Халиловић, М. Егер

Погонска снага је битан критеријум за већину машина као и за различите уређаје за пражњење као што су тракасти или пужни транспортери који могу бити лоцирани у доњем положају. Међутим, да би се одредила потребна моторна сила прво је потребно знати колико је оптерећење које се преноси са силоса на уређај за пражњење.

У раду се разматрају ефекти интеракције ове две компоненте коришћењем модела бункера са испусном траком. Затим се испитују могућности и аналитички прорачун и упоређују са резултатима симулације применом методе дискретних елемената.