SZENT ISTVÁN UNIVERSITY

GRAVITATIONAL AND VIBRATIONAL DISCHARGE OF SILOS

Thesis of PhD Work

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Notations:

A	amplitude	[mm]
a	outlet width of rectangular silo	[mm]
$b,\ c$	depth and width of rectangular silo	[mm]
D	diameter of silo	[mm]
d	diameter of silo outlet	[-]
d_p	characteristic dimension of grains	[mm]
E	Young-modulus	[MPa]
f	frequency	[Hz]
g	gravitational acceleration	$[\frac{\mathrm{m}}{\mathrm{s}^2}]$
Q	flow rate	$[\frac{\mathrm{m}^3}{\mathrm{s}}]$
r_p	radius of particles	[mm]
W	discharge rate	$[\frac{\mathrm{kg}}{\mathrm{s}}]$

Greek letters:

α, α_0, α_1	phase angles	[-]
δ	shape coefficient of the arch	[-]
θ	cone half angle	[°]
μ_b	internal friction coefficient	[-]
ν	Poisson-ratio	[-]
ρ_h	bulk density	$[\frac{\mathrm{kg}}{\mathrm{m}^3}]$
Ψ	discharge rate ratio	[-]

1. INTORDUCTION, OBJECTIVES

1.1. Actuality and importance of the topic

Primary commodities and raw materials are in granular form in almost all field of industry. These can be found for example in chemical- or food industry, in agrucultural or in mining industry. Transporting and storing of materials like these is a complex question, because of special mechanical properties of granulars (which comes from discrete structure of assemblies). A granular material (e.g. a bag of wheat) under certain circumstances can be like a fluid, but in different condition the same assembly can be like a solid material. Because of this duality the description of mechanical state of granulars is a complicated problem for practical engineers.

The nowadays developing numerical procedure, the Discrete Element Method (DEM) can help the solution of design problems arising from special mechanical behaviours of granular materials. Essence of this method is a simulation cycle which based on solution of equations of motion on single particles. To describe the movement of single particles, Newton's second law of motion and the general rotational dynamics equation are repeatedly solved. The contact forces and the moments are calculated based on displacement of particles in every time steps with help of contact models. This method is commonly used to define behaviours and motion of granular materials in several fields of research included granular phenomena. By using this method, the mechanical properties of granules can be described and beneficial information could be obtained to understand complex behaviour of these materials. However determination of micromechanical parameters (calibration of the discrete model) and computational demand of simulations are two main shortcomings of DEM.

1.2. Objectives and aims

Based on the introduction; there are three main topics of this work: improvement of the used numerical method; description of gravitational discharge of mass flow silos and examination of vibrational discharge in case of cylindrical, agricultural silos.

To extend practical usage of DEM; procedures and algorithms are developed. Aims according to this topic are:

- Simplifying and improving calibration method of DEM models (namely the determination of micromechanical parameters of granulars). Development of a procedure, which is suitable for simplifying and automation of DEM models's calibration process.
- Development of an algorithm which is suitable for reducing computational time of discrete simulations based on granule's clustering. Reduction of computation efforts of numerical calulations without the changing of macroscopic behaviours of the granular assembly.

Because nowdays there is not an universally usable model, which is suitable for determine discharge rate of mass flow silos aims according to this topic are:

- Development of an accurate, validated discharge modell to determine discharge rate of mass flow silos.

– Extension of Oldal's discharge model to rectangular hoppers. Examination of Oldal's theory in case of a silo with rectangular cross section.

Formation of stable arches is a serious problem on agricultural mixing plants; because of stopping the material flow. Phenomenon of arching is very ruinous; since it keeps from discharge the stored material, whereupon the silo will be unusable. To avoid phenomenon of arching and to ensure granular flow in agriculture usually vibrational flow promoting devices are used. However the design and choosing process of these devices currently based on experiences and observations, because exact influence of vibration on silo discharge nowadays is not known. Aims in topic of vibrational silo discharge are:

– Examination of influence of vibrational parameters (frequency and amplitude) on discharge of cohesionless granular assemblies from a cylindrical silo with laboratory experiments.

– Examination of influence of vibrational parameters (frequency and amplitude) on discharge of cohesive granular assemblies from a cylindrical silo with laboratory experiments.

In this section the used laboratory experiments and modeling methods are descirbed.

2.1. Experimentally silo models

To understand mechanical behaviours of granular materials and to validate the developed numerical and analytical models laboratory outflow experiments were made.

2.1.1. Examination of gravitational discharge of cylindrical silos

The used measuring arrangement is shown on Figure 2.1.

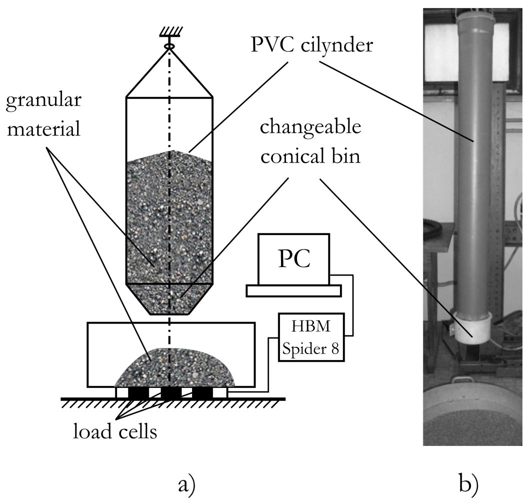


Figure 2.1. Measuring arrangement for examination of gravitational discharge of cylindrical silos

To determine outflow properties of silos, model silos were created with seven different types of conical bins. The half angle of the conical bins were 10°, 20°, 30°, 40°, 50°, 60°, and 70°. The model silo was a PVC cylinder with 105 mm inner diameter and 700 mm height; the bins were made from polyamide, with different cone half angle and with 35 mm outlet diameter (Figure 2.1). The ratio between diameter of silo's body (D) and outlet diameter (d) is 3.14, which is suitable for the dimensions of real storing equipment (generally the $D/d > 2.5$ ratio is conventional). The experiments were carried out with wheat, which is suitable for storage (moisture content of wheat is typically about 12-14%), while the total mass of stored wheat was about 4,5±0,5 kg, depending on the cone half angle of bin. During design of this silo model the ratio between the particle dimensions and the outlet diameter was also investigated. In case of examination of gravitational discharge of cohesionless granular material (e.g. wheat) the outlet diameter need to be higher than 3.5-4 times the characteristic dimension of the particles. In case of this model silo this ration is $d/d_p = 6.36$, consequently this model considered as a proportionel silo model.

Mass of discharged material was measured by three force transducers. The measurements were repeated five times in case of every bin. The aim of the measurements was the determination of discharge rate for the validation of the numerical model. For mass measurements three HBM (Hottinger Baldwin Messtechnik) C9B type load cell and the HBM Spider8 measuring amplifier were used. The sampling rate was 50 Hz in all case off measurements.

2.1.2. Examination of gravitational discharge of rectangular bins

To expand the analitycal discharge model of Oldal similar laboratory experiments were made as previous, but with a rectangular model silo (Figure 2.2). Such hoppers are used in pharmaceutical industry or at agricultural mixing units, where the precise dosage is an important question.

The model silos with rectangular cross section were made from steel plate with thickness 0.3 mm, also with changeable, slant-walled hoppers with different apex angle (apex half angle was respectively 10°, 20°, 30°, 40°, 50°, 60°, and 70°) (Figure 2.3\a). Dimensions of the rectangular unit were 20 × 100 and the widthness of model was constant ($c = 100$ mm). In addition depth of the silo could be changed between 25 and 125 mm (apex half angle was constant, 60°). In this way the width-depth ration of the model silo could be changed in range $c/b = 0.8 - 4$.

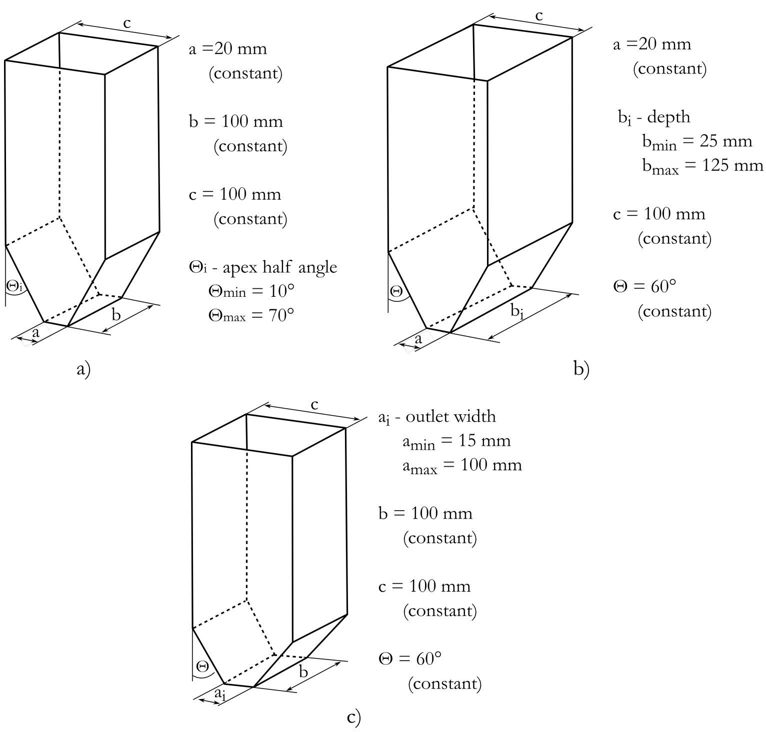


Figure 2.2. Silo models with rectangular cross section

2.1.3. Examination of vibrational discharge of cylindrical silos

To improve design process of vibrational flow promoting devices (discharge aids) we need to understand the relationship between vibrational parameters (frequency and amplitude) and silo discharge properties. For this, the measuring arrangement on Figure 2.1 was augmented with an excenter vibrator (with changeable speed) and with an ADXL326 type MEMS accelerometer (Figure 2.3).

The vibrator was fixed on the conical bin, perpendicular to the silo axis. The acceleration sensor was fixed on the opposite side of the bin, so in this way vibration of the conical bin could be mausered. With this measuring arrangement vibrational frequency of the bin could be changed in range 0-145 Hz and the amplitude could be changed between 0 and 0.11 mm. Based on the measured acceleration-time data the frequency and amplitude of the bin's motion were determined with Fast Fourier Transform (FFT) (Figure 2.3).

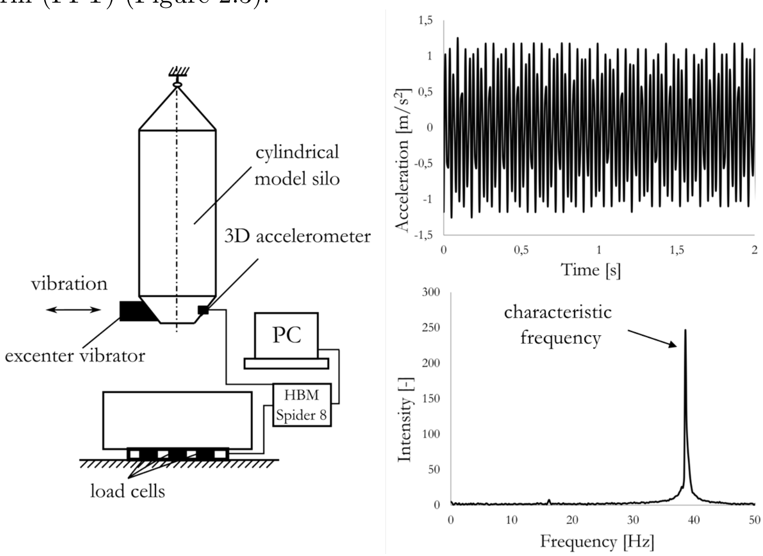


Figure 2.3. Measuring arrangement for examination of vibrational discharge of cylindrical silos and a measured acceleration data with the FFT spectra

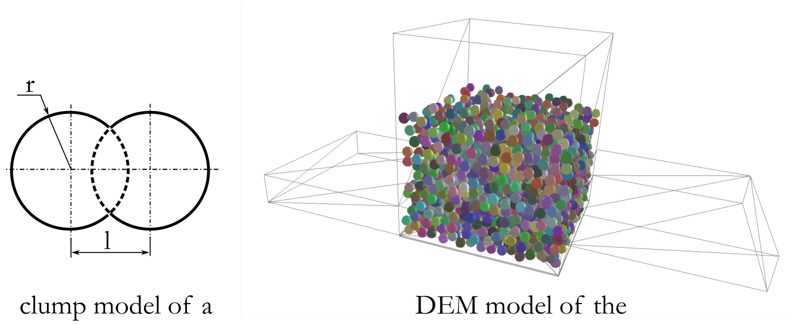
2.2. Applicability limits of DEM

Nowadays DEM is a dinamically developing numerical procedure to describe mechanical behaviour of granular assemblies. However determination of micromechanical parameters (calibration of the discrete model) and computational demand of simulations are two main shortcomings of DEM. Using this numerical technique, macro behaviour of granular assemblies is modeled with multiple, so-called micromechanical parameters of individual elements, nevertheless nowadays there is no suitable method for calibrating these parameters, thus macro behaviour of particulate systems are highly dependent on micro behaviours. To improve practical applicability of DEM a new calibration algorithm and a computational time reducing method was developed.

2.2.1. Determination of micromechanical parameters

If correlation between micromechanical parameters of individual elements and macro behaviour of the whole assembly is known, then calibration process of DEM models can be significant simplified and accelerated. However, multiple number of micromechanical parameters governing the model behaviour must be considered which makes the adequate determination of the actual parameter value challenging. It would be preferable to be able to measure the parameters directly, but in most of the cases it is impossible. It can also happen that even the measured parameters would not be suitable for modeling purposes, as the constitutive equations used during the numerical calculations are only approximate ones. Due to this problem, in most of the cases the proper measured values of these parameters are not needed, but a combination of parameters ensuring the modeled macro behaviour to be the same as the measured one.

To properly determine effect of different micromechanical parameters on macro behaviour of granular materials the standard shear test as the typical model of granular assembly was used. Using the shear test for calibration makes it possible to use the calibrated results in a wide range of compressing forces.



clump model of a grain of wheatl

a)

DEM model of the standard shear test

b)

Figure 2.4. Particle model and DEM model of the standard shear test

In this work a slightly modified version of Jenike's shear cell was used for discrete element modelling purposes, as in my case the lid is rectangular (Figure 2.4). The size of the shear box was: 0.1 m x 0.1 m x 0.05 m. Size of one particle clump was 6.3 mm, so the clump size – shear box size ratio was 0.1/0.0063 = 15.87.

2.2.2. Computational time reducing of DEM simulations

Other main disadvantage of discrete element based calculations is their great computational demand. Approximate interaction detection and solving dynamic equations on all single elements in every discrete time steps is a challenge even for the best computers, because not only the number of particles, but also total number of calculation steps increases simulation time. One of the most difficult problems during discrete modeling is the simulation of industrial scale processes, namely even simplest procedure involves several billion of interactions and particles, and for this reason it is impossible to model these both from practical and computing viewpoint.

According to works of other researchers there are several possible solutions for reduce computational time of discrete simulations, such as software and hardware optimization, improving DEM algorithms, parallel computing or simplifying simulation process. With development of special discrete element software, like YADE the communication between hardware and software can be quicken and the simulation algorithms could be optimized, since main part of computational demand usually arises from collision detection. In most cases researchers simplify their calculations using lower spring stiffness, mono-sized elements, higher particle density, reducing of particle number or using cut-off distance for long-range forces. Reduction of particle number is possible with scaling down the original phenomenon or with scaling up size of elements or by simultaneously using both methods. While we are using these speed up techniques, it is important to take care of the macro behaviour of investigated particulate material.

To get same macro behaviour with numerical simulations, parallel with reduction of element number, micromechanical parameters of single granules must be changed. To choose suitable micromechanical parameters for scaled up elements, phenomenon of granular clustering can be a main idea, because the deformation of whole granular assembly is caused not by the displacement of individual particles, but by the displacement of particle groups, called clusters. This process usually could be observed in granular flows or in vibrated powders. According the literature, granular clustering occurs because of instabilities in collective motion of particles which arises from nonuniform energy distribution. This interesting property of particulate materials appears in a region in which the particle density is increased and frequency of particle collision is higher than elsewhere. In these regions the impact of particles is plastic because of energy dissipation of the whole system. Mechanical properties of formatted clusters are different than single particles because of dilatancy of clusters. Size, external friction properties and elasticity of clusters are different compared to individual particles.

Standard shear test and linearized failure curve of particulate materials were applied to model the macro behaviour of the whole system, wherewith in this way it is possible to define micro parameters which could be used in a wide range of compression forces. During simulations spherical elements with cohesionless material properties were investigated, taking into consideration the effect of the scaling up of particle diameter. Actually after a sensitivity test a series of discrete simulations were accomplished to identify which micromechanical parameters need to change to get the same macro behaviour of whole system with scaled up elements.

2.3. DEM model of silo discharge

Since of the discharge rate of silos is a fundamental parameter in design process of technological equipment being attached to the silo, several theories were formed to determine the discharge rate of cohesionless granular materials. From these

Beverloo's empirical and Oldal's analytical model can be used in practice with adequate accuracy, but these are restricted to the case funnel flow. In case of mass flow the Johanson's model describes the characteristic of phenomenon, but the difference between the model results and the measurements is too significant for practice (Figure 2.5). At this moment no discharge model is suitable for determining adequately the discharge rate of silos in case of mass flow.

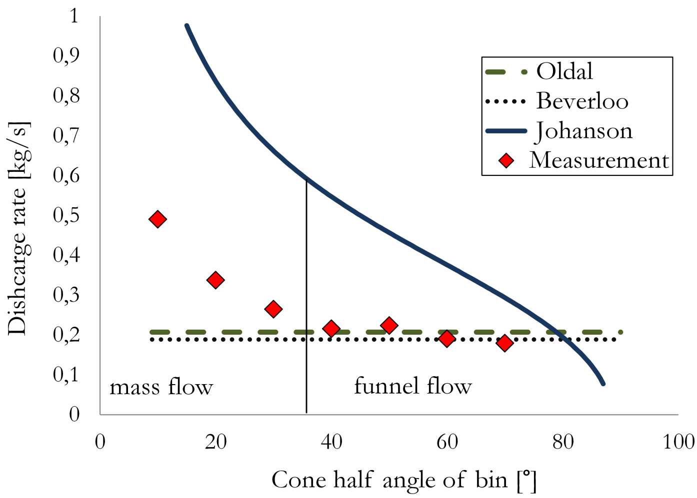
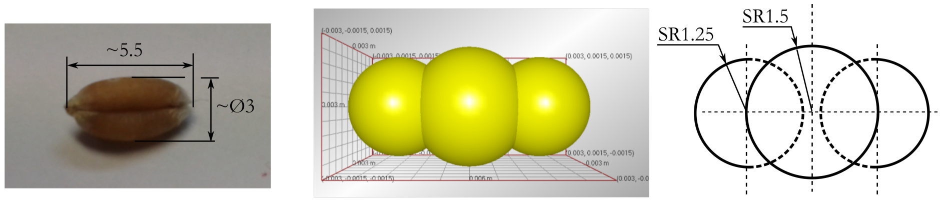


Figure 2.5. Measured and predicted discharge rates in function of half angle of bin

Besides the analytical calculations an extensively developing numerical technique, the Discrete Element Method (DEM) is also usable to determine discharge properties of silos. Few authors used this method to model hopper or silo discharge until now, however it is not known for which flow mode this method is suitable. In this work applicability of DEM model in case of mass flow and funnel flow is examined. My numerical discharge model was created with a modification of other works then it was validated with laboratory experiments, finally the numerical results were compared with analytical and experimental results. Both of the simulations and outflow measurements were carried out with wheat.

2.3.1. Contact and particle model

All simulations were carried out using EDEM Academic discrete element software. Hertz-Mindlin no slip contact model was used to model the outflow of wheat. The particle model has been created as the clump of three spheres, having radiuses 1.5 mm and 1.25 mm respectively. The distance between the centre of the spheres on the edges was 1.5 mm (Figure 2.6). The mass of one particle was 0.0356 g, the principal moments of inertia of one particle were $2.918 \cdot 10^{-11}$ kgm^2 and $7.654 \cdot 10^{-11}$ kgm^2.



a) b) c)

Figure 2.6. Particle model of a grain of wheat

Table 2.1 Micromechanical parameters

Micormechanical parameter	**Wheat**	**Steel**
Poisson-ratio, ν	0.4	0.3
Density, ρ, $^{kg}/_{m^3}$	1430	7500
Shear modulus, G, Pa	$3.58 \cdot 10^8$	$8 \cdot 10^8$
Coefficient of restitution, C_r	Wheat: 0.5 Steel: 0.6	Wheat: 0.6 -
Coefficient of static friction, μ_0	Wheat: 0.3 Steel: 0.25	Wheat: 0.25 -
Coefficient of rolling friction, f	Wheat: 0.01 Steel: 0.01	Wheat: 0.01 -

2.3.2. Description of the simulation process

Seven different geometrical models were used in the present work (having the same dimension as the measurements). A cylinder with a diameter of 105 mm and a conical bin with outlet diameter of 35 mm and a half angles of 10°, 20°, 30°, 40°, 50°, 60°, and 70° were used. To reduce the computational demand, the cylindrical body was 400 mm high in all cases (Figure 2.7). Because the discharge rate of granular assemblies is independent of the filling level, the computational demand can be successfully reduced in this way.

First step in the simulation was the generation of all of the particles; these were generated randomly in the silo. The generated particles were allowed to fall under gravity; this was the filling of the silo. During the filling process the outlet of the silo was closed by a polymer plate. The second step was the emptying of the silo. When the particles reached a static state (kinetic energy of these is about zero) then the outlet of the silo was opened, and all of the particles were discharged. The filling process took 2.1 s in all cases, under this time the bulk reached a static state. The simulation was stopped if all of the particles discharged from the silo. The process took about 5 s (depending on the half angle of the bin). 6The number of particles was between 45.000 and 60.000 depending on the cone half angle of the bin. The total mass of the discharged bulk material was about 0.7±0.1 kg (depending on the half angle of the bin). In all cases of bin the simulations were repeated five times. The steps of the simulation process can be seen in Fig. 10.

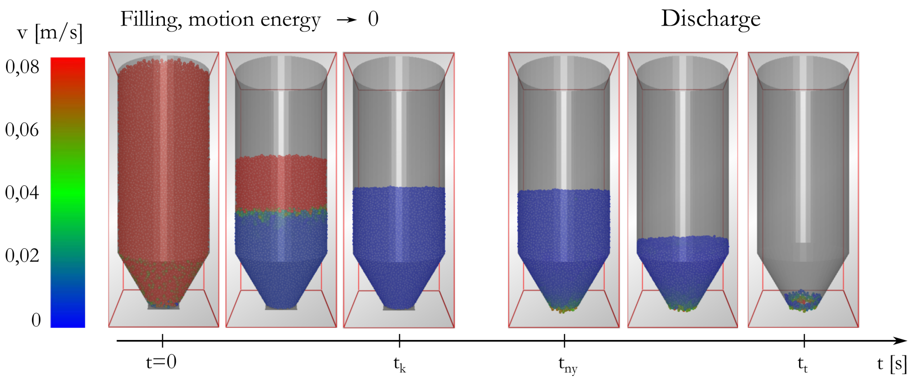


Figure 2.7. Steps of DEM simulation

In this section the reached results, developed algorithms and procedures are introduced.

3.1. New calibration method for DEM simulations

Based on DEM model of standard shear test a procedure was made which is suitable for making the simulation with different normal loads and determination of macro properties with help of linear regression is also possible. Flow chart of this procedure can be seen on Figure 3.1.

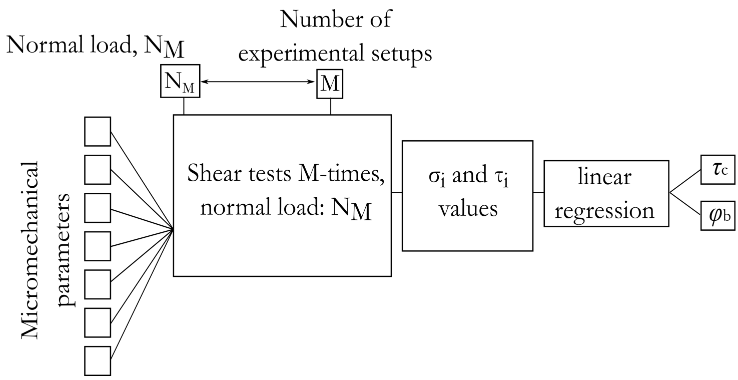


Figure 3.1. Flow chart of failure line making algorithm

With accomplishing standard shear tests with different compressive loads and the shear stress values in function of given normal stress values is plotted the failure line of the particulate material could be determine in form $T = tg\varphi_b \cdot N + \tau_c$, where T is the shear stress, N is the normal stress, φ_b is called the internal friction angle of the assembly (and μ_b is the internal friction coefficient) and τ_c is the value of cohesion (Figure 3.2). Failure curve of different granulates naturally is not always linear, even so the linear approximation is a common method to describe macromechanical behavior of particulate assemblies.

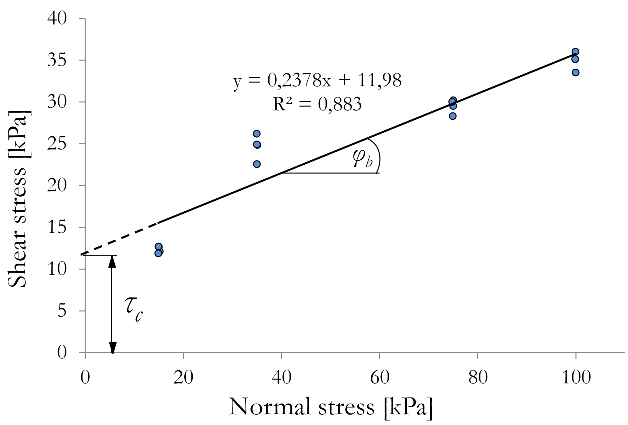


Figure 3.2. A simulated linearized failure line

With help of this procedure arbitrary numbered shear test simulation can be made without any interfering of the researcher. Before starting the work just number of normal loads and the initial set of micromechanical parameters need to be define. Till now an automated procedure like this was not available, because of this every single simulation needed to set up, start and evaulate.

3.1.1. Sensitivity test

With the previously presented procedure effect of each micormechanical parameters regarding to the macro behaviour of the whole assembly (internal friction coefficient, μ_b; and cohesion, τ_c) was analyzed. Initial set of micro parameters was found based on a previuos, manually calibration regarding to sand. Effect of each micromechanical parameters can be seen in Table 3.1.

Table 3.1 Results of sensitivity test

Micromechanical parameter	**Change of cohesion**	**Change of internal friction anfgle**
Density	Linear	Linear
Young modulus	Parabolic	Parabolic
Poisson-ratio	Linear	Parabolic
Friction coefficient	Linear	Linear
Bond normal strength	Constant	Constant
Bond shear strength	Linear	Linear
Form of particles	Parabolic	Constant
Timestep	Linear	Parabolic

3.1.2. Semi-automatic calibration algorithm

Based on the results of previously introduced sensitivity test a highly autonomous calibration algorithm was constructed, which is capable to find desired macromechanical behavior by systematic modification of micromechanical parameters.

To use this algorithm an initial set of micromechanical parameters and measured reference values need to define. The inputs of the calibration algorithm are the desired values of the shear failure line, and the micromechanical parameters related to a "starting point". As a first step, the slope of the failure line is calibrated, and then the calibration of the cohesion is done. A sensitivity test is important part of the calibration, because we have to decide, which parameters should be changed to reach the desired parameters of the failure line (Figure 3.3).

To calibrate manually the micromechanical parameters related to the desired cohesion and internal friction values, we needed 320 hours of computation time. The automatic calibration algorithm, starting from the "point", managed to reach the desired micromechanical values in 60 hours.

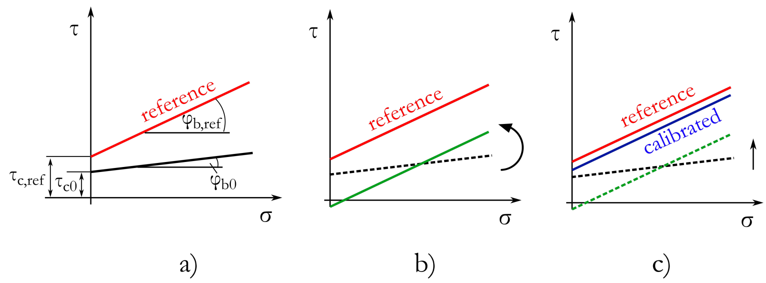


Figure 3.3. Steps of semi-automatic calibration algorithm

3.2. Extension of DEM's applicability

Based on cluster phenomenon, the correlation between element size enlargement and macromechanical parameters was examined with help of the previously introduced failure line based sensitivity test.

3.2.1. Sensitivity test

With the sensitivity test computational time in function of particle radius (with using initial micromechanical parameters) and effect of particle scaling up on cohesion and internal friction coefficient of particulate assembly was investigated. The particle radius was changed respectively 1mm, 1.5 mm, 2 mm, 3 mm, 5 mm, and 7 mm, to have a better insight in effect of particle scaling up was this wide range of particle radius examined.

Referring to internal friction coefficient very strong, linear correlation can be observed in function of particle radius (Figure 3.4). In the examined range with increasing of particle radius, internal friction coefficient of assembly is also increasing. After all the relationship between particle radius and cohesion is constant, deviation of data series is very high. Consequently change of internal friction angle need to compensate with suitable modification of either micro parameters to get reference macro behavior with scaled up particles.

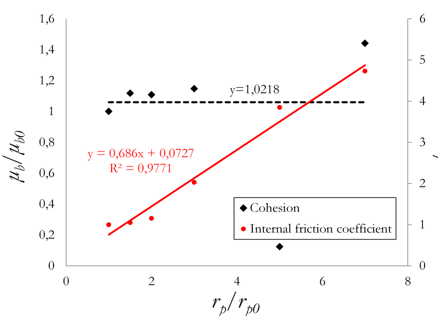


Figure 3.4. Effect of particle enlargement

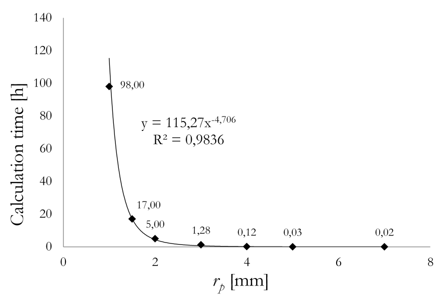


Figure 3.5. Computational time in function of particle radius

The relationship between computational time and particle radius is the essence of this work, consequently this relationship was also investigated. The simulation time decreased with enlargement of particle radius according to hyperbolic function (Figure 3.5), because of this doubling of particle radius results very serious computational time reduction with 94.9% in case of cohesionless assemblies.

In next step based on above parameter sensitivity test and effect of particle scaling up we had to select which micromechanical parameter need to change to get reference macro behavior of the granular assembly. According to phenomenon of particle clustering the deformation of whole assembly proceeds with displacement of particle groups and these clusters are less rigid than individual particles, because the particles can move internally the cluster. Consequently the elastic properties of clusters are different than the behavior of single particles, hence Young modulus and Poisson's ratio were changed for scaled up particles. (Figure 3.6).

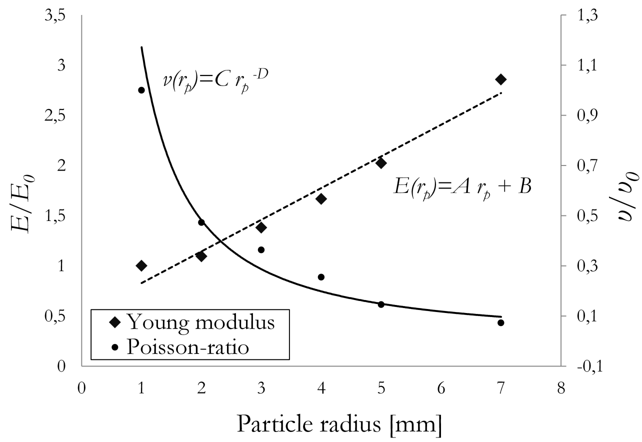


Figure 3.6. Needed modification of Young modulus and Poisson-ratio

Young modulus need to change with a linear function referring to particle radius:

$$E(r_p) = 91.52r_p + 148.86. \tag{3.1}$$

To get reference macro behaviors with scaled up particles the Poisson's ratio need to change with a hyperbolic function referring to particle radius:

$$\nu(r_p) = 0.2344 \cdot r_p^{-1.282}. \tag{3.2}$$

With the usage of aboved functions very similar macro behavior is given than in case of particle radius 1 mm and the computational time is significantly reduced. The value of internal friction coefficient in the whole examined range are near by reference value, however the value of cohesion above particle radius 4 mm significantly differs from reference value. Particle enlargement in discrete simulations in every cases is limited by extents of technological equipment which can be seen also in our case: Possible reason of significant different of cohesion from reference value according to particle radius 5 and 7 mm can be that the ratio between shear box extents and particle size is excessively great. It is still not a problem because with double sized particles the simulation time was less with almost 95% than with initial parameters.

3.3. Generalized, numerical silo model

3.3.1. Determination of flow pattern

To validate the numerical discharge model, which is described in the 2.3. section first the flow patterns are determined. Based on the results of the simulation the flow mode were determined in all cases. In addition, the geometrical model was sectioned with its symmetry plane during the discharge process. The particles were painted according to their vertical velocity: vertical velocity of the blue particles is minimal and the vertical velocity of red particles is maximal. As it was expected based on the design charts by Jenike, the flow mode is mass flow under 30° bin half angle, mixed flow between 30° and 40° bin half angle and funnel flow over 40° bin half angle (Figure 3.7). Since the results of the simulations agree with the design charts, this method is suitable for determining the flow mode.

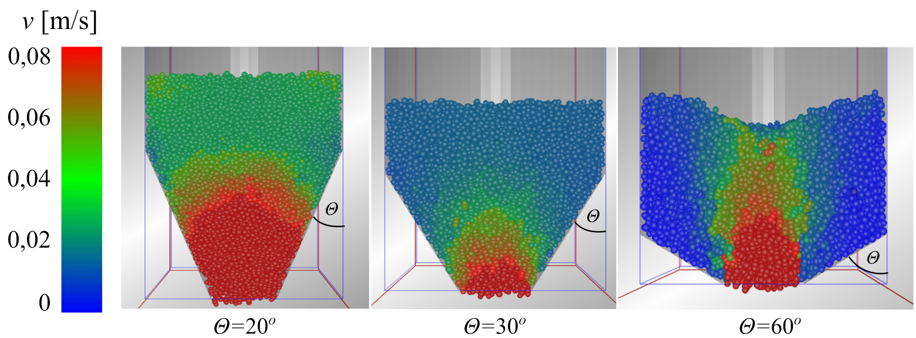


Figure 3.7. Flow patterns based on numerical results

3.3.2. Determination of discharge rate

After examination of flow pattern the mass-change functions were determined based on the experiments and also on the simulations. As it was expected the mass-change functions are linear in all cases. This means, that the discharge rate is constant, since this is the slope of the linear function. Consequently the discharge rate is independent of the filling level of silo. The slope of the mass-change functions based on the simulation results are in good agreement with the experimental results. This means that the numerical model describes the phenomenon adequately. The novelty of the model lies in the fact that none of the earlier mentioned analytical models are able to describe the process in the non-stationary case.

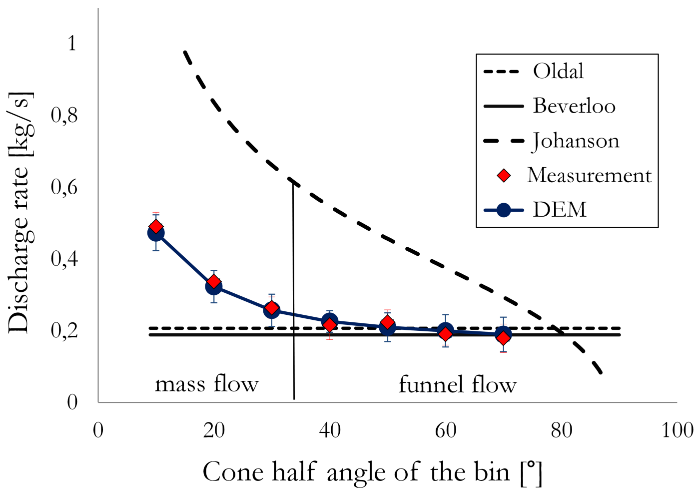


Figure 3.8. Measured, simulated and predicted average discharge rate

The available analytical and numerical discharge models were examined in depth. The average discharge rate (the slope of the mass-time functions) was determined based on the results of simulations and measurements, and the results were compared with the three most exact discharge model (Figure 3.8). Beverloo's empirical and Oldal's analytical model are adequate approach in case of funnel flow. The characteristic of Johanson's discharge model resembles the measurement results in case of mass flow; however the deviation of this model is almost 150%. With our numerical model the difference to the measurements is less than 5% in case of mass flow and also in case of funnel flow. Consequently with the presented numerical model the whole domain of cone half angle can be described with adequate accuracy (Figure 3.8). In case of our model the flow mode does not have to be chosen, since this model describes not only the mass flow discharge which, was set as aim of this paper, but also the funnel flow discharge (without modification) adequately. This model indicates the flow mode and also the discharge rate of the silo at once. For the practice it is absolutely useful since before the design of new equipment neither the flow mode, nor the suitable discharge model have to be defined.

3.4. Extension of Oldal's analytical discharge model

The Oldal's analytical discharge model is the only practical usable method which can describe the phisycal phenomenon of discharge and the velocity distribution. Disadvantage of this equation is that this is valid for gravitational discharged cylindrical silos. Because in pharmaceutical industry and at agricultural mixing plants are very important question the precise dosage from rectangular hoppers extension opportunities of the Oldal's model was examined. Oldal describe the outflow of granular material is a process of formation and collapse of arches in the silo's bin section. Arching means the formation of self supporting arch like "layers" of granular material inside the granular assembly stored in the silo. The granular material is supposed to have free fall condition below this arch. Flow velocity at the outlet depends on only the height of the fall. Thus the first requirement is satisfied by the model: the discharge velocity is constant over the height of the bulk material. In order to determine the value of mass flow we have to calculate this velocity.

In case of a cylindrical bin the shape of an arch is a parabolic surface. Based on my observations in case of funnel flow, the boundary conditions are the same than in case of cylindrical silo body, consequently in case of a rectangular hopper the shape of arches is also parabolic (Figure 3.9).

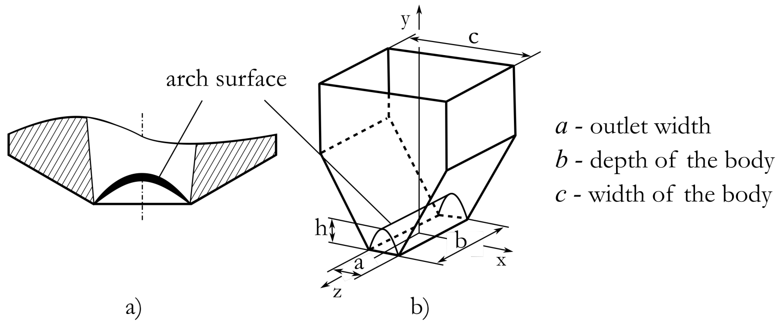


Figure 3.9. Surface of the arch and dimensions of the rectangular hopper

Surface of the arch in a rectangular hopper, in coordinate-system x, y, z:

$$f(x,z) = h\left(1-\left(\frac{2x}{a}\right)^2\right), \quad x \in \left[-\frac{a}{2};\frac{a}{2}\right], \quad z \in \left[-\frac{b}{2},\frac{b}{2}\right]. \tag{3.3}$$

Using the aboved surface the velocity distribution is obtained:

$$v(x,z) = \sqrt{2g\delta a}\sqrt{1-\left(\frac{2x}{a}\right)^2}. \tag{3.4}$$

Based on this the flow rate:

$$Q = \int_A v\, dA = \frac{\pi}{4}\sqrt{2g\delta a}\cdot ab. \tag{3.5}$$

With using bulk density (ρ_h) the discharge rate:

$$W = \frac{\pi\sqrt{2g}}{4}\sqrt{\delta}\cdot\rho_h\cdot b(a-d_p)^{3/2}. \tag{3.6}$$

3.5. Vibrational discharge of cohesionless granular materials

To examine correlation between vibrational parameters and discharge of cohesionless granular materials laboratory experiments were made. First amplitude of vibration was changed (beside constant frequency). Based on this; in the examined range (0 – 0.11 mm) effect of vibration amplitude is neglible regarding to the discharge rate and the empirical deviations are less than 5% in every cases. In examined range I do not found influence of amplitude on discharge of wheat.

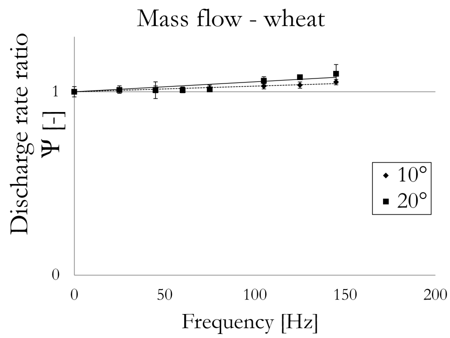


Figure 3.10. Effect of vibrational frequency in case of mass flow discharge

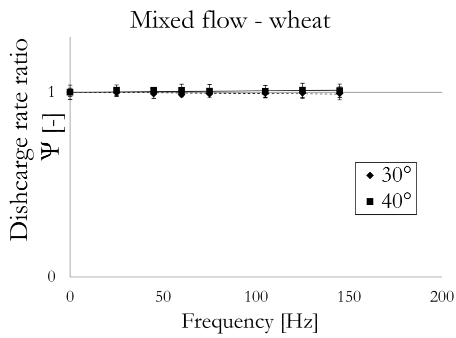


Figure 3.11. Effect of vibrational frequency in case of mixed flow discharge

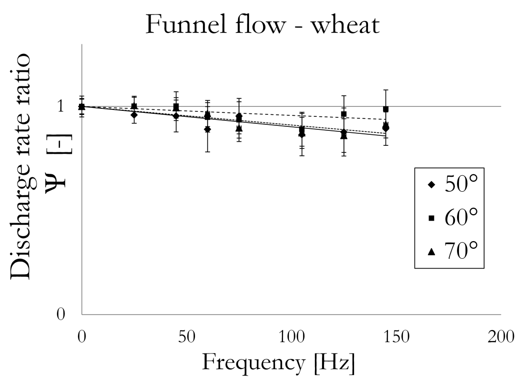


Figure 3.12. Effect of vibrational frequency in case of funnel flow discharge

In the next phase effect of vibrational frequency was analyzed. Based on the aboved figures it can find out that effect of vibrational frequency is depend on half angle of conical bin, namely on flow mode. In case of mass flow (10°, 20°) the discharge rate increases with the vibrational frequency and the standard deviations are neglible (Figure 3.10). If cone half angle is 30° and 40° (mixed flow discharge) then the discharge rate is not change and standard deviations are also neglible (Figure 3.11). In case of funnel flow discharge (50°, 60° and 70°) the discharge rate is decreased and standard deviations are very significant (Figure 3.12).

According to my observations and measurements the reason of this phenomenon is that excitation helps the particles to moving in case mass and transitional flow, but in case of funnel release the stagnant particles at the wall of bin which can disturb the outflow.

3.6. Vibrational discharge of cohesive granular materials

Essential difference compared to cohesionless granular materials is the formation of stable arches in case of meal. In case of cohesive granulars, like meal ($\sigma_I/\sigma_c < 2$) gravitational discharge from the silo starts just in case of small cone half angles. During the laboratory experiments with meal it was observed that stable, solid arch was formed and the material flow was stopped if the cone half angle greater than 10°. The granular material could discharge if vibration with suitable frequency was applied on the model. This frequency was denominated as *cut-off frequency* which depends on the material properties and the container geometry.

After reaching the cut-off frequency in case of a certain bin geometry, further change of vibrational frequency was not observed simirlaly to the vibrational amplitude (in the examined range).

1. New calibration method for DEM simulations

A semi-automatic calibartion algorithm, based on linearized failure line was developed, which is able to determine usable micromechanical parameters of *cohesive* granular materials in *YADE* system. The determined set of micromechanical parameters is suitable for describe real physical phenomenons with same pressure characteristic than the normal loads were used by determination of failure line. With this new method the calibration of DEM models is about five times faster and effectiver than with manual calibration, and the defined set of micromechanical parameters are usable as material properties in a wide range of normal loads.

2. Extension of DEM's applicability

It was proved that calcution time of discrete simulations can be decreased with particle enlargement in *YADE* system. In this case Young modulus of particles need to be changed according to a linear; Poisson-ratio with a hyperbolic function:

$$E(r_p) = A\ r_p + B;$$
$$\nu(r_p) = C\ \frac{1}{r_p^D}.$$

Using these equations computational time of discrete simulations could be decreased about 90% and change of macromechanical behaviours of the whole granular assembly (internal friction coefficient and cohesion) is neglible (less than 5%). It was proved with numerical simulations that constants A, B, C and D depend on the initial set of micromechanical parameters.

3. Generalized, numerical silo model

A discrete numerical model was made, which is able to determine discharge rate of cylindrical, gravitational emptied silos independetly from flow pattern. With this model discharge rate of cohesionless granular materials can be determined also in case of mass flow with neglible standard deviations (in the whole range of cone half angle less than 5%).

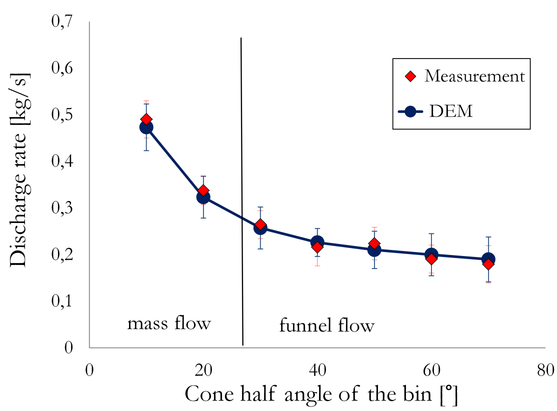


Figure 4.1. Measured and calculated discharge rates

4. Extension of Oldal's analytical discharge model

With extension of Oldal's analytical discharge model the following equation was developed to determine discharge rate of rectangular, funnel flow hoppers:

$$W = \frac{\pi\sqrt{2g}}{4}\sqrt{\delta} \cdot \rho_h \cdot b(a - d_p)^{3/2},$$

where:
- g, gravitational acceleration,
- δ, shape coefficient of the arch,
- ρ_h, bulk density,
- a, outlet width,
- b, depth of the silo,
- d_p, characteristic dimension of particles.

Validity limits of the extended model were experimentally and numerically found out:

$$1 \leq \frac{c}{b} \leq 4,$$

$$0,15 \leq \frac{a}{c} \leq 0,7,$$

where:
- a, outlet width,
- b, depth of the silo,
- c, width of the silo.

5. Vibrational discharge of cohesionless granular materials

It was experimentally proved, that in case of vibrational discharge of cohesionless granular materials (e.g. wheat); effect of vibrational amplitude is neglible in the investigated range. Opposed to this, effect of vibrational frequency is very significant and depends on the bin geometry. In case of mass flow the discharge rate was increased with vibrational frequency and the standard deviations were neglible. In case of mixed flow, the effect of vibrational frequency was not observed and in case of funnel flow the discharge rate was globally decreased and the standard deviatons were significantly increased.

In addition it was found that in case of perpendicular excitation to the cylindrical silo axis in the examined range ($A = 0 - 0.11$ mm and $f = 0 - 125$ Hz):

- mass of the stored material is linearly decreased in function of time,
- effect of vibrational amplitude is neglible,
- effect of vibrational frequency is significant and depends on the bin geometry,
- in case of vibration the discharge rate is not increasing in all cases.

6. Vibrational discharge of cohesive granular materials

With laboratory experiments was proved that in case of vibrational discharge of cohesive, fine particled granular materials, exist a special frequency. When an excitation is applied with this frequency, the formated stable arche can be broke up and the material flow can be started. This frequency is depend on the material properties and on the bin geometry and it was denominated as a *discharge cut-off frequency.* In the examined range ($A = 0 - 0.11$ mm and $f = 0 - 125$ Hz) effect of vibrational amplitude was not observed also in case of cohesive granular materials.

5. CONCLUSIONS AND SUGGESTIONS

Due to the special mechanical properties of granular materials the design process of storing- and processing equipment has long been a subject of interest to both researchers and process engineers.

One of the main topics of these research is the improvement and extension of applicability of a numerical procedure, the Discrete Element Method (DEM). To achieve this aim a semi-automatic calibration algorithm and a computation-time reducing method were developed. With these new methods calibration process of DEM models can be simplified and speeded up, consequently the numerical modeling can be more effective. In engineering practice during numerical simulation of industrial scale processes of fine-grained materials the computational demand is still a considerable problem. In case of simple processes billions of particles and interactions need to model in every time step therefore simulation time can be whether few weeks or months. With use of the introduced approach, the computational time can be significantly decreased (more than 90%) with acceptable changing of macromechanical behavior of the cohesionless granular assembly.

Second main topic of this research is the analysis of gravitational silo discharge. The available analytical and numerical discharge models can not universally (independently from flow pattern) use. A numerical discharge model was made by DEM and the average discharge rate (the slope of the mass-time functions) was determined based on the results of simulations and measurements in all cases. The results were compared with the three most exact, analytical discharge model. Beverloo's empirical and Oldal's analytical model are adequate approach in case of funnel flow. The characteristic of Johanson's discharge model resembles the measurement results in case of mass flow; however the deviation of this model is almost 150%. With our numerical model the difference to the measurements is less than 5% in case of mass flow and also in case of funnel flow. Consequently with the presented numerical model the whole domain of cone half angle can be described with adequate accuracy. In case of our model the flow mode does not have to be chosen, since this model describes not only the mass flow discharge which, was set as aim of this paper, but also the funnel flow discharge (without modification) adequately. This model indicates the flow mode and also the discharge rate of the silo at once. For the practice it is absolutely useful since before the design of new equipment neither the flow mode, nor the suitable discharge model have to be defined.

Arch formation is also an important question in agriculture, because of this last main topic of this research the examination of effect of flow promoting devices. Laboratory experiments were made to analyse effect of vibrational parameters (amplitude and frequency) reggarding to outflow porperties of silos. These empirical results are very beneficial for design- and process engineers and agricultural plants to ensure continous material flow.

6. SUMMARY

Storage and processing of particulate materials is a common problem in agriculture, because of their special physical, mechanical properties. By this reason it is very important to understand mechanics of granular materials and to examine modeling possibillities. To ensure economic operation of agricultural storing and mixing units it is neccesary to know functional parameters of storing equipment and the development of eccifient design methods.

Based on the above, purposes of my research were the development of modeling methods for granular materials and silo design methods as well as the approvement of solution opportunities according to storing problems. To achieve these aims the literature of these topics was reviewed. Based on this the suitable modeling methods were selected and shortcomings of these procedures were examined. In addition solution and prevention opportunities of storing problems were also mapped.

To describe certain phenomenon a numerical procedure, the Discrete Element Method (DEM) was applied. Practical adaptation of this continously developing method nowadays is very restricted, therefore new procedures were developed to calibrate the model parameters and to decrease computational effort of simulations.

In next phase of research DEM model of silo discharge was created wherewith the well known empirical and theoretical discharge models are usable just in a narrow range of cone half angle. The developed numerical model was validated by laboratory outflow experiments. Based on the experimental results this model can be used regardless of the cone half angle. After this an analytical formula was created to calculate outflow rate of rectangular silo bins based on Oldal's discharge model. This calculation method can be used in agricultural or in the chemical industry well, where it is important the accurate dosage of individual components. The analytical model was also validated with laboratory outflow experiments. Based on the measurements this is suitable for calculating discharge rate in case of funnel flow.

Last phase of my research was the experimentally investigation of vibrational silo discharge. Common problem of agricultural storing and mixing units is the stop of material flow through formation of stable arches. To prevent this phenomenon and to ensure material flow vibrational discharge aids are used, which are operated on empirical way. It was proved with experimental results that outflow rate of cohesionless granulars is variable in function of vibrational frequency based on discharge mode of silo. Finally outflow of cohesive praticulate materials was examined. Emprically was proved that in case of all half angle of conical bins exist an outflow cut-off frequency. If excitation was applied with this cut-off frequency the stable arch can be broken and the material flow can be started.

Summarizing it can be asserted that work of practical engineers can be simplified with the new numerical results and methods and the operation cost of agricultural storing and mixing units is reducible based on my empirical conclusions.

7. MOST IMPORTANT PUBLICATIONS RELATED TO THE THESIS

Referred articles in foreign language:

1. Keppler I., Safranyik F., Oldal I. (2016), Shear test as calibration experiment for DEM simulations: a sensitivity study, Engineering Computations (IF: 0.691*), Vol. 33 (3), pp. 742–758.

2. Oldal I., Keppler I., Bablena A., Safranyik, F., Varga, A. (2014), On the discrete element modeling of agricultural granular materials, Mechanical Engineering Letters, Vol. 11, pp. 8-17.

3. Oldal I., Safranyik F. (2015), Extension of silo discharge model based on discrete element method, Journal of Mechanical Science and Technology (IF: 0.761*), Vol. 29 (9), pp. 3789-3796.

4. Oldal I., Safranyik F., Keppler I. (2016): Reducing computational time of cohesionless discrete simulations based on particle clusters, accepted for publication in Engineering Computations (IF: 0.691*) on 15. 04. 2016

5. Safranyik F., Csatár A., Varga A. (2015), Experimental Method for Examination of State Dependent Friction, Progress in Agricultural Engineering Sciences, Vol. 11 (1), pp. 29-42.

6. Safranyik F., Oldal I. (2013), 3D DEM model of silo discharge, Poljoprivredna tehnika, Vol. 38 (2), pp. 23-34, ISSN 0554-5587

Referred articles in Hungarian language:

1. Safranyik F. (2016), A diszkrét elemes módszer alkalmazása lengőrosták hatékonyságának vizsgálatára, GÉP LXVII. évfolyam (2016/4.), 44-47. o.

2. Safranyik F., Oldal I., M. Csizmadia B. (2015), Gerjesztett silók kísérleti elemzése, Mezőgazdasági Technika, LVI. évfolyam, 2015. június, 2-5. o.

3. Safranyik F., M. Csizmadia B., (2015), Kalibrációs módszer szemcsés halmazok mikromechanikai jellemzőinek meghatározásához, Műszaki Tudományos Közlemények, 2015 (3), 267-271 o.