Soil & Tillage Research 166 (2017) 43–51

Contents lists available at ScienceDirect

Soil & Tillage Research

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

A 3D simulation model of corn stubble cutting using finite element method

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ARTICLE INFO

Article history:
Received 30 May 2016
Received in revised form 31 August 2016
Accepted 2 October 2016
Available online 17 October 2016

Keywords:
Finite element method
Corn stubble properties
Stubble-soil interaction
Resistance force

ABSTRACT

The finite element method (FEM) has been widely used to model interaction of tillage tool and soil, because it is capable to provide an accurate prediction of tillage resistance. However, there is little research on modeling soil-root interaction in soil tillage practice. The object of this paper is to advance a well adaptable numerical assistance to simulate the root-soil interaction and predict the resistance force on a stubble cutting tool. A 3D dynamic simulation model using the FEM was established to predict the resistance acting on the stubble-cutting blade in the present work. Soil was modeled as elastic-plastic material, corn stubble was simplified as an assembly of lines with various diameters, and soil and stubble were tied together as a complex. Two stubble-cutting blades with different cutting edges and two forward velocities were examined using a FE computation model and verified experimentally by field tests. Comparison result of simulation and experiment showed that the prediction from the FE model agreed well with the measurements in a field test. It can be concluded from these results that the FE model designed in this work is capable of being used as a convenient and dependable prediction tool in analysis and development of the working capacity of tillage tool.

1. Introduction

Soil tillage resistance is one key factor considered in the development of agricultural machinery, because the high resistance of the soil acting on the tillage devices will cause high energy consumption. Optimization design of tillage tools is an effective way for energy saving in tillage practices; however, most of the current tillage tools have been developed from numerous trial and error field tests (Abu-Hamdeh and Reeder, 2003). Thus there is a need to find more convenient and efficient approaches for the design of tillage tools to predict soil resistance. Simulation and prediction of resistance force from tillage operation are capable to evaluate the working performance of tillage tools, and more importantly, to reduce field-test times and shorten the development cycle of new tools. Of the numerous numerical methods, the finite element method (FEM) is a powerful method and is commonly used for analyzing soil related problems, because FEM excels in the analysis of dynamic problems regarding material failure and large scale deformation (Upadhyaya et al., 2002). Many researchers have used FEM to investigate soil properties (Duncan and Chang 1970; Sandler et al., 1976; Raper and Erbach, 1990; Block et al., 1994; Kelln et al., 2008; Richards and Peth, 2009). Moreover, FEM has also been widely used to simulate soil-tool interaction and predict soil resistance on the tillage tools (e.g. Kushwaha and Shen, 1995; Mouazen and Neményi, 1996; Fielke, 1999). Abo-Elnor et al. (2003, 2004) performed a dynamic FEM analysis to model soil-tool interaction using Abaqus and found that the forward velocity of a plough affected the resistance force of soil on the plough. Gebregziabher et al. (2007) used an FEM computation model to examine the relation between soil and a plough, and they found that traction force of the plough increased with the tractive angle. Topakci et al. (2010) optimized the design of plough tip using a 3D FEM simulation model. Tagar et al. (2015) established an FEM simulation model to compare the modes of soil failure in laboratory and field.

Most of these research models were performed and verified using laboratory soil or soil bin test, and only a few were actually tested in the field (Hemmat et al., 2012). In laboratory tests, soil properties (Stafford, 1979) and operational variables can be more

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http://dx.doi.org/10.1016/j.still.2016.10.003
0167-1987/

easily manipulated (Wegscheid and Myers, 1967) to conduct repeated tests. However, it is not suitable to predict and analyze the behavior of natural and undisturbed field soil using the remolded lab soil (Dexter and Bird, 2001). This is especially true during agricultural tillage, where soil deformation should be observed to evaluate the working performance of tillage tools. Consequently, a study of an analytical model that allows the simulation of the interaction between tillage implements and actual field soil is necessary and important.

Moreover, in conventional tillage practice, plant roots should be removed from the land before seeding, especially for the corn of which the stubble is tightly and deeply embedded in the soil. Generally, the tillage tools dealing with plant stubble, such as rotary blade and plow, will experience huge soil resistance forces. Although there are many existing models to describe the soil-tool interaction or analyze the force acting on tillage tools, there is little research on modeling the root-soil-tool interaction. It is well known that roots can reinforce the soil shear resistance (Wu, 2013; Savioli et al., 2014), and the modeling of root-soil interaction is a challenge considering the complex physical link between these two phases and the differences of their properties. There are some numerical methods that can model explicit surface-to-surface interaction by using constraints performed with Lagrange multipliers or interface elements. But, these models are usually too complicated and large in scale, which could easily result in convergence difficulties during computation. Additionally, these root-soil models available have been developed for botanizing plant growth and examining tree anchorage (Mickovski et al., 2011; Yang et al., 2014). In terms of farming, the stubble influences the properties of soil and enhances the strength of soil, which make stubble and soil become a complex. During the stubble-cutting operation, the stubble-cutting tool cuts off the underground roots and the soil block embedded in the roots will follow the movements of stubble. The stubble-cutting process is more complicated than cutting pure soil. Therefore an adequate prediction model that is capable of providing a better determination of the performance of tillage tool will be beneficial to the design and development of tillage implements.

This work was intended to build a well adaptable and simple numerical model to simulate the root-soil complex and to predict the resistance force acting on stubble cutting tools. In the simulation model developed in this study, soil was assumed to

Table 1
Soil mechanical parameters used in FEM model.

Property	value
Bulk density, ρ(Mg/m^3)	1.79
Young' modulus,E (MPa)	1.2
Poisson's ratio, υ	0.3
Friction angle,β (deg.)	12.21
Stress ratio,k	1
Dilation angle,ψ (deg.)	0
Soil moisture,%	20.03
Soil-metal friction coefficient	0.2

a b c


Fig. 1. Corn stubble sample (a) root width (b) root depth (c) root body parts.