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On the effect of stress dependent interparticle friction in direct shear tests

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ABSTRACT

Contact friction is a key influence factor for the shearing behaviour of granular media. In the discrete element method (DEM) contact friction is usually modelled with Coulomb's law assuming a constant interparticle friction coefficient. From tribology it is known that friction is influenced by several factors, e.g., temperature, normal stress, surface condition, etc. None of these influences can be modelled with the constant interparticle friction coefficient from Coulomb's law. For a given granular material (particle shape distribution), the usage of constant interparticle friction in DEM models generally results in constant bulk friction coefficients in the simulation of direct shear tests. While this is frequently seen in experiments with equi-sized spherical particles, papers exist in literature which report a stress dependency of bulk friction for non-spherical particles of certain materials. In this work, a stress dependency of bulk friction is obtained by introducing a model for stress dependent interparticle friction in DEM simulations. For validation experimental results of direct shear tests conducted on single or paired glass beads are used. While the bulk friction of paired spheres clearly decreases with increasing normal stress, it is nearly constant for single spheres. DEM simulations with the stress dependent interparticle friction are in good accordance with the experimental results of both single and paired spheres. A comparison with simulations, using constant interparticle friction, clearly shows the advantage of the proposed model.

1. Introduction

In DEM simulations of granular material, the modelling of friction at particle–particle and particle–environment contacts has a significant influence on the predicted shear behaviour of the bulk material. In the sense of a tribological system friction is influenced by several parameters like contact normal load, relative motion, surface roughness, contact temperature and contact conditions (dry, wet, lubricated, …), etc.

Regarding the simulation of the mechanical behaviour of solid-like granular materials, the discrete (distinct) element method (DEM), as introduced by Cundall and Strack [1], is a widely used tool. In DEM the force, which results at each contact, is decomposed in normal and tangential directions, F_n and F_t. Several models exist for the calculation of both quantities. In tangential direction, the force, which can be transferred, is bounded. The commonly used model is Coulomb's law with a constant interparticle friction coefficient, μ. For cohesionless materials Coulomb's law can be written as follows:

$$F_t = \min(\mu F_n, \widetilde{F}_t), \tag{1}$$

where $\widetilde{F}_t$ is the pre-sliding shear force calculated using the contact constitutive model. Coulomb's law can also be stated using the internal friction angle, ϕ, which is connected to the interparticle friction coefficient by $\mu = \tan(\phi)$.

Frequently used tests for the investigation of the shear behaviour of granular materials are the triaxial test and the direct shear (or shear box) test. Usually, the Mohr–Coulomb failure criterion is used which reads as:

$$\tau_f = \tan(\Phi)\sigma_n + c, \tag{2}$$

where τ_f is the final shear stress, Φ is the bulk friction angle and c is a material parameter representing cohesion of the granular material, i.e., $c = 0$ for cohesionless materials. The bulk friction angle of a granular material is an important characteristic for its shear behaviour. Alternatively, the peak friction angle can be determined, where the maximal shear stress instead of the final one is used in Eq. (2).

The bulk friction angle of a granular material depends on the porosity of the packing as well as on particle properties, e.g., size, shape and surface roughness. Regarding particle roughness several works in literature state a strong influence of the interparticle friction on the bulk friction angle, e.g., in [2–4], direct shear tests were simulated and compared to experiments.

Many papers in the literature state that the bulk/peak friction angle is constant, i.e., independent of the normal stress. In the opinion of the authors of this work this has mainly two reasons. One reason is that often equi-sized spherical particles are considered, where the dependency of the bulk friction coefficient on the normal stress is usually negligible. The second reason is that the way of analysing the results can

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sometimes be misleading. A frequently found plot is shear stress over normal stress. Here it is very hard to see deviations from the linear trend. To investigate a stress dependency of the bulk friction coefficient other representations can be more helpful, e.g., bulk friction over normal stress or bulk friction over porosity. This point will be addressed also later on.

Regarding equi-sized spherical particles one example is the work of Cui and O'Sullivan [3], who conducted direct shear tests on steel balls. Within the regime of applied normal stresses (55 kPa–164 kPa), a linear relation between the measured shear stress and normal stress was found. This justifies the application of the Mohr–Coulomb criterion, and the bulk friction angle can be considered constant.

Härtl and Ooi carried out direct shear tests on single and paired glass beads, see [4,5]. The applied normal stress ranged from 3 kPa to 24 kPa. For the single glass beads the relation between shear stress and applied normal stress was nearly linear, thus the bulk friction angle was constant. On the contrary, a clearly non-linear relation between shear stress and applied normal stress was found for the paired glass beads. This nonlinearity was hardly seen in the plot of shear stress over normal stress. However, when the bulk friction coefficient over initial porosity was plotted, the stress dependency of the bulk friction angle was clearly seen.

Indraratna et al. found similar experimental results in [6], regarding a stress dependency of the bulk friction angle of railway ballast in direct shear tests. The normal stress was varied between 15 kPa and 75 kPa and a nonlinear dependency between shear stress and normal stress was shown. In several citations of works on rock-fill materials, given in this work, a non-linear relationship is stated, which is significant at low normal stresses and gradually reduces as the normal stress increases.

This description matches well with the results of Tuzun and Walton, see [7]. A stress dependent coefficient of friction between smooth silo walls and particles was found for small normal stresses. It seems that depending on the considered material and particle shape, a non-linear relation between shear stress and normal stress can be observed for low normal stresses.

The above experimental findings on granular materials and results obtained by the authors on the wheel–rail contact for steel, were the motivation to introduce a non-constant coefficient of friction in DEM simulations. This aims at an improved prediction of the observed normal stress dependency of the bulk friction angle. In [8], Suhr and Six, conducted DEM simulations using the contact model with normal stress dependent friction. Direct shear tests on steel spheres of a given size distribution were considered. Steel was chosen as material for the spheres, as the experiments for the stress dependency of the interparticle friction coefficient were given for steel, see [9]. Although no experimental results on the direct shear tests were available for a quantitative comparison, the following qualitative behaviour of the granular material was found. A variation of the constant interparticle friction coefficient demonstrated a strong dependency of the bulk friction angle on interparticle friction. For a constant interparticle friction coefficient the resulting bulk friction angle showed no normal stress dependency. When the non-constant (stress dependent) friction coefficient was used, the stress dependency of the bulk friction angle could be seen clearly.

In this paper, the contact model with normal stress dependent friction will be used to investigate the normal stress dependency of the bulk friction coefficient, as seen from the experiments on glass beads in [4,5].

The paper is organised as follows. In Section 2 an overview of the main experimental findings from the direct shear tests of [4,5] will be given. The third section summarises the used DEM contact model with the stress dependent friction coefficient. In Section 4 DEM simulations with constant and stress dependent interparticle friction coefficient will be presented. The influence of the model parameters will be pointed out and a comparison with experimental results is shown. Finally conclusions are drawn in Section 5.

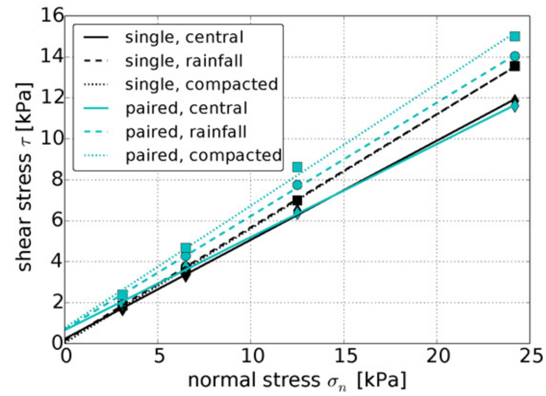

Fig. 1. Shear stress over applied normal stress of single and paired glass spheres. Data taken from [4].

Table 1
Material parameters of single glass beads.

Diameter [mm]	6
Density [kg/m^3]	2550
Poisson's ratio [−]	0.22
Shear modulus [N/m^2]	1.67e + 10
Friction coefficient (glass–steel) [−]	0.13
Friction coefficient (glass–glass) [−]	0.2
Coefficient of restitution [−]	0.87

2. Jenike shear tests — experimental results

All experimental results shown here stem from Härtl and Ooi [4,5]. Only the main findings will be shown, for details the reader is referred to the original works. A Jenike shear tester with a 143 mm diameter cylindrical cell was used. The height of the lower ring and upper ring was 19 mm and 24 mm respectively. Both top and bottom plates were roughened with grooves as recommended by the standard [10]. The used glass beads had a diameter of 6 mm. Their material parameters for single spheres can be found in Table 1. Paired spheres were made by gluing two spheres together. Three different filling methods were compared: central filling (filling through a central funnel), rainfall (filling through a sieve) and compacted filling (manually compaction). The filling methods resulted in different initial porosities. Four different levels of applied normal stress were

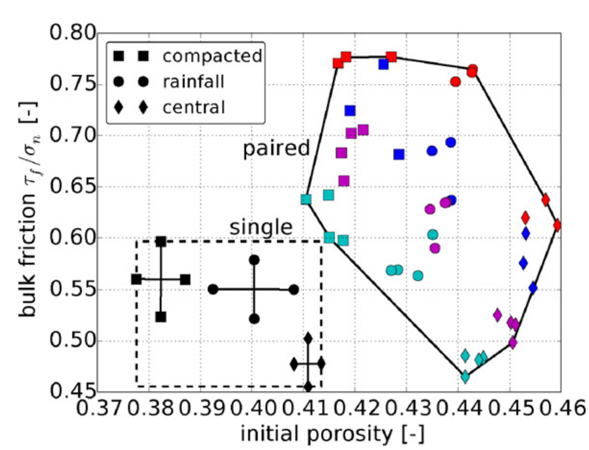

Fig. 2. Stress dependency in bulk friction, taken from [5]. Marker types corresponding to filling of paired spheres; compacted: square, rainfall: circle, central: diamond. Colouring of applied normal stresses: 3.1 kPa: red, 6.4 kPa: blue, 12.5 kPa: magenta, 24.2 kPa: cyan.