

DEALING WITH A STICKY SITUATION...

Modelling cohesive frictional granular solids.

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Introduction

Powders and bulk solids are stored and handled in large quantities in many industries. The materials can differ greatly in size, shape and type but are commonly affected by handling and storage difficulties, such as the blockage of silo outlets or transfer points, which occur as a result of the development of cohesion.



Fig. 1 Some Typical Granular Materials



Fig. 2 A More 'Useful' Example of Cohesion in Action

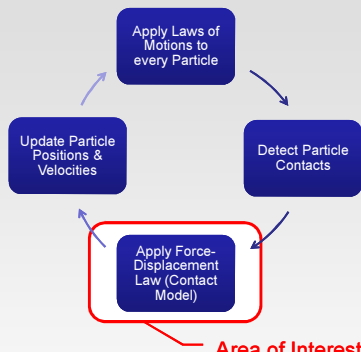
Adhesive forces between particles in a granular material are known to be dependent on the external forces previously exerted on the bulk solid. As a result, the previous stress states of a bulk solid need to be considered when evaluating the adhesive strength of a bulk material.

Discrete Element Method (DEM)

The Discrete Element Method (DEM) is an extensively used tool for the modelling of powders and bulk solids, in which the motion and interactions of individual particles are modelled in detail.

It is often used where continuum methods, such as Finite Element (FE), have difficulty capturing the local slips and large deformations that can occur in granular mediums such as soils and bulk solids.

Few of the currently available contact models for commercial DEM codes that account for adhesive forces also account for the previous stress state, and therefore fail to capture the stress-history dependent behaviour that affects granular bulk solids.



Area of Interest

A Cohesive-Frictional (C-Φ) Contact Model

A meso-scale modelling strategy has led to the development of a DEM contact model that accounts for the stress-history dependent behaviour. It has been implemented through the API capabilities of the commercial DEM code EDEM®.

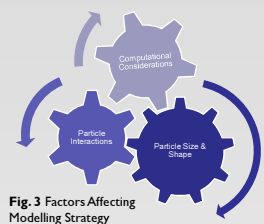


Fig. 3 Factors Affecting Modelling Strategy



Fig. 4 Model Scale Relationship - From Meso to Macro (Top Left: Iron Ore Agglomerate, Top Right: Industrial Silo, Bottom Right: Experiment)

The contact model is a linear/non-linear spring model for elastic-plastic deformation. It includes adhesion as a function of plastic deformation. 6 parameters: f_0 , k_1 , k_2 , F_{min} , n , x

$$f_{hys} = \begin{cases} k_1 \delta^n & \text{if } k_2(\delta^n - \delta_p^n) \geq k_1 \delta^n \\ k_2(\delta^n - \delta_p^n) & \text{if } k_1 \delta^n > k_2(\delta^n - \delta_p^n) > -k_{adh} \delta^n \\ -k_{adh} \delta^n & \text{if } -k_{adh} \delta^n \geq k_2(\delta^n - \delta_p^n) \end{cases}$$

The model parameters for the simulations are phenomenologically based with the target in capturing the key bulk characteristics exhibited by the solid.

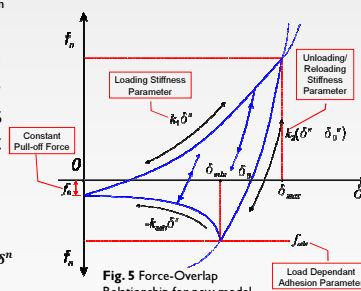


Fig. 5 Force-Overlap Relationship for new model

Calibration of DEM From Bulk Experiments

The Edinburgh Powder Tester (EPT) is a semi-automated uniaxial tester, in which the cohesive strength of a bulk solid is evaluated from an unconfined compression test following a period of consolidation at a pre-defined stress.



Fig. 6 EPT Test: 1) EPT Tester 2) Confined Consolidation 3) Exposed Sample 4) Unconfined Compression to Failure 5) Failed Sample 6) Typical Measured Stress-Strain Behavior at Various Consolidation Stresses

The unconfined stress-strain relationship and stress history dependence of a wide range of bulk solids has been evaluated using the EPT. The stress-strain response and bulk density variation during confined consolidation is also evaluated by the EPT.

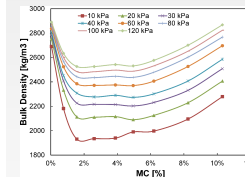


Fig. 7 Bulk Density Variation For LKAB Iron Ore Fines at Various Moisture Contents

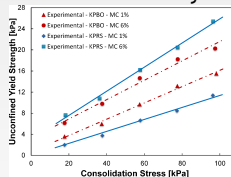


Fig. 8 Flow Function For LKAB Iron Ore Fines at Various Moisture Contents

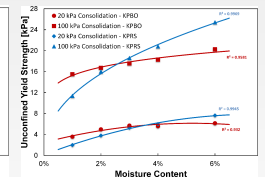


Fig. 9 Stress-Moisture Function For LKAB Iron Ore Fines at Various Stresses

Numerical Results

As well as demonstrating a stress history dependence, a new model must also capture the correct failure mode (Fig. 10).

The numerical simulation shows a typical shear failure with a conjugate pair of shear bands, which is similar to the experiment, as can be seen in figure 6.

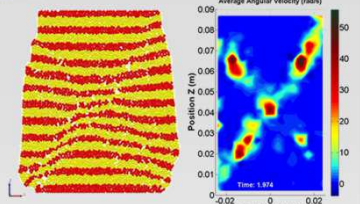


Fig. 10 Shear Band Prediction From Single Layer Planar Model

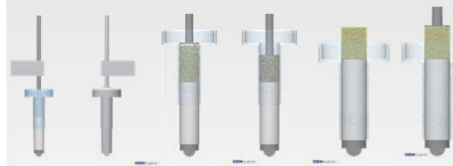


Fig. 11 EPT Simulation in EDEM: (1) 3D Model (2) Filled Sample (3) Confined Consolidation (4) Unconfined Sample (5) Crushing to Failure

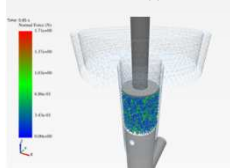


Fig. 12 Force Chain Network During Consolidation

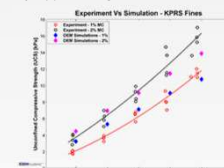


Fig. 13 Flow Function Comparison Between Experiment & DEM

3D numerical simulations of mono-sized non-spherical particles have been carried out and compared with the unconfined compression results from the EPT.

The simulation process, depicted in Figure 11, replicates the experiment and is found to be in excellent agreement with the experimental results.

Industrial Application – Silo Discharge

DEM simulations were found to capture the major phenomena that exists during silo discharge such as different flow zones in the silo and the effective transition height. A strong correlation was observed between the silo wall pressures and the stresses within the bulk solids. DEM simulations were also used to investigate the effect of cohesion on discharge.

Although cohesion leads to reduced discharge rates, the observed flow patterns were not significantly altered. Extreme levels of cohesion were found to lead to eventual blockage.

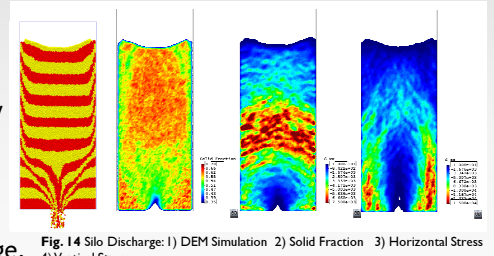


Fig. 14 Silo Discharge: 1) DEM Simulation 2) Solid Fraction 3) Horizontal Stress 4) Vertical Stress

References:

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