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The effect of tine geometry during vertical movement on soil penetration resistance using finite element analysis

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A B S T R A C T

New tillage and planting tools causing low soil disturbance and minimizing vegetation deterioration are desired in the conservation tillage technology development. This paper attempted to study the effect of tine geometry in its vertical movement on penetration resistance. Four kinds of tines were defined (i.e. rectangle, triangle, crescent and mososeries) based on the geometry of the cutting edge. The effects of tine geometry, thickness, and penetration depth on soil penetration resistance were investigated and side soil disturbance evaluated. Finite element method with a Drucker–Prager elasto-plastic model was introduced to simulate the material behavior of sandy loam soil taken from Hebei province in China. Each tine was considered as a discrete rigid body with a reference point at the top-midpoint of the central plane, at which the vertical force (penetration resistance) was calculated. Results indicated that the rectangle tine obtained the highest penetration resistance as compared to the others. Penetration resistances of all the tines increased with the attack surface area with a power function, nonlinear tendency with thickness and a quadratic function with penetration depth. A crescent soil deformation area existed through the penetration process. It can be concluded that the FEM can maximize the understanding of tine geometry effects on penetration resistance and soil deformation area.

1. Introduction

In conventional agriculture, tillage is a very important operation to improve soil physical characteristics for better aeration, permeability, root development, and as a result plant growth and yield. The type and degree of soil disturbance is the prime factor when selecting tillage implements but this must be considered together with the draught and penetration forces for efficient operation (Godwin, 2007). The tool forces during soil working are extremely important for designers to design cultivation equipment to be effective over a wide range of soil types and conditions as well (Godwin and O'Dogherty, 2007). Most studies have been conducted to research soil-tool interaction including predicting the draught force acting on tool and the soil disturbance ahead of the tool. The two concerned objects of soil-tool interaction are soil and tool, and most of the studies were focused on changes in soil physical conditions. By studying the pattern and mechanism of soil failure, several models were well developed to describe the process of soil-tool interaction. Karmakar and Kushwaha (2006) concluded that there were five major methods that had been used as approaches to solve problems in the area of soil-tool interaction and failure mechanism, namely empirical and semi-empirical, dimensional analysis, finite element method (FEM), discrete or distinct element method (DEM) and artificial neural network (ANN). Liu and Kushwaha (2008) classified modeling of soil-tool interaction into three types: soil movement, static/dynamic forces required to move a tool, and combination of both movement and forces. Many experiments are needed to be carried out for a complete search or investigation of the soil tool interaction with a controlled situation in a range of variations in soil physical conditions (e.g. water content and bulk density). The finite element method (FEM) has been widely used to analyze soil-tool interaction problems in recent years since most interaction problems involve both material and geometric nonlinearities (Bentaher et al., 2013; Li et al., 2013; Naderi-Boldaji et al., 2013; Tagar et al., 2015). The finite element model can be efficiently used to predict the forces on a tool working through the soil, and it is helpful for modeling to estimate tillage forces and energy consumption for different tools geometries (Bentaher et al., 2013; Naderi-Boldaji et al., 2014).

Abbreviations: FEM, finite element method; DEM, discrete or distinct element method; ANN, artificial neural network.

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Table 1
Mechanical component of soil samples used in the simulation model.

Grain size (mm)	1–0.5	0.5–0.25	0.25–0.1	0.1–0.05	0.05–0.005	0.005–0.002	<0.002
Mass percent (%)	2.80	9.41	25.79	19.80	32.00	8.20	2.00

As for conventional soil tillage equipments such as ploughs or subsoilers, their working tools were always used to create a totally new soil condition by overturning soil or breaking compacted layers. With development of conservation tillage technology, new tillage and planting tools causing low soil surface residues coverage disturbance are desired, especially for soil aeration implements mentioned by Harrigan et al. (2006), and soil-gashing and root-cutting mechanism reported by You et al. (2010). These mechanisms were designed to remove compacted soil layers or remedy degraded grassland by improving soil drainage and aeration. A rotary soil cutting mechanism with a function of soil-gashing and root-cutting was designed to improve degraded natural Leymus chinensis grassland with negligible soil disturbance by You et al. (2012). Godwin and O'Dogherty (2007) classified simple tines into three types (i.e. wide tines, narrow tines and very narrow tines) based on the depth/width (d/w) ratio. Based on the above classification, the blades reported in You's (2012) investigation belong to the narrow tines and very narrow tines. In You's study, the soil-gashing and root cutting movements can be divided into many combined processes with penetration and rotation, and different performance and soil disturbance emerged because of different blade types, which indicated that the blade geometry was one of the factors causing the difference between the operational performances.

Few literatures on the soil-blade interactions, especially the penetration interaction have been found. The objectives of this study were (a) to simulate the penetration resistance acting on four single tines with different geometries when they were penetrated vertically into a sandy-loam soil bin by FEM, (b) to study the effect of the geometry, thickness and depth on penetration resistance and (c) to study the influence of tine geometry on the soil disturbance.

2. Materials and methods

2.1. Soil model and measurement

2.1.1. Soil material model

The soil mechanical behavior under external load of tillage implement was modeled with different yield criteria. The Drucker-Prager model and its extended forms are used to model frictional materials, such as soils and rock, where material yield is associated with hardening (i.e. the material strength increases with stress level). The extended forms include a linear, a hyperbolic and a general exponential form available in ABAQUS; the linear one is the most appropriate for soil materials (ABAQUS, 2010). Several researchers used the Drucker-Prager model and its extended linear form to simulate the interaction between the soil and tillage tools (Naderi-Boldaji et al., 2013; Ibrahmi et al., 2015). In the present work, the soil was modeled as an elastic–plastic with hardening property using the linear form of the extended Druck-Prager model (ABAQUS/Explicit). The model is defined as follows:

$$F = t - p\tan\beta - d \qquad (1)$$

where F is the yield function, t is the deviatoric stress, p is the normal stress, β is the internal friction angle, and d is the cohesion of the material. The normal (p) and deviatoric (t) stresses are given by the equations as follows:

Table 2
Yield stresses and corresponding plastic strain values used in ABAQUS.

Yield stress (kPa)	Plastic strain (%)
12.5	0
25	0.125
50	0.267
100	0.663
200	1.388

Table 3
Soil parameters used in FEM model.

Parameters	Value
Density, (g/cm^3)	1.429
Young's modulus, E (kPa)	617
Poisson's ratio, v	0.432
Internal friction angle, Mohr-Coulomb φ (°)	13.77
Internal friction angle, Drucker-Prager β (°)	27.34
Flow stress ratio, K	0.85
Dilatation angle, Ψ (°)	0
Cohension, C (kPa)	44.814
Soil-metal coefficient of friction, f	0.5
Precompression stress, σ_{pc} (kPa)	12.5

$$p = \frac{1}{3}(\sigma_1 + \sigma_2 + \sigma_3) \qquad (2)$$

$$t = \frac{1}{2}q\left[1 + \frac{1}{K} - \left(1 - \frac{1}{K}\right)\left(\frac{r}{q}\right)^3\right] \qquad (3)$$

$$q = (\sigma_1 - \sigma_3) \qquad (4)$$

$$r^3 = -(\sigma_1 - \sigma_3)^3 = -q^3 \qquad (5)$$

where K (flow stress ratio) is the ratio of the tension yield stress to the compression yield stress in triaxial test ($0.778 \leqslant K \leqslant 1$) (ABAQUS, 2010). If $K = 1$ then $t = q$ and the yield surface in this case is identical to the Von Mises circle in the deviatoric principal stress plane. $\sigma_1, \sigma_2 = \sigma_3$ are compressive stress in triaxial test; r is the third invariant of deviatoric stress.

2.1.2. Measurement of soil material and soil-metal properties

The soil samples were sandy loam soil taken from Guyuan Grassland Ecosystem Observation and Research Station (115°41′E, 41°45′N, Alt. 1400 m) located in Hebei province with dry bulk density of 1429 kg/m^3 and moisture content of 27.24% (d.b.). Soil mechanical component analysis was done as shown in Table 1.

The soil Young's modulus was determined by unconfined uniaxial compression test (Eggers et al., 2006), and the Poisson ratio was calculated using Eq. (6) (Yang, 2014).

$$v = \frac{1 - \sin\varphi}{1 + (1 - \sin\varphi)} \qquad (6)$$

where v is the Poisson ratio, and φ is the Mohr-Coulomb internal angle of friction.