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Discrete Element Modeling (DEM) of Cone Penetration Testing on Soil With Varying Relative Soil Density

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ABSTRACT. Modeling soil-tool interaction is essential for equipment design and performance evaluation on soil behavior responses under loading. Computational tools based on particle-based mechanics such as Discrete Element Modeling (DEM) and Smoothed Particle Hydrodynamics (SPH) have potential in modeling large strain soil dynamic behaviors from soil-tool interaction. The objective of this study is to validate the accuracy and robustness of DEM calibration methodology as it relates to soil deformation during cone penetration on varying initial soil relative density. The influence of factors such as DEM material properties and cone to particle size ratio on DEM cone penetration simulation will be investigated. The paper presents a comparison of DEM predicted cone penetration resistance and laboratory measured penetration data on Norfolk sandy loam. Soil mechanical behavior was modeled with Hertz-Mindlin (HM) contact stiffness model and a new coupled frictional law for static and rolling resistance coefficients. The DEM material properties were calibrated using residual strength from direct shear test. DEM simulations were performed using LIGGGHTS, open source DEM code. Cone penetrometer experiments using an ASABE standard cone with 12.53 mm cone base diameter and 30-degree cone tip were used to validate the calibrated DEM model. DEM prediction of cone penetration resistance trend and steady state values were in close agreement with the laboratory measured data for relative density range from 5 to 30%. At higher dense states (relative density of 90%), DEM calibration requires further improvement.

Keywords. Soil Modeling, Relative Density, Discrete Element Model, Soil Cone Penetration.
### Introduction

Cone penetrometer testing is a simple and easy method for characterizing in-situ soil strength. Modeling soil reaction from conical tip penetration for Discrete Element Modeling (DEM) material calibration can be helpful to predict dynamic soil behaviors including shear, compression and cutting (Gill and VandenBerg, 1968) for simulation of tool-soil interaction problems. Asaf et al. (2007) simulated wedge sinkage on soil and performed energy analysis that showed that friction energy is the dominant source of resistance to deformation. Calibration was performed using two different wedge angles because non-unique solutions were found when minimizing error with a single wedge. Their studies showed that 20 and 30 iterations were required to minimize the objective function until matching the penetration energy into soil from a physical experiment. Ucgul et al. (2014) used angle of repose tests to calibrate a soil model for cone and disk penetration simulation. Interestingly enough, hysteretic contact models used by Ucgul et al. (2014) exhibited better correlation than Hertz-Mindlin to physical test results, but it is unclear as to whether or not hysteretic contact stiffness is required for such simulations. The number of DEM particles contacting the ASABE cone is also factor in the accuracy of solution. Bolton and Gui (1993) showed that cone penetration resistance test was insensitive on soil container radii larger than 40 times the cone base radius. The ASABE (ASAE standards, 1999) cone base has a diameter of 12.53 mm. Following Bolton and Gui’s (1993) suggestion, a DEM virtual container with a diameter of 501.2 mm could be used for DEM cone penetrometer modeling. Preliminary DEM simulation showed that the experimental container size effects can be attenuated or amplified by DEM particle size, stiffness, and friction. Many studies used different approaches in modeling cone penetration in soil to address DEM particle scaling, contact models and boundary to median particle size (B/d50) (Table-1). Previous experimental and DEM simulation studies showed that calibration procedure of DEM material properties using simple test such as cone penetrometer requires further understanding of particle size to cone penetrometer ratio, simulation versus laboratory tests geometry scaling ratio and robust DEM material properties calibration methodology.

### Table 1. Review of DEM simulation formulation and parameters for virtual cone penetrometer (and similar) studies.

<table>
<thead>
<tr>
<th>Study</th>
<th>Type</th>
<th>Particle Size</th>
<th>Initial State</th>
<th>$\mu_s$</th>
<th>$\mu_k$</th>
<th>Normal Stiffness</th>
<th>B/d50</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alvaro and Ooi 2016</td>
<td>30 deg ASABE</td>
<td>5mm +/-10%</td>
<td>Porosity = 0.53 before consolidation</td>
<td>0.2-0.8</td>
<td>0.1</td>
<td>Hookean-Hysteretic, 100/500-2500 kN/m</td>
<td>NR[b]</td>
</tr>
<tr>
<td>Arroyo et al 2011</td>
<td>CPT[a]</td>
<td>26.5mm =1.31</td>
<td>$C_u$ = 0.75-$D_i&lt;$0.97</td>
<td>0.35</td>
<td>0 and inf</td>
<td>Hookean, 300MN/m</td>
<td>2.7</td>
</tr>
<tr>
<td>Falagush et al 2015</td>
<td>CPT</td>
<td>1-2mm</td>
<td>Porosity 0.37-0.42</td>
<td>0.2-1.0</td>
<td>prohibited</td>
<td>Hookean, 500 KN/m</td>
<td>18</td>
</tr>
<tr>
<td>Jiang et al 2014</td>
<td>CPT</td>
<td>7.6mm $C_u$=1.3</td>
<td>2D Void Ratio = 0.27</td>
<td>0-0.5</td>
<td>n/a</td>
<td>Hookean,75MN/m</td>
<td>21</td>
</tr>
</tbody>
</table>

[a] CPT refers to Cone Penetration Test commonly used in geotechnical site characterization  
[b] NR- Not Reported  
[c] $C_u$ = Coefficient of Uniformity

The objective of the study was to develop DEM calibration of sandy loam soil with different initial relative density and validate the DEM model using ASABE standard cone penetrometer testing.

### Materials and Methods

#### Cone Penetrometer Test

A cone penetrometer was developed with commercial-off-the-shelf components. An analog S-type load cell (500-lb capacity) was fixed to a smooth rod and ASABE cone tip (a 30-degree cone and 12.53 mm cone base diameter). The analog signal from the load cell was read using the ADC built into the Arduino which was used to transfer data back to a PC for analysis. An ultrasound range finder was used to determine depth of penetration. The cone penetrometer device was used to measure cone penetration resistances of Norfolk Sandy Loam (NSL) that has particle size distribution of 72% sand, 17% silt and 11% clay (Batchelor, 1984).
Norfolk Sandy Loam (NSL) was provided from the National Soil Dynamics Laboratory in Auburn, AL. The soil was prepared at a moisture content of 6.3% (d.b.). To simplify calibration, NSL will be calibrated as cohesion-less media. Soil bulk densities of 1.71 Mg/m$^3$ and 1.22 Mg/m$^3$ (Tekeste et. al, 2007) were assumed as the maximum and minimum bulk density for initial bulk density in DEM simulation.

Cone penetration resistance of NSL was measured using ASAE standard cone penetrometer (Figure-1). The soil specimens were prepared in a section of PVC pipe that was 102 mm in diameter. Specimens were pluviated and tamped periodically to attain desired bulk densities that correspond to the relative densities. The specimen height inside the PVC pipe section ranged from 200 to 230 mm. The PVC pipe section and data acquisition system is shown in Figure 1. The cone penetrometer was manually plunged into the NSL very slowly at approximate speed of 16.5 mm/sec. to maintain quasi-static conditions.

![Image](image1.png)

**Figure 1.** PVC pipe section filled with loose Norfolk sandy loam soil at 6.3% moisture content (A); Arduino data acquisition system ans S-beam load cell (B); and ASABE 30- deg cone (C).

**DEM Soil Cone Penetrometer and DEM Model Calibration**

*Modeling the Cone Penetrometer*

The 30 degree ASABE cone has a diameter of 12.53 mm. The diameter of the virtual container was modeled to be 500 mm. The depth of the virtual container was 300 mm. The DEM particle radius was 2 mm. Comparing characteristic lengths of the ASABE cone to the particle provides, a cone diameter to particle diameter of three was used to ensure three particles at randomly in contact to the cone at once.

*DEM Material Properties Calibration*

The DEM calibration procedure after (Syed et al., 2017) was used to determine DEM soil parameters including the initial soil assembly structural states of the virtual NSL DEM soil model. The DEM algorithm (Figure 2) comprised of the assumption that relative density and bulk density strongly influences the kinematic and inertial behaviors of particle dynamic systems; and the residual soil strength strongly affects the kinetic particle dynamic behaviors. Assuming this cause-effect relationship of soil properties and mechanical behaviors, the DEM material properties (sliding friction coefficient, rolling friction coefficients, contact stiffness) were calibrated using automated iterative DEM simulations in LIGGGHTS (Open source DEM code) (Syed et al., 2017). The initial void ratio and particle scale density were also iteratively adjusted in relation to the DEM particle size and bulk density. Viscous damping DEM properties were assumed to have less influence for quasi-static tool-soil DEM simulation and were not included in the DEM calibration methodology.
Residual soil to soil internal angle of friction was estimated from quick direct shear tests at low normal stresses. Based triaxial test estimated relationship between octahedral shear stress and octahedral normal stress, a yield function with non-cohesion (Bailey and Johnson, 1989) was assumed for the DEM soil contact model selection. The estimated friction coefficient values of sliding ($\mu_s=0.03$) and rolling ($\mu_R=0.025$) were used for the DEM simulation. Relative densities of 5%, 30%, and 90% were used to determine the initial void ratios for DEM simulations of three density conditions. From simulations described in Salot et al. 2009, the maximum and minimum void ratios for the virtual NSL are $e_{\text{max}}=0.66$ and $e_{\text{min}}=0.42$. Therefore, three DEM cone penetrometer simulations will be performed at void ratios near $e_{\text{loose}}=0.65$, $e_{\text{medium}}=0.61$, and $e_{\text{dense}}=0.44$. Relative density (RD) was characterized as $RD = \frac{e_{\text{max}} - e}{e_{\text{max}} - e_{\text{min}}}$.

**Stable DEM Soil Specimens**

A technique was developed to create stable DEM soil assembly in the cylindrical specimens at initial states (Figure 3). DEM particles were initialized in a cylindrical container with a rigid base and a temporary lid, and were allowed to equilibrate over many DEM cycles. During this time, the reaction force on the lid of the cylinder was monitored. The reaction force decreased over the DEM calculation cycles as the specimen tended toward the minimum potential energy state. Eventually, the specimen could no longer equilibrate, at which point, the cylinder was transversely vibrated with amplitude of 0.1\times Particle Radius at 30 Hz. The vibration is turned off when the lid reaction reaches zero. At this point, the sample is completely stable and the lid can be removed. Figure 4 shows the trend of lid reaction as equilibration progresses.
Figure 3. DEM cone penetrometer simulation side view.

Figure 4. Lid reaction forces over time.
**DEM Particle Size Sensitivity**

DEM particle size were varied to assess their contribution to the reaction force of an ASABE cone penetrating a dense granular assembly at 16.5 mm/s. Effect of particle size on signal noise (Figure 5) showed smaller particles seem to reduce the noise in the cone resistance data.

![Figure 5. Effect of particle size on DEM predicted signal noise.](image)

It is computationally infeasible to run multiple iterations of the DEM simulation with DEM particle similar to the physical soil particle size distribution or at 1-mm particle diameter size. As particle size decreases, critical stable time step and particle count take computationally long simulation times. After preliminary tests, DEM particle radius of 2 mm was chosen to validate the DEM simulation of cone penetrometer at different relative density.

**Results and Discussion**

**Norfolk Sandy Loam Cone Penetrometer Test**

The results from physical cone penetrometer testing are shown in Figure 6. The soil penetration resistance exhibited softening for all initial relative density values. The loose specimens exhibited softening before 50 mm of penetration, while the densest specimen softened at around 110 mm of penetration. In a remolded uniform soil specimens without hardpan, the relatively uniform steady-state deformation after the softening could be explained by the cavity-expansion theory of soil penetration tests as noted in Yu and Mitchel (1998).
Figure 6. Cone penetration resistance measurement from Norfolk Sandy Loam soils for three Relative Density (RD) values of 5%, 20% and 90%.

NSL Cone Penetrometer DEM Simulation

The DEM soil model for NSL was calibrated using direct shear test data. A Hertzian particle contact formulation was used with Young’s modulus = 1x10^8 Pa and Poisson’s ratio =0.3. The sliding and rolling friction coefficients were 0.03 and 0.025, respectively. The particle density was 2000 kg/m³. Initial void ratios were varied to approximate the physical relative density values of NSL. Tables 2 and 3 show the approximate physical and DEM relative densities.

Table 2. Initial states of soil used for cone penetration tests

<table>
<thead>
<tr>
<th>Physical Specimen #</th>
<th>Condition</th>
<th>Physical relative soil density</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Loose</td>
<td>5.0%</td>
</tr>
<tr>
<td>2</td>
<td>Medium</td>
<td>30%</td>
</tr>
<tr>
<td>3</td>
<td>Dense</td>
<td>90%</td>
</tr>
</tbody>
</table>

Table 3. Initial states of virtual cone penetrometer tests

<table>
<thead>
<tr>
<th>Virtual Specimen #</th>
<th>Condition</th>
<th>Virtual Relative Density</th>
<th>DEM Initial Void Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Loose</td>
<td>7%</td>
<td>0.641</td>
</tr>
<tr>
<td>2</td>
<td>Loose</td>
<td>22%</td>
<td>0.606</td>
</tr>
<tr>
<td>3</td>
<td>Medium</td>
<td>43%</td>
<td>0.556</td>
</tr>
<tr>
<td>4</td>
<td>Medium</td>
<td>52%</td>
<td>0.534</td>
</tr>
</tbody>
</table>

The DEM particle radius was chosen to be 2 mm for reasonable computation times, and as a result, the noisy cone resistance signal needed to be smoothed using a moving average technique which used the arithmetic mean of +/- 20 data points for each step. Figure 7 shows how the moving average and raw signal of DEM simulation cone penetration resistance.
Figure 7. Comparing moving averaged to raw DEM cone penetration resistance, red line = moving average, blue points = raw DEM cone resistance.

The data points from raw DEM in Figure 7 exhibit considerable scatter because the contact between the virtual cone penetrometer and the DEM particles is intermittent. Effect of particle size on DEM predicted signal noise shows that the noise can be reduced considerably by reducing the particle size, and consequently, increasing the tool diameter-to-particle diameter ratio.

Figure 8. Comparing Comparison of physical and virtual experiments of the cone penetrometer test, RD=relative density.
The comparison between the physical tests and calibrated DEM simulations are shown in Figure 8. The trend of increasing cone resistance as initial density increases for both physical and virtual experiments (Figure 8). The cone penetration resistance for the dense state 90% RD physical was not successfully modeled in DEM. Further DEM calibration will be required for dense soil conditions. Utilizing direct shear test (less than 100 kPa consolidation stress) in our DEM calibration may also affect the robustness of the DEM calibration for reproducing the initial void ratio and optimize the DEM parameters. In predicting soil compaction behavior from wheel loading, Bailey and Johnson (1989) soil compaction model for Norfolk sandy loam was developed from triaxial test with 500 kPa confining stress. As shown in Figure 8 and a close-up comparison between the physical RD=5% and virtual RD=7% conditions in Figure 9, DEM predicted transient and steady state cone resistance force in close agreement to the physical experiment.

![Comparison of virtual and physical tests at low relative density.](image)

Comparing the mean steady state or near steady state cone penetration resistance between the DEM simulation and physical experiments (Figure 10), DEM predicted steady state forces were similar to the physical data except for the 90% physical relative density.
Figure 10. Comparison of physical and virtual steady state cone penetration resistance for different relative density.

Figure 10 also showed the increased in cone penetration resistance with increase in relative density was captured both in DEM and physical tests. The hypothesis proposed by Salot et al (2009) that physical relative density can be set equal to virtual relative density is supported by the data (Figure 10).

Conclusion

DEM model for Norfolk Sandy Loam (NSL) was developed using the proposed DEM calibration methodology and validated using cone penetration test. Within the range of 5 to 30% relative density, DEM model predicted the soil cone penetration resistance with reasonable minimum errors. Relative density, a critical soil property parameter, was successfully integrated into DEM calibration methodology and showed strong influence on both physical test and DEM simulation of cone resistance. The current DEM calibration methodology requires further improvement for simulation and DEM material properties calibration of higher relative density. The quasi-static calibration algorithm developed for DEM soil model uses residual internal friction angle as an anchor and requires that engineers determine the appropriate relative density of the material without altering other DEM parameters. Future work will involve creating very dense DEM model, yet stable DEM specimens to verify whether the proposed calibration applies to high density soils subject to cone penetrometer testing.

References


