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Calibration of soil compaction behavior using Discrete Element Method (DEM)

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ABSTRACT. Soil compaction has potential to reduce crop yield by resisting seed germination and root growth. Modern agricultural farm equipment is getting bigger in size and axle weight that could cause excessive soil compaction. Natures of soil compaction in agricultural fields are not predictable because of non-homogeneous soil condition, and inconsistent wheel trafficking in the field. In this study predicting soil compaction behaviour will be studied for under different three soil moisture using Discrete Element Method (DEM). Discrete Element Method (DEM) is capable to simulate the elastic-plastic soil compaction behavior. Selection of appropriate DEM contact model and calibration of the DEM material properties is essential to simulate bulk soil dynamic behavior under compaction loading. DEM soil model using parallel bond model (PBM) available in PFC^{3D} was calibrated to match soil penetration resistance from a conical probe penetration on three-layered soil column. DEM model predicted the mean values of soil penetration resistance for middle (soil density of 1400 kg m^{-3}) and bottom (1550 kg m^{-3}) within 10% relative error for “dry” and “wet” soil moisture conditions. With the DEM calibration approach utilized in this study, soil penetration resistance for loose top layer were under predicted The DEM soil can be used for simulation of tire-soil interaction under uniaxial loading cases for various soil types, soil conditions, loading..

Keywords. *Bulk density, calibration, compaction, Discrete Element Method (DEM), soil.*

Introduction

Agricultural soil compaction is a global concern because of the potential negative effects on crop yield by resisting seed germination and root growth. Modern agricultural farm equipment keeps getting bigger in size and weight along with the concerns on soil compaction from excessive axle loading on compactible soil conditions. Axle loads from modern tractors, combines with full grain tank, grain carts

(30 m^3 (850-bushel) capacity) and liquid manure tanks (38,000 L (10,000 U.S. gallon) capacity) have exceeded the 10 Mg axle load limit for a single axle, for deep soil compaction and road infrastructure carrying capacities (PM1901B, 2015). With the increased axle load and excessive field trafficking, soil compaction becoming a prevalent problem. Soil cone index is a widely used method for measuring the magnitude of soil compaction (Tessier et al., 1997). ASAE standardized (ASAE, 1999) soil cone penetrometer measures soil penetration resistance from a 30-deg conical tip inserted into the soil. Researchers have shown that soil properties affect the soil CI reading. Drier soils have higher cone index than wetter soil (Elhers et al., 1983, Tekeste et al., 2008) and soils with higher soil bulk density has higher soil CI values (Hakansson et al., 1989; Lipiec and Hatano, 2003; and Tekeste et al., 2008). Soil CI also varies within the soil depth profile. Lower soil CI values are associated with a tilled layer near the soil surface, while higher CI values are associated with a compact soil layer below the tilled layer (Chen and Tessier, 1997; Doan et al., 2005).

Predicting and management of soil compaction requires understanding soil compaction behavior under tool penetration tests. Prediction of the soil dynamic behaviors from tool penetration tests under varying soil conditions provide values to support design and performance of tractive devices or soil cutting equipment. Previous studies attempted to quantify the behavior of soil reaction to cone penetration for example X-ray computer tomography (Tollner et al. (1987) and bearing capacity theory (Yu and Mitchel, 1998). Researchers also developed several analytical models for studying nature of soil compaction process from wheel loading (Defossez and Richard, 2002), stress distribution in a semi-infinite and homogeneous medium when a load is applied on its surface (Ricardo and Achim, 1998). FEA also has been used to model cone penetration in soils with limited success (Markauskas et al., 2002; Foster et al., 2005). Tekeste et al. (2007) used FEA to study soil compaction and hardpan detection. Semi-empirical methods and finite element methods are limited for modeling discontinues elasto-plastic soil dynamic behavior from tools penetrating into soils. Discrete Element Method (DEM), a numerical technique that models material behavior as discrete particles, is a powerful alternative numerical tool to predict dynamic soil reactions from tool-soil interactions. In the DEM, material is modelled as discrete particles. Particles are given specific properties (named micro-properties of particle), and the contacts between particles are governed by certain micro-mechanics constitutive laws, so that the contact behaviors of the model particles reflect the bulk behavior of the material to be simulated. Researchers have shown the predictive capability of DEM to model behavior of granular materials based on Hertz-Mendlin contact theory (Cundall and Strack, 1979). Shmulevich et al. (2007) and Asaf et al. (2007) were able to model in DEM wedge penetration in soil and 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 on cohesionless soils. Others also demonstrated simulation of hydraulic excavator digging process using confining stress dependent DEM cohesive soil model (Obermayr et al., 2014). Previous studies on DEM calibration for simulation of tool-soil interactions were limited in modeling the elasto-plastic behaviors of agricultural soils conditions in particular variation in soil moisture content and compaction layering that exhibit cohesive, elasto-plastic behaviors and variations of soil moisture contents.

The specific objectives of this study were to

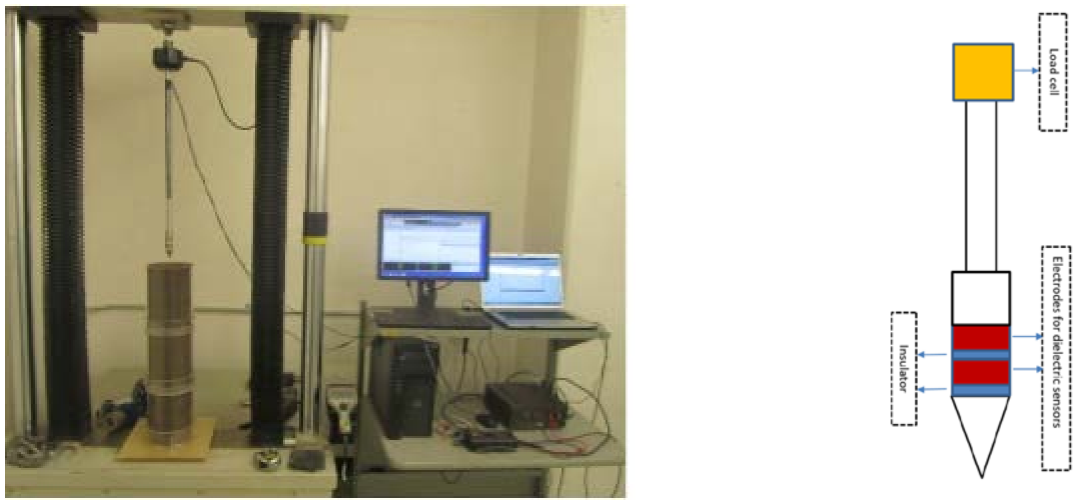
(1) develop a three-dimensional numerical DEM soil model to simulate the soil-cone penetrometer interaction using PFC^{3D},
(2) calibrate the model microproperties using laboratory measurements for two soil moisture conditions.

Material and Methods

Soil Compaction Test

Soil compaction test was conducted using Loam soil for two different moisture contents. Soil was collected from Iowa State University-Agricultural Engineering Farm in Boone, Iowa. A predetermined soil mass for each soil moisture conditions (“wet” 12.4% mc and relatively “dry” 9.2% m.c.) was loosely filled into a cylinder (150 mm diameter and 200 mm height) and the soil was compressed using a cylinder plunger (150 mm) to the targeted soil bulk density levels of 1400 Mgm^{-3} on the bottom layer, 1550 Mg m^{-3} in the middle layer and 1250 Mg m^{-3} in the top layer. Compression was conducted at a speed 5 mm s^{-1} till the desired material height for each bulk density layers using Instron machine (Fig 1). Soil moisture content was measured using over dry method at 105^0 C for 24 hrs.

Conical Tip Penetration Resistance After creating the three soil compaction layers for each soil moisture contents, a conical tip 45^0 and a cone base diameter of 25 mm was inserted at 50 mm s^{-1} to measure the penetration resistance force.

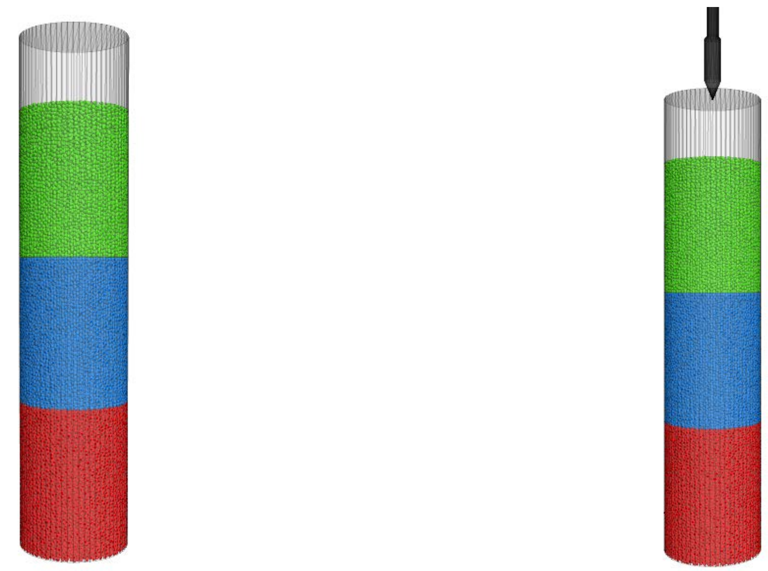


(a) (b)

Fig 1: Soil preparation and cone index measurement in the laboratory: (a) three soil layers; (b) cone penetrometer probe with multiple sensors for measurement of penetration forces and moisture content.

Discrete Element Model Soil-Cone Penetration

Soil cone penetration model was developed using Particle Flow Code in Three Dimensions (PFC^{3D}, Itasca Consulting Group, Inc., Minneapolis, Minn.) to virtually reproduce the laboratory measurements. The DEM simulation development included CAD cone penetrometer, generation of soil particles, and assigning the probe insertion speed of 50-mm s^{-1} the DEM soil particles assembly. Soil cylinder, cone penetrometer and probe insertion speed matching the laboratory specifications were created in a PFC^{3D} and assigned wall features. DEM soil single-sphere (5-mm diameter) particles were generated in three layers similar to the laboratory test method. Soil porosity and particle density were used to generate the soil particles with similar bulk density in each layer (Fig 2a). After generating the DEM soil particles in the container the cone penetrometer inserted at 50-mm s^{-1} into the generated DEM soil particles to measure the penetration resistance reaction force at the cone (Fig 2b). To avoid the frictional effect of the cylinder soil containing tube, only the vertical force of the conic wall was monitored during the simulation to determine the probe Cone Index (CI) value.



(a) (b)

Fig 2: Soil cone penetration DEM model: (a) soil container with different layer of soils; (b) penetration test using the cone penetrometer.

DEM Soil Model Calibration

The linear contact model and parallel bond model (PBM) were implemented in PFC^{3D} to define the contact micro-mechanics to calculate the interaction between particles; and particles and wall (please verify the wall). The bond between particles transmitted force and moment between particles in tangent and normal directions and thus prevented particles from excessive rotation. The PBM also reflected the cohesive behavior of agricultural soils.

The friction coefficient between the probe and soil was assumed to be 0.40, which was the friction coefficient between soil and tools suggested by Godwin (2007). This value has been used previously for soil-tool friction in simulation of soil-tool interactions using PFC^{3D} by other researchers (Chen et al., 2013; Zeng and Chen, 2016). Cone of the penetrometer are made from steel thus the steel normal stiffness and shear stiffness used for model probes, 1.0×10^9 N m-1 (Mak et al., 2012). The container sidewall was assumed to be frictionless to avoid edge effects where not soil movements were observed from the experimental test. The conical probe was assigned 50-mm s^{-1} insertation speed. The cone tip stopped after reaching 600 mm depth from the top of the soil surface. As the probe moved down, the interaction force between the soil and the cone in the vertical direction was monitored to simulate the penetration resistance of the penetrometer. The CI was then calculated by dividing the penetration resistance by the base area of the cone.

Soil-Soil Interaction DEM Properties

The PBM requires eight micro-properties as inputs namely particle normal stiffness (K_n, N m^{-1}), particle shear stiffness (K_s, N m^{-1}), particle friction coefficient (μ, dimensionless), bond normal stiffness ($\overline{K}_n$, Pa m^{-1}), bond shear stiffness ($\overline{K}_s$, Pa m^{-1}), bond normal strength (σ, Pa), bond shear strength (τ, Pa), and bond radius multiplier (R_m, dimensionless). Ideally, all the parameters that affect model outputs would need to be calibrated. So far the interaction effects of each parameter at the micro-mechanics contact law are not well established; therefore, researchers consider that all these parameters collectively determine the model output. In this study, calibration of each parameter was conducted one at a time. Sadek and Chen (2015) showed that Young's modulus (a function of particle stiffness, K_n) is the most sensitive parameter for the model output of tool-soil interaction problems. Zeng and Chen (2016) also calibrated particle stiffness (K_n) for predicting CI using micropenetrometer (cone tip angle of 57^0 and cone base diameter of 2.75 mm). Based on the previous DEM parameters influences on tool-soil DEM simulation, particle stiffness was assumed to strongly influence DEM prediction of probe penetration resistance. For particle friction coefficient and strength parameters, we assumed values from Zeng and Chen (2016). Model parameters used in the model are listed in table 1. In this study, the calibration of K_n was carried out using the penetration resistance data from the laboratory tests. Using conical-tip probe penetration tests for DEM calibration may provide better calibration of bulk soil reactions to cone penetration including soil cutting, compression, shear or combination of these (Gill and VandenBerg, 1968). Traditionally material testing methods such as direct shear or triaxial testing have limited capability to provide complex soil dynamic behaviors and soil layering commonly observed in agricultural soil and equipment interactions. With a series of assumed K_n values, the model CI values were recorded and compared with the measured values from each bulk density layers. The final K_n was recorded, which resulted in the best match between the simulated and measured CI values. Similar procedure was used for the different soil moisture contents.

Table 1: Model initial microproperties (Zeng and Chen, 2016)

Model Parameter	Value
Particle size	5 mm
Particle density	2232 kg m^{-3}
Ball Normal and shear stiffness	10300 N m^{-1}
Ball friction	0.93
PB normal and shear stiffness	$1e^6$ Pa m^{-1}
PB normal and shear strength	$1e^6$ Pa

Results and Discussion

Soil Cone Index (CI)

Soil CI measured both in test and simulation. The CI-depth curve comparison between test and simulation for both dry and wet soils are shown in Fig 3. Three distinct stages for three different soil bulk density layers are visible from the laboratory measurement. In the laboratory results, the CI on the top layer (0-200 mm) increased very slowly, then middle layer (200-400 mm) the CI value increased rapidly and reduced again at the bottom layer (400-600 mm). The DEM simulation captured the changing soil responses with soil layers as probe penetrates the top layer, the middle and bottom soil layers. The DEM under predicted the magnitude of CI value on the top layer which might imply DEM parameters besides the stiffness need to be included for calibration of loose soil top layer. Soil tends to dilate with shearing at the top boundary interface as conical probes penetrate into soil as noted in bearing capacity soil failure theory and finite element soil deformation (Yu and Mitchel, 1998; and Tekeste et al., 2007). Middle layer had higher CI value because of higher bulk density. As the bottom layer was less compare to middle layer thus the CI value reduced at the end. Similar to the test result simulation results also had different CI value trend in three different layers. On the top layer the CI increased with the depth increased then the value increased suddenly and remained similar until reached to the end of middle layer. On bottom layer the CI valued jumped again and remain similar for the full depth. As the model had more consistent particle distribution on each layer thus the variation on CI did not change much for middle and bottom layer. On the top layer the CI value increased because more and more particle came in contact with the cone as the cone moved into the soil. As the top layer is not the ideal case for CI measurement as the cone does not come into fill contact until it reach to a certain thus the average CI on the middle and bottom layer was considered for calibration process.

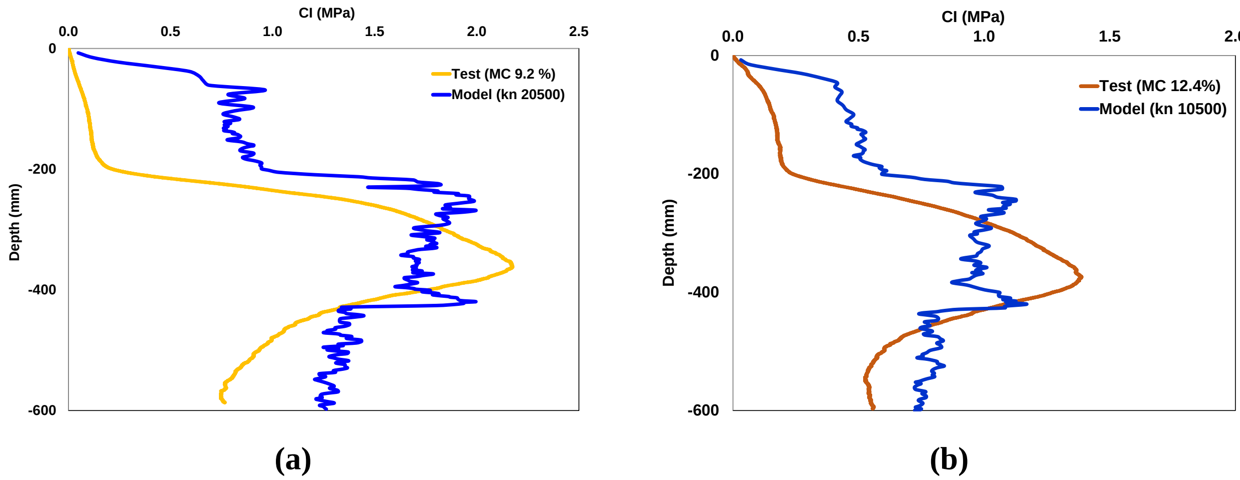


Fig 3: Soil CI measurement in laboratory and simulation; (a) dry soil, (b) wet soil.

Calibration Result

Bulk densities at different layers of the soil were reproduced in the DEM simulation in PFC^{3D} within 10% relative error (Table-2). For calibration, the model probes were assigned higher penetration speed of 5000 mm s^{-1}. Actual penetration speed cannot be used because the computer power was not sufficient to finish the simulation with an acceptable time. Zeng & Chen (2016) described the effect of penetration speed on CI response. Their study showed that ASABE standard CI did not vary significantly with penetration speed. Running the simulation at larger magnitude than the physical test allowed us to accelerate DEM calibration of PBM microproperties.

Table 2: Comparison of the measured and simulated bulk density

Layer	Target Bulk density (kg m^{-3})	Measured Bulk density (kg m^{-3})	Relative Error (%)
Top	1250	1250	0.00
Middle	1550	1495	3.54
Bottom	1400	1362	2.71

The initial calibration was done for dry soil by adjusting the calibrated parameter (Ball normal shear strength, K_n) value for dry and wet soil until the simulated average CI matched the average CI measured in the laboratory tests. The agreement between simulation and measurement was evaluated using the relative error. The calibrated ball stiffness K_n was found 2.05e^4 N m^{-1} and 1.05e^4 N m^{-1} for dry and wet soil respectively. Table 3 shows the relative errors between measured and simulated CI found for both dry and we soil.

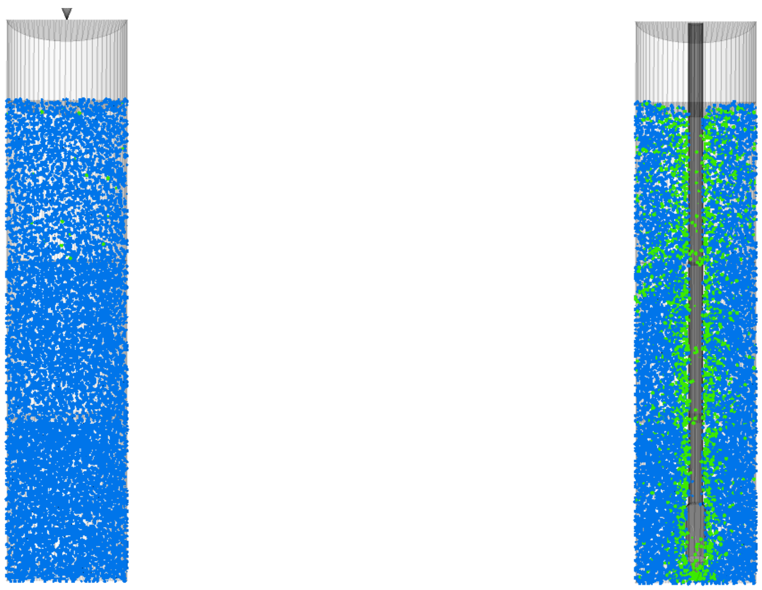
The CI varied from 0.08 MPa to 1.60 MPa for dry soil and 0.13 MPa to 1.0 MPa for wet soil. The simulated CI varied from 0.77 MPa to 1.72 MPa for dry soil and 0.47 MPa to 0.98 MPa for wet soil. The relative error was very high for top layer because high variation in CI measurement discussed earlier. The relative error on middle layer was relatively low, 7.5% for dry soil and 2.0% for wet soil. Similarly the relative error on bottom layer was 35.92% on dry soil and 15.49% on wet soil. Wet soil had good match with test result. Simulated CI for dry soil can be further improved my by choosing different K_n value. Other microproperties such as bond strength effect can be considered for improving simulated CI value for different moisture content as noted in (Sadek et. al., 2011) where DEM model calibration approach using soil direct shear force behavior of a sandy soil were successfully modeled for different soil conditions.

Table 3: CI mean values comparison DEM model vs test

Layer	Dry soil Measured CI (MPa)	Dry soil Simulated CI (MPa)	Dry soil Relative Error (%)	Wet soil Measured CI (MPa)	Wet soil Simulated CI (MPa)	Wet soil Relative Error (%)
Top	0.08	0.77	827.71	0.13	0.47	261.54
Middle	1.60	1.72	7.50	1.00	0.98	2.00
Bottom	1.03	1.40	35.92	0.71	0.82	15.49

Contact Force Network

Soil contact force network was observed during simulation process. For before and after penetration, a cutting plane passing through the center of the container was obtained to show the contact force chains on the plane (Fig. 4). It was observed that the contact force network was denser on the middle layer compare to top and bottom layer (Fig 4a). During penetration most compressive contact force was near the tip of the cone. As seen from the screen captures, the stress concentration area due to penetration is generally within a cylinder centered on the probe with a radius of approximately 15 mm.



(a) **(b)**

Fig 4: DEM contact networks; (a) before cone penetration, (b) after cone penetration

Conclusions

The soil-cone penetrometer model was developed using PFC^{3D} produced results similar to laboratory measurements in terms of the variation of cone index (CI) with penetration depth and soil moisture contents. The calibrated particle stiffness was 2.05e^{4} N m^{-1} for dry soil and 1.05e^{4} N m^{-1} for wet soil. The DEM predicted CI values agreed well with the mean CI values as demonstrated by the low relative errors (15%) for two soil conditions (Dry and Wet) for middle and bottom dense layers (1400 kg m^{-3}.and 1550 kg m^{-3}). In the loose top soil layer (1250 kg m^{-3}), the DEM calibration methodology needs improvement. The results demonstrated calibration of DEM soil models using simple penetration testing will help for prediction of compaction from tire-soil interaction under uniaxial loading cases for various soil types, soil conditions, loading.

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