Numerical modelling of granular subglacial deformation using the discrete element method

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Introduction
Deformation of subglacial sediment can be a major contributor to the overall movement of warm-based glaciers and ice streams (e.g. [5,6,16,21,22]). Discrete Element Method (DEM) simulations of the subglacial material are used to model the mechanical behaviour of the subglacial material. A discrete element model approach can provide the numerical solution of the subglacial deformation. As a supplement to laboratory experiments, numerical modelling is often used to control over all model parameters, such as grain size distribution, geometrical properties of the material, and boundary conditions. This facilitates a more transparent experimental setup, where it is possible to repeat experiments, and to quantify the effect of all input parameters.

Laboratory experiments
Ring-shear experiments have previously been used to investigate the mechanical behaviour of glacial till (e.g. [15]). Here, stress measurements from ring-shear experiments are used as a method of validating the simulated granular behaviour.

Discrete Element Method
The Discrete Element Method simulates the microstructural behaviour and interaction of discrete, unbreakable particles with their own mass and inertia. Particles interact using a conventional linear-elastic contact model, where the magnitude of the tangential force is limited by the Coulomb-friction criterion of static and dynamic friction.

Results
A series of strain-rate controlled shear tests are performed to compare the geotechnical behaviour of the laboratory material to the DEM numerical method. In all materials, the magnitude of the effective normal stress ($\sigma$) proves to be the controlling parameter on the peak shear strength ($\tau_p$) and ultimate shear strength ($\tau_u$). Consistent with the Mohr-Coulomb failure criterion. The material strengths are constant in the range of tested strain rates, and the granular materials are inferred to be deforming in a pseudo-static state.

Results (continued)
- Stress is distributed heterogeneously in the granular material (Fig. 2).
- The stress distribution of the non-fixed particles (Fig. 3).
- Particle kinematics inside the shear zone at three times during the DEM experiment with $(\tau = 50\text{ kPa})$. The particles are visualized as discs according to their interaction with a center (red) plane. The particle color corresponds to the contact normal velocity. The particle color is shown with blue (negative) and green (positive). Inter-particle slip-velocities are shown with green arrows.

Highlights
- Deformation takes place as a combination of frictional slip on inter-particle contacts and grain rotation.
- The magnitude of the effective normal stress controls the depth of deformation and therefore also the subglacial sediment transport rate.
- The shear zones are characterized by increased porosity, causing a net mechanical softening in drained experiments.
- Stress is distributed heterogeneously in the granular material, where the contact network is mainly aligned parallel to the maximum compressive stress.
- The failure and redistributions of force chains in the stress network cause fluctuations in the shear strength in the material.
- The local stress level in a force chain can be an order of magnitude greater than the average stress.

Conclusions and outlook
The Discrete Element Method, although parameterized by microstructural properties, is useful for modeling the microscopic mechanical properties of simple, granular materials, sheared under drained conditions. The laboratory experiments show higher shear strengths with increasing grain angularity. From ring-shear experiments on a range of normal stresses, it was shown how relatively high values of normal stress result in deep, distributed profiles of deformation, and a thick zone of increased porosity. Low normal stresses result in a relatively narrow, boundary layer of deformation, with a high porosity value. Higher values of normal stress result in greater volumetric expansion during shear. The kinematics of the particles are rapidly reconfiguring during shear, highlighting the dynamic behaviour of granular materials. Future studies will focus on quantifying the effect of aspherical grain shapes on the mechanical strength of the material, and how the grain size distribution evolves during progressive shear. These investigations will be enabled by incorporating breakable inter-particle bonds. Subsequent development will focus on the mechanical interaction between the DEM particles and an interparticle fluid, implemented by the Latice-Boltzmann method.

References