Computers and Electronics in Agriculture 125 (2016) 63–73

Contents lists available at ScienceDirect

Computers and Electronics in Agriculture

journal homepage: www.elsevier.com/locate/compag

Original papers

Numerical simulation of soil–cone penetrometer interaction using discrete element method

Krisztián Kotrocz [a,*], Abdul M. Mouazen [b], György Kerényi [a]

[a] Department of Machine and Product Design, Budapest University of Technology and Economics, Műegyetem rkp. 3, H–1111 Budapest, Hungary
[b] Cranfield Soil and AgriFood Institute, Cranfield University, Cranfield MK43 0AL, UK

ARTICLE INFO

Article history:
Received 18 November 2015
Received in revised form 5 April 2016
Accepted 24 April 2016

Keywords:
Discrete element method
Cone penetrometer
Soil mechanics

ABSTRACT

One of the most common methods to measure soil strength in-situ is cone penetrometers. In this paper the development of a three dimensional (3D) discrete element model (DEM) for the simulation of the soil–cone penetrometer interaction in a slightly cohesive loamy sand soil is presented. The aim was to investigate the effects of the soil model's geometrical (e.g., soil model cross section shape and size and model's height) changes on variations in the soil penetration resistance. The model area ratio and height ratio values were adopted to analyse the effects of the cross section size and the model's height, respectively. The results of penetration resistance of the DEM simulations were compared with the in-situ measurement with a cone penetrometer of the same geometry. This comparison allowed the derivation of the contact properties between the elements. To simulate the soil material the so-called Parallel Bond and Linear Models were used in the 3D version of the Particle Flow Code (PFC) software. Finally the mechanical properties of the soil, namely the cohesion and internal friction angle were estimated by DEM simulation of direct shear box.

Results showed that the penetration process can be simulated very well using the DEM. The model's calculated penetration resistance and the corresponding in-situ measurement were in good agreement, with mean error of 14.74%. The best performing models were a rectangular model with an area ratio of 72 and a height ratio of 1.33 and a circular model with an area ratio of 32 and a height ratio of 2. The simulation output of soil material properties with direct shear box resulted in representative values of real loamy sand soils, with cohesion values range of 6.61–8.66 kPa and internal friction angle values range of 41.34–41.60°. It can be concluded that the DEM can be successfully used to simulate the interaction between soil and cone penetrometers in agricultural soils.

1. Introduction

Soil compaction is the most known natural and manmade problem that negatively affects crop growth and yield, reduces soil hydraulic properties and increases soil susceptibility to erosion (Hamza and Anderson, 2005; Fleige and Horn, 2000). It directly results in increasing the cost of agriculture production due to the need for tillage operations (Garner et al., 1987; Mouazen and Ramon, 2002), which is a highly consuming energy operation. With the increase in agriculture machine size, machine mass tends to increase dramatically in the last few decades, which resulted in increasing the amount of normal stress applied into agriculture soils by both the driving and non-driving wheels and tracks. However, the traction produced under the driving wheels also leads to the generation of shear stress. Both the normal and shear stresses augment soil strength and as a result soil compaction is increased. One of the most common methods to measure soil strength is cone penetrometers.

Cone penetrometers are commonly used to measure the penetration resistance at a certain speed (McKyes, 1985), throughout the soil profile. The output of the measurement is the cone index (C. I.), which can be determined by dividing the penetration force to the cone projected area. The cone index depends on the soil properties, namely the water content, bulk density and particle size distribution (Sudduth et al., 2008). A second main reason to use cone penetrometers in the field is that they measure the bearing capacity of the soil, which is important not only in civil engineering projects but in agriculture too. Since penetrometers have small projected area of 1–2 cm^2, they demand smaller penetration

---

* Corresponding author.
E-mail address: kotrocz.krisztian@gt3.bme.hu (K. Kotrocz).

http://dx.doi.org/10.1016/j.compag.2016.04.023
0168-1699/© 2016 Elsevier B.V. All rights reserved.

forces that can be provided by an operator (Laib, 2002). However, during field measurement penetrometers readings show high standard deviation, which is normally attributed to the heterogeneity of the soil, e.g., presence of stones or holes with the same dimension or bigger than the cone projected area (Sudduth et al., 2008; Fountas et al., 2013). This disadvantage can be compensated by performing high number of penetration tests on the same spot in the field (Laib, 2002), after which an average value can be calculated. However, performing multiple measurements on the same spot is a time consuming and costly operation. Therefore, efforts have been made to automatically measure penetration resistance, by utilising the tractor's three point linkage and hydraulic power. Multiple penetrometers were designed and combined with GPS receivers to obtain multiple measurements at the same time (Fountas et al., 2013).

Numerical simulation methods e.g., the finite element method (FEM) and discrete element method (DEM) are good alternative approaches to substitute the in-situ tedious, costly and time consuming experimental work. With the recent evolution of the information technology numerical simulations, particularly for soil–tillage and soil–wheel interaction become more popular (Mouazen and Neményi, 1998b). The most common simulation methods used so far are FEM (Chi and Kushwaha, 1990; Kerényi, 1996; Mouazen and Neményi, 1999; Bentaher et al., 2013; Fervers, 2004), DEM (Shmulevich et al., 2007; Knuth et al., 2012; Tamás et al., 2013) and computational fluid dynamics (CFD) (Formato et al., 2005). The FEM has been used to simulate both homogenous (e.g. Chi and Kushwaha, 1990) and non-homogeneous (e.g. Mouazen and Neményi, 1998a) soil material, modelled as a continuum. Less effort was reported on the simulation of soil penetration (Tekeste et al., 2007; Foster et al., 2005). Since soil consists of individual particles of different size, the simulation is more appropriate to be done with the DEM, established by Cundall and Strack (1979). This method can be used to simulate granular assemblies because the material is modelled as a group of individual elements with their contacts. DEM has been used in several agricultural fields, e.g. to model the interaction between soil and tillage tools (e.g., Tamás et al., 2013; Chen et al., 2013), and to simulate the material overflow and the discharging process from silos (e.g., Keppler et al., 2012; Goda and Ebert, 2005). There are also several published works about the simulation of the soil–wheel interaction using the DEM (Smith and Peng, 2013; Khot et al., 2007). Many research works were published about the use of the DEM to study the dynamic motion of the Mars rover's or the lunar rover's wheel (Knuth et al., 2012; Nakashima et al., 2010). To our best knowledge only limited research on the simulation of the soil–cone penetrometer was reported in the literature, particularly in agricultural soils. Wang and Zhao (2014) and Tanaka et al. (2000) used the DEM to simulate this phenomenon in two dimension (2D) and Butlanska et al. (2014) and Lin and Wu (2012) in three dimension (3D) but only for non-cohesive soils. Arroyo et al. (2009) investigated the effects of homogeneity and symmetry of the discrete element model on cone penetration and experienced differences in the soil resistance between, the half, quarter and full size model. Furthermore, large portion of error in DEM simulations is attributed to the difficulties associated with the determination of contacts properties between soil particles at micro scale correctly, which necessitates further research to accurately determine these contact properties.

This paper aims at the development of a 3D DEM model for the simulation of the soil penetration with a cone penetrometer in a slightly cohesive loamy sand soil. It will aim at the optimisation of the dimensions of the soil model (shape and size of the cross section and model height) for accurate prediction of penetration resistance.

2. Development of the discrete element model

2.1. In-situ tests

In-situ tests for the measurement of penetration resistance were performed at the experimental farm of Szent István University of Gödöllő (Máthé et al., 2013; Máthé, 2014), using a standard Eijkelkamp penetrologger (Eijkelkamp, Netherland) in the track of the GAZ-69 (69A) type of vehicle.

The cone's bevel angle was 60° and its projected area was 0.0002 m^2 (see Fig. 1). Two measurement series with 10 repetitions each were performed, namely one series in front of the left wheel and one in front of the right wheel of the vehicle pushing the penetrometer with velocity of 0.01 $m\,s^{-1}$ into the soil. The 10 measurement of each series were averaged in one value. According to the results of the measurements the soil penetration resistance has high standard deviation of 0.48 MPa, 0.55 MPa and 0.52 MPa at depth of 0.05 m, 0.1 m and 0.15 m, respectively, which can be experienced in real soils (Laib, 2002; Sudduth et al., 2008; Fountas et al., 2013). During penetration resistance measurement, soil samples were collected with core cylinders to determine the average bulk density, moisture content and porosity (Table 1).

2.2. Construction of discrete element model

The simulation of soil penetration with the same cone penetrometer of Eijkelkamp penetrologger (Eijkelkamp, Netherland) was carried out using the Particle Flow Code software (PFC3D ITASCA™, USA). In the PFC3D software the material can be modelled using only rigid ball elements. Each particle can be in contact with the adjacent balls and walls. If a contact exists between two elements (ball and ball or ball and wall) the contact force can be calculated from the stiffness and the relative position of the contacting elements (Potyondy and Cundall, 2004). Afterwards, the displacement of each element is determined according to the Newton's second law, expressed by the following two vector equations (Itasca, 1999):

$$F_i = m \cdot (\ddot{x}_i - g_i) \tag{1}$$

for translational motion, where F_i is the resultant force (the sum of the all externally applied forces acting on the particle) in N, m is the total mass of the particle in kg, $\ddot{x}_i$ is the acceleration of the particle in $m\,s^{-2}$ and g_i is the gravity loading in $m\,s^{-2}$.

For rotational motion, the following equations were used, which can be written when the particle's local coordinate system lies along the principal axes of inertia of the particle:

$$\begin{aligned} M_1 &= I_1 \cdot \dot{\omega}_1 + (I_3 - I_2) \cdot \omega_3 \cdot \omega_2 \\ M_2 &= I_2 \cdot \dot{\omega}_2 + (I_1 - I_3) \cdot \omega_1 \cdot \omega_3 \\ M_3 &= I_3 \cdot \dot{\omega}_3 + (I_2 - I_1) \cdot \omega_2 \cdot \omega_1 \end{aligned} \tag{2}$$

where M_1, M_2, M_3 are the components of the resultant moment acting on the particle referred to the principal axes in N m, I_1, I_2, I_3 are the principal moments of inertia of the particle in kg m^2 and $\dot{\omega}_1,\ \dot{\omega}_2,\ \dot{\omega}_3$ are the angular accelerations about the principal axes in rad s^{-2}. These two vector equations are integrated using the centred finite difference procedure involving timestep of Δt, resulting the velocities (translational and rotational), which are used to update the positions and the structure of the particles. Finally, the whole iteration process is repeated from the beginning so that the displacements of the elements can be calculated in every timestep.

The DEM simulations of soil penetration were performed with rectangular and circular cross section models (Fig. 1). During DEM model construction several steps were followed to set up the final model. Firstly, a huge number of particles (in the range of 3378–24,585 depending on the model's dimensions) were