



Using the Elasto-plastic Adhesion Model: Example Problem

Authors:

John P. MORRISSEY

Subhash. C. THAKUR

Jin Y. OOI

*School of Engineering,
University of Edinburgh*

© 2014

v1.0f

June 8, 2015

Contents

List of Figures	ii
List of Tables	ii
1 Example Problem	1
2 Problem Description and Parameters	2
3 Example Results	6
4 References	9

List of Figures

1	DEM model of uniaxial test	1
2	Paired particle consisting of two spheres	2
3	Initial Filling of Assembly	2
4	Confined and Unconfined compression of sample	3
5	Influence of cohesion	6
6	Stress-Strain Response	7
7	Bulk Density Variation	7
8	Porosity Variation	8
9	Stress-Strain Response	8

List of Tables

1	Simulation properties	5
---	---------------------------------	---

1 EXAMPLE PROBLEM

The following section introduces a simple problem to highlight the cohesive contact model in use. A DEM Model (Figure 1) of equal dimensions to the Edinburgh Powder Tester (EPT) [1; 6; 9–11] has been created within EDEM to replicate the experimental setup. The three main stages of the experiments are shown from the simulation in Figure 1 and include the filling of sample, the confined compression and the unloading and unconfined compression to failure of a sample.

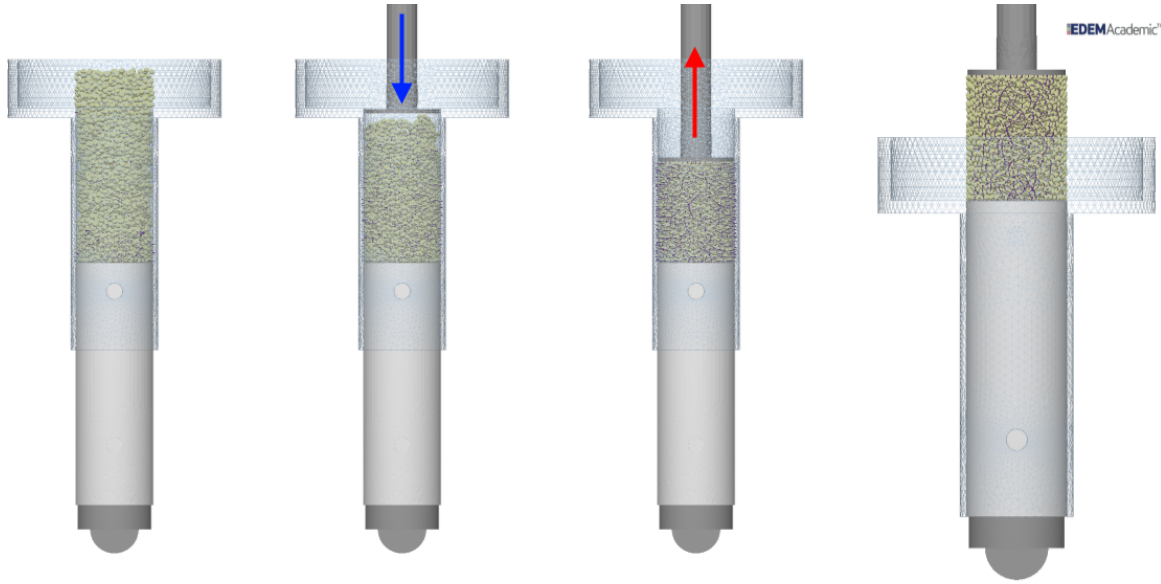


FIGURE 1: DEM model of uniaxial test - From L to R: a) filling, b) loading, c) unloading, and d) unconfined compression

The above DEM setup has been simplified to a simple cylinder of 40mm diameter and 80mm height is used to represent the mould, with the top and bottom platens also represented by cylindrical geometries. While the dimensions of the test setup are maintained, a favourable number of particles with respect to computational cost were selected as the mesoscopic representation of the agglomerated real particles, where each DEM particle represents a cohesive agglomerate.

2 PROBLEM DESCRIPTION AND PARAMETERS

Non-spherical particles each consisting of two overlapping spheres of 1.25 mm diameter giving a particle aspect ratio of 1.5 (see Figure 2) are used. Mono-sized particles were employed for the simulations presented.

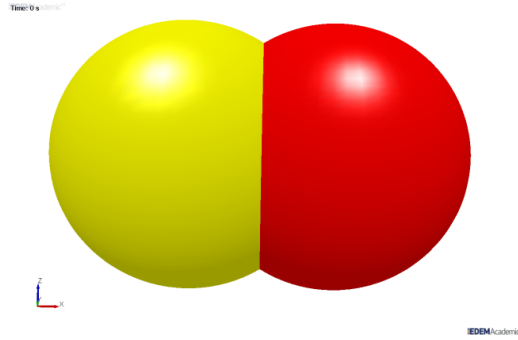


FIGURE 2: Paired particle consisting of two spheres - Aspect ratio of 1.5

Each simulation consists of three stages - filling the cylindrical mould to form the initial packing used for all stress levels; confined consolidation to the required stress level and subsequent unloading; and finally unconfined compression of the sample to failure after the removal of the mould. The process is visualised in Figures 3 and 4. The various stages of the assemblies are provided in example simulations decks.

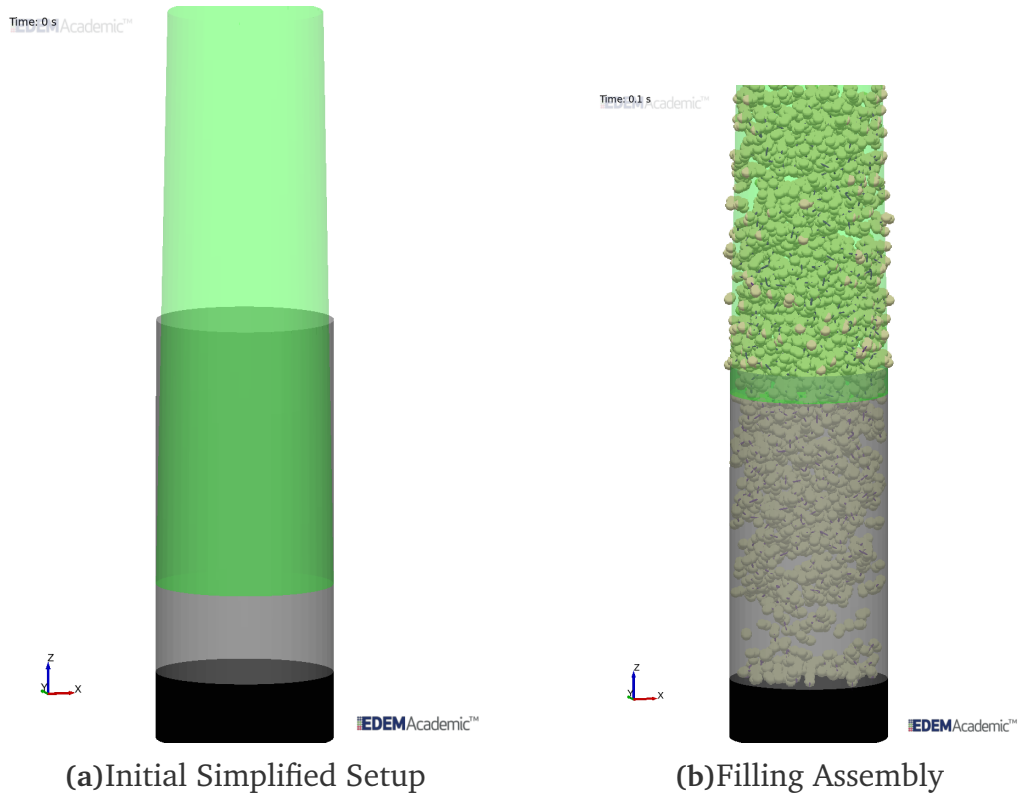


FIGURE 3: Initial Filling of Assembly

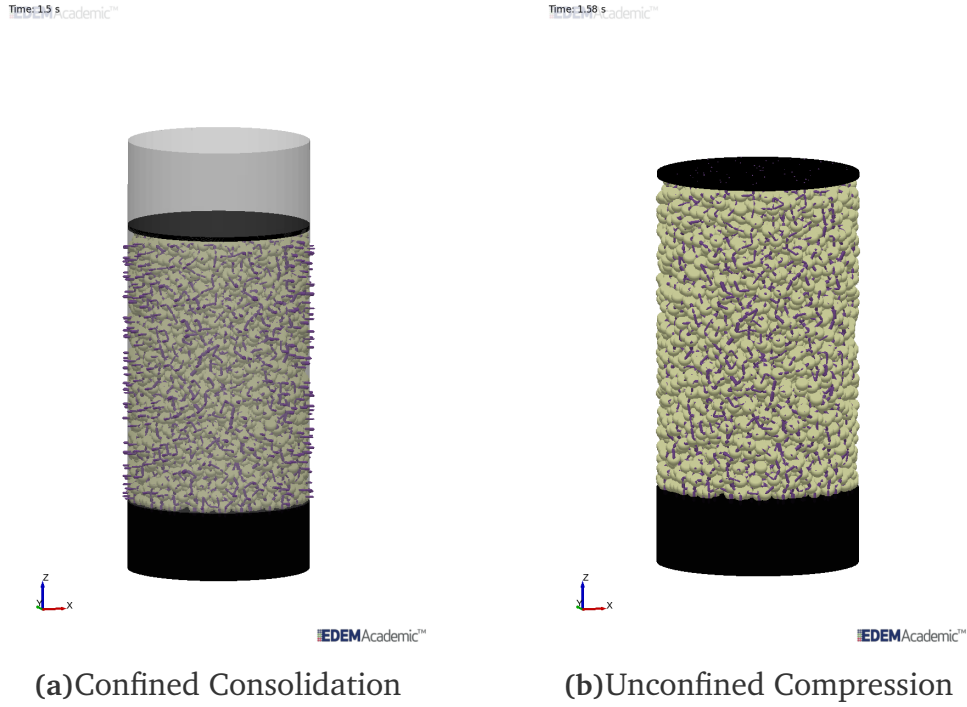


FIGURE 4: Confined and Unconfined compression of sample

The cohesion contact model was only applied to particle-particle interactions while particle-geometry interactions were modelled using the Hertz-Mindlin (no-slip) contact model, therefore no particle-geometry adhesion was considered. In an attempt to replicate the two way compression that occurs in the experimental setup, friction between cylinder and particles was set to zero during confined compression. This means for each test the force acting on the top and bottom platens is approximately equal, with the bottom platen carrying the additional load of the particles also. The friction coefficient between platens and particles was set to 0.25 and its main purpose is to provide lateral stability and prevent slippage of sample during unconfined compression.

Based on the findings in the literature [2; 7], the simulation time-step was chosen to be less than or equal to $0.17\sqrt{m/k_2}$. The main parameters used in the study are presented in Table 1. The simulation parameters are set in the “*ECM_Parameters.txt*” as shown below. The preference file should be included in the same directory as the contact model library file. All particle-particle and particle-geometry interactions should be included in the preference file.

Preference File Input Parameters

```

1 ##NumberOfParticleTypes
2 1
3
4 ##ParticleList
5 ParticleA
6
7 ##InteractionProperties
8 ParticleA:ParticleA
9 fo -0.001
10 SurfaceEnergy 25
11 ContactPlasticity 0.8
12 SlopeExp_n 1.5
13 TensileExp_X 20
14 TangentStiffMultiplier 0.4
15
16 ParticleA:Walls
17 fo 0
18 SurfaceEnergy 0
19 ContactPlasticity 0
20 SlopeExp_n 1.5
21 TensileExp_X 20
22 TangentStiffMultiplier 0.667

```

NOTE 1: PARAMETERS USED

The parameters specified for the particle-geometry interactions in this example preference file will describe a cohesionless Hertz-Mindlin interaction with the tangential stiffness modified according to the suggestion by Di Renzo and Di Maio [3].

The adhesion parameter f_0 is **always** defined as a *negative* force.

Following particle generation, a rest period was provided for all simulations to allow particles to settle and ensure that the systems were in a quasi-static state before the commencement of loading. Loading only commenced when the kinetic energy in the system reached a constant value that was less than approximately 10^{-8} J. This ensured that average particle velocities were in the order of 10^{-3} m/s, with a constant coordination number.

The confined consolidation process was conducted by translating the top platen vertically downwards at a constant rate of 20 mm/s (strain rate ≈ 0.25 s $^{-1}$) to apply a vertical compression. The process is similar to the procedure in the experiments. After consolidating the

TABLE 1: Simulation properties

Number of Particles	3500 paired (Aspect ratio = 1.5)
Sphere Radius, r (m)	0.00125
Particle Density, ρ (kg/m³)	4350
Particle Shear Modulus, G (Pa)	1×10^8
Level of Contact Plasticity, λ_p	0.8
Adhesive Force, f_0, (N)	-0.001
Adhesive Surface Energy (J/m²)	25
Adhesion branch exponent	20
Particle Static Friction, μ_s	0.5
Particle Rolling Friction, μ_r	0.0
Wall Friction, μ_w	0
Top and Bottom Platen Friction, μ_P	0.25
Simulation Time-step (s)	1×10^{-6}

sample to the desired stress level, the assembly was unloaded by translating the top platen upwards at the same constant speed. The lateral confining walls were removed when the unloading was complete and the unconfined sample was allowed to relax for a short period of time to again leave the kinetic energy generated from the removal of the confining wall and upward movement of the top platen to dissipate and drop to an acceptable stable value.

The sample was then crushed to failure by moving the top platen downwards again at a constant rate of 5 mm/s (strain rate $\approx 0.05 \text{ s}^{-1}$). A higher compression rate was used for the confined compression as the inertial effect of the higher loading rate is not as significant as in the unconfined compression test, where a high platen velocity can lead to impact damage of the sample at the point of initial loading in the unconfined test. However, in both cases the inertia number [4; 5; 8] is less than 10^{-3} , confirming that the simulations are in the quasi-static regime.

In all simulations the bottom platen, which represents the stationary base in the experiments, remained stationary in all stages. The results for these simulations are presented in the following sections and the effect on the filled, confined and unconfined stages of the simulation are assessed.

3 EXAMPLE RESULTS

The effect of cohesion on a simple packing is shown in Figure 5 where a significantly looser, lower density packing is obtained due to the inclusion of cohesion.

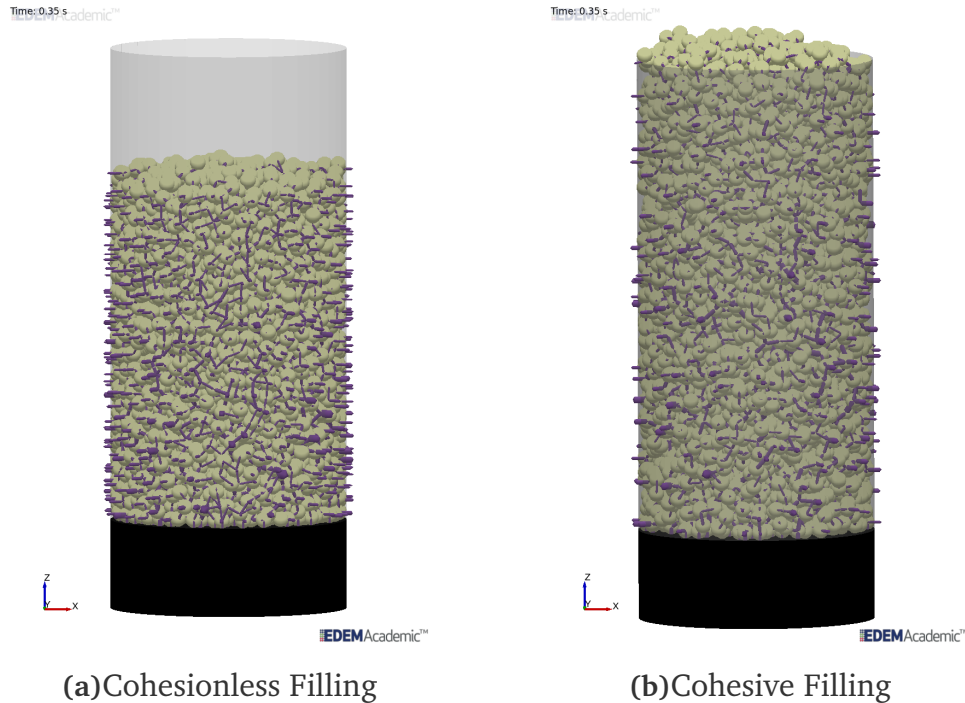


FIGURE 5: Influence of cohesion - Increased cohesion leads to a looser, lower density assembly

Measuring the force and displacement of the top platen, the bulk stress-strain response can be recovered such as in Figure 6 for the consolidation stage, where the permanent plastic deformation of the assembly is also recorded.

The bulk density and porosity for the confined consolidation can also be recovered, as shown by Figures 7 and 8.

The unconfined shear strength of the sample from the unconfined compression of the sample is shown in Figure 9, where the over-consolidated behaviour to be found in experiments is observed.

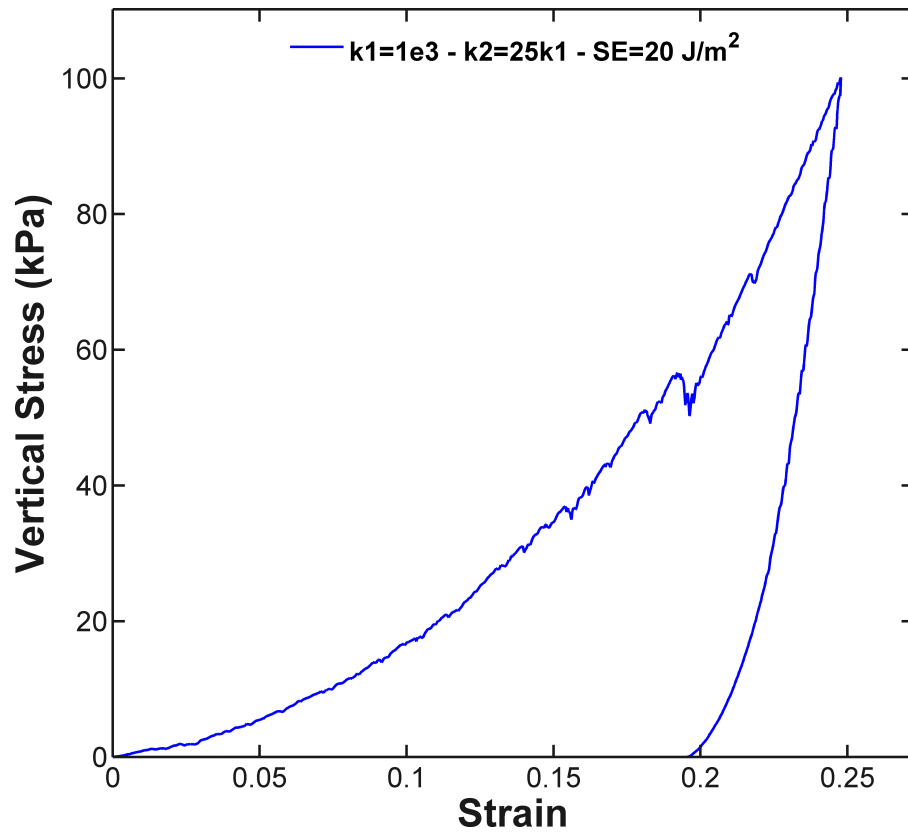


FIGURE 6: Stress-Strain Response - For confined compression

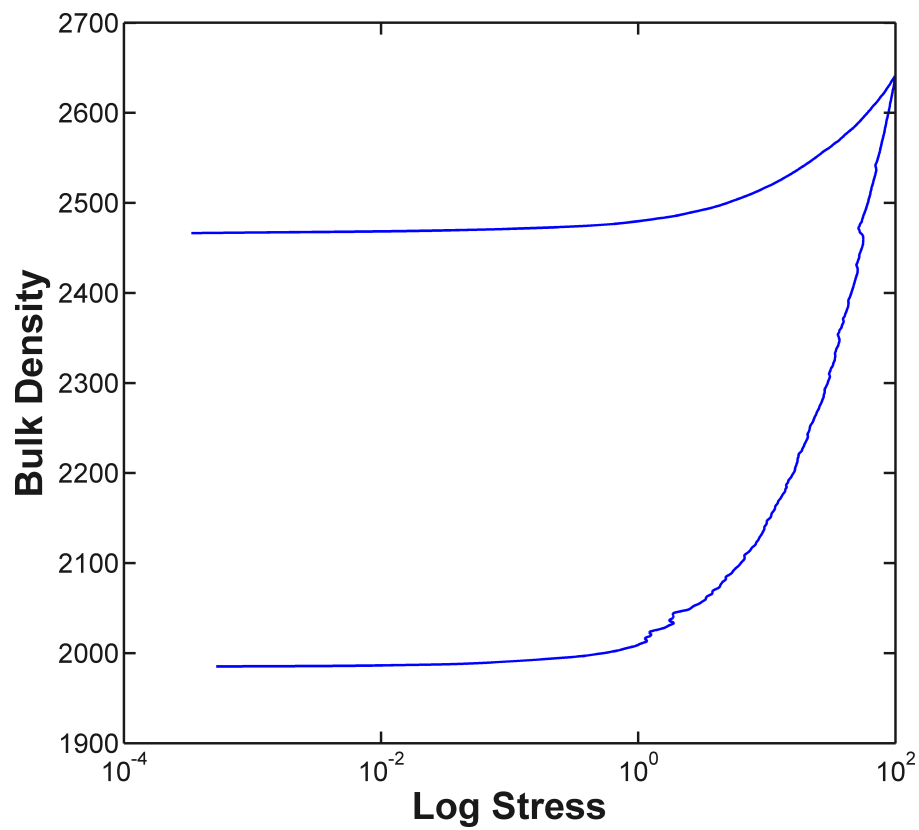


FIGURE 7: Bulk Density Variation - For confined compression

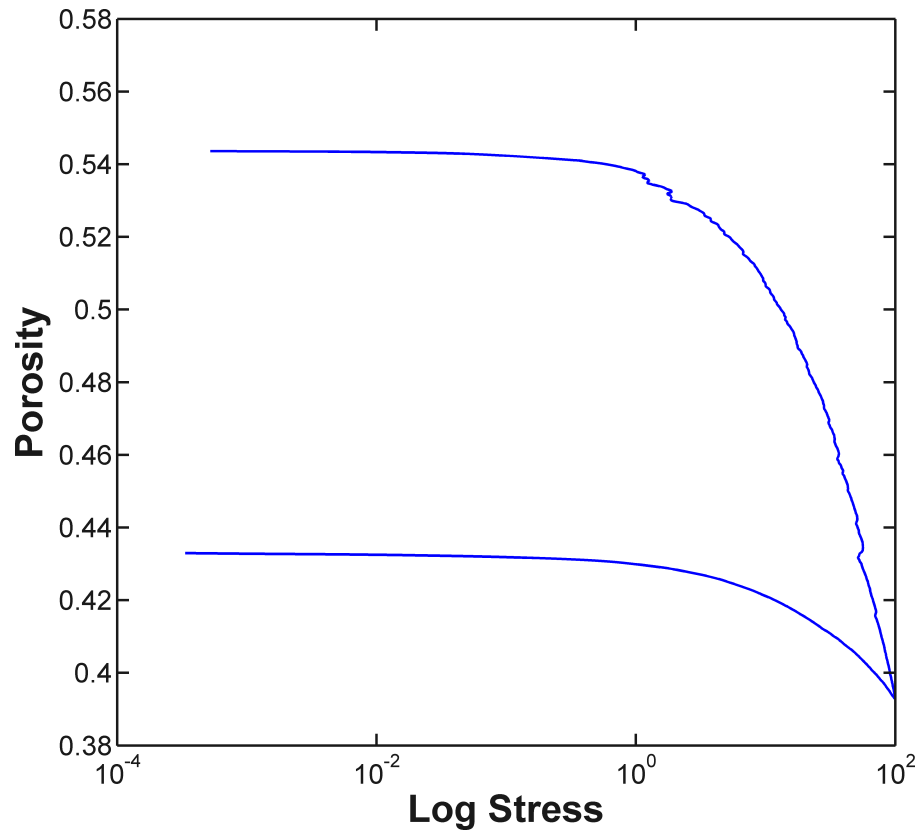


FIGURE 8: Porosity Variation - For confined compression

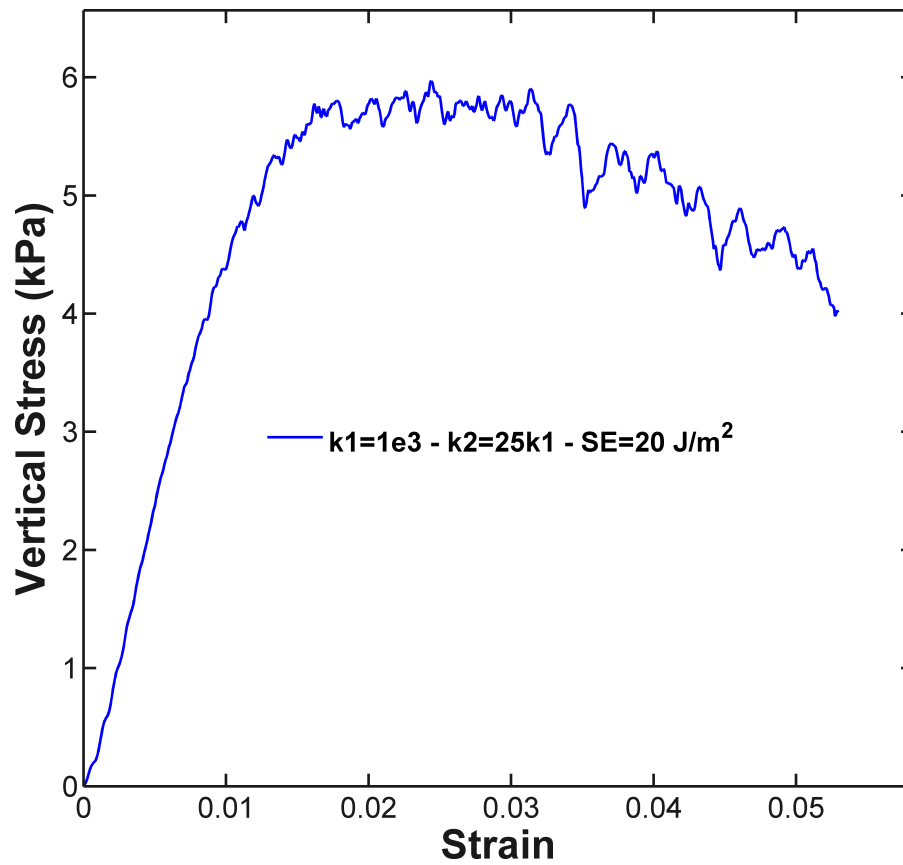


FIGURE 9: Stress-Strain Response - For unconfined compression

4 References

- [1] Bell, T.A., Catalano, E.J., Zhong, Z., Ooi, J.Y., and Rotter, J.M. (2007). Evaluation of the Edinburgh powder tester. In: *PARTEC 2007 - Congress on Particle Technology*, University of Edinburgh, Nürnberg, pp. 1–6. (page 1).
- [2] Cleary, P.W. (2000). DEM simulation of industrial particle flows: case studies of dragline excavators, mixing in tumblers and centrifugal mills. *Powder Technology*, **109**(1-3): pp. 83–104, doi:10.1016/S0032-5910(99)00229-6. (page 3).
- [3] Di Renzo, A. and Di Maio, F.P. (2005). An improved integral non-linear model for the contact of particles in distinct element simulations. *Chemical Engineering Science*, **60**(5): pp. 1303–1312, doi:10.1016/j.ces.2004.10.004. (page 4).
- [4] GDR Midi (2004). On dense granular flows. *The European physical journal. E, Soft matter*, **14**(4): pp. 341–65, doi:10.1140/epje/i2003-10153-0. (page 5).
- [5] Langston, P.A., Ai, J., and Yu, H.S. (2013). Simple shear in 3D DEM polyhedral particles and in a simplified 2D continuum model. *Granular Matter*: pp. 13–15, doi:10.1007/s10035-013-0421-0. (page 5).
- [6] Morrissey, J.P. (2013). *Discrete Element Modelling of Iron Ore Fines to Include the Effects of Moisture and Fines*. Ph.d. thesis, University of Edinburgh. (page 1).
- [7] O’ Sullivan, C. and Bray, J.D. (2004). Selecting a suitable time step for discrete element simulations that use the central difference time integration scheme. *Engineering Computations*, **21**(2/3/4): pp. 278–303, doi:10.1108/02644400410519794. (page 3).
- [8] Sun, J. and Sundaresan, S. (2011). A constitutive model with microstructure evolution for flow of rate-independent granular materials. *Journal of Fluid Mechanics*, **682**(2011): pp. 590–616, doi:10.1017/jfm.2011.251. (page 5).
- [9] Thakur, S., Morrissey, J., Sun, J., Chen, J., and Ooi, J. (2014). Micromechanical analysis of cohesive granular materials using the discrete element method with an adhesive elasto-plastic contact model. *Granular Matter*, **16**(3): pp. 383–400, doi:10.1007/s10035-014-0506-4. (page 1).
- [10] Thakur, S.C. (2014). *Mesoscopic discrete element modelling of cohesive powders for bulk handling applications*. Ph.d. thesis, University of Edinburgh.
- [11] Thakur, S.C., Ahmadian, H., Sun, J., and Ooi, J.Y. (2013). An experimental and numerical study of packing, compression, and caking behaviour of detergent powders. *Particuology*, (2013), doi: 10.1016/j.partic.2013.06.009. (page 1).