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# Evaluating methods for direct determination of contact parameters for DEM-simulations involving sand

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ABSTRACT: DEM-simulations incorporating sand are an important tool for investigating different processes at a particular scale. To achieve reliable and applicable results, the simulation parameters for the sand particles need to be determined. This specifically concerns the particle's material parameters density, Young's modulus and Poisson's ratio, as well as the particle interaction properties restitution coefficient, sliding friction and rolling friction.

The conventional way to determine these parameters is to use multiple experiments (ideally as many as parameters to be determined), which are then back calculated in DEM-simulations. The parameters of the sand particles are adjusted until the simulations match the experimental results. This is a time consuming and intensive process. Another option is to directly determine the simulation parameters. This however requires appropriate experimental setups, to separate the different parameters from each other. One issue for this method, however, is the heterogeneity of sand. Due to the variability of sand particles in shape, size and even properties, direct determination of the simulation parameters becomes more difficult compared to more homogenous materials.

Therefore, different ways to directly measure DEM simulation parameters are investigated and their applicability to sand samples is tested. Afterwards, parameter sets for a sand are created using the direct as well as the indirect parameter determination such that both approaches can be compared.

KEYWORDS: Discrete Element Method, sand, parameter calibration, parameter measurement

## 1 INTRODUCTION

For the numerical simulation of sand, the Discrete Element Method (DEM) has proven itself suitable to investigate behavior of granular material on a particle scale. DEM is a numerical, particle-based method, simulating the interactions between single particles as well as other geometries. It can for example be used to investigate behavior during shearing (Grabowski and Nitka 2021) or during cone penetration tests (Khosravi 2020). However, one important aspect of these simulations is choosing the set of simulation parameters to describe the sand particles and their interactions. If these parameters are not selected appropriately, the simulation results will not depict real-life behavior.

A common contact model for simulations of sand using DEM is the Hertz-Mindlin model, which was chosen for the following investigations. This model combines the normal interaction of Hertz theory with the tangential interaction by Mindlin and Deresiewicz (Di Renzo and Di Maio 2004). This contact model uses three material properties (density, Young's modulus and Poisson's ratio) and three interaction parameters (coefficient of restitution, sliding friction and rolling friction) to determine the particle behavior. For parameter determination three different approaches can be taken.

First, the parameters can be derived from literature values. This method usually requires the least amount of time. However, the identified parameters will not be specific to the investigated sand and simulations may deviate from real-life behavior. Therefore, this method is not suitable for most detailed applications, especially when comparing different sand samples. However, this method is useful for general investigations or preliminary simulations, as well as evaluating the suitability of parameter values determined by different means.

Secondly, the parameters can be calibrated. For this, several different physical comparison experiments need to be performed and recreated in the simulation. Here, the simulation parameters need to be varied until the numerical results sufficiently match the physical experiments. While there are different methods to improve the calibration process, like calibration algorithms or limiting the number of varied parameters, calibration still requires a lot of time and computational power, due to the number of simulations that need to be performed.

Thirdly, the parameters can be directly measured considering singular grains, which is a faster process than parameter calibration as the repetitive process of simulation, evaluation and parameter adjustment is not required. Another benefit is that possible simulation effects, such as simulation boundaries, simplifications and assumptions do not occur. The downside, however, is the difficulty of achieving appropriate measurements. This is due to the heterogeneity of the sand, both in the minerals of different grains and the variability between different particles of the same material. The latter is due to variations in shape and roughness as well as imperfection in the grains. Therefore, using measurements from singular grains and extrapolating to properties of the sand mass can prove to be difficult. Another issue is the size of the sand grains. The small dimensions make direct measurements more difficult and decrease accuracy.

Therefore, both approaches parameter calibration and parameter measurement have advantages and disadvantages. To investigate which method is more suitable to determine the simulation parameters, two parameter sets will be created: one by calibration and one by measurement. These sets will then be compared and tested.

## 2 SIMULATION PARAMETERS FROM LITERATURE

To be able to properly evaluate the parameters in this study, comparisons to previous studies and the specified simulation parameters need to be drawn. These parameters also allow for a range or starting point for the calibration simulations, which reduces the necessary computational time. However, as seen by the ranges of the parameters found in literature, variations between different sands are to be expected.

The variation in density is mainly due to the different minerals found in sand. For sands containing mostly silica with a density of 2.65 g/cm³, a similar density can be assumed. However, other minerals have different densities. Therefore, giving a general range of possible grain densities for different sands is not sensible.

The Young's modulus and Poisson's ratio show a wide variation. For the Young's modulus values between $1.7 \cdot 10^6$ Pa (Widuliński et al. 2009) and $6.5 \cdot 10^{10}$ Pa (Balamonica1 et al. 2019) could be found. However, these values were determined for different sands using different methods. For Poisson's ratio the values vary between 0.18 and 0.32 (Gu et al. 2013).

Regarding the friction parameters, it was more difficult to find comparison values. In most publications, the parameters rolling and sliding friction were not differentiated, and therefore only one friction parameter was given. The values varied between 0.2 (Ciu et al. 2025) and 0.84 (Widuliński et al. 2009).

Finally, it was also difficult to find appropriate values for the coefficient of restitution. Most values given in literature only concerned interactions of sand grains with other materials, while the here determined values should depict the mechanical behavior between sand grains. However, values generally ranged from 0.64 to 0.94 (Balamonica1 et al. 2019).

## 3 GENERAL ASPECTS OF THE INVESTIGATIONS

### 3.1 *Physical Sand*

The sand chosen for the experimental investigation is a natural sand containing different minerals, though mainly quartz. While the initial sand contained grains between 5 mm and 0.063 mm diameter, the sand was sieved with remaining grains between 1.0 mm and 0.5 mm. This allowed for easier measurement and simulation due to the improved uniformity of the sand. Another benefit was that for more difficult measurements, larger particles with very similar properties were available as replacement material.

### 3.2 *General simulation aspects*

The software used for these investigations was open-source DEM software MUSEN (Dosta and Skorych 2020).

For numerical representation of the sand grains spherical particles with a scaling factor of five were used. To mimic the grading of the sample, a weight-equal distribution of the sand particles between 0.5 mm and 1.0 mm was assumed. This grading was divided into three equal parts to calculate the fraction of the numerical particles. The distribution was determined using equations (1) and (2), where $\chi$ is the part and $d$ the diameter of the equivalent grain size. The grading was calculated to approximately 57.8% of 2.92 mm, 27.2% of 3.75 mm and 15.0% of 4.58 mm particles. This grading was used for all following simulations.

$$d_1^3 * \chi_1 = d_2^3 * \chi_2 = d_3^3 * \chi_3 \tag{1}$$

$$\chi_1 + \chi_2 + \chi_3 = 1 \tag{2}$$

Next to the simulation parameters of the sands, which will be varied in these investigations, the material and contact parameters of the geometries, like funnel, shearing as well as oedometer devices need to be chosen. For simplicity, only one material (steel) was used besides the sand and parameters remained consistent during all simulations. The material and contact parameters for steel parts are given in table 1. As different geometries do not interact in MUSEN, contact parameters between steel and steel did not have to be chosen.

Table 1. Material parameters for steel and contact parameters to sand

| Parameter | Symbol | Value | Unit |
|---|---|---|---|
| Density | $\rho$ | 7800 | kg/m$^3$ |
| Young's modulus | $E$ | $2.1 \cdot 10^{11}$ | N/m$^2$ |
| Poisson's ratio | $v$ | 0.285 | - |
| Coefficient of restitution | $e$ | 0.8 | - |
| Sliding friction | $\mu_S$ | 0.35 | - |
| Rolling friction | $\mu_R$ | 0.08 | - |

The required time step for the simulation was calculated using Rayleigh time (Burns et al. 2009). Here the smallest determined time step, resulting from smallest particle, was used.

## 4 PARAMETER CALIBRATION

### 4.1 *Comparison Experiments*

To achieve appropriate parameter calibration, suitable experiments need to be chosen. These need to represent the different simulation parameters as directly as possible. Furthermore, the parameters should be captured independently within the experiments, which is however partly dependable on the parameter. While differentiation between friction and Young's modulus is possible, differentiating between coefficient of restitution and friction, both rolling and sliding, is significantly more difficult. This also means that when calibrating, the more independent parameters need to be determined first. Due to this, it was decided on the following sequence for calibration: sliding and rolling friction, Young's modulus, Poisson's ratio and coefficient of restitution.

Four different physical experiments were chosen as basis for the calibration in the following sequence: (I) angle of repose, (II) oedometer test, (III) direct shear test and a (IV) drop test. These tests were capable of adjusting all parameters except density. This parameter was assumed to be 2.650 kg/m$^3$ due to the main sand mineral being quartz.

### 4.2 *Calibration of angle of repose*

The experiment determining the angle of repose was used for the calibration of sliding and rolling friction. For this, both the achieved angle as well as the shape of the sand cone were used for calibration. Due to the slow movements and lack of pressure on the particles the other mechanical parameters, except density, should have negligible effect on the above-mentioned friction parameters.

The comparison experiment was conducted using a funnel filled with sand being slowly lifted. The resulting cone had an angle of repose of 31.8° and a pointy to slightly rounded tip with straight slopes.

The procedure was replicated in the numerical simulation. The sand particles were randomly created in the funnel and then allowed to settle. Afterwards the funnel was slowly lifted such that a sand cone formed. After eight simulations, an agreement of the shape and an angle of repose of 31.3° could be reached for sliding friction coefficient of 0.26 and rolling friction coefficient of 0.17. Both the physical as well as the numerical angle of repose can be seen in figure 1.

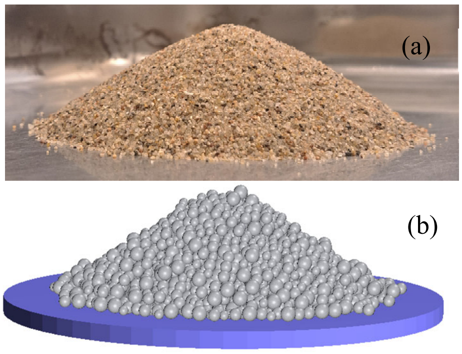

Figure 1. Comparison between physical (a) and numerical (b) angle of repose

### 4.3 *Calibration of oedometer test*

The next calibration was conducted using an oedometer test with an oedometer cell measuring both transverse stress on the cell wall as well as normal stress on the cell bottom in addition to load and settlement. Therefore, it was possible to both calibrate Young's modulus and Poisson's ratio with the same experiment: the Poisson's ratio was calibrated using the ratio between normal and traverse stresses, while Young's modulus was calibrated using the settlements.

In the physical test, four load steps 100 kPa, 50 kPa, 100 kPa and 200 kPa were used, so loading and unloading could be depicted. The sample was reconstructed by hand with an achieved porosity of 0.248 which corresponds to medium bulk density. In the numerical simulation it was important to replicate the relative bulk density and therefore the porosity as well as possible, due to its important effect of the load-settlement behavior. However, the porosity in the simulation will always be higher due to the bulk material being less graded. On average, porosities of 0.37 were reached before loading. This should replicate the medium bulk density in the physical sample and allow for a comparison between the physical and numerical tests.

During the simulation, all loads were applied until the settlements did not increase further. An intermediate step of the 3rd loading phase (100 kPa) can be seen in figure 2. After ten simulations Young's modulus was determined to be $4 \cdot 10^8$ Pa, as for this value the load-settlement behavior of the simulated sample showed best accordance to the physical test.

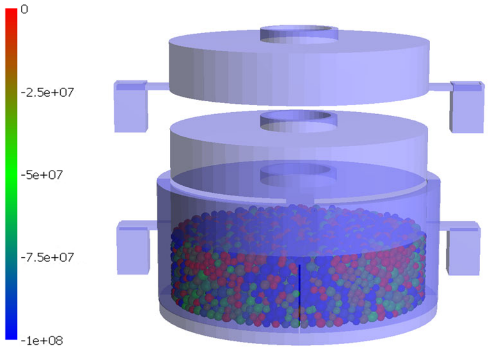

Figure 2. Simulation of oedometer test during third load step (100 kPa), colored by vertical stress [mm]

During four further simulations Poisson's ratio was determined. However, the behavior of the transverse and normal pressure used for the calibration did not show a large variation during the simulations, even though Poisson's ratios between 0.15 and 0.35 were investigated. Best agreement was reached for a Poisson's ratio of 0.3, however the ratios of transversal and normal pressures from the physical test were still only partially replicated.

This points to an issue regarding the numerical simulation, which could be a non-accordance of simulation and physical experiment. Regarding the DEM-simulations, the walls of the oedometer test cell are completely rigid and do not stretch, while the real material in the physical model expands under pressure. This in turn might influence transverse pressure and impede the calibration of Poisson's ratio. Another issue could be the particle packing. While the achieved packing might be able to simulate the settling behavior, it may not allow for simulation of the dilatancy behavior of the sample, and therefore the singular particles. Finally, inhomogeneities could be present in the physical sample, which are not replicated in the simulation. Therefore, further investigations into the calibration of Poisson's ratio using oedometer tests are needed.

### 4.4 *Calibration of direct shear test*

The direct shear test was supposed to further calibrate the friction parameters rolling and sliding friction, because it was unclear if the adjustment using only the angle of repose was sufficient. However, it was necessary to first calibrate Young's modulus and Poisson's ratio due to the settling behavior during shearing.

The physical experiment was conducted using a normal pressure of 100 kPa. The sample was reconstructed by hand and then sheared. Maximum horizontal stress was 80 kPa showing dilatancy behavior of the investigated soil sample.

In the numerical simulation, the sample was constructed using the same method as for the oedometer test. With the values determined during the angle of repose and oedometer simulations, both a maximal horizontal stress of 82 kPa as well as dilatancy behavior could be observed. Due to the good agreement, it was decided that further calibration of the parameters was not necessary, and that in the present case angle of repose and oedometer are sufficient to calibrate the parameters.

### 4.5 *Calibration of drop experiments*

As a final step, calibration of the coefficient of restitution was necessary. Thus, a dynamic experiment representing the behavior of the bulk was required. It was decided on a drop test, in which a larger object is dropped into a sample of the bulk material. The sample was created by hand pluviation into an proctor test device with a diameter of 100 mm and a height of 120 mm. The average porosity of the samples was 0.253. To make sure that the coefficient of restitution for the sand is calibrated, the dropped objects need to be coated with the investigated bulk material.

For the drop test conducted in this study, a small cube with 25 mm edge length was coated in a glued sand layer, resulting in a drop object with a weight of 8.5 g. This object was dropped into the bulk sand from a height of 300 mm. This resulted in sand grains being pushed up to the height of the block during impact, and the drop object sinking a fourth of its height into the sand. The result of one test can be seen in Figure 3.

Figure 3. Result of the drop test

For the simulation, both the sample and the drop object were replicated, without scaling weight or geometries and an average porosity in the simulation before impact of 0.37. This led to a coefficient of restitution of 0.75 after eleven simulations.

### 4.6 *Parameter Set*

The different calibration simulations resulted in the following parameter set for the investigated sand, see table 2.

Table 2. Calibrated parameter set

| Parameter | Symbol | Value | Unit |
|---|---|---|---|
| Density | ρ | 2650 | kg/m³ |
| Young's modulus | $E$ | $4 \cdot 10^8$ | N/m$^2$ |
| Poisson's ratio | $v$ | 0.3 | - |
| Coefficient of restitution | $e$ | 0.75 | - |
| Sliding friction | $\mu_S$ | 0.26 | - |
| Rolling friction | $\mu_R$ | 0.17 | - |

### 4.7 *Required computational times*

For proper evaluation of the effort required for the simulation, computational times for the calibration simulations are needed. As these times depend on many different factors besides the simulations themselves, like capabilities of the computer and parallel processes, only a qualitive assessment is shown. This assessment is based on the necessary simulation time and particle number. These are the two main factors contributing to the longer computational time: a higher particle number requires more processing power for contact calculation, which is necessary for calculation the forces and movements of the particles. A longer simulation time equally results in more required processing and therefore computational time. The results of the evaluation can be seen in table 3.

Table 3. Required computational time of the simulations

| Simulation | Particle number | Simulation time | Computational time |
|---|---|---|---|
| Angle of repose | 3000 | 20 s | Medium |
| Oedometer test | 7900 | 30 s | High |
| Shearing test | 4500 | 30 s | High |
| Drop test | 26800 | 2.2 s | Low |

## 5 DIRECT PARAMETER MEASURENTS

When directly measuring the different simulation parameters for sand particles several aspects need to be considered. First, sand is a heterogeneous bulk material. The grains vary in material, size, shape and internal structure, and therefore also in their simulation properties, which increases the difficulty of the measurements. This difficulty increases even further considering the geometrical representation of the sand grains in the DEM-simulations where all sand grains are represented as homogenous spheres without any variation in shape. Therefore, the measurements need to consider the shapes of the particles.

For parameter measurement it was decided to use simple constructions and equipment, which are present in a laboratory or could easily be procured. The goal was to find and evaluate simple and efficient methods. While specialized equipment for parameter measurement on particle scale does exist, construction and testing of this equipment would increase the time required for parameter measurement and negate the positive benefits compared to calibration.

One issue, however, was that no feasible method for measuring Poisson's ratio was identified. Most of the methods found relied on specific particle shapes, which in sand could not be replicated. An alternative option would be to determine bulk modulus κ by change in volume during compression and then calculating Poisson's ratio ν. However, the changes in volume to be measured are very small, which can lead to large inaccuracies. Therefore, it was decided to use the calibrated Poisson's ratio with a value of 0.30.

### 5.1 *Density*

Regarding the parameter density grain density was measured according to DIN EN ISO 17892-3 (2016). The resulting value was determined to be 2.618 kg/m³. This shows only a small difference to the assumed density of quartz sand, which is due to other minerals found in the sand.

### 5.2 *Young's modulus*

Measurement of Young's modulus of the sand grains was conducted using a substitute material of fine gravel grains from the same sediment the experimental sand was extracted from. Therefore, the assumption was made that the determined elastic properties are equal to those of the sand particles. During the measurement, attention was paid to replicating the composition of the sample. For this, the mineral make-up of the chosen gravel grains replicated the sand particles as well as possible.

For determination of Young's modulus, the particles need to be compressed, and both the necessary force $F$ and deformation $\Delta s$ need to be measured. The simplest way to achieve this is to place the particles between two parallel disks. The measurements for this study were conducted using an oedometer test stand, which allowed both for the measurement of distance and force. To achieve two parallel disks, three grains of approximately equal size were measured at the same time. Under the assumption that the two disks, which consisted of steel plates, had a significantly higher Young's modulus than the sand particles, Young's modulus of the particles could then be determined by the following equation (3) (Puttock and Thwaite 1969).

$$E_{sand} = \frac{3 * F}{\sqrt{d_{particle} * \Delta s^3}} * \left(1 - \nu_{sand}^2\right) \tag{3}$$

In the experimental setup used, the force F is ideally distributed equally over all three grains and therefore divided by three. The particle diameter $d_{particle}$ was calculated as the average out of grain width, length and height. Poisson's ratio of the sand particles $\nu_{sand}$ was assumed to be 0.30. With this, nine measurements in total could be conducted, measuring 27 particles. The determined Young's moduli varied between $2.2 \cdot 10^8$ and $12.8 \cdot 10^8$ Pa, which due to the different minerals is not surprising. The average Young's modulus was determined to be $8.1 \cdot 10^8$ Pa.

### 5.3 *Sliding friction*

When determining sliding friction, it is important to measure dynamic friction as opposed to static friction, and to measure friction between the sand particles and not between particles and another material. Therefore, the friction needs to be measured during movement and between two sand surfaces.

To allow for this, a measuring device was constructed after Cao et al. (2021), which consisted of a sloped surface with different possible angles θ to be selected. The slope was coated with the sample sand, which was glued to the surface to avoid movement of the particles. Furthermore, a matching test piece was created, also coated in sand grains, which could slide along the slope. The test device as well as the test piece are shown in figure 4.

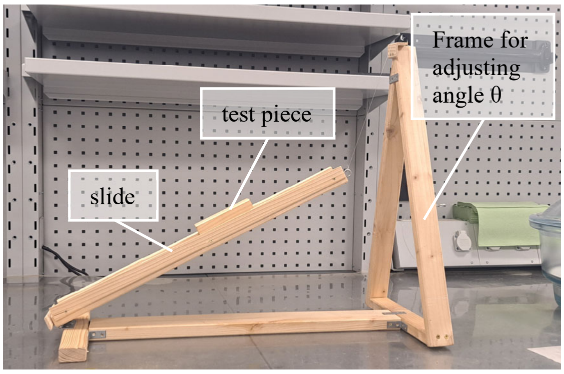

Figure 4. Slide and test piece for the measurement of sliding friction

The sliding friction coefficient is then determined by measuring the angle of the slope θ, the traveled distance $L$ and the time $t$ necessary for the slide. While different methods for measuring the time $t$ are possible, for simplicity the sliding process was recorded and the time determined from the video. Sliding friction can then be calculated using the following equation (4).

$$\mu = tan(\theta) - \frac{2 * L}{g * t^2 * cos(\theta)} \tag{4}$$

With this, an average sliding friction of 0.55 was measured.

### 5.4 *Rolling friction*

Investigating rolling friction, the same measuring device and set-up were used as for the sliding friction. However, a thin layer of loose sand particles was placed on the slope, to encourage rolling of the grains between the slope and the test piece. With this set-up, a rolling friction of 0.41 was measured.

### 5.5 *Coefficient of restitution*

To measure the coefficient of restitution, the same substitute material as for determining Young's modulus was used. For the measurement, the fine gravel grains were dropped from a certain height onto a surface covered in sand grains, which were glued to prevent movement.

By determining the falling height $h_{fall}$ of the particles as well as the time $\Delta t_{jump}$, horizontal distances $\Delta x$ and $\Delta y$ and jump height $h_{jump}$ between the first and second impact (after the jump), the velocities before and after the first impact can be determined, and the coefficient of restitution $e$ can be calculated using equation (5). This more complex approach was necessary due to the deflection from the sand layer, as the impact did not redirect the gravel grains up vertically again. Further, this procedure does not consider air resistance; however, the influence should be negligible at lower falling heights and velocities. The grain drop tests were conducted in front of a grid and recorded using a camera with a high frame rate, which allowed for precise time, height, and distance measurement. The derived values for coefficient of restitution vary from 0.19 to 0.60, with an average of 0.36.

$$e = -\sqrt{\frac{\frac{\Delta x^2 + \Delta y^2}{\Delta t_{jump}{}^2} + 2 * g * h_{jump}}{2 * g * h_{fall}}} \tag{5}$$

### 5.6 *Parameter set*

The measurements resulted in the parameter set in table 4.

Table 4. Measured parameter set

| Parameter | Symbol | Value | Unit |
|---|---|---|---|
| Density | ρ | 2618 | kg/m³ |
| Young's modulus | $E$ | $8{,}1 \cdot 10^8$ | N/m² |
| Poisson's ratio | $\nu$ | 0.30 | - |
| Coefficient of restitution | $e$ | 0.36 | - |
| Sliding friction | $\mu_S$ | 0.55 | - |
| Rolling friction | $\mu_R$ | 0.41 | - |

## 6 COMPARISON

To evaluate the methods for determination of the simulation parameters, several aspects need to be considered. First, the measured values need to lead to good simulation results. For this, they will be compared to literature values and calibrated values and, were possible, tested using the calibration simulations. Second, the effort in determining the parameters by measurement needs to be compared to the effort during calibration by means of physical testing.

### 6.1 *Density*

The values of the assumed and measured density of sand grains are very similar to each other. However, as even small differences affect many different processes, from angle of repose to dynamic processes, the density should be determined as accurate as possible. Therefore, the measurement is still advisable, especially when different minerals can be found in the sand and with respect to the low effort and time requirements for grain density measurement.

### 6.2 *Sliding und rolling friction*

Regarding the friction parameters, differences between measured and the calibrated parameters are quite large. Here, the values of the direct measurements are twice as large as the calibrated parameters. When testing the friction parameters with the angle of repose simulation, the achieved angle was significantly too high with 53°. Therefore, the determined values do not match the actual sand behavior.

One issue could be an overestimation of the interparticle friction due to the particle shape, where the uneven surfaces of the slide and the test piece created higher friction than just between two sliding particles. This was especially true due to interlocking between the slide and the test piece, where the particles became wedged to each other. However completely removing the shape or structure of the particles would also lead to a false result, because the shape and surface structure of the particles influence the friction between them (Cho et al. 2006). This would also not be depicted in the simulation, because the particles are simplified as spheres.

To evaluate this effect, a zero-friction simulation was run. This simulation represented the sliding friction experiment using zero friction particles (sliding and rolling friction set to 0.001). To avoid interparticle movement the particles were interconnected using bonds and anchored to the slide and to the test piece. The sliding friction coefficient was calculated using the same formula (4) as given in chapter 5.3. However, when determining the sliding friction for zero friction particles, the value came to 0.41, which would result in an adjusted sliding friction of 0.14. This value would be too low to properly model the behavior of the sand when, for example, simulating the angle of repose. When the same simulation was conducted with a layer of loose sand, the test objects did not slide, which means that no zero-friction rolling friction could be determined. Thus, the adjustment simulation was not successful.

Therefore, it has to be concluded that the friction parameters are too complex to be measured using simple techniques, especially considering the increased difficulty due to the simulation simplifications, such as particle shape and grading.

### 6.3 *Young's modulus and Poisson's ratio*

Regarding determination of Young's modulus the measured value was approximately twice as large as the calibrated value. Nonetheless, due to the wide range of possible values found in literature, it was still a good approximation. However, the measurements in this study were conducted using a replacement material of a fine gravel from the same original material. If the actual sand had been used, especially with smaller grain sizes, the measurements would not have been accurate enough. Therefore, if no larger replacement material is available, a specific measuring device needs to be constructed.

When using only the measured parameter values for the oedometer simulations, the settlement behavior of the sample was underestimated in the oedometer simulations. Therefore, the Young's modulus will need to be further calibrated after the measurements, to properly depict the behavior of the bulk material. Considering the simplicity, using the measurement to pre-calibrate the value would save significant amount of time during calibration, especially considering the high computational time needed for oedometer simulations.

Regarding Poisson's ratio the "measured" value was based on the calibrated value such that an actual comparison is not possible. However, what can be said is that the calibrated value does fit into the range of literature values given and the simulations match the results of physical experiments. However, due to the range of possible values found in literature, if direct measurement is not possible, calibration is required for good simulation results.

Due to the possible success regarding Young's modulus, it may be interesting to create an actual measuring device allowing for proper measurement of finer sand grains. This device would need to allow for more accurate measurement of displacement and applied force on grain size scale. Furthermore, creation of a specific device might also allow for measurement of Poisson's ratio, if changes in grain volume during loading are recorded. However, the necessary time and effort for creating this device are only justified if parameters for many different sands on a regular basis need to be determined.

### 6.4 *Coefficient of restitution*

While the measurement for the coefficient of restitution was simple to conduct, the measured value did not match either the range found in literature or the calibrated value. This means that the experiment was not suitable to measure the desired parameter in sufficient accuracy. This could be due to the properties of the sand during impact, which may have created too much friction and therefore reduced the velocities after the jump and lowering the coefficient of restitution. Another issue could be the replacement material, which was the fine gravel used for measurement of Young's modulus. Here, the properties of the larger grains may significantly differ from those of the smaller grains. This means that if the coefficient of restitution needs to be measured, an alternative method for determination needs to be considered. However, due to the ease and low required computational time for calibration purposes, a calibration of the coefficient of restitution is probably preferable, especially if the measurements require more time or equipment.

## 7 CONCLUSIONS

During the investigations conducted in this study, it was shown that directly measuring simulation parameters for sand has many difficulties. Especially the measurement of friction parameters was complex due to the particle shapes and the bulk properties. However, measurement of density and Young's modulus do allow for an improvement in parameter determination. The latter is especially important when considering the required computational time of necessary oedometer calibration.

Therefore, based on these investigations, the following sequence for determination of simulations parameters for sand used in DEM-simulations is recommended:

1. Measurement of grain density
2. Calibration of sliding and rolling friction using the angle of repose test
3. Pre-measurement of Young's modulus followed by a fine calibration using simulations of oedometer tests. Calibration of Poisson's ratio using oedometer tests with measurement of the transverse pressure
4. Optional: Control of the determined parameters using a direct shear test
5. Calibration of the coefficient of restitution using the drop test.

This sequence should allow for a relatively fast but accurate determination of simulations parameters for the discrete element modelling of sand.

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