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Discrete Element Modelling (DEM) For Earthmoving Equipment Design and Analysis: Opportunities and Challenges

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ABSTRACT
Simulation of granular materials (soil, rocks) interaction with earthmoving machines provides opportunities to accelerate new equipment design and improve efficiency of earthmoving machine performances. Discrete Element Modelling (DEM) has a strong potential to model soil and rocks bulk behavior in response to forces applied through interaction with machinery. Numerical representation of granular materials and methodology to validate and verify constitutive micro-mechanical models in DEM will be presented. In addition, how DEM codes can be integrated to CAE tools such as multibody dynamics will also be discussed. A case study of tillage bar-soil interaction was modeled in EDEM to predict tillage draft force and soil failure zone in front of tool moving at 2.68-m/sec and depth of 102-mm. The draft force and soil failure zone was predicted at 10% and 20% error from laboratory measured data.

Key words: soil (geomaterials)—discrete element modelling—off-road machinery—calibration

BACKGROUND: SIMULATION BASED DESIGN USING DISCRETE ELEMENT MODELLING
Earthmoving machinery product development and verification tests involve interaction of machine equipment with granular materials (soil, biomass and rock). The geomaterial properties and their conditions impact the equipment performance in terms of productivity, efficiency and durability. The traditional and iterative product development cycle of “Design--Physically build prototype—Field test” is laborious, costly and time demanding. Virtual engineering tools have potential to accelerate product design engineering and reduce field testing. Automation of earthmoving system modelling architect (Cannon and Singh, 2002) will need a geomaterial-tool interaction model component to simulate earthmoving equipment trajectory motion. Simulation of soil-tool interaction is essential for virtual earth-moving product development and automation of earth moving operations.

Simulation based tools consist of generating CAD geometry surface mesh, pre-processing, material model, solver, post-processing and data analytics for engineering decision support. Modelling geomaterial - tool interaction will require versatile material models, quick and easy testing methods to generate data for model parameters calibration and numerical tool to solve geomaterial-tool interaction responses. Generally there are two broad categories of geomaterial-tool interaction problems 1) load loosening processes for instance in tillage tools, soil flow from bulldozer blades, soil fill in loader buckets; and 2) load bearing process in soil to vehicle tractive devices interactions where soil supports vehicle loads and helps generate

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traction. The desired engineering objectives are generally to reduce energy expenditure during
cutting and tillage processes, maximize soil fill on buckets, easy soil flow from crawler blades,
maximize traction and optimal soil density for growing crops.

Discrete Element Modelling (DEM) has the potential to simulate soil-tool interaction and could
also be integrated in co-simulation with other systems modelling tools such as Finite Element
Analysis (FEA), Multi-Body Dynamics (MBD) and Computational Fluid Dynamics (CFD). DEM
formulation comprises numerical representation of the particle shape and size, assembly of
particles, constitutive micro-mechanics contact laws that defines force vs. displacement
relationships; and every time step contact detection and explicit numerical integration governed
by Newton’s law of motion (Cundall and Strack, 1997). Details in contact laws and their
formulation are available in literature (Walton and Braun, 1986; Luding, 2008; Cleary, 2010;
EDEM, 2011). The DEM contact laws originated based on Hertizian contact theory and now
there are advanced contact models that defines the relationship between forces and
displacement using material normal and tangential stiffness, coulomb friction coefficient,
damping coefficient, rolling resistance coefficient, cohesion/adhesion and bond parameters.

Researchers have shown the predictive capability of DEM to model behaviour of granular
materials since late 70’s after Cundall and Strack (1979). Some of the works related to
earthmoving include DEM modelling of wide cutting blade to soil interaction on scaled
experimental box to predict forces on crawler blades and soil flow in front of the cutting blade
(Shmulevich et al., 2007); simulation of hydraulic excavator digging process using confining
stress dependent DEM cohesive soil model (Obermayr et al., 2014); and DEM modelling of soft
ground cutterhead (4.2-m in diameter) predicting torque performance for different Tunnel Boring
Machine (TBM) cutterhead designs (Mongillo and Alsaleh, 2011).

OPPORTUNITIES AND CHALLENGES FOR USE OF DEM IN EARTHMOVING INDUSTRY

In theory DEM, a particle based modelling technique, is able to simulate particles interaction
with earth moving equipment and makes it ideal fit to integrate the tool into the engineering work
flow for product design and performance. DEM has shown to be a proven research and
development tool in manufacturing and process industry (Favier, 2011) especially where
particles are non-cohesive, resemble to spherical shape and the size of engineering problem
are manageable using desktop multi-core computers. With the continuous increase in
computing power and efficiency in parallel computing, DEM has started to become a useful tool
for large scale applications in mining and construction industries (Cleary, 2010; Mongillo and
Alsaleh, 2011).

This paper illustrates potential opportunities and challenges with DEM for earthmoving machine
virtual prototyping construction equipment and automation process. The discussion in this paper
may apply to the interactions of crawler blade (over 3-m X 3-m blade width X blade height for
instance John Deere 1050K and CAT D9), bucket (with loader capacity over 6 M³ (Yd³) for
instance John Deere 844 and CAT 980) and ripper tine with geomaterials ranging from clay-
sized (less than 0.002-mm) to gravel (75-mm).

The challenges with utilizing DEM arise from the difficulty with particle based approximation of
geomaterial and its dynamic behaviour. Geomaterials have spatial-temporal variations in
conditions (wet to dry), wide range of particle sizes (clay to gravel size) and their response to
loading have stochastic bulk response behaviour. Approximation of these realistic geomaterial
type, size and conditions using DEM spheres and solving bulk geomaterial to large size
machine interaction using micro-mechanics contact laws are either computationally prohibitive or impossible to fit within reasonable engineering work flow. DEM based engineering analysis in earth moving industry thus demands a methodology that is adaptive towards the desired systems engineering, existing DEM code requirement and simulation process that will provide industry value added results.

DEM USE FOR ENGINEERING DESIGN ANALYSIS

DEM simulation work flow for simple geometry motion, granular shape close to spheres and small number of particles is fairly straight forward. For large scale industrial applications that require DEM integrated into earth moving product development cycle and transient coupling with other methods such as FEA, MBD and CFD for systems modelling, DEM simulation work flow can be looked as a component of system engineering. The system layers proposed in Figure-1 may apply to earth moving simulation based design and automation. This may capture the requirements from the application, simulation and granular mechanics know-how to systematically define DEM shape and size approximation, calibrate DEM particle model and simulation of application with reduced uncertainty and controlled variance for design and system optimization.

<table>
<thead>
<tr>
<th>(1) Defining systems requirement and setup for material model calibration</th>
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<tr>
<td>• Design and systems application requirements</td>
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<td>• Material boundary condition</td>
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<tr>
<td>• Experimental test development</td>
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<td>• Upscale benchmark test development</td>
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<tr>
<th>(2) Material model calibration and simplification for application simulation</th>
</tr>
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<tr>
<td>• Material model properties fit for the defined requirement</td>
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<td>• DEM advance physics and co-simulation</td>
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<td>• Computing efficiency (upscaling, simplification of geometry boundary)</td>
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</table>

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<th>(3) Application product simulation</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Accelerate virtual product development</td>
</tr>
<tr>
<td>• Accelerate computing within defined accuracy</td>
</tr>
<tr>
<td>• Data analytics and optimization</td>
</tr>
</tbody>
</table>

![Figure 1. DEM for simulation in systems engineering](image)

DEM Material Properties Development

The major steps in DEM particle model development consists 1) define the shape and particle size representation; 2) identify micro-mechanics contact model that captures the expected geomaterial behaviour (elastic, plastic, cohesive and non-cohesive); and 3) determine the material model properties.

Shape and Particle Size Approximation

Shape and particle size approximation have strong influence on the dynamics of granular system and computational effort. The shape of DEM assembly of particles affect packing of particles (void ratio), shear strength, angle of repose and discharge from hoppers and relative particle velocity on conveying (Cleary, 2010; Lu et al., 2015).

In DEM codes particle shape is approximated using spheres, glued (clumped) spheres and non-spherical particles (for instance polyhedron, ellipsoids). Spherical DEM particle representation
has benefit in terms of relatively easier contact detection algorithm, simpler overlap based force-displacement calculation and reduced computational effort. According to Cleary (2010), the computational cost with superquadrics was 2 to 3 times compared with spheres. Commercial DEM codes such as EDEM from DEM solutions UK and Particle Flow Code (PFC) from Itasca Consulting Group, Inc have overlap spherical capability and rolling resistance DEM models to numerically reproduce mechanical interlocking effect on dynamics of granular systems. Lee et al. (2012) used non-spherical primitive shape from polyhedral DEM code. Hohner et al. (2015) studied various non-spherical particle shape approximation types (polyhedra, multi-sphere cluster, superellipsoids) on hopper discharge and found out that shear strength of the particle bed and discharge from hopper were affected by sphericity and aspect ratio but less on fine scale resolutions of shape surface approximation. The choice of spherical or non-spherical shape approximation depends on user know how on engineering problem, dimensional measured properties of the geomaterial, bulk material behaviours, affordable computational effort and availability of shape library in the DEM code. For most of natural geomaterials (cohesive and non-cohesive soils) expect gravel, measurement of geometric shape parameters such as sphericity, angularity, aspect ratio and surface roughness are difficult to obtain and easily reproduce in DEM primitive shapes. For non-spherical and angular materials that exhibit mechanical interlocking and affect their initial packing density, it is important to make significant effort to use non-spherical DEM shape approximation using clumped sphere, non-spherical primitive shapes or rolling resistance contact models.

Similar to shape representations, particle size approximation to real geomaterial size distribution also influences DEM bulk material response behaviour and computation effort. The smallest DEM particle size derives the explicit time step value for DEM calculation. Geomaterial DEM modelling, it is computationally prohibitive to match equivalent clay, silt and sand size fractions.

DEM particle size scaling is thus necessary and can be done using linear scaling factor of DEM mean particle size, particle size distribution or ratio number of particle to geometry (wall) dimension. Lee et al. (2012) applied DEM particle size scaling by a factor of 10 times larger than the experimentally measured sub-angular uniformly graded fine sand distribution and normalized by $D_{50}$. DEM simulation of triaxial compression with polyhedral particle shape, Lee et al. (2012) successfully reproduced initial packing density and stress-strain of undrained triaxial compression sand soil test.

Limited studies are available that investigate various DEM shape approximations and particle scaling methodology and how they relate to achieve the desired quality of dynamics of bulk material response behaviour and computational effort. Similarly studies are needed on upscaling methodology from small size simulation used for calibration of DEM model parameters, shape and size to simulation of large size earth moving applications.
**Experimental test and calibration methodology**

Simulation of bulk (macro) geomaterial behaviour interaction with equipment using DEM assembly of spherical or non-spherical particles and micro-mechanics laws can only be achieved through calibration of the DEM parameters with measured response variables. Methodology to generate DEM material properties fit for the approximation of bulk material response to equipment interaction within relatively short time is often more relevant than to measure individual granular particle to particle or particle to geometry model parameters. As shown in Figure -1, the steps for system requirement and material properties development will help to identify experimental tests and measured response variables for model calibration.

Soil mechanical properties (stress-strain, angle of internal friction, cohesion) obtained from geotechnical ASTM standard tests (tri-axial, shear and others) can be good candidates. Other experimental tests that reflect in-situ geomaterial behaviour and allow to measure multiple dependent variables such as angle of repose, deformation, torque and forces will provide enhanced accuracy for wider granular dynamics behaviour.

DEM calibration process involves first reproducing initial packing density (void ratio) of particle assembly with estimated initial model parameters. DEM virtual experiments are then conducted taking the model parameters as independent variables and response properties similar to the experimental test as dependent variables. Besides to the material model parameters (stiffness and coefficients), shape and size parameters can be added as independent variables during calibration process. Reducing the number of model parameters for calibration is always helpful. For instance in quasi-static engineering systems, determination of coefficient of restitution may be less important than shear stiffness and friction coefficients. In dynamic system application for instance in grind milling and transfer chutes where system performance is dependent on collision energy losses characterization, coefficient of restitution is important. Sensitivity and optimization scheme will then be deployed to generate calibrated DEM particle model and properties to be used for application simulation.

**Simulation of Application**

**Upscaling and computational accuracy**

The main engineering value from DEM modelling is obtained from simulation of industrial application using the calibrated DEM particle model. Depending on the simulation domain of industrial application, the particle size or distribution used in the calibration process may need scaling before using it for application simulation. Upscaling DEM particle model into large size simulation will need know-how on particle: geometry system similarity and scale-invariance of contact models (Feng et al., 2009). Interpretation of DEM results from virtual equipment design changes may not necessarily eliminate the uncertainty/stochastic natural geomaterial behaviour and their associated equipment performance. Having DEM results with acceptable variance and showed value-added trends of improved performance from virtual equipment changes can be considered successful outcome.

Some engineering design and analysis may require coupling with CFD, FEM and MBD. For earth-moving application, coupling of DEM with MBD and FEM will be more applicable to transfer transient loads from geomaterials into rigid or flexible multibody mechanical or hydraulic driven systems for equipment (excavator buckets, blade) kinematics motion control and structural stress analysis. DEM coupling with other tools will involve surface element position mapping, interpolation and synchronization of sampling time (Favier, 2011) that will affect the stability and accuracy. For automation of earth-moving operation with soil-tool interaction in the
loop with actuator-control algorithms for equipment trajectory as proposed in Cannon and Singh (2000) can be implemented using DEM coupling technique.

**Predicting Tillage Force**

Simple tillage-soil interaction was modelled in EDEM Academic (EDEM, 2011) to predict forces and soil failure. EDEM model was developed with Hertz-Mindlin (with no slip) contact model to replicate the tillage tool bar from linear soil bin test in Becker (2008). The test parameters from Becker (2008) are shown in Table-1.

**Table 1. Tool dimension and test parameters (Becker, 2008)**

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Dimension Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Geometer</td>
<td>42</td>
</tr>
<tr>
<td>Width (mm)</td>
<td>50.8</td>
</tr>
<tr>
<td>Length (mm)</td>
<td>203.2</td>
</tr>
<tr>
<td>Thickness (mm)</td>
<td>12.7</td>
</tr>
<tr>
<td>Tool depth (mm)</td>
<td>102</td>
</tr>
<tr>
<td>Tool velocity (mm/sec)</td>
<td>268</td>
</tr>
<tr>
<td>Density (kg/m³)</td>
<td>1760</td>
</tr>
<tr>
<td>Moisture content (% d.b.)</td>
<td>9.15</td>
</tr>
</tbody>
</table>

**Initial Feasibility Simulation using 5-mm and 10-mm particle size**

Assembly of single sphere particle and two sizes (5-mm and 10-mm particle diameter) in simulation soil box (length = 790-mm, width = 265-mm; and depth = 408-mm) in EDEM 2.7. The total number in the soil box were 274494 and 36432 with 5-mm and 10-mm, respectively. Baseline properties shown in Table-2 were used for DEM parameters of particle size sensitive. Steel geometry was used for the tool and the soil box. The values for coefficient of static friction was estimated from angle of internal friction coefficient of soil composition and bulk density reported in Becker (2008). The soil-tool interaction parameter was assumed as 10% lower than the soil:soil interaction. The other interaction parameters were best guess and quick sensitivity EDEM runs (not reported). Particle were generated using EDEM factory creator filling the soil box and compressed at 0.02m/sec to obtain stable and maximum bulk density. The bulk density after relaxed DEM soil particle assembly for 5-mm and 10-mm was 1700 kg/m³ (3% lower than the measured bulk density). Simulation was run for 0.19-sec with time step of 1.0e-06 sec using 12- CPU cores. Output variables tool forces (horizontal and vertical) and velocity to predict soil failure zone in front of tillage tool were sampled at 0.01-sec interval.

**Table 2. Base line DEM properties for Hertz-Mendlin (No Slip) (EDEM, 2011)**

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Poisson's ratio</td>
<td>0.3</td>
</tr>
<tr>
<td>Shear modulus (Pa)</td>
<td>1e+06</td>
</tr>
<tr>
<td>Density (kg/m³)</td>
<td>2650</td>
</tr>
<tr>
<td>Soil:Soil Interaction</td>
<td></td>
</tr>
<tr>
<td>Coefficient of restitution</td>
<td>0.01</td>
</tr>
<tr>
<td>Coefficient of static friction</td>
<td>0.36</td>
</tr>
<tr>
<td>Coefficient of rolling friction</td>
<td>0.4</td>
</tr>
<tr>
<td>Soil:Steel Interaction</td>
<td></td>
</tr>
<tr>
<td>Coefficient of restitution</td>
<td>0.01</td>
</tr>
<tr>
<td>Coefficient of static friction</td>
<td>0.33</td>
</tr>
<tr>
<td>Coefficient of rolling friction</td>
<td>0.2</td>
</tr>
</tbody>
</table>
The predicted horizontal (draft) force from 10-mm DEM particle was higher and closer to the lab measured (Becker, 2008) draft forces (Mean = 416 N and Standard deviation = 36.9 N) than the 5-mm DEM particle. DEM elapsed computational time with 5-mm was 1.5 times greater than 10-mm particle size. Thus to understand the sensitivity of Hertz-Mendlin contact model parameters to predict force and soil failure flow, 10-mm particle size DEM model was used.

Figure 2. DEM predicted Horizontal (draft) force for the rigid flat bar for 5-mm and 10-mm. The lab measured draft force was 416 N (Standard deviation = 36.9 N).

Sensitivity of Forces and Soil Failure to DEM model parameters
For the sensitivity study of soil:soil and soil:steel interaction parameters, four EDEM runs represented as base line; HH = High:High; MM= Medium:Medium; and ML = Medium:Low (Table-3) were simulated. The material parameters of density, poisson’s ratio and shear modulus; and coefficient of restitution for the soil:soil and soil:steel were kept constant. Assumption was made the change in coefficient of restitution may not influence the soil flow in front of tool traveling at 2.68 m/sec.

Table 3. DEM parameters used for sensitivity study (Base line was considered as lowest value; HH = High High; MM= Medium Medium; and ML = Medium Low showed ranking for soil:soil and soil:steel interaction ranges).

<table>
<thead>
<tr>
<th>DEM Parameters</th>
<th>Sensitivity Classes for EDEM runs</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Base</td>
</tr>
<tr>
<td>Soil:soil Coefficient of static friction</td>
<td>0.36</td>
</tr>
<tr>
<td>Soil:soil Coefficient of rolling friction</td>
<td>0.40</td>
</tr>
<tr>
<td>Soil:steel Coefficient of static friction</td>
<td>0.33</td>
</tr>
<tr>
<td>Soil:steel Coefficient of rolling friction</td>
<td>0.20</td>
</tr>
</tbody>
</table>

The results for predicting horizontal force (draft) and soil failure from tool bar interaction with soil are shown in Figure 3. Medium Low (ML) values DEM interaction parameters showed good prediction (10% error) in horizontal force compared to the lab measured value. The soil failure zone in front of the tool were better predicted with the base line properties at 20% error. The DEM parameters providing better estimate for force prediction and soil flow are in different ranges especially on the soil:soil particle interaction parameters. Further study is needed to optimize DEM parameters for two conflicting objective functions. The shear modulus may affect the force prediction and should be considered in next optimization steps.
With the sensitivity study of DEM tool-soil interactions, bulk tool-soil interaction response variables from simple tests can be used to obtain better estimate range of combination of DEM parameters. The simple test used in this experiment captures soil response behaviour similar to cultivator sweep (shovel) interaction for tillage operations.

This exercises demonstrates implementation of the value of adaptive system approach and know-how of the engineering problem for calibration DEM parameters instead of depending on individual DEM parameters measurement.

![DEM predicted Horizontal (draft) force](image1)

![DEM predicted soil failure zone](image2)

Figure 3. DEM predicted Horizontal (draft) force and soil failure zone from sensitivity model parameters of 10-mm particle. The lab measured draft force was 416 N (Standard deviation = 36.9 N) and soil failure zone was 133-mm.

CONCLUSION AND FUTURE STUDIES

- DEM based simulation of earth-moving equipment interaction with goematerials has strong potential for off-road machinery industry to support virtual prototyping in design and process improvements.

- Effective utilization of DEM for earth-moving requires adaptive system approach to improve the inherent limitations of DEM in terms of trade-off in shape approximation and particle size definitions versus real geomaterials; calibration methodology from micro-
mechanics to macro-experimental mechanical behaviour; and scaling principles in mechanical, geometry and particle size from simple tests to application simulation sizes.

- Simulation of tillage bar-soil interaction was run in EDEM and showed the sensitivity of Hertz-Mendlin contact model parameters for predicting horizontal tillage tool force and soil failure zones. This demonstrates the value of adaptive system approach in utilizing DEM model for tool-soil interaction problems.

- Future research studies are needed on “realistic” geomaterial shape approximate vs. accuracy of dynamic granular behaviour, development of material tests fit for DEM calibration purposes, robust calibration and optimization methodology for shape, particle size and material models; and methods to evaluate application simulation output uncertainty and variance for earth-moving virtual product development.

REFERENCES


