Stress Analysis of Tractor Tire Interacting with Soil using 2D Finite Element Method

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Abstract: Soil compaction under tractors tires is becoming a major concern as larger machines are being used in recent years. The heavy duty off-road machines particularly those related to agricultural practices drastically compact the soil causing higher energy consumption and lower yield. The size and form of the tire and soil interaction as well as soil type are important in stress distribution. The objective of this study was to develop a model for soft soil responding to tire pressure and axel load using finite element (FE) technique. A 2D-axisymmetric Drucker-Prager material FE model was developed for analysis of soil behaviour under different load and tire inflation pressure. A 2D symmetric Moony-Rivilin model was also used for soil and tire interaction and compared with measured field response data available in literature. The maximum soil-tire pressure of 83.7 kpa was found for 70 kpa inflation pressure and 15kN axel load which were approximately 30% less than the stress at the tire contact patch in the field test as reported in the literature. Maximum vertical stress at contact area was 98.6 kPa for 150kPa inflation pressure and 15 kN axel load which was not statistically significant while comparing with 101 kPa previously reported 3D analysis. The maximum distributed stress was found at tire side wall. Results also showed that 2D axisymmetric model is able to monitor the soil-tire stresses with an acceptable accuracy.

Keywords: Contact Stress, Finite Element Method, Inflation Pressure, Tire.

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1 INTRODUCTION

Modern tractors are becoming larger and consequently their load capacity is greater than previous models. Heavier vehicles have the potential to cause higher stress to the soil. When a vehicle runs over the soil, the soil surface is exposed to mechanical stresses due to the tire or track load which causes soil compaction [1]. Soil compaction due to machinery manoeuvring is one of the important concerns in agricultural practices where higher compaction introduces higher energy consumption for soil preparation and lower yield due to lower plant development [2]. Therefore, the study on soil compaction could lead to an efficient modification of agricultural implements particularly those operating on soil. The stress below a tire is a function of tire shape, tire inflation, axial load and soil conditions. In order to predict the stress in soil due to wheel pressure, the stress has to be determined on the soil and wheel surface area. The effect of surface stress distribution on soil stress decreases with increasing depth [3]. The vertical stress in the upper subsoil (down to 1m depth) depends on both ground contact stress and wheel load [3]. Way and Kishimoto (2004) have shown that the stress in the contact area is not uniformly distributed and the maximum stress may be many times greater than tire inflation pressure [4]. The finite element (FE) technique is a numerical tool in evaluating different effects of tires on soil. This method is a very useful numerical tool in evaluating different effects on components of tire performance. It can predict different behaviour of tire in various conditions [5]. The use of predictive FE models in tire design and analysis has been widely used [1-3], [5-8], [11], [12] in recent years. The distribution of internal soil stress can be practically predicted using FE where it is very complicate to measure them experimentally. Various tire models are also constructed to simulate the physical nature of tire materials and their interaction with the soil [6]. It is sufficient to use a two-dimensional (2D) axisymmetric tire model for the numerical simulation of tire inflation [7]. This simulation option represents a computationally inexpensive alternative to a full three-dimensional (3D) tire model designed for severe loading or extreme operations. A 2D FE model for agricultural tires was previously reported based upon the equivalent elastic modulus given different tire situation and thickness variations versus tire cross-section [8]. In this methodology, it is assumed that the bead, sidewall, tread and lugs have different elastic behaviour in FE model for estimation of the tire deformation and normal contact pressure. The majority of FE tire models are concerned with car tires and very few are related to truck tires. The dimensional geometry, material properties of each layer, inflation pressure and, the loading conditions of tractor tires are quite different from those of truck tires. Therefore, there is still a need for higher accuracy and reliability in modelling tractor tires on deformable soil. Several investigations have shown that the distribution of vertical stress in soil just below a loaded tire is not uniform. Several investigations showed that the performance of soil compaction models is highly dependent upon a correct input of the surface soil stress distribution [9]. The objectives of this study were:

- To develop a 2D multi-laminated model of a tractor tire on soil.
- To verify the efficiency of the model with measured field response data in previous literature.
- To determine the effect of load and inflation pressure on mean and peak tire–soil interface stresses.
- To model the response of soft soil, in relation to tire pressure and axle load
- To compare this analysis with 3D analysis in previous literature

2 MATERIALS AND METHODS

A FE model was developed for deep profile soil structure by means of meshing the soil cross-section to analyze the soft soil material model behavior with large deflection, large strain capabilities and plasticity. The four node plan element 42 available in the ANSYS element library are used in conjunction with Drucker-Prager material model which is applicable to granular material such as soils, rock, and concrete[10].
Rubber is generally considered to be a non-linear, incompressible or nearly incompressible, hyper-elastic material, which often experiences very large deformations upon loading [9]. Moony-Rivilin option is a model specially for modeling natural incompressibility rubbers. Incompressible rubber model is very identical to the 2-parameter existing Moony-Rivilin model [10]. The form of the strain energy potential for 2-parameter Moony-Rivilin model is [10]:

$$
\begin{aligned}
W &= C_{10}(\bar{I}_1 - 3) + C_{01}(\bar{I}_2 - 3) + \frac{1}{d}(J-1)^2 \\
\mu &= 2(C_{10} + C_{01}) \\
k &= 2/d
\end{aligned} \tag{1}
$$

where: C_{10}, C_{01}, d = Material constants.

The initial shear modulus is given by μ and the initial bulk modulus is k. I_1, I_2 = invariants of C_{ij} which are components of the right Cauchy-Green deformation tensor.

$$I_1 = \lambda_1^2 + \lambda_2^2 + \lambda_3^2 \quad (2)$$

$$\bar{I}_2 = \lambda_1^2\lambda_2^2 + \lambda_2^2\lambda_3^2 + \lambda_1^2\lambda_3^2$$

The eigenvalues (principal stretch ratios) of C_{ij} are $\lambda_1^2, \lambda_2^2, \lambda_3^2$ and exist only if:

$$\det\left(C_{ij} - \lambda_p^2 \delta_{ij}\right) = 0$$

$$P = 1,2,3 \quad (3)$$

δ_{ij} = Kronecker delta

3 MATERIAL PROPERTIES DESCRIPTION

A radial tractor tire (Goodyear 16.9 R 38 R-1 agricultural tractor tire) was selected as it is widely used. To formulate the strain energy density for the hyper-elastic element in the FE tire model the Mooney-Rivilin constants and linear elastic approximation were used in Table 2 and 3, respectively, referring to the data reported (Table 2) [11].

Table 1 Material properties for Moony-Rivilin material model and linear elastic approximation [11]

Rubber material	C_{10}	C_{01}	v	$E(GPa)$
Bead filler (mPa)	14.14	21.26		
Under tread	140.4	427		
Sidewall (kPa)	171.8	830.3	0.45	0.0055
Tread (mPa)	0.8061	1.805	0.45	0.14
Textile belts			0.3	3.4
Steel belts			0.3	200

In this study, a 2D-axisymmetric tire model was used in a wide profile of soil where computational modeling procedure is more effective. The structural elements of the tire considered in simulation were; sidewall, bead bundle, tread and under tread. A ring was assembled to the tire. The tire was modelled as a hyper-elastic material and the Drucker-Prager model was used for soil behaviour. The FE type selected for analyzing the tire was plan 182 and the soil was analyzed through plan 42. This element is normally used for 2D modelling and defined by four nodes having two degrees of freedom at each node (translations in the nodal x and y directions) [10]. The tire model was developed assuming that the inflated tire is connected or fixed to the rigid rim through common nodes on the rigid rim. The tire model was subjected to loading in two sequential steps. The initial loading was caused by the tire inflation pressure, which was assumed to be uniform within the tire. The inflated static tire is then subjected to normal loading through application of a specified normal deflection of the tire at the contact region (Fig. 1 and 2).

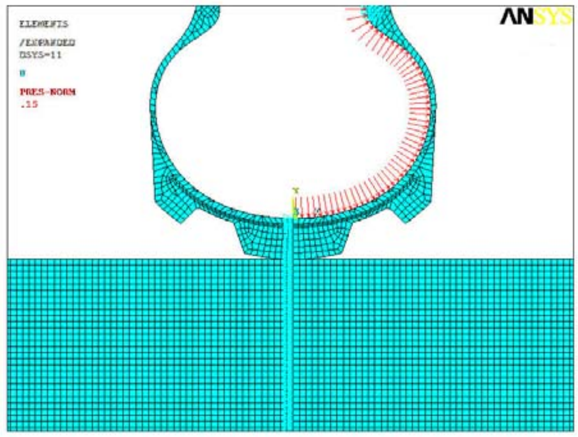

Fig. 1 Developed uniform 150 kPa inflation pressure without vertical load

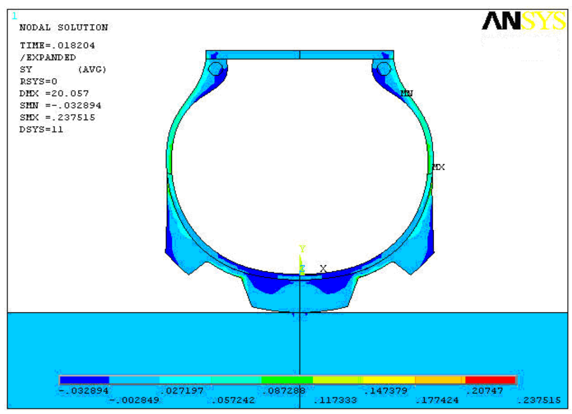

Fig. 2 Stresses after 150 kPa inflated tire with uniform inflation pressure

4 EXPERIMENTAL WORK AND MODEL VALIDATION

An experiment has been carried out at Newcastle, Dublin (Ireland), to investigate the effect of tire–road interface at different inflation pressures and loads. The experiment was performed with two levels of load (15 and 25 kN), and two levels of inflation pressure (70 and 150 kPa) [1]. In the present study tire-soil interface condition was simulated and compared with experimental data in literature. Tijink (1994) found that the contact pressures increases where the rigidity of the surface increases and this increasing trend also exists while moving from soil surface towards a rigid surface [11]. Since the motion resistance will add a vertical force on the tire, the tangential forces and the static analysis was only performed to prevent complexity.

5 RESULTS AND DISCUSSION

Similar to findings of Keller (2005) and Arvidsson et al. (2002) who measured vertical stresses below the wheel of the sugar beet harvester [12], [13] (Fig. 3), the maximum soil-tire pressure of 83.7 kpa was determined for 70 kpa inflation pressure and 15kN axel load which were approximately 30% less than the stress observed at the tire contact patch in the field test as reported in the literature [5]. While in previous research it was 36% less using 3D model simulation (Fig. 4 and 5).

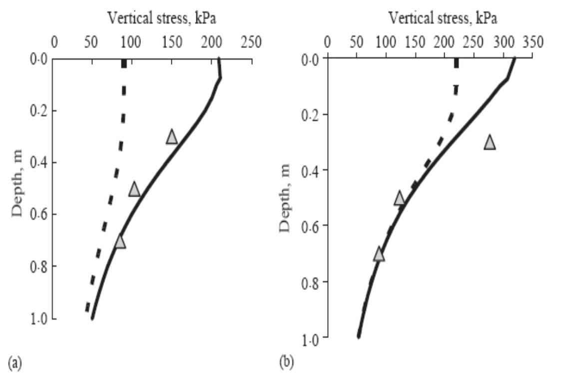

Fig. 3 Measured vertical stress (triangles) for a wheel load of 81.6 kN, and a tire inflation pressure of (a) 90 kPa and (b) 220 kPa; and calculated stress according to Sohne (1953) assuming a circular contact area with a uniform stress distribution (broken curves) and using generated contact stress distribution according to the proposed model (solid curves); measured values from Arvidsson et al. (2002) [12].

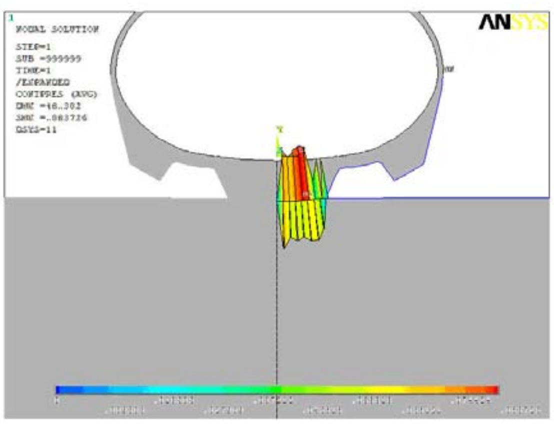

Fig. 4 stress distribution below the calculated tire model. It shows analyzed stress distribution similar to the pattern measured by (T. Keller, 2005) and (Arvidsson et al., 2002). and the Sohne model.

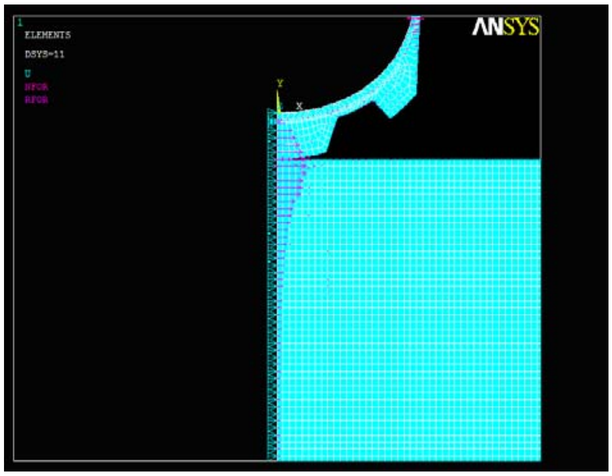

Fig. 5 Contact stress calculated for 15 kN vertical load and 150 kPa inflation pressure.

Maximum vertical stress for 150 kPa inflation pressure and 15 kN load was measured to be 98.6 kPa. Compared to the previous measurement which reported 101 kPa vertical stress, no significant difference was observed (Fig. 6).

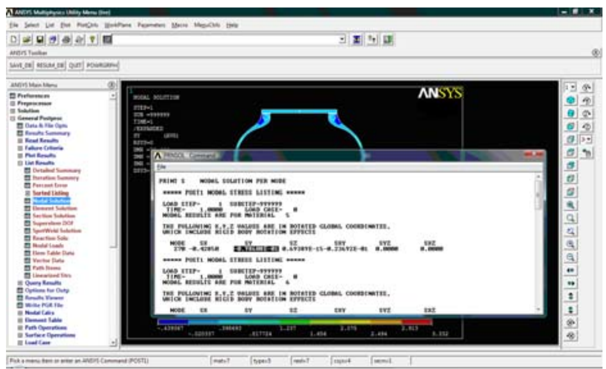

Fig. 6 Vertical stress calculated for 150 kPa inflation pressure and 15 kN vertical loads.

The results showed that the maximum stresses in tire occurred at the side wall. Fig. 10 shows measured stress distribution for 150 kPa inflation pressure and 24 kN load which agrees with previous reports [5].

6 CONCLUSIONS

A non-linear FE tractor tire model, assumed as incompressible tread rubber block on soft soil, was developed to predict soil-tire interface stresses. The model provides a reliable pattern of soil-tire interface stress distribution. The average results of the tire stress distribution model have been solely validated for rigid surfaces and soft soil. Based on adequately measured geometric and material properties, the model is able to provide reliable stress fields in the tire–road stress under a wide range of normal loads and inflation pressures. In general, compared to the 3-D analysis reported by Mohsenimanesh, et al. (2008), more accuracy is observed in the present 2-D model, due to using fine meshing soil particle. This investigation proves that maximum stresses in tire occur at the side wall. Additional factors needs to be further investigated in the future, such as simulation of dynamic behavior of the tire, shear stress, contact surface friction, tread width effect and validation with field tests.

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