Journal of Terramechanics 80 (2018) 1–9

Contents lists available at ScienceDirect

Journal of Terramechanics

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

Use of explicit finite-element formulation to predict the rolling radius and slip of an agricultural tire during travel over loose soil

Dror Rubinstein, Itzhak Shmulevich, Nicolay Frenckel

Technion, Faculty of Civil Engineering, Research Center of Agricultural Engineering, Haifa 3200003, Israel

ARTICLE INFO

Article history:
Received 10 June 2018
Accepted 19 September 2018

Keywords:
Soil wheel interaction
Gross traction
Net traction
Finite element
Eulerian
Lagrangian
Zero slip

ABSTRACT

Theoretically, there is zero slip between two bodies when there is no relative motion in their contact points. In the contact between a wheel and a surface, zero slip can be obtained only in the case of a single contact point. In this case, the wheel and the surface must be rigid. The theoretical zero-slip condition can't be obtained in the contact between tire and terrain surface. In much of the scientific literature, two alternatives are suggested for a practical definition of the zero-slip condition: the point at which the gross traction force is equal to zero, or the point at which the net traction force is equal to zero. In the ASABE (2013), there is still no unique definition for the practical zero-slip condition. According to the definition of zero-slip condition, the rolling radius is not constant and depends on the slip.

A detailed finite-element model using Lagrangian elements was built for each tire, taking into account the effect of all tire materials and their arrangement, lug shape, and inflation pressure. The soil model was built with Eulerian elements, which allow a large degree of deformation and flow of the soil. The initial verification experiments of the tire models were conducted by pressing the tires against a rigid plane. Each tire was examined under several different inflation pressures. Very good correlations were obtained between the experimental and model results. The verification test for the gross and net traction forces was performed in the soil-bin laboratory at the Technion. Special equipment was built, including a heavy dragging platform and a cell to hook the tire. This equipment allows control of the tire slip. The net traction force, gross traction force, and vertical load were measured in each test. Good correlations were obtained between the experimental and model results.

Using the FEM model developed, some definitions for zero-slip condition were examined. The results indicate that the best criterion for zero-slip condition is definition of the point at which the gross traction force is equal to zero.

1. Introduction

The work deals with the interaction between an agricultural tire and loose soil. The agricultural tire has complex geometry, which includes the lugs on its perimeter. The loose soil, especially in the vicinity of its interface with the tire, is characterized by large deformation, failure, and even flow. For the study of travel over loose soil, it is necessary to develop a reliable model that takes this geometry, deformation, failure, and flow into consideration.

Traction performances can be predicted using empirical, semi-empirical, and analytical models. The value of the gross traction force, net traction force, and rolling resistance can be determined using such a model (Upadhyaya, 2009). These forces depend on the slip and the rolling radius. However, there is still no unique and clear definition of the slip and the rolling radius. The zero condition is a condition when the slip is equal to zero. The proposed solution is to assume the zero-condition option. For this purpose, two options have been suggested: (a) to set zero slip where the gross traction is equal to zero, (b) to set zero slip where the net traction is equal to zero. The value of the rolling radius can be calculated based on the definition of the zero condition. In this case, it is assumed that the rolling radius is constant and independent of the slip. The standard ASABE (2013) does not provide a unique criterion for the zero condition and allows for multiple options.

The most familiar empirical models are those of Wismer and Luth (1974) and of Brixius (1987). In both models, the mechanical properties of the soil are presented by a single parameter, which is the cone index. The best known semi-empirical model is the one developed by Bekker (1960). Over the years, many researchers, such as Shmulevich and Osetinsky (2003), have suggested improvements to the semi-empirical models.

E-mail address: agrdror@technion.ac.il (D. Rubinstein)

https://doi.org/10.1016/j.jterra.2018.09.002

Nomenclature

F	point of the instantaneous axis of rotation
G	a point at the lower part of the wheel on a vertical line that crosses the wheel center
Gr	resultant force applied on the tire
GT	gross traction force
N	normal force
NT	net traction force
O	a point that represents the geometrical center of the wheel
P	a point on the perimeter of the tire through which the resultant force passes
R	the nominal radius of the tire
TF	rolling resistance force
Xc, Yc	the coordinates of the tire center
Xr, Yr	the location of point P relative to the wheel center
Y_r	the vertical distance to point P
d%	the relative deviation in percentages
r	rolling radius
r'	the assumed rolling radius
r_0	the rolling radius at zero condition (where the slip is zero)
r_m	the mean value of the rolling radius
r^*	the instantaneous radius of rotation
s	slip
s'	the measured slip
s_0	the measured slip at zero condition (where the slip is zero)
v_a	velocity of the wheel center
Δs	the difference between the measured slip and real slip
ω	angular velocity of the wheel

The analytical models are based mainly on finite-element or discrete-element approaches. There have been many publications on finite-element models of the interaction between a tire and soil. One of the first works published was by Perumpral et al. (1971). The Drucker–Pager elasto-plastic failure model is widely used in finite-element analysis of loose soil. Some researchers have used this model in the analysis of tire–soil interaction (Chiroux et al., 2005, Fervers, 2004, Schmid, 1995, Shoop, 2001, Shoop et al., 2004). In all the publications surveyed, the Lagrangian elements were used in the soil modeling. The Lagrangian element is the classical finite-element approach, which is used in solid mechanics problems. The Eulerian elements are used in fluid mechanics problems (Qiu et al., 2011). The Eulerian elements are preferred in cases of large deformation or flow (Donea et al., 1982, Kennedy and Belytschko, 1981). The researchers Asaf et al. (2006) and Nakashima and Takatsu (2008) developed two-dimensional discrete-element models of tire–soil interaction. The discrete element approach is designed to deal with large deformation and flow of the particles, and it is suitable for soil analysis (Shmulevich et al., 2009). However, this method consumes an extremely large amount of computation time, especially in three-dimensional cases.

The goal of this research was to develop a reliable model of the interaction between a tire and loose soil. An additional goal was to define the rolling radius and determine the preferred criterion for the zero condition.

2. Finite-element model

The finite-element model of the tire, soil, and their interaction was created using Abaqus 6.10. The tire model was built using Lagrangian elements and the soil model was based on Eulerian elements. The finite-element solution of a combination of Lagrangian and Eulerian elements requires an explicit numerical approach. The explicit approach significantly increases the calculation time. Therefore, in this case, as described below, it was necessary to simplify the tire model.

2.1. Tire model

The chosen tire for this study was AGRI-STAR R-1 W (650/65R38-300) of the Alliance company. A photo of the tire is shown in Fig. 1. A precise model of the tire, which takes into the account all the materials and the layers of the tire, was built. This so-called complex model of the tire consists of 321,450 elements. As described below, the soil model was based on Eulerian elements. The integration between the complex tire model and the soil model is too complicated to be solved within a reasonable time. Therefore, it was necessary to simplify the tire model. The simplified tire model was built using homogenous elastic linear material and 43,734 elements. The geometry of the tire is fully described in the simplified model. Description of the complex and simplified tire models are provided in Figs. 2 and 3, respectively.

Fig. 1. Side view of AGRI-STAR R-1 W tire.

Simulations of the deflection of the complex and simplified tires were performed under various loads and inflation pressures. In order to determine the mechanical properties of the simplified tire, different properties were checked in the simulations. Based on comparison of the simulation results of the two tires, the mechanical properties of the best fitting results were chosen. The simplified tire model was equivalent to the complex tire model in terms of the deflection simulation results. The properties that were used in the simulation were: Young's modulus 29 MPa, Poisson's ratio 0.32, and density $1000\ \text{kg/m}^3$. Deflection simulations of the complex tire model and simplified tire model were performed under inflation pressures of 1.1 bar and 2 bars. The simulation results are shown in Fig. 4. The correlation between the simulation results of the complex model and the simplified model was almost 100%. Therefore, the simulation lines in the figure present both models.

2.2. Soil model

In loose soil, especially in the interface area (between the tire and the soil), soils have large deformation, to the point of failure