

# ENERGY DISSIPATION IN GRANULAR MATERIAL UNDER 1D COMPRESSION

\*R.A. Mukwiri<sup>1</sup>, Y. Ghaffari Motlagh<sup>1</sup>, W.M. Coombs<sup>1</sup> and C.E. Augarde<sup>1</sup>

<sup>1</sup>School of Engineering & Computing Sciences, Durham University, South Road, Durham, DH1 3LE, UK

\*r.a.mukwiri@durham.ac.uk

## ABSTRACT

In recent years it has been shown that the micro-mechanics of one-dimensional normal compression of sands can be modelled in three-dimensions within the discrete element method [7]. The compression is displacement driven such that the top platen of the enclosing sample case is allowed to move at a constant or variable velocity. The test has been used to investigate sand behaviour such as compressibility and the evolution of the particle size distribution when particle crushing is permitted. This paper focuses on the findings related to energy dissipation under one-dimensional compression without particle crushing using the LIGGGHTS open source software. Energy tracing is done throughout the simulations by applying the energy conservation principle at every time step. This allows the evolution of energy dissipation to be determined. The relationship between energy dissipation and particle size distribution was investigated and is discussed in this paper. Understanding the relationship between grain scale properties and energy dissipation will help in the formulation of a constitutive relationship based on a hyperplasticity framework [8]. This could potentially lead to a shift in the way that continuum constitutive models are formulated, with numerical models truly being based on the constituents that they represent.

**Key Words:** DEM; energy dissipation; compression; particle size distribution; hyperplasticity

## 1. Introduction

The Discrete Element Method (DEM) has been used for numerical simulations of particle assemblies since its introduction in 1979 by Cundall and Strack [6]. More recently DEM has been used to model the one-dimensional normal compression of sands [7]. This work has aided in the study of sand behaviour such as compressibility and the evolution of the particle size distribution when particle crushing is permitted. However, in this paper particle crushing is not investigated.

Energy dissipation in granular media has been a subject of study in recent years using the DEM. Wang and Huang [13], for example, presented a DEM analysis of energy dissipation in crushable soils in which it was observed that crushability strongly affect energy dissipation. Zhang *et al.* [14] investigated the relationship between energy dissipation and shear band formation under rolling resistance. The effect of grain roughness on energy dissipation was investigated during a quasi-static homogeneous triaxial compression test on cohesionless sand under constant lateral pressure [10]. Shamy and Denissen [11] studied energy dissipation response due to seismic loading.

By obtaining an energy dissipation function for a material, a yield surface and plastic flow rule can be derived to describe the inelastic behaviour of a material based on the framework of hyperplasticity [8]. However, current dissipation functions are driven by obtaining better curve fits to experimental data rather than deep understanding of the underlying physics. Investigating the relationship of energy dissipation at a grain scale level will facilitate the transition from the convention by allowing the constituents of granular materials (sands here in particular) to dictate the form of the dissipation function. One of these constituents is the particle size distribution which is investigated in this paper. It was quantified by varying the coefficient of uniformity parameter, which is defined as

$$CU = \frac{D_{60}}{D_{10}} \quad (1)$$

where  $D_{60}$  grain diameter at 60% passing and  $D_{10}$  grain diameter at 10% passing. The grain diameter here defines the sieve sizes through which the particles of soils and sands pass during soil grading. Soil grading is a classification of soil based on its different particle sizes. If the soil or sand is predominantly of one grain size, it will be classed as poorly graded and will have a coefficient of uniformity close to one. A well graded soil will have a wide range of particle sizes in it with a CU value  $> 4$  for gravels or  $CU \geq 6$  for sands.

## 2. Energy dissipation in DEM

To account for the dissipated energy, energy conservation is applied through either a simplified approach or a detailed consideration of the energy terms in the system. Houlsby *et al.* [9] for example, in the study of landslides take the dissipated energy to be the remainder of the total potential energy at the start of the simulation minus the sum of the potential energy and the kinetic energy at each stage of the simulation. Asmar *et al.* [5] explicitly worked out the dissipated energy from damping and friction. Other forms of energy: the elastic energy, potential energy, kinetic energy, and the input energy were also monitored. Wang and Yan [12] also included a bond energy between particles during particle breaking.

Wang and Yan [12] showed that at every stage of shearing (in the direct shear test of agglomerates), the conservation of energy equation is given by

$$dW + dW_g = dE_s + dE_b + dE_f + dE_k + dE_d \quad (2)$$

where the energy terms are: boundary work  $dW$ , potential energy  $dW_g$ , strain energy  $dE_s$ , bond energy  $dE_b$ , frictional dissipation  $dE_f$ , kinetic energy  $dE_k$  and damping dissipation  $dE_d$ . This is consistent with other literature (for example; [5]) when the effect of particle bonding is ignored. The energy loss due to damping is due to the need to dissipate excess kinetic energy.

## 3. Numerical simulations

There are a number of commercial and open source DEM software currently in use for the study of particulates (e.g EDEM, PFC, LIGGGHTS, etc. [1, 3, 2]). For the simulations in this paper, the open source LIGGGHTS software was used. Unlike many commercial codes, LIGGGHTS has no graphical user interface. The user drives the simulation using a text-based input script. This input script is read sequentially rendering the ordering of the statements important. The simulations for this paper consisted of four parts:

1. *Initialization*: parameters that need to be defined before the particles are created are set. The boundary was set to be non periodic and moving to allow for the one-dimensional compression. Other parameters such as the domain to run the simulation in and the style of particles specified.
2. *Setup*: material properties and geometry defined. The particle generation procedure was also detailed during the problem setup. The material properties are shown in Table 1 where  $\mu$  is the friction coefficient between particles,  $E$  the particle Young's modulus,  $\nu$  the Poisson's ratio, and  $\rho$  the particle density.
3. *Detailed settings*: settings that correspond to speed and memory utilisation were specified and the output options were also created.
4. *Execution*: actual run command that executes the simulation. The simulations were run in a number of stages. The first stage was to insert the particles into the simulation cylinder. These were then allowed to settle and then compressed at constant velocity by moving the top platen for a specified number of time steps at and then unloading by moving the platen upwards.

Table 1: 1D Compression test parameters

Sample size: $Dia \times H$ (mm)	$\mu$	$E$ (Mpa)	$\nu$	$\rho$ (Kg/m <sup>3</sup> )
18×10	0.5	70	0.25	2650

There are two basic types of statements in a LIGGGHTS input deck - individual commands and fixes. The commands establish the settings of the simulations (e.g. the time step) while the fixes are used to set particular aspects of the simulation (e.g. material properties and meshes). For the simulations conducted in this paper, separate meshes were generated using the gmesh software and input as STereoLithography (STL) files via a fix statement in the input script.

Once the simulations were complete, the output files were run through the LIGGGHTS Post-Processing (LPP) software in which the Visualisation Toolkit (VTK) files were generated. They were then visualised using ParaView [4] and processed for energy dissipation using Matlab.

### 3.1. Results and discussion

Figure 1 shows the boundary energy input during the loading and unloading of sand samples of different coefficients of uniformity. The area enclosed between these two curves is proportional to the dissipated energy during the loading and unloading cycle. The top platens compressed the sand samples to 0.3 mm strains before unloading back to the same position. It was found that as the coefficient of uniformity was increased, the area between the loading and unloading curves also increased. More tests are currently being done to determine if the coefficient of uniformity is an accurate measure of the particle size distributions.

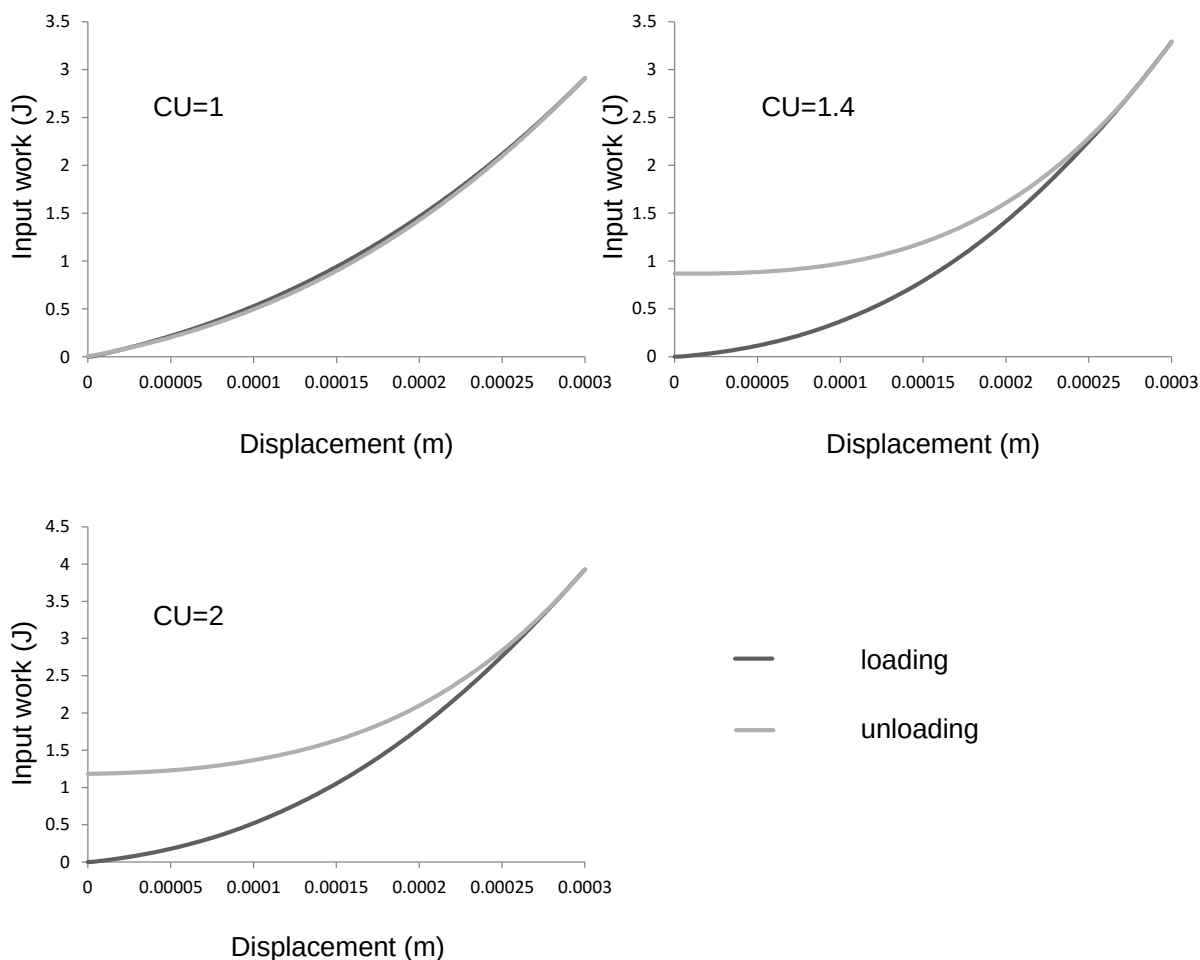


Figure 1: Energy input versus displacement for one dimensional compression tests with different CU values

#### 4. Conclusions

One-dimension compression of sand has been carried out to study how energy is dissipated with a variety of particle size distributions using the DEM. The results suggest that more energy is dissipated as the coefficient of uniformity is increased. Further investigation is being done to determine if the particle size distribution is uniquely defined by the coefficient of uniformity for the purpose of the energy dissipation study. A parametric study is currently being carried out for other grain scale parameters such as coefficient of friction, particle density, voids ratio and compressibility and the results will be used to formulate a one dimensional dissipation function for sands. Experimental validations will then be carried out to ensure that the formulations made are consistent with the observed physical phenomena.

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