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A DEM study

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PENETRATION RESISTANCE OF COHESIVE IRON ORE: A DEM STUDY

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Key Words: Discrete Element Method, cohesive iron ore, calibration, penetration resistance, consolidation

Abstract
The performance of bulk solids digging equipment, such as grabs and bucket-wheel excavators, are highly dependent on their penetration process. Additionally, majority of bulk solids show cohesive behavior and consequently their penetration resistance is dependent on level of consolidation. Therefore, this paper aims to develop a reliable simulation using Discrete Element Method (DEM) that is able to quantitatively replicate the relationship between the penetration resistance and the pre-consolidation stress. Both laboratory experiments and simulations were performed in order to analyze differences in penetration under various pre-consolidation stress levels. The developed DEM simulation will be used for further improvements in the penetration process of bulk solids digging equipment.

1. INTRODUCTION

Iron ore cargoes are transported around the world, with the largest dry bulk trading volume per year [1]. When an ocean going bulk carrier arrives at the terminal, the cargo of cohesive iron ore is partially consolidated [2]. To determine the relationship between the penetration resistance and level of consolidation, a laboratory test method was designed in [3]. Next step is to replicate this process in a virtual environment, which makes it possible to evaluate innovative design concepts for improving the bulk handling process.

The Discrete Element Method (DEM) has been successfully applied in simulating penetration tests of non-cohesive materials, some of the examples are [4], [5] and [6]. To the best of our knowledge, only [7] successfully simulated the dependency of the penetration resistance of cohesive solids to the consolidation stress history. An Elasto-plastic adhesive contact model, EEPA [8], was used in their research that was capable of qualitatively reproducing the typical trend of the penetration resistance profile of cone-shaped tools in cohesive solids. However, no comparison to laboratory measurements was made.

Therefore, this paper aims at developing a stable simulation using Discrete Element Method to quantitatively replicate the stress-history dependent behavior of cohesive iron ore fines in the consolidation-penetration test. To achieve this objective, first in Section 2, the DEM simulation setup including contact models and particle properties is discussed. Section 3 first describes the steps to set up a stable DEM simulation; next, the influence of the contact model on the simulation output is discussed. Finally, Section 4 provides conclusions of the study and recommendations for future research on this topic.

2. SIMULATION SETUP

The laboratory consolidation-penetration test method that was developed in [3], is used in this study for determining the penetration resistance of a cohesive iron ore sample. A simplified virtual apparatus similar to the experimental apparatus is created in the DEM commercial software package EDEM2018, which is displayed in Figure 1. The only difference between the real and virtual apparatus is that instead of the Plexiglass, a periodic boundary condition is used in the simulation. In the container, the particles are created using a dynamic factory and placed in random positions. They are allowed enough time to reach a quasi-static condition, where the average velocity of particles is smaller than 10^{-5} m/s.

The test consists of two stages, the consolidation and the penetration. Once the DEM particles are relaxed, the consolidation stage is commenced, in which the lid plate moves downward with a small velocity of 0.02 m/s. After occurring first contact between the lid plate and particles, a constant pressure between them are maintained to mimic the consolidation stage in the real experiment. The magnitude of the applied pressure is referred as the pre-consolidation stress in this article. After compressing the particles for 1 second, the lid plate is moved upward at the same velocity.

After preparing a consolidated sample, the wedge-shaped penetration tool moves downward with the constant velocity of 1 mm/s, similar to the penetration stage in the real experiment. The reaction force on the wedge-shaped tool during penetration into the cohesive iron ore sample is measured, a smoothing operation is used to reduce the possible effects of noise in the measurements: by integrating the resulting force, *F* [N], over the depth, *s* [m], the penetration resistance, *W* [J] is obtained.

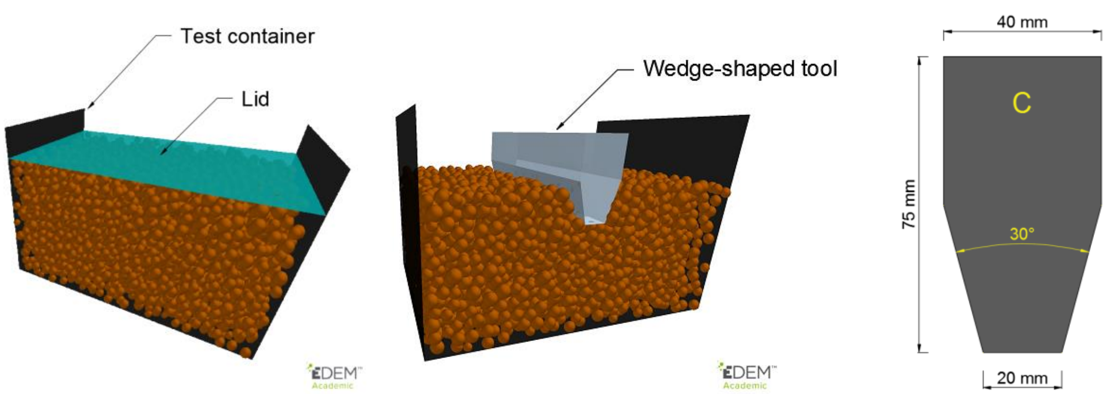

Figure 1. Virtual apparatus in EDEM2018. Left: the consolidation stage; middle: the penetration stage; right: wedge-shaped tool

This study compares two DEM contact models, first the Hertz-Mindlin (no-slip) combined with Linear Cohesion (HMLC) [9], second the Edinburgh Elasto-Plastic Adhesion (EEPA) [8]. The first contact model, Hertz-Mindlin, is a non-linear elastic model and has been used in most recent DEM studies [10]. To replicate the cohesive behavior of the iron ore sample, the Linear Cohesion model is added to the base contact model that modifies the normal contact force by adding the following force:

$$F_c = 2.k.\pi.R.\delta_n \qquad \textbf{Equation 1}$$

Where, k, R and δ_n are the cohesion energy density [J/m^3], particle radius [m], and normal overlap between particles [m] respectively. We use a constant cohesion energy density of 50 kJ/m^3 in our simulations. The contact parameters of the EEPA model are selected similar to [11]; only a smaller Surface Energy value (8 J/m^2) is used to create bulk density and void ratio similar to the real experiment.

The wall friction test was done using a ring shear cell, according to [12]. Since no adhesion strength was observed between the iron ore particles and the steel material, only the Hertz-Mindlin (no-slip) contact model is used for modelling the interaction of particles with the geometries.

The particles of iron ore fines are irregular in shapes having a wide size distribution [13]. In this study, however, particle shapes are simplified to spheres. To compensate the simplification of the particle shapes, the influence of restricting rolling of the particles on simulation output is therefore investigated. By restricting rolling of the particles, their angular motion is prevented. So, a better interlocking between particles is created. Additionally, a small size distribution with the standard deviation of 0.1 is used to prevent any possible perfect packing. A mean particle size of 11 mm in diameter is used, which is around 10 times larger than the real particles; using a realistic particle representation of cohesive iron ore in the virtual simulation would have resulted in an unfeasible computational time per simulation.

The particle shear modulus (*G*) is also selected to be 5 MPa in our simulations, which is close to the value used by [14] for modelling cohesive iron ore. However, [15] showed using a value smaller than 100 MPa might result in undesirable effects in the penetration of a wedge into bulk material. They advised that the approach should be verified when the particle shear modulus is altered.

Therefore, as displayed in Table 1, an experimental plan is applied to develop a stable DEM simulation of the consolidation-penetration test. Three different independent variables are included, contact model, integration time-step, and the ability of particle to roll. The simulation output is analyzed though three dependent variables, $\Delta\rho_{b,0}$, W_{50} and W_{80}. Here, $\Delta\rho_{b,0}$ is defined as the change in bulk density in the loose condition (0 kPa), and is calculated by comparing the bulk density after filling the container, and the bulk density before the first contact between the wedge tool and the particles. W_{50} and W_{80} are defined as the dimensionless penetration resistance at the penetration depths of 50 mm and 80 mm, respectively, which are calculated using equation 2. Once a stable DEM simulation of the compression-penetration test is developed, the influence of the contact models on capturing the dependency to the pre-consolidation stress is investigated.

$$W_z\,[-] = \frac{1000 \times \text{Penetration resistance [J] at depth of } z}{\text{Weight of iron ore sample [N]} \times \text{Length of the wedge tool [m]}} \qquad \textbf{Equation 2}$$

Table 1. Experimental plan to develop a stable DEM simulation

Independent variables	Range of investigation
Contact model	[HMLC EEPA]
Time-step	Percentage of Rayleigh time step [%]: [1.5 3 6.25 12.5 25 50] Corresponding absolute value [10^{-5} s]: [0.62 1.25 2.80 5.60 10.4 20.6]
Rolling of particles	[Allowed Restricted]

3. RESULTS AND DISCUSSION

In this section, first we describe the results of the experimental plan for developing a stable DEM simulation. Figure 2 displays the influence of the investigated independent variables on the dimensionless penetration resistance, W_{50} and W_{80}. In the case of allowing particles to roll, both contact models show a high sensitivity to the integration time-step. On the other hand, when the rolling of the particles is restricted, the results are more stable, except for the 50% of Rayleigh time-step. When the time-step is too large, important data during contact detection and calculation is missed. Figure 3 also confirms the findings about effect of rolling; when the rolling of the particles is activated, the bulk density changes during the simulation for both contact models. Therefore, we capped rolling of the particles for both contact models in the prospective simulations.

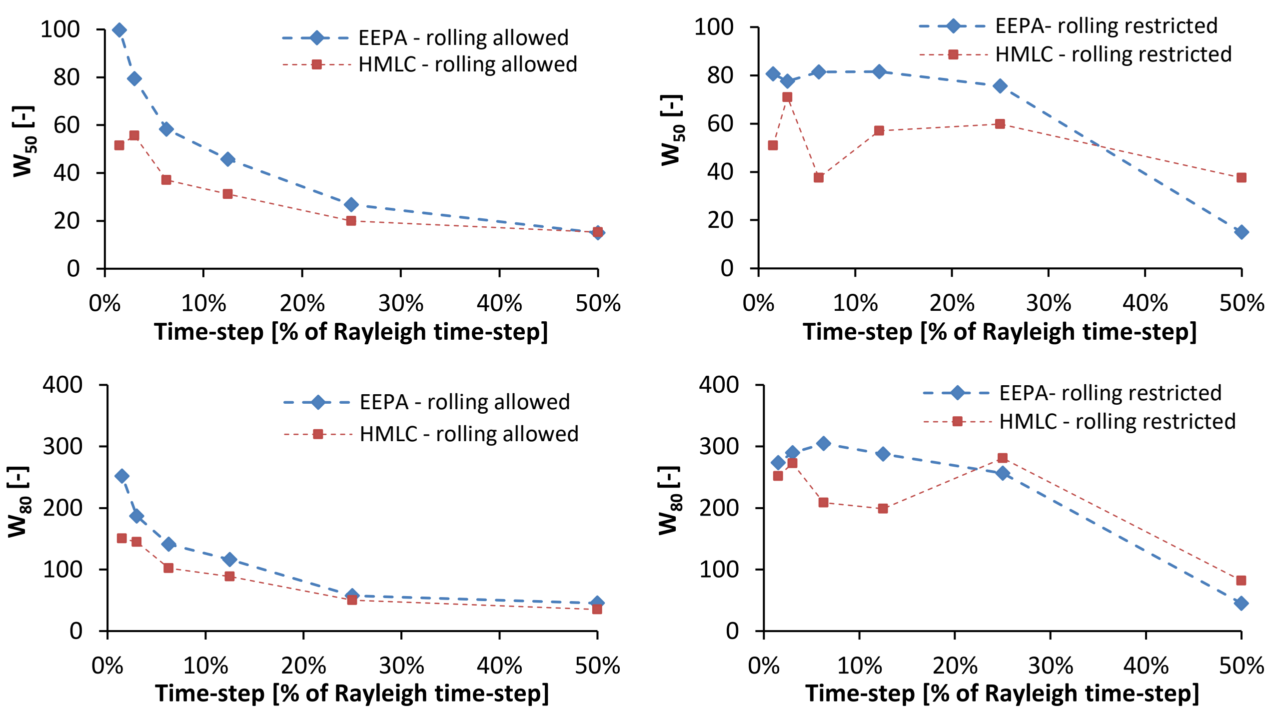

Figure 2. Influence of time-step on the dimensionless penetration resistance. Left: rolling is allowed; right: rolling is restricted

Next, we investigate how the difference in the contact model influences the dependency of the simulation output to the applied pre-consolidation stress. In Figure 4, the results are also compared with some initial experimental results obtained from our laboratory tests. In this experiment, three different levels of pre-consolidation stress were applied to the sample, 0, 8 and 65 kPa. As illustrated in Figure 4, a higher pre-consolidation stress results in a higher penetration resistance in both laboratory tests and the DEM simulations. The elastic contact model, HMLC (red squares), shows a lower dependency to the pre-consolidation stress, especially in the larger depth. This is probably caused by incapability of this contact model of capturing a realistic compressibility of the cohesive iron ore between the penetration tool and bottom of the container. On the other hand, the Elasto-plastic contact model, EEPA (blue diamonds), is capable to better replicate the dependency of the penetration resistance to the consolidation level. Although, the EEPA model underestimates W_{80} at the pre-consolidation of 8 kPa; calibrating the contact stiffness will probably improve the results.

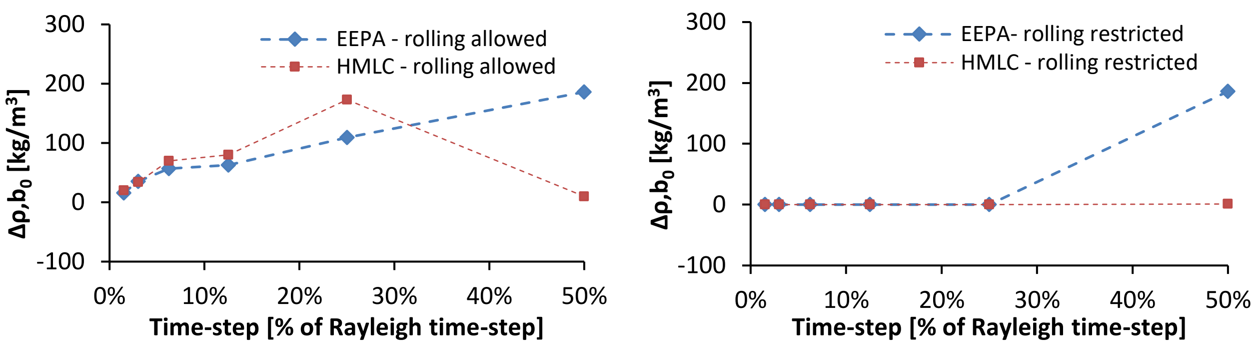

Figure 3. Influence of time-step on the bulk density change in the loose condition. Left: rolling is allowed; right: rolling is restricted

Figure 5 displays the change in the bulk density before and after the consolidation stage. Similar to the penetration resistance, the EEPA model is more successful in replicating the laboratory results, with the exception in 8 kPa pre-consolidation stress.

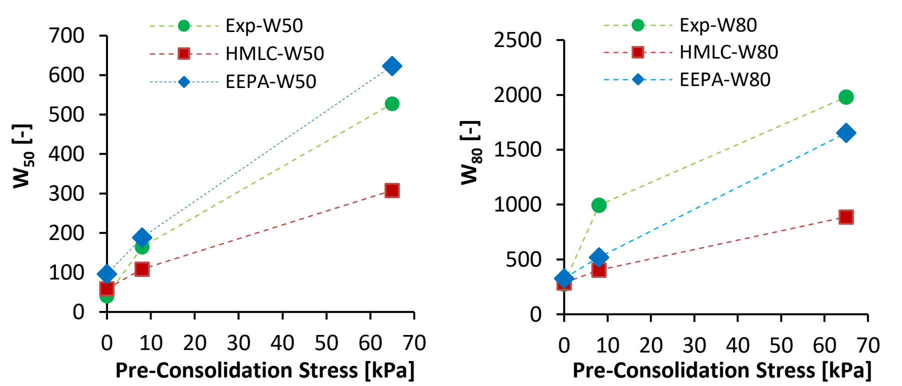

Figure 4. Effect of pre-consolidation stress on the penetration resistance. Left: Dimensionless penetration resistance at depth of 50 mm; right: Dimensionless penetration resistance at depth of 80 mm

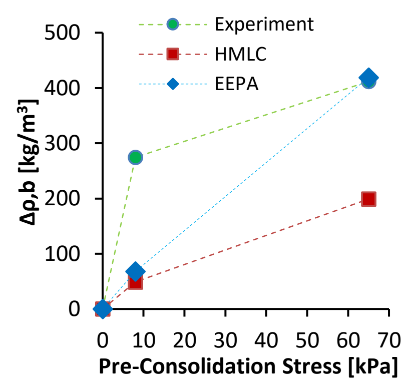

Figure 5. Effect of pre-consolidation stress on bulk density

4. CONCLUSIONS & RECOMMENDATIONS

First, this research shows that applying a systematic experimental plan helps to develop a reliable DEM simulation, which is crucial before starting its calibration. Restricting rolling of particles enhanced stability of the simulation. Second, choosing an appropriate contact model is an important decision for modelling cohesive materials. The EEPA model shows a lower sensitivity to time-step and seems capable to better replicate the experimental results.

Future research will focus on using the EEPA model in calibrating the DEM parameters of cohesive iron ore. Also, a ring shear tester will be used in the DEM calibration process to ensure the flow properties of the cohesive iron ore are accurately replicated as well.

5. ACKNOWLEDGEMENTS

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