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DETERMINING THE COEFFICIENT OF FRICTION BY SHEAR TESTER SIMULATION

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Abstract. *The flow behaviour of very dense particle regimes such as in a moving or fluidized bed is highly dependent on the inter-particle friction, which can be characterized by the coefficient of friction. Since only rough guide values for common material pairs are available in the literature, we determine the exact parameters by fitting numerical simulations to experimental measurements of a simplified Jenike shear tester [1, 2].*

The open-source discrete-element-method code LIGGGHTS [3] is used to model the shear cell, which is built of triangulated meshes. In order to preload the bulk solid in the shear cell with a constant principal stress, the movement of these walls is controlled by a prescribed load.

A comprehensive sensitivity study shows that the results are nearly insensitive to the spatial dimensions of the shear tester as well as all other material properties. Therefore, this set-up is applicable to determine the coefficient of friction.

Furthermore, we calculate the coefficient of friction of glass beads showing very good agreement with literature data and in-house experiments. Hence, this procedure can be used to deduce material parameters for the numerical simulation of dense granular flows.

1 INTRODUCTION

A variety of processes in several industries such as the manufacturing of plastics and the steel production include moving and fluidized beds. Therefore, those very dense particle flow regimes are the subject of many recently published studies, for instance Goniva et al. [4] and Schneiderbauer et al. [5]. Besides the fluid-solid phase interaction

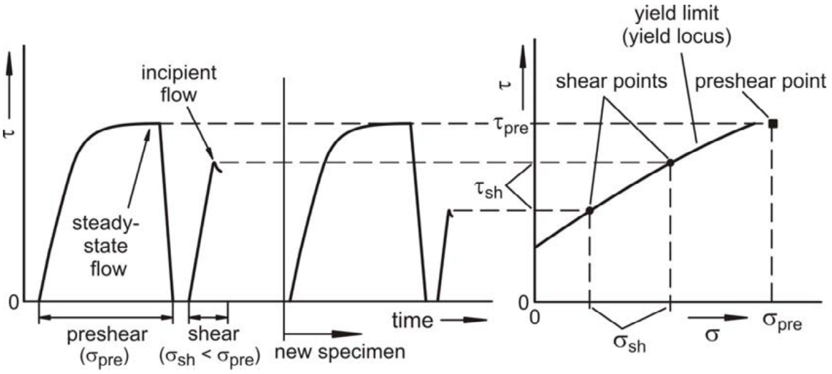

Figure 1: Plot of shear stress vs. time; yield locus [2]

one dominant force component is the inter-particle friction, which can be characterized by the coefficient of friction (COF). In the literature only rough guide values for common material pairs are available. Moreover, the frictional properties can vary for different granulates of the same material due to, for instance, different surface roughness caused by manufacturing processes [7]. Hence, this study deals with the determination of the exact parameters of a specific bulk granular material by fitting numerical simulations to experimental measurements of a simplified Jenike shear tester [1, 2].

The simulation tool of choice is the open-source, discrete-element-method (DEM) code LIGGGHTS [3]. For one thing, it is a very efficient and well parallelized code. For another, the open-source code can be enhanced easily by required, additional tools. In course of this study an force controlled wall was implemented that makes it possible to preload the bulk solid in the shear cell with a constant principal stress.

2 EXPERIMENT

Usually companies, laboratories, and others use shear testers to measure the flow properties of fine-grained bulk solids, which are characterized by the so-called yield locus. Therefore, the material is compressed by a constant principal stress σ while one part of the shear tester moves (translational or rotational) with constant velocity. The measured quantity is the force or torque required for this movement that can be converted to the shear stress τ. In order to determine the whole yield locus an extensive measurement cycle is required, where the principal stress σ acting on the material varies for each run. Figure 1 shows a schematic time curve of the shear stress during a typical measurement cycle.

Since the aim of the study is the determination of the coefficient of friction for numerical simulations by parameter fitting, only one measurement of the shear stress τ for one defined principal stress (σ_{pre} in figure 1) is required. Other data points may be used for validation purposes.

The experimental set-up used in the study is based on the Jenike shear tester [1], with

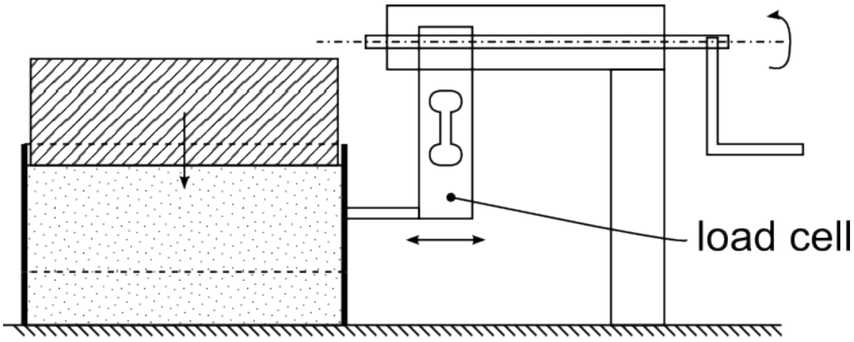

Figure 2: Simplified version of a Jenike shear tester.

a translational moving upper ring. Figure 2 shows the sketch of the simplified shear tester that consists of two closed, superimposed rings of equal diameter. The principal stress is applied using a well-defined, cylindrical mass. The motion of the upper ring is controlled by turning the crank, whilst the load cell measures the required force F_{shear}. From this, the shear stress can be calculated by

$$\tau = \frac{F_{\text{shear}}}{A_{\text{cell}}} \tag{1}$$

where A_{cell} denotes the cross-sectional area of the shear cell, where the bulk solid is in contact. Since one ring is in motion, this contact area will change over time. Figure 3b shows two displaced circles and the resulting contact area. Provided that the cylinder radius r_{cyl} and the displacement of the two rings δ are known the current area is given by

$$h = r_{\text{cyl}} - \frac{\delta}{2} \tag{2}$$

$$\alpha = 2 \arccos \left(1 - \frac{h}{r_{\text{cyl}}} \right) \tag{3}$$

$$A_{\text{cell}} = r_{\text{cyl}}^2 \left(\alpha - \sin(\alpha) \right) \tag{4}$$

Substituting the dimensions of the experimental set-up ($r_{\text{cyl}} = 50\,\text{mm}$ and $\delta_{\max} = \pm 3\,\text{mm}$) the contact area is at least 96.1 % of the maximum cross-sectional area $A_{\text{cell,max}} = r_{\text{cyl}}^2 \pi$, thus the area change can be neglected.

3 SIMULATION

The simulation toolbox used, LIGGGHTS, meets some requirements in order to model the shear tester described above. First, it is capable to import triangulated meshes of the two rings and a top lid. Since the real set-up has a wall thickness both rings have additional horizontal wall that prevent the particles falling out of the shear cell (see figure 3a). Further, all particle-wall contact forces acting on a mesh are summed up and can be saved, thus the determination of the shear force is available out of the box. Moreover,

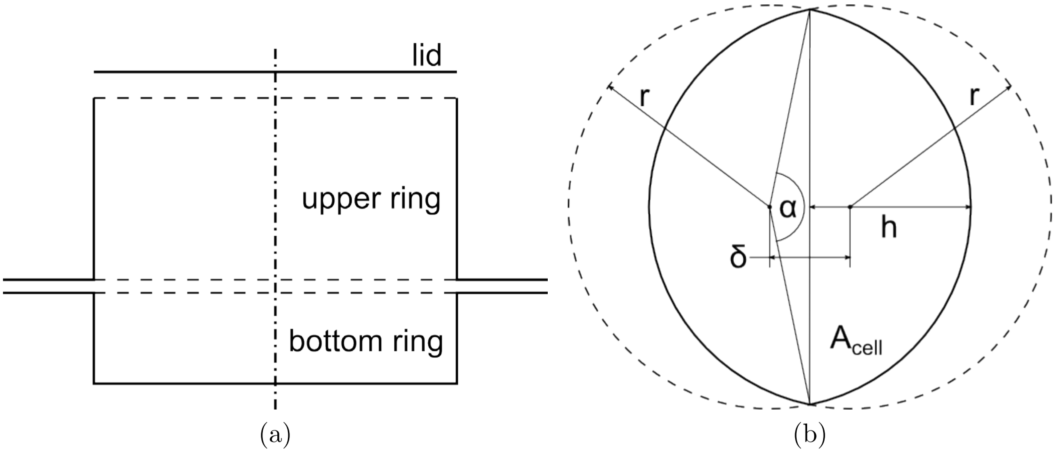

Figure 3: (a) The simulated shear cell consists of three parts. Both rings have additional horizontal walls in order to model the wall thickness of the real experimental set-up. The bulk solid is prestressed by the lid. (b) Intersection of two circles of equal radius r displaced by δ

the code can move a mesh with constant velocity as required for the measurement. As the code is open-source it is possible to adapt the code for their own needs. LIGGGHTS is a well parallelized and very efficient code so that it minimize the computational costs of the loop of simulations required for parameter fitting.

For the determination of the shear stress the bulk solid has to be prestressed with a constant principal stress. Therefore, a new implemented wall type, referred to as *servo-wall*, is applied to the lid. Thus, the velocity of the mesh v_{wall} is controlled by a standard PID controller that compares the current acting force f_{total} with the predefined target value f_{SP} (figure 4). In addition the controller is equipped with an anti-windup mechanism and output limitation. The latter ensures that particle-wall contacts are detected for a given

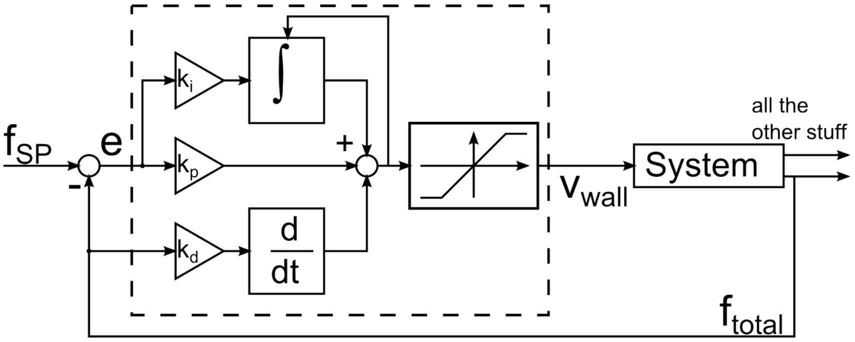

Figure 4: Block diagram of the PID controller implemented in the new wall type *servo-wall*. In addition anti-windup meachanism and output limitation are implemented.

Table 1: Material properties of glass beads and simulation parameters that are used for presented simulations.

Property name	Unit	Value
Particle diameter	μm	500
Density	$\mathrm{kg\,m^{-3}}$	2500
Young's modulus	GPa	65
Poisson's ratio	-	0.45
Coefficient of restitution	-	0.9
Coefficient of friction	-	0.1-0.3
Coefficient of rolling friction	-	0.06
Constant ring velocity	$\mathrm{m\,s^{-1}}$	0.7

time step.

A simulation run consists of three phases. In the first phase, the shear cell is filled with the granulate material and it can settle. Second, the top lid starts to move downwards and applies the constant stress to the bulk solid. Finally, the ring motion starts and the required shear force is measured. In contrary to the original experiment the bottom ring is moved because otherwise two geometries (upper ring and lid) have to move at the same time, which could cause numerical problems.

According to [6] the hertz contact model is used for the particle-particle as well as the particle-wall interaction. Table 1 shows the material properties of glass beads that are used for all presented results.

4 SENSITIVITY STUDY

Because this parameter fitting procedure is designed to be applied to various different bulk solids and each material requires several simulation runs, it is very important to minimize the computational costs. Therefore, a study to determine the dependency of the shear stress on the shear cell size is carried out. The cylinder diameter d_{cyl} varies between 25 and 100 times the particle diameter d_{p}. In comparison the real experimental set-up corresponds $200 \cdot d_{\mathrm{p}}$. Since the cylinder radius is decreased only and not the maximum displacement of the two rings, the change of contact-area from equation 4 has to be taken into consideration for the calculation of the shear stress.

The comparison of the results in figure 5 shows that they agree vary well for all diameters. But for a smooth and well comparable force signal a cylinder diameter of at least $d_{\mathrm{cyl}} = 50 \cdot d_{\mathrm{p}}$ is recommended.

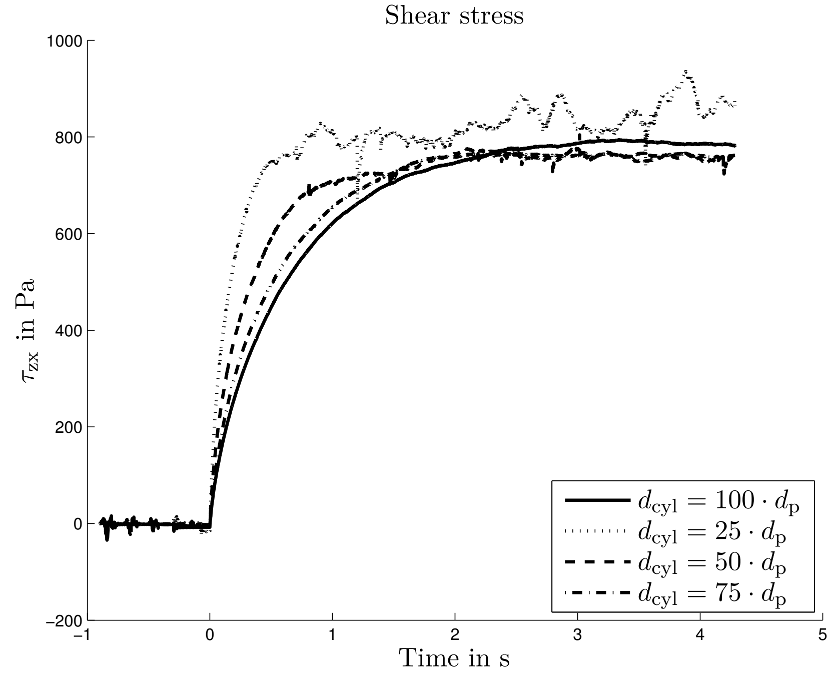

Figure 5: Comparison of the shear stress for various cylinder diameters.

5 DETERMINING THE COEFFICIENT OF FRICTION

The experimental measurements provide a good start value for the coefficient of friction that can be used for the first simulation. Further simulations with small variations of the COF are done in order to fit the maximum, simulated shear stress to the experimental results. For instance, in figure 6 the shear stress with different coefficient of friction are compared to the measurement data. In case of $\mu_r = 0.2$ the results agree very well and this also corresponds with values available in the literature.

6 CONCLUSIONS

In this study a small and efficient procedure for the determination of the coefficient of friction was presented, where a numerical model as well as a small experimental set-up of a simplified Jenike shear tester were build up. In case of glass beads as example material the obtained results agree very well with known literature values.

Further, a sensitivity study was carried out and showed that the simulated shear stress is generally independent on the size of the shear cell. Therefore, the computational costs of the numerical model can be minimized.

The new LIGGGHTS wall-type, *servo-wall*, is an ideal tool to model compression of granular material. Using this new feature the required, constant principal stress of the shear cell was applied by the top lid.

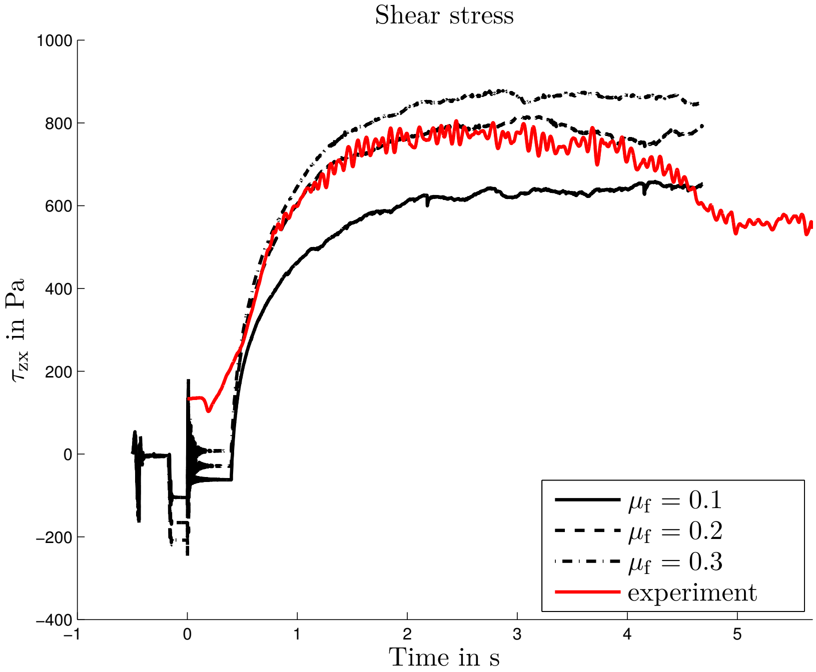

Figure 6: Shear stress over time for different coefficient of friction and compared to experimental measurements.

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