3D finite element model to simulate the rolling resistance of a radial ply tire validated by experiments in soil bin testing facility

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Abstract

The present study adopts finite element method (FEM) for the simulation of soil-wheel interaction and analyzing the effects of tire inflation pressure, wheel load and velocity on rolling resistance. The Drucker-Prager/Cap model implemented in ABAQUS/Explicit environment was used to model the elastic-plastic parameters of the soil behavior where the pneumatic tire was modeled using finite strain hyper-elastic material model. Large mesh distortions and contact problems can occur due to the large deformations such that a convergent solution cannot be achieved. A new Coupled Eulerian-Lagrangian (CEL) method was used to describe soil-wheel interaction to overcome this drawback. Experimental tests were carried out in a soil bin facility using single-wheeled tester as affected by five levels of wheel load, three levels of tire inflation pressure and three levels of velocity. The model showed that rolling resistance increases by the increment of wheel load and decrement of tire inflation pressure. However, velocity has no significant effect on rolling resistance. The results of FEM indicated promising fitness to the experimental values whilst the predicted results can be used for analytical deterministic and stochastic simulation of soil-wheel interaction.

Keywords: Coupled Eulerian–Lagrangian; Drucker–Prager; Finite element method; Rolling resistance

1. Introduction

Soil-wheel interaction is a highly difficult research context and is considered as a critical subject to design run-off-road machines. Accurate solutions are necessary to gain a better insight into soil-wheel interactions which can lead to convenient analysis of tractive performance parameters as well as the influence of machine on terrain. Computer based numerical simulations are functional techniques to provide the optimized tire design at various operational configurations of tire parameters. The modeling allows making recommendations to the farmers and advisors with regard to the technologies and agricultural equipment to be used at the minimum of cost and operational time. Furthermore, 3D modeling of tire-terrain interaction establishes functional information for tire and machine designers to monitor the behavior of the running tire over a terrain profile. Rolling resistance is of substantial tractive performance parameters that can be estimated by stochastic numerical finite element method (FEM). Rolling resistance is regarded as a major source of energy dissipation in Terramechanics and is defined as the summation effect of tire deflection and soil deformation under the traversing wheel. In contrast to the present analytical and empirical methods, the finite element has the ability of modeling the soil-wheel interaction in a very complete method without introducing simplifying assumptions, especially on the dynamic contact part [1]. The tire can be simulated as a flexible body using finite strain hyper-elastic material model. As a robust numerical tool, finite element has been extensively applied for stress and deformation analysis where the advantage of FEM model for tire/terrain interaction is that impermeability and traction situations can be better dealt with at the contact interface [1].

Xia [1] used finite element modeling of tire/terrain interaction to predict soil compaction and tire mobility as well as a finite strain hyper-elasticity model for modeling of rubber materials using the Drucker–Prager/Cap model implemented in ABAQUS. Based on the report by Xia [1], it was stated that where empirical field tests can be extremely expensive and time consuming, FEM showed to be a robust technique with acceptable accuracy in the field of tire/terrain interactions. In a recent study, three dimensional finite element model of soil compaction caused by agricultural tire traffic was assessed [2]. The research was performed with the objective of developing a FEM based model, valid for soil compaction simulation created by agricultural tire traffic that permits research factors that cause soil compaction of a Rhodic Ferralsol soil. The depth at which soil compaction was produced for each combination of tire inflation pressure and tire load, and the relationship between the tire inflation pressure, contact stress and tire load with soil compaction was predicted. In a similar study for the investigation of the induced snow stresses, finite element modeling of interfacial forces and contact stresses of pneumatic tire on fresh snow for combined longitudinal and lateral slips was carried out by Lee [3]. The traction, motion resistance, drawbar pull, tire sinkage, tire deflection, snow density, contact pressure and contact shear stresses were obtained as a function of longitudinal slip and lateral slip. There are
other studies in the literature to report the effect of rolling tire on soil characteristic addressing the indentation and rolling by Hambleton and Drescher [4,5] using a combination of analytic and numerical approach.

As far as our literature review is concerned, literature lacks the study to address FEM based numerical modeling of tire rolling resistance on deformable soil as affected by wheel load, velocity and tire inflation pressure. Hence, the authors encouraged to simulate the soil-wheel interaction using the FEM approach and to validate the results of the model by experimental dataset obtained from series of experiments in a soil bin facility.

Fig. 1. The general soil bin testing facility with the test rig used for experimental stage.

Fig. 2. Various layers of tire being simulated.

Fig. 3. Figure 3- a) Drawing the tire by positioning from a real cut profile of the tire, b) imported sketch of the tire geometry.

2. Materials and Method

2.1 Data Collecting
Tests were carried out in the soil bin facility of Urmia University utilizing the single-wheel tester under the effect of three variables of tire inflation pressure, velocity and wheel load. The soil bin was filled with clay loam soil as the prominent soil type of test location with the detailed specifications in Table 1. An electromotor connected to one inverter was employed to apply different levels of forward velocity to the single-wheel tester using a chain system at sides of the channel. Wheel load was controlled using a vertically situated load cell between the power bolt and the tester hub with the rotation of the power bolt handle. Rolling resistance was quantified using four load cells horizontally installed on four arms which connect the single-wheel tester to the carriage. Data were simultaneously transmitted to the corresponding digital indicators and then to the laptop computer (Fig. 1). An interested reader may refer to the published work of authors with detailed information of the soil bin facility mechanism [6].

2.2. Development of the finite element tire model

A 9.5L-14 radial ply pneumatic tire was selected for the modeling. Since it is a complex and expensive task to obtain the real mechanical properties of a tire [2], the linear elastic properties were employed to characterize the tire constitutive model. The tire constitutive consists of three major sections of tread, inner layer of reinforced rubber plies (i.e. belt and carcass) and ring (Fig. 2). The reinforced rubber ply section is incorporated of 7 different layers with four belts which are presses to the tire tread. The thicknesses of the layers and belts as well as the belt directions were measured from a cut profile of the tire. The angles were +22° and -22° for belt layers and 90° for the carcass layer. The structure of the rubber tire is modeled by planar with four nod element using the reduced integral formulation to increase the convergence and decrease the solution time. Furthermore, for modeling the tread section of the tire, a mechanical property of incompressible hyperelastic with Mooney-Rivlin coefficients was used [7,8]. The process of modeling the tire geometry from the cut tire is illustrated in Fig. 3.

Soil constituents and specifications used for the simulation in the present study are presented in Table 1. Soil profile was therefore considered as perfectly elastic-plastic material. Linear elastic properties were employed for representation of soil characteristic and plasticity Drucker–Prager model based on Mohr–Coulomb method to establish the plastic behavior of soil. Furthermore, Coupled Eulerian–Lagrangian (CEL) approach was adopted to formulate the soil profile by Eulerian and tire characteristic by Lagrangian (deformable) approach, respectively. In order to obtain rolling resistance, it is essential to carry out the dynamic soil-wheel interaction analysis. Central difference explicit method was preferred to Newmark implicit approach owing to applying diagonal matrix of mass in central difference method which can drastically reduce the processing time [9]. Additionally, standard explicit finite element method can accurately predict the soil compaction while the tire (RP as the reference point) 0.5 s in the second step simply requires a contact coefficient to produce the stiffness matrix.

Soil was meshed using 8-node linear Eulerian brick, reduced integration, hourglass control (EC3D8R) while three different element types were selected for three tire layers. 8-node linear brick, reduced integration, hourglass control (C3D8R) represented for the tread and 4-node doubly curved thin or thick shell, reduced integration, hourglass control, finite membrane strains (S4R) was chosen to signify the rubber. S4R has the capacity for the computation of large rotations, limited strains and thickness variations at each nod. Finally, 4-node 3-D bilinear rigid quadrilateral (R3D4) element was employed for tire ring owing to the rigidity of the ring and being a non-deformable layer (Fig. 4). Fig. 5 shows the meshed soil profile and tire on terrain at the assembled configuration. Size of elements can drastically affect the convergence of the problem. The region where the accuracy is required had finer size and the area with no critical importance had coarser element size. Number of the element and nodes used in the study are detailed in Table 2. Furthermore, Poisson’s ratio and Young Modulus in the principal (x) and (y) direction of tire layers are shown in Table 3.

The contact between two surfaces (i.e. soil as Eulerian and tire as Lagrangian parts) was implemented by dynamic explicit approach based on tangential frictional modeling using penalty method. Soil-wheel interaction was simulated using interfacial friction contact method which enables to control the transmission of shear stresses and tangential forces. The frictional coefficient in the entire simulations was considered [10]. To describe the contact between two deformable regions, tire and soil were considered as the master and slave surfaces, respectively. Surface-to-surface is an appropriate contact type for the description of soil-wheel interaction problem and provides large deformations using various frictional models. Contact element was used as proposed by Darnell [11] which use the penalty function to constraint the movement of series of nodes. This also establishes interaction-slip tendency for the modeling of soil-wheel interaction [12]. Surface-to-surface contact with finite sliding was used to describe the contact between the tread and the inner layer of reinforced rubber plies and also between the inner layer of reinforced rubber plies and the ring. The nodes of tire in the vicinity of the ring were constrained to the ring using the penalty function method. Tie and coupling configurations were employed for the interconnections between the tread, inner layer and the ring. Finally, the following steps were implemented to simulate the rolling of tire on the terrain.

Step 1: Applying the desired tire inflation pressures at different levels to the tire in 0.2 sec where all degrees of freedom at the center of the tire were fixed applying contact pressure to the inner layer of the tire [3].

Step 2: Applying desired level of wheel load at the center of

Step 3: Applying the desired velocity to the RP leading to the rolling of the tire on terrain.
Fig. 4. Meshing of a) tread, b) inner layer, and c) ring.

Fig. 5. a) Meshed soil profile and b) assembly of the tire on the soil profile.

Fig. 6. Variation of rolling resistance with respect to the tire displacement at five different levels of velocity

Table 1. Soil constituents and its measured properties

<table>
<thead>
<tr>
<th>Item</th>
<th>Value</th>
</tr>
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<tbody>
<tr>
<td>Item</td>
<td>Value</td>
</tr>
<tr>
<td>Soil Property</td>
<td>Value</td>
</tr>
<tr>
<td>----------------------</td>
<td>-------</td>
</tr>
<tr>
<td>Sand (%)</td>
<td>34.3</td>
</tr>
<tr>
<td>Silt (%)</td>
<td>22.2</td>
</tr>
<tr>
<td>Clay (%)</td>
<td>43.5</td>
</tr>
<tr>
<td>Bulk density (kg/m³)</td>
<td>2360</td>
</tr>
<tr>
<td>Frictional angle (°)</td>
<td>32</td>
</tr>
<tr>
<td>Cone Index (kPa)</td>
<td>700</td>
</tr>
<tr>
<td>Cohesion (kg/cm²)</td>
<td>0.003</td>
</tr>
<tr>
<td>Poisson coefficient</td>
<td>0.3</td>
</tr>
</tbody>
</table>

Table 2. Element and node numbers in different parts of the developed model

<table>
<thead>
<tr>
<th>Number</th>
<th>Ring</th>
<th>Inner layer of multiple rubber plies</th>
<th>Tread</th>
<th>Soil</th>
</tr>
</thead>
<tbody>
<tr>
<td>Element</td>
<td>1596</td>
<td>4316</td>
<td>4843</td>
<td>156600</td>
</tr>
<tr>
<td>Node</td>
<td>1596</td>
<td>4482</td>
<td>10020</td>
<td>167462</td>
</tr>
</tbody>
</table>

Table 3. Poisson’s ratio and Young Modulus in the principal (x) and (y) direction [7].

<table>
<thead>
<tr>
<th>Belt</th>
<th>Poisson’s Ratio</th>
<th>Ex</th>
<th>Ey</th>
<th>Poisson’s Ratio</th>
<th>Ex</th>
<th>Ey</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carcass</td>
<td>0.5</td>
<td>11.7</td>
<td>29.1</td>
<td>0.27</td>
<td>13.82</td>
<td>12.12</td>
</tr>
</tbody>
</table>

Fig. 7. Close fitting of the experimental data to the FEM based numerical modeling results (R is rolling resistance and W is wheel load).

Fig. 8. Variation of rolling resistance with respect to the tire displacement at five different levels of wheel load.

Fig. 9. The tire stresses due to soil-wheel interactions at 100 kPa inflation pressure, velocity of 0.65 m/s at a) 1 kN and b) 3 kN.
Fig. 10. Stress propagation in the soil profile at 100 kPa inflation pressure, velocity of 0.65 m/s at a) 1 kN and b) 3 kN.

Fig. 11. Close fitting of the experimental data to the FEM based numerical modeling results (R is rolling resistance and W is wheel load).
Fig. 12. Variation of rolling resistance with respect to the tire displacement at three different levels of tire inflation pressure.

Fig. 13. Close fitting of the experimental data to the FEM based numerical modeling results (R is rolling resistance, P is tire inflation pressure and W is wheel load).

3. Results and Discussion

Five levels of velocity were used in the simulations at the tire inflation pressure of 100 kPa and wheel load of 2 kN as depicted in Fig. 6 for the displacement of tire during 2 m of traversing. As appreciated from Fig. 6, by increase of velocity, significant variations are observed at the initiation of the movement which is then damped and at different velocities; the rolling resistance is more converged particularly after stabilization of rolling resistance with respect to the displacement. It is further inferred that velocity has no significant effect on rolling resistance especially at lower levels. Insignificant effect of velocity on rolling resistance could be attributed to the insignificant variation of tire deflection and soil deformation with respect to the forward velocity. Furthermore, it is proved that contact area is not significantly affected by the increase of velocity that leads not negligible change of rolling resistance versus velocity [6]. These findings are in good agreement with the experimental data (Fig. 7) and those of published papers in the literature [6, 13-15]. Coefficient of rolling resistance versus velocity is shown in Fig. 6 that demonstrates good agreement between the experimental data and numerical method of FEM although the results of FEM are presented for an extended range of velocity than that of experimental range. The variations at the initiation of the movement are not significant as statistically approved by Taghavifar and Mardani [6] and Kawase et al. [16] who confirmed the vibrations at the initiation of the movement for an agricultural tire.

The results of five levels of applied wheel loads are depicted in Fig. 8 versus displacement of tire. It is clear that increased wheel load leads to the increment of rolling resistance. As expected, the lowest rolling resistance corresponded to the
minimum applied wheel load where the greatest rolling resistance was formed due to the greatest wheel load. At increased wheel load, tire deflection and soil deformation increase considerably that result in augmentation of the dissipated energy while traversing. Accordingly, there is a significant increment of rolling resistance with respect to the wheel load. It is interesting to note that at increased wheel loads, rolling resistance increase with respect to displacement. This should be due to gathering of soil volume in front of the traversing wheel at higher wheel loads that functions as a continuous obstacle impeding tire from rolling. To obtain a better understanding in this regard, Fig. 9 and Fig. 10 are presented at two sample loads of 1 and 3 kN to illustrate the effect of soil-wheel interactions on the tire and soil. Coefficient of rolling resistance versus wheel load is shown in Fig. 11 that demonstrates good agreement between the experimental data and numerical method of FEM. The results of the present study are comparable with the literature studies [6, 17].

The results of FEM for the simulation of the rolling resistance versus three tire inflation pressure levels are presented in Fig. 12. As seen from Fig. 12, increased tire inflation pressure results in decrease of rolling resistance. The greatest rolling resistance corresponded to the lowest tire inflation pressure at 100 kPa and reversely, the lowest rolling resistance corresponded to the greatest tire inflation pressure of 300 kPa. This phenomenon is attributed to the bulging effect where at inflated tire, the stiffness of tire increases by increase of the pressure. This increases the resistance of tire versus tire deflection and the rolling resistance decreases accordingly. Coefficient of rolling resistance versus tire inflation pressure is shown in Fig. 13 that demonstrates good agreement between the experimental data and numerical method of FEM. The results of the present study are comparable with the studies in literature [6, 18].

4. Conclusions

A three-dimensional finite element model of rolling resistance caused by agricultural tire traversing under the effect of wheel load, velocity and tire inflation pressure which was validated in experiments on a soil bin is presented in this paper. The Drucker–Prager/Cap model implemented in ABAQUS/Explicit was used to model the elastic–plastic parameters of the soil behavior where the pneumatic tire was modeled using finite strain hyper-elastic material model. A new coupled Eulerian–Lagrangian (CEL) method was used to describe soil–wheel interaction to permit large deformations of the elements. The model showed that rolling resistance increases by increment of wheel load and decrement of tire inflation pressure. However, velocity has no significant effect on rolling resistance. The results of FEM indicated promising fitness to the experimental values whilst the predicted results can be used for analytical deterministic and stochastic simulation of soil–wheel interaction.

References