

Numerical simulation of tire/soil interaction using a verified 3D finite element model

Namjoo Moslem, Golbakhshi Hossein

Department of Agricultural Machinery Engineering, Faculty of Agriculture,
University of Jiroft, Jiroft 78671-61167, Iran

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Abstract: The compaction and stress generation on terrain were always investigated based on empirical approaches or testing methods for tire/soil interaction. However, the analysis should be performed for various tires and at different soil strengths. With the increasing capacity of numerical computers and simulation software, finite element modeling of tire/terrain interaction seems a good approach for predicting the effect of change on the parameters. In this work, an elaborated 3D model fully complying with the geometry of radial tire 115/60R13 was established, using commercial code Solidwork Simulation. The hyper-elastic and incompressible rubber as tire main material was analyzed by Moony-Rivlin model. The Drucker-Prager yield criterion was used to model the soil compaction. Results show that the model realistically predicts the laboratory tests outputs of the modeled tire on the soft soil.

Key words: tire/soil interaction; finite element method (FEM); soil compaction; stress distribution; inflation pressure

1 Introduction

Operation of heavy implements on unpaved soft soil is a considerable topic research in agriculture [1]. The compaction of soil layers caused by tire/terrain interaction can be reduced by well analysis of effective factors including load magnitude, tire inflation pressure, tire structure and terrain stiffness.

Because of low tensile strength, the soil yields and becomes permanently deformed. So, any modeling effort including soil interaction seems to be non-linear with high variability of the soil material. The major effort to analyze the tire/soil interaction was focused on empirical approaches or field tests in the past. It has been proved to be extremely expensive and time consuming to test tire performance using field tests. These methods produce results that are valid only for the particular testing conditions which are intrinsically difficult to be evaluated. Furthermore, it is extremely difficult to measure and maintain the experimental parameters during testing. The real soil hardly behaves as a homogeneous material and its properties easily change with location and weather conditions [2].

Compared to existing analytical and empirical methods, computational methods, e.g., the finite element method, have the capability of modeling machine-terrain

interaction in a very detailed manner without introducing many simplifying assumptions. Some researchers [3–5] also attempted to model the soil with discrete element (DE). However, finite element method (FEM) has increasingly been utilized to analyze non-linear and non-elastic materials such as soil.

Based on many idealizations like the soil being isotropic, elastic, and with a prescribed contact area, the early simplified numerical works, e.g. Ref. [6], conducted on simulation of machine-terrain interaction. YONG et al [7–8] using a non-linear elastic constitutive relation for soil studied the deformation (compaction) in the soil caused by wheel load. By providing some numerical facilities such as non-linear modeling and improved contact algorithm in commercial software like ABAQUS, the simulation of soil-machine interaction have been considerably advanced. Using the pressure dependent Drucker-Prager model for the soil and taking into account its frictional behavior, AUBEL [9] achieved more realistic results for the analysis of rolling wheels on the soft soil. FERVERS [10] developed a two-dimensional (2-D) FEM model with acceptable accuracy for the analysis of an air-filled tire interaction on soft soil and rigid road.

Reducing the highly non-linear analysis of tire interaction with a plastic deformable soil into a 2D finite element model seems to be reasonable for avoiding high

computational efforts. But the carcass, as the only element that transmits the axial load from the rim to the ground, is intensely influenced by deformation in the third dimension. So, the existing 2-D tire models are not satisfying.

Nowadays, by considerable improvement in personal computers, various 3D detailed models were developed for numerical simulation of tire/soil interaction. Furthermore, using higher-order hexahedral instead of conventional tetrahedral elements for the solid model converts into a discrete mesh, the required calculations can be dramatically reduced.

Researchers have given due importance to the inclusion of tread pattern in tire analyses. SHIRAISHI et al [11] modeled the complicated tread pattern using tetrahedron elements. CHAO et al [12] presented an innovative mesh generation program for tread pattern modeling with all hexahedral elements. In their work, they have found improvement in footprint pressure distribution over the conventional approach.

Through an elaborated three-dimensional finite element model, the interaction of radial tire 115/60R13 with moderate tread size was studied on the soil ground. Compared with the test results, it demonstrates that numerical model can serve as a robust tool on predicting soil compaction and stress field, without engaging in previously mentioned limits associated with the experimental methods.

2 Material and method

2.1 Experimental set-up for FEM model validation

To validate the numerical model, it is important to design an experiment which can provide needed data for comparison. Laboratory and field experiments were carried out at the Agricultural College of Shiraz University in 2011.

The experimental program was performed on a soil bin with inside dimension of 5000 mm long, 800 mm deep and 600 mm wide. The tire holding frame was pushed on the soil surface by means of three hydraulic jacks, which was driven by an electromotor. The scheme of the stand is presented in Fig. 1. By measuring the same points relative to a fixed base, before and after the tire passed over the test lane, the soil deformation or sinkage can be determined. The soil frictional angle and cohesion which are constitutive parameters for the Drucker-Prager model, are measured to be $\phi=30^\circ$ and $c=0.03$ MPa, respectively. The elastic modulus, Poisson ratio and mass density of the considered soil are also found to be $E=0.03$ MPa, $\nu=0.3$ and $\rho=1600$ kg/m³.

The high exerted axial load guarantees the tire will be driven with no slip in this simulation. The coefficient of friction is taken to be $\mu=0.5$ on the soil-tire interface.

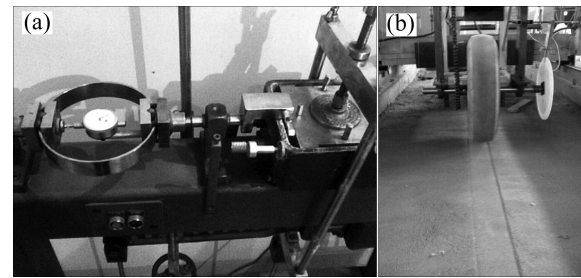


Fig. 1 General view of experimental equipment: (a) Instrument used for estimation of soft soil parameters; (b) Laboratory stand for moving tire on terrain surface

2.2 Tire modeling

The interaction of 115/60R13 steel belted radial tire with a soft terrain surface was analyzed using Solidworks Simulation Software. From structural point of view, the pneumatic tires have two categories of components: the carcass that holds the air pressure of the tire and withstands external loads and wear resistant tread block providing necessary traction at leading and trailing edges of tire are just made by rubber. The layers of circumference belts which are used to stiffen the tread and strengthen the carcass or the tire body are made by reinforced materials.

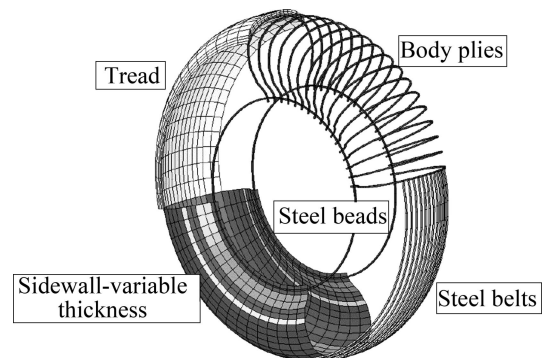


Fig. 2 Radial tire components modeled in Solidworks Simulation Software

By considering the rubber as a hyper-elastic and incompressible material, the behavior of pneumatic tire can be described by the amount of stored strain energy in deformed body evaluated from Mooney-Rivlin equation:

$${}^tW = C_{01} ({}^tI_1 - 3) + C_{10} ({}^tI_2 - 3) \quad (1)$$

where tW is the stored strain energy; tI_1 and tI_2 are constant strains; C_{01} and C_{10} are coefficients.

The thicknesses of treads, sidewalls and ring were 10 mm, 7 mm and 5 mm, respectively. For tire meshing, 8-node linear hexahedral elements with dimensions of 1 mm and aspect ratio of 1.5 was used. Finally, using 2956 nodes and 1478 elements, the tire domain was modeled. The mechanical properties of rubber and steel ring are listed in Table 1. The rim is modeled as a rigid

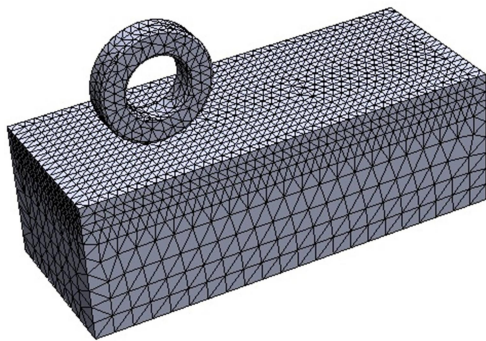
Table 1 Material properties used in tire FE model [13].

Parameter	Thread	Belt	Carcass
C_{01}	8.061	—	—
C_{10}	1.806	—	—
Density, $\rho(\text{kg}\cdot\text{m}^{-3})$	1400	7644	1390
Modulus of elasticity, E/GPa	—	55	0.794
Poisson ratio, ν	—	03	0.45

body. So, the distance between the tire center and bead area remains constant during the analysis. The inflation pressure was applied to the inner surface of tire cross-section.

2.3 Soil modeling

The terrain part considered in this work is 3000 mm in length, 1000 mm in width and 800 mm in depth. The soil boundaries are far enough from the tire location to have virtually no effect on the deformation field. The soil volume is regarded as two regions discretized using different mesh densities; a thin layer in contact with the tire and a thick bottom layer (Fig. 3). This approach allows a great reduction in storage requirements and run time due to relatively coarse mesh used outside the contact area. All the terrain parts are modeled using 80653 solid elements.

**Fig. 3** Mesh generation for analysis of tire/terrain interaction

The soil deformation mainly owes to plastic flow when the yield stress is reached. So, the use of an appropriate yield criterion is very crucial for the analysis of plastic behavior of the soil. In this work, the Drucker-Prager model is used to calculate stress and strain of the soil.

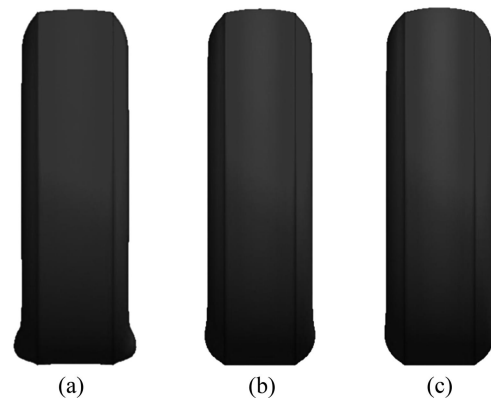
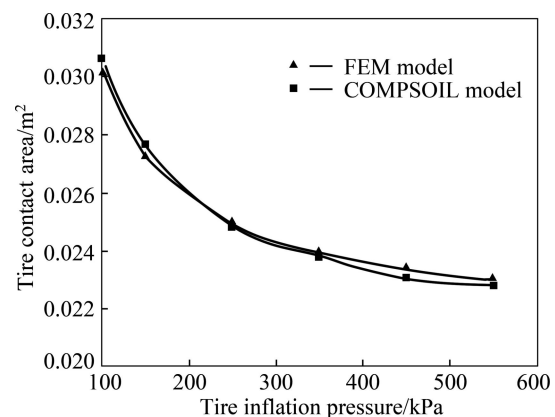
3 Results and discussion

The simulation results for tire contact area and vertical displacement, deformation in soil configuration and stress variation on tire/terrain interface, are presented and compared to available empirical results to demonstrate validity of the model.

For the same vertical load of 4 kN, deformations of

the tire with three inflation pressures, 100 kPa, 200 kPa and 300 kPa, are shown in Fig. 4. The lower contact area on soft ground is observed for inflation pressure of 300 kPa. The results have perfect similarity with XIA's [14] prediction for tire deformed body.

The output results for contact area are plotted versus tire inflation pressure in Fig. 5. The area will decrease with increasing the inflation pressure. For comparison, the results of COMPSOIL model [15] for contact area are also plotted in the same figure. The results given by the numerical analysis have a good agreement, as shown in Fig. 5.

**Fig. 4** Tire deformation with different inflation pressures: (a) 100 kPa; (b) 200 kPa; (c) 300 kPa**Fig. 5** Tire contact area versus tire inflation pressure

The vertical displacements of tire hub for two values of inflation pressure, are plotted in Fig. 6. A very good agreement can be found between numerical and experimental results. Moreover, this agrees with the results of Ref. [10] for simulation of tire/road interaction. This implies the fact that tire deformation, rather than soil effect, plays more dominant role to control the hub vertical displacement.

For the axle load of 4 kN, Fig. 7 shows the variation of vertical displacement of tire hub with inflation pressure. The obtained results are quite similar to Ref. [14]. It can be found that higher inflated and stiffer tire undergoes less vertical displacement under the same

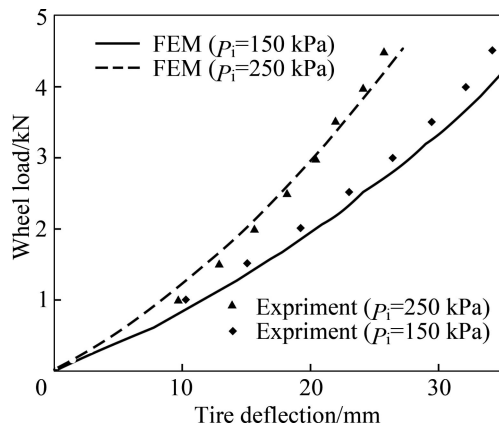


Fig. 6 Tire hub displacement versus axial load

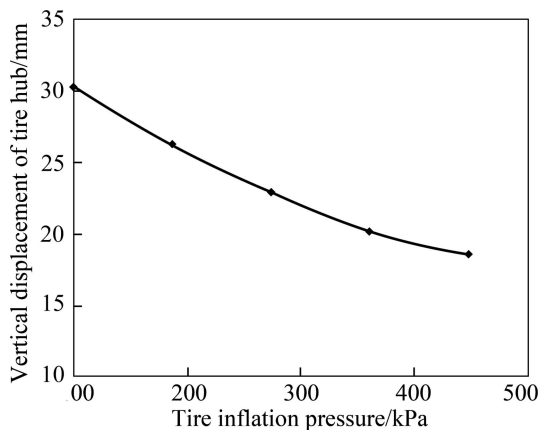


Fig. 7 Tire hub displacement versus inflation pressure

axle load. The difference between simulation results and experimental observations seems to be caused by non-optimum mechanical parameters estimated for the soil.

The vertical stress distributions on the soil surface for different inflation pressures are depicted in Fig. 8. According to the simulation outputs, by decreasing the inflation pressure, the position of maximum contact stress shifts from center to the side wall of contact regions. The results show well agreement with the suggestions of Ref. [16]. Distribution of stress inside the soil is shown in Fig. 9. It appears that reduction of the inflation pressure has not any considerable effect on the generated vertical stress reaching depths below 100 mm. Whereas, the topsoil stress will significantly increase with tire inflation pressure; that is consistent with the observations from Ref. [17].

It is known that greater amount of strain energy will store on more deformed bodies. So, the soil regions with maximum volume change can be predicted.

Figure 10 depicts the stored strain energy in the soil for the tires with 150 kPa and 550 kPa inflation pressures. It can be found that in both cases, the top layer of the soil is well compacted, whereas in deeper layers, negligible compaction occurs. However, the reduced inflation

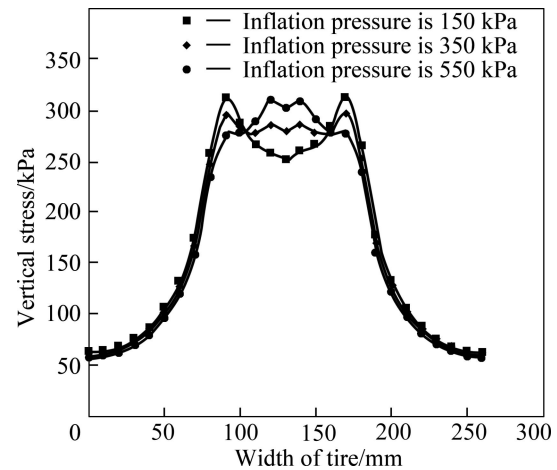


Fig. 8 Vertical stress distributions on soil surface

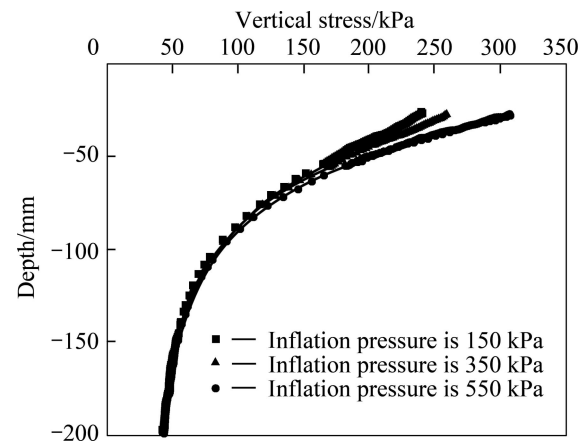
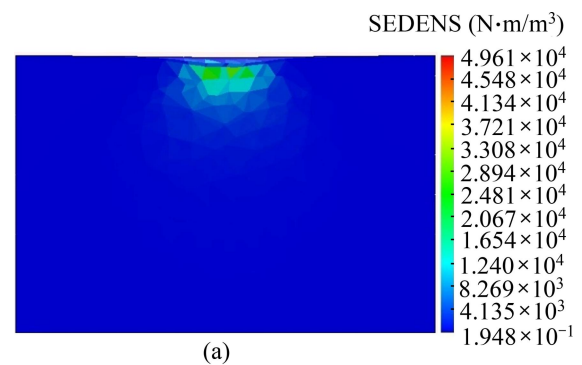
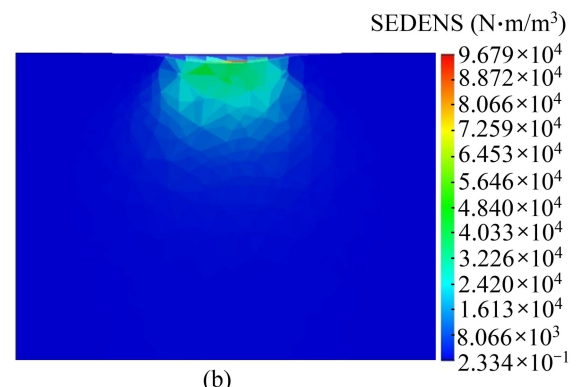


Fig. 9 Vertical stress distribution in soil profile



(a)



(b)

Fig. 10 Stored strain energy in deformed soil ground: (a) For 150 kPa inflation pressure; (b) For 550 kPa inflation pressure

pressure leads to lower compaction in the soil. It can be explained by the fact that any reduction in inflation pressure will increase the contact area and diminish the compressive effect of interaction on terrain surface.

4 Conclusions

In the past, the main approach for analysis of tire/soil interaction problem is focused on extremely expensive and time consuming field tests. A robust three-dimensional finite element model is presented in this work that accurately predicts the empirical results and observations. Using Mooney-Rivlin model for simulation of hyper-elastic behavior of the rubber and Drucker-Prager yield criterion for the soil, the effects of tire inflation pressure and axial load on tire/terrain interaction are well evaluated. Comparing the results with available field data proves the abilities of this model.

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