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Finite Element Method in Modeling the Tractive Performances of Flotation Tires Running on Wetland Paddy Fields in Malaysia

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ABSTRACT

Efficient tire mobility and low terrain compaction are the two pertinent requirements in any study of off-road wheel traction on low bearing capacity terrain. Soft terrain can drastically reduce the traction performance of tires up to the point of making the motion impossible. However, the use of finite element method (FEM) has shown to be an appropriate approach in tire-soil interaction modelling. In this work, the essential figuration on modeling soil compaction and tire mobility issues are further informed. An improved 3D model with the geometry of tire 29-12.50x15 4PR flotation was founded. The hyper-elastic rubber as tire main material was analyzed by Mooney-Rivlin model, for modelling the soil compaction, the Drucker-Prager yield criterion proceeded in ABAQUS was used. Delegate simulations are provided to elucidate how the tire-terrain interaction model can be used to predict soil compaction and tire mobility in the paddy field. The results show that the model realistically predicts the longitudinal and lateral forces providing at the same time good appreciations of the slip-sinkage behavior and tire parameters sensitivity: this aspect is essential in order to realistically estimate the traction efficiency.

KEYWORDS

Finite element method, Flotation tire, Deformable soil, Tire mobility, Tire sinkage.

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INTRODUCTION

The dynamic performance of vehicles is mostly affected by the tire dynamic properties, tire–soil interaction has been studied extensively both in experimental and analytical approaches. However, experimental data are available only for large size tires used in multi-purpose farm tractors. Since the experimental data is difficult to obtain, time consuming and uneconomical, analytical models have found wide acceptability. These models require certain tire parameters which can be easily measured experimentally in the laboratory. Also, analytical tire models can be used directly for vehicle simulations. Numerous terramechanics studies have been conducted to represent the tire dynamic properties to the tire deformations properties based on the finite element method (Yong, R. and Fattah, E., 1976) (Regli, G. et al., 1993) (Fervers, C. W., 2004) (Chiroux, R. et al., 2005) (Hambleton, J. and Drescher, A., 2008, 2009) (Xia, K., 2011) (González, O. *et al.*, 2013) (Meirion-Griffith, G. andSpenko, M., 2013) (González, O. *et al.*, 2016) (Recuero, A. *et al.*, 2017); however, the contact conditions of soil and thrust elements are often not characterized by uniform and even surfaces, but rather by textured shapes because of the tread patterns of tires. Interactions between the soil and a tire, such as frictional sliding and shear, can occur at boundaries. In some cases, they can also occur within the soil, so they can be considered to be normally mixed.

Vehicle mobility on soft terrain is important to the agriculture as well as to military, forestry, mining, and construction industries. The problems can be grouped into two major categories: predicting tire performance on various terrains (will it get stuck; how much traction or pull is available to climb or pull) and estimating the consequences of the vehicle passage (rut formation, shearing/tearing of roots, soil compaction, and the effects of these on vegetation and erosion) (Shoop, S. A., 2001) {Shoop, 2001 #2}. The goals of the terramechanics field are to study the interaction between the running gear of a vehicle and the terrain and to establish guidelines for the development and testing of off-road wheels/tires/tracks and the vehicles on which they are mounted (Wong, J., 1984). The usual approach to considering the prediction of tractor performance is to begin with the study of the performance of single wheels. Furthermore, numerical methods such as Finite Element Method/Analysis (FEM/FEA), and more recently Discrete Element Method (DEM) are very useful tools for simulating stresses in soil and flow of soil when displaced (Ani, O. A. *et al.*, 2018).

The most important factors that have a significant influence in the process of artificial compaction of agricultural soil are: the type of the soil, moisture content of the soil, intensity of external load, area of the contact surface between the soil and the tire, shape of the contact surface, and the number of passes (Biriş, S. Ş. *et al.*)

Because the agricultural soil is not a homogeneous, isotropic, and ideal elastic material, the mathematical modelling of stress propagation phenomenon is very difficult. Many mathematical models of stress propagation in the soil under different traction devices are based on the Boussinesq equations, which describe the stress distribution under a load point (Figure 1) acting on a homogeneous, isotropic, semi-infinite, and ideal elastic medium (Hammel, K., 1994).

Many models of dynamic soil behavior are using elastic properties of soil, and when the soil is represented by a linearly elastic, homogenous, isotropic, weightless material, the elastic properties required to fully account for the behavior of the material are: Young's modulus (E), shear modulus (G), and Poisson's ratio (υ).

The Finite Element Method (FEM) is proving to be very promising for modelling this propagation phenomenon. For agricultural soils, the relationships between stresses and strains are measured on soil samples in the laboratory or directly in the field. The stress-strain relationships are given by constitutive equations (Gee-Clough, D. *et al.*, 1994).

The objective of this project is to produce a three-dimensional finite element model of tire-terrain interaction that can be used to explore the effects of tire and terrain variables on vehicle mobility and terrain deformation. Such a model would enable detailed analysis of the complex interactions resulting from contact friction and would further the understanding of off-road vehicle mobility by defining critical mechanisms involved in flotation tire traction. Ultimately the model generated would be used for tire design and specification for off-road vehicles, for vehicle performance prediction, and for terrain damage prediction and reduction of the environmental impact of off-road travel. Previously a three-dimensional simulation of contact between a deformable tire and deformable terrain had been too difficult and computationally time consuming. Recent advancements in the contact formulations of general-purpose finite element codes (e.g. ABAQUS, HKS 1998) and increases in computer processing speeds have brought such a model into the realm of possibility.

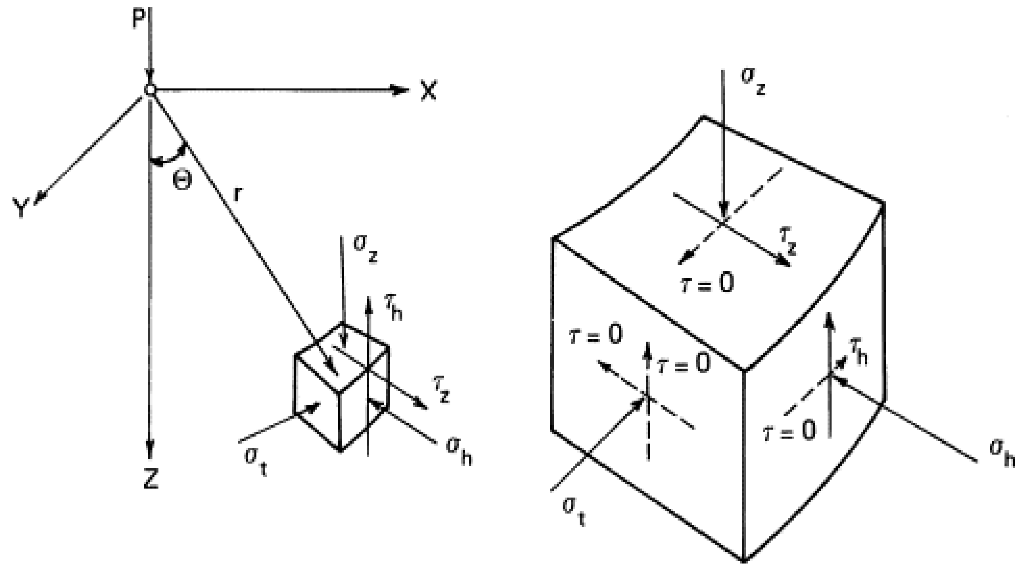

Figure 1: Stress state produced by a concentrated vertical load (Van den Akker, 2004)

MATERIALS AND METHODS

There are broadly two main approaches in modeling and predicting the tractive performance of an off-road pneumatic tired wheel as described by (Dwyer, M., 1984). In the first approach the equations use the Coulomb properties of cohesion and internal angle of friction as a measure of soil shear strength. The second approach uses the penetrometer cone index as a measure of soil strength and dimensional analysis and empirical data to determine the prediction equations and can be considered as a semi-empirical approach. There are also equations and definitions derived from empirical data that are concerned more with go/no go mobility (Maclaurin, B., 2007). Newer techniques such as finite element analysis and discrete element analysis have also been found useful and have considerable application and potential. Prediction equations have been developed primarily for military, agricultural, forestry and construction vehicle use.

Tire parameters

Modern tires are structurally quite complex, consisting of layers of belts, plies and bead steel imbedded in rubber. Materials are often anisotropic, and rubber compounds vary throughout the tire structure. Models developed for tire design are extremely detailed, account for each material within the tire and enable computational engineering analyses of internal tire stresses, wear and vibrational response. Toward that end, a simpler treaded tire model, described below, is developed and tested in this work.

A single-tire considered in the present work (CARLISLE Tru Power 29x12.50-15) is a modern flotation tire, its dimensions are 300 mm width and 730 mm diameter, using with 10 psi as inflation pressure (Figures 2 and 3). Nakashima, H. and Wong, J, (1993) stated that a tire is considered rigid if the terrain is sufficiently soft and the tire has little deflection. On the other hand, a tire is said to be elastic if the terrain is firm enough relative to the tire and there is significant tire deflection with the lower portion of the tire in contact with the terrain is almost flat. Tire deflection at a given level of inflation pressure is a primary measure of the tire structural response to vertical load. Deflection is defined as the difference between the unloaded and loaded section height and is usually normalized by the unloaded section height.
Mathematically,

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Tire is rigid if $P_{cr} < (P_i + P_c)$
Tire is elastic if $P_{cr} \geq (P_i + P_c)$

Where P_{cr}: tire critical ground pressure (kPa), P_i: tire inflation pressure (kPa), P_c: tire carcass stiffness pressure (kPa).

$$Pcr = [\frac{Kc}{b} + K\emptyset]^{n/2n+1}[\frac{3W}{(3-n)\sqrt{D}}]^{2n/2n+1} \quad (1)$$

Where:

D: tire diameter, m
b: tire width, m
W: tire load, kN
n, K_c and $K_ø$: pressure sinkage parameters constants

Having W=5kN, D=0.73m, b=0.305m, n=0.4, K_c = 1.87 kN/m $^{n+1}$ and $K_ø$= 96.08 kN/m^{n+2}, the computed value of P_{cr} *is 29.65* kPa.

The tire sinkage could be computed by the following formula by (Bekker, G., 1960):

$$z = [\frac{3W}{b(3-n)\left(\frac{Kc}{b}+K\emptyset\right)\sqrt{D}}]^{2/(2n=1)} \quad (2)$$

Where:

z: tire sinkage, m
D: tire diameter, m
b: tire width, m
W: tire load. kN
n, K_c and $K_ø$: pressure sinkage parameters constants.

Having W=3.5 kN, D=0.73m, b=0.305m, n=0.4, K_c = 1.87 kN/m $^{n+1}$ and $K_ø$= 96.08 kN/m$^{n+2,}$, the computed value of z is 0.125 m.

The inflation pressure for flotation tire 29x12.50-15 at rated load of 3.5 kN is 10 PSI (68.95 kPa). Since the magnitude of the inflation pressure for a tire alone without taking into account the tire carcass stiffness pressure is greater than the computed tire critical ground pressure, the earlier considered tire configuration could be regarded as rigid.

The tire contact length under rigid mode in Figure 2 could be geometrically computed as follows:

$$L = 2\sqrt{r^2 - (r-z)^2} \quad (3)$$

Where:

L: tire contact length, m
r: tire radius, m
z: tire sinkage, m

Having z=0.125m and r= 0.365 m, the computed value of L is 0.55 m.

The effective tire rolling radius with respect to slippage as proposed by Ellis (1994) could be predicted using the following formula:

$$r_0 = r - (\frac{z}{3}) \quad (4)$$

Where:

r_0 effective tire rolling resistance m,
r: tire radius, m
z: tire sinkage, m

Having r = 0.365 m and z = 0.125 m, the computed value of r_0 is 0.324 m.

Having the assumption that the tire have flat and rectangular contact patch with uniform normal pressure while the weight is uniformly distributed among the tire, the thrust developed by the tire at a given tire slippage could be computed by the following formula:

$$F = n\left[cbL + \left(W_p/n\right)tan\emptyset\right][\,1 - \exp(-iL/k)] \quad (5)$$

Where:

F: prime mover thrust, kN
n: number of tires, dimensionless
c: soil cohesiveness, kPa
b: tire width, m
Wp: vertical total weight, kN
Ø: angle of internal shearing resistance of soil, degree.
i: tire slippage, proportion
L: tire contact length, m
k: soil shear deformation modulus, m

The optimum tire slippage range for tractor running on soft soils in the range of 14% to 16% in accordance to ASAE Standard: ASAE EP496.3 (ASABE, 2006). Assuming i = 0.14 with Wp = 3.5 kN, n =1, c = 6.25 kPa, b = 0.305 m, Ø = 30.2 degrees, L = 0.55 m and k = 0.065 m, the computed values of F is 2.14 kN.

The driving torque of the tire is given as follows:

$$T = \frac{F}{n} * r_0 \quad (6)$$

Where:

T: tire torque, kN.m
F: prime mover thrust, kN
r_0: tire rolling radius, m
n: number of tires, dimensionless

Having F = 2.14 kN, r_0 = 0.55 m and n = 4, the computed value of T is 1.177 kN.m.

The input power of the tire is given as follows:

$$P_t = \frac{T*V}{(1-i)r_0*3.6} \quad (7)$$

Where:

P_t: input power at a tire, kW
T: tire torque, kN.m
V: operating speed, km/h
r_0: tire rolling radius, m
i: tire slippage, proportional.

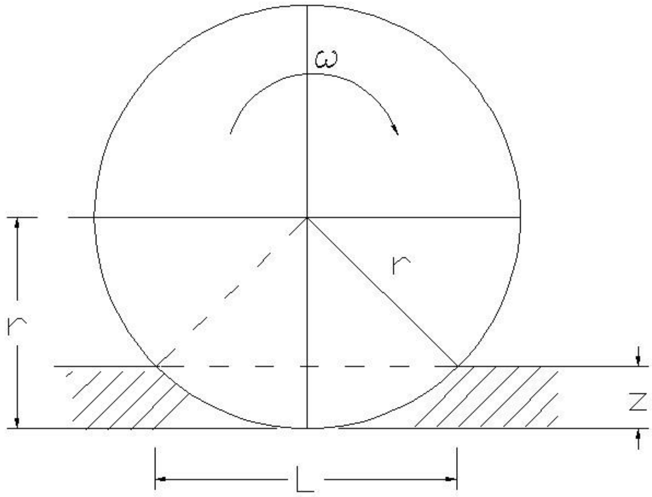

Figure 2: Tire -terrain geometrics under rigid mode

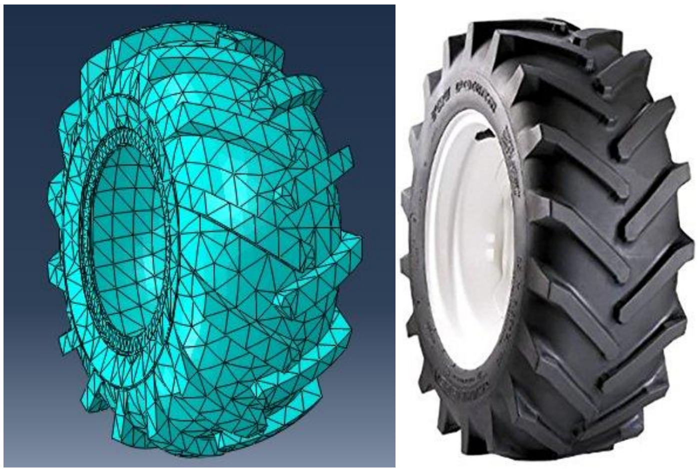

Figure 3: CARLISLE Tru Power 29x12.50-15

The numerical values for the hyper-elastic material properties used in the model, and tire specifications are shown in Tables 1 and Table 2.

Table 1: Hyper-elastic properties Rubber material

	$C10$	$C01$	Density $(kg/m3)$
Tread	805 kPa	1.8 MPa	1180
Sidewall	170 kPa	845 kPa	1100

Table 2: Tire specification

TIRE	SIZE	PRODUCT CODE	PLY	DIA	WIDTH	RIM WIDTH	MAX LOAD@30 MPH	MAX PSI	TIRE WEIGHT
Tru Power	29x12.50-15	5233D4	6	730 mm	305 mm	254 mm	1650 kg	30	43 kg

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Deformable terrain

A study was conducted to determine the mechanical properties of paddy field in Kuala Selangor. The area topography was landing. The moisture content was 26% on dry basis when sampling were made for the mechanical properties determination.

The Drucker-Prager plasticity model can be used to simulate the behavior of agricultural soil. Using this material model, the following considerations should be noted: strains are assumed to be small; problems with large displacements can be handled providing that the small strains assumption is still valid; the use of NR (Newton-Raphson) iterative method is recommended; material parameters Ø and c must be bounded in the following ranges:
90≥ Ø ≥ 0 and c ≥ 0.

The required input parameters for the constitutive model of the of Paddy Soil in Malaysia are (Abubakar, M. S. A. *et al.*, 2010), as shown in Table 3.

Table 3. Plastic properties of soil material

Soil cohesion (c)	6.25 kPa
Internal friction angle of soil (Ø)	30.2
Soil density (γ)	1240 kg/m^3
Poisson's ratio (υ_s)	0.329
Young's modulus (E)	5000 kPa

Finite Element Method (FEM)

The tire tread investigated in this study is described as a continuous body using the well-known Finite Element Method. Therefore, the method discretized the volume of a body by means of a mesh. This mesh is represented by a finite number of nodes spanning a finite number element over the body volume. The displacements of the body shape are predicted at the mesh nodes and thus the deformations and stresses are derived over the finite elements (Figure 4).

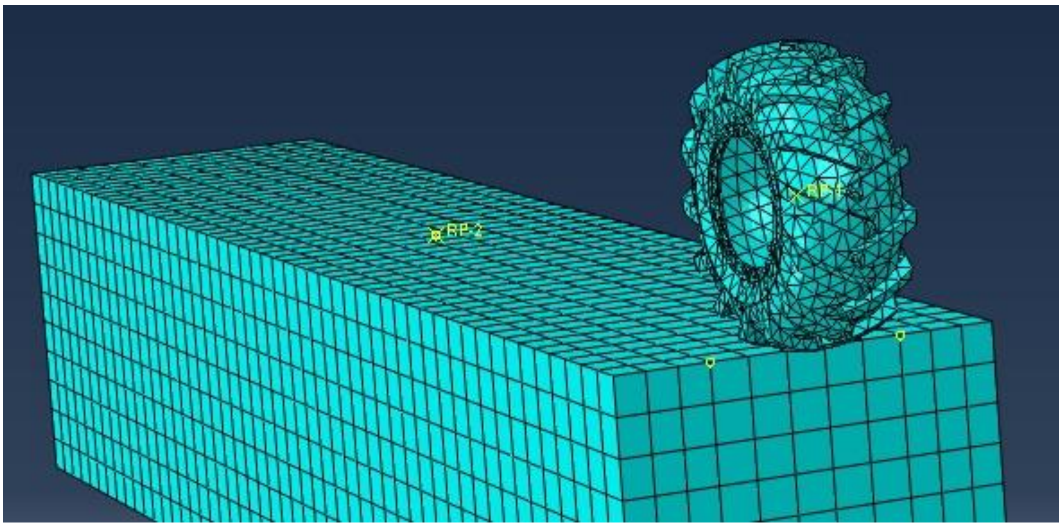

Figure 4. Static tire-soil interaction

RESULTS AND DISCUSSIONS

A three-dimensional FEM simulation of a vehicle on soft ground would basically be possible as well, but would require a very much higher computer capacity. In this section and its sub sections, the main results obtained in the present work are presented and discussed.

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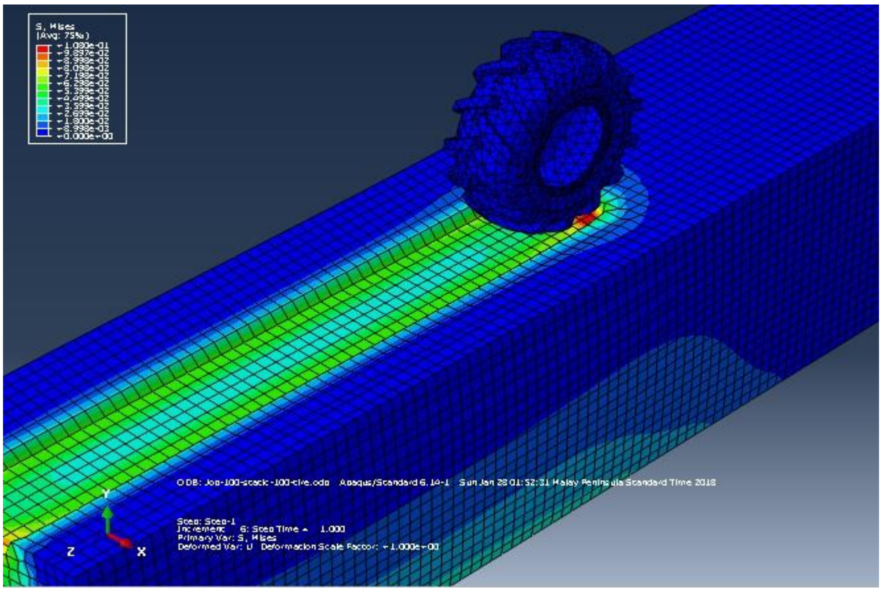
Validation of the tire model

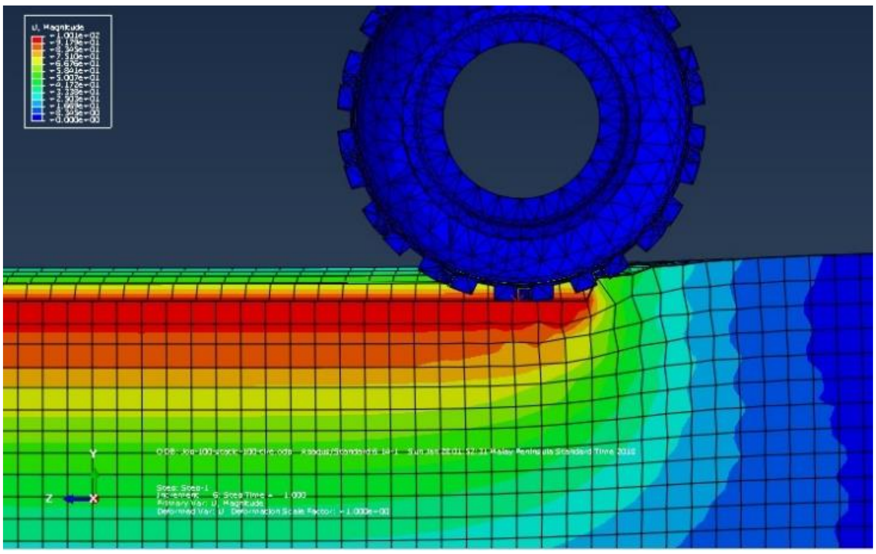
As discussed earlier, to validate the tire model a multi-step computational analysis of tire contact and rolling over a rigid-road surface was first investigated. The analysis included tire inflation, bringing the tire in contact with the road, application of the vertical load and tire rolling (the wheel's center point was translated while allowing it to freely rotate about its axis due to friction, simulating a "towed-wheel" case).

Tire-Soil interaction

Figure 5 shows the tire-soil interaction in dynamic state and Figure 5 shows the deformation of soil under load 4.88 kN with 3.6 km/h operating speed.



A: tire-soil interaction simulation with 3.15 kN vertical load and 3.6 km/h forward speed



B: profile explains the dynamic tire-soil interaction with 3.15 kN vertical load and 3.6 km/h forward speed

Figure 5: An example of tire-soil interaction visualization in ABAQUS 6.14.1

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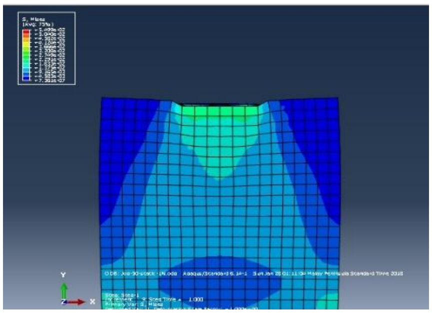
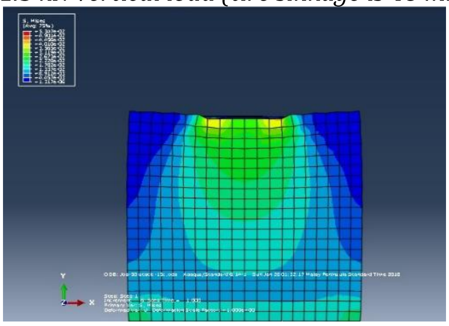
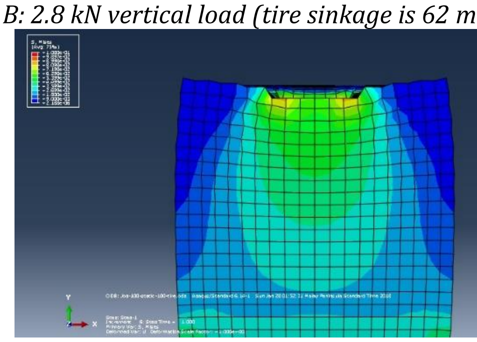


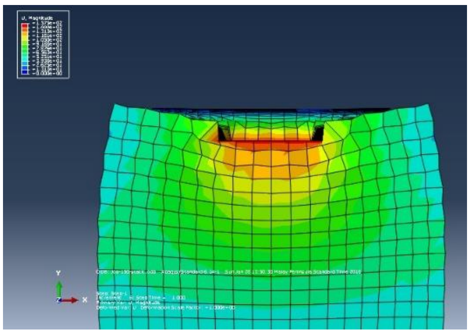
A: 1.5 kN vertical load (tire sinkage is 48 mm)



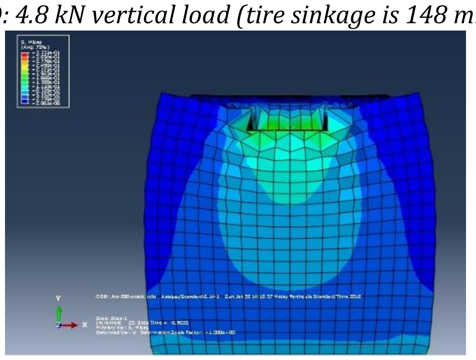
B: 2.8 kN vertical load (tire sinkage is 62 mm)



C: 3.6 kN vertical load (tire sinkage is 102 mm)



D: 4.8 kN vertical load (tire sinkage is 148 mm)



E: 5.6 kN vertical load (tire sinkage is 180 mm)

Figure 6: Deformation of soil (compaction) under load 4.88kN

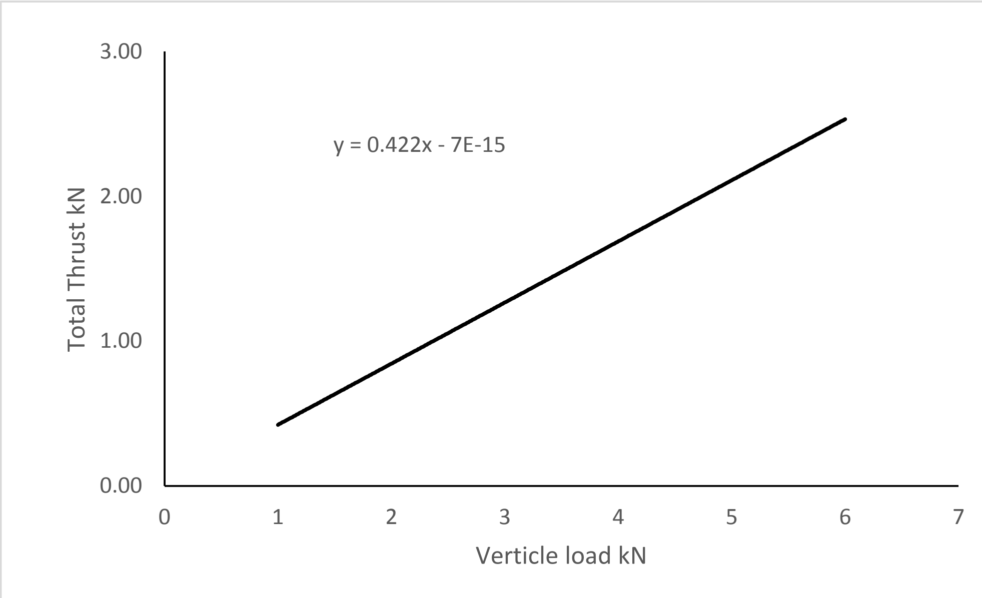


Figure 7: Vertical load versus total thrust of the tire

Figures 7, 8, and 9 show the relationship of vertical load against each of thrust, torque, and draft power of the tire. Where the traction requirements are going to increase when increase the load the tire. From the other view, increasing the load lead to boost the required mechanical effort of tire to move in reasonable stability on soft terrain.

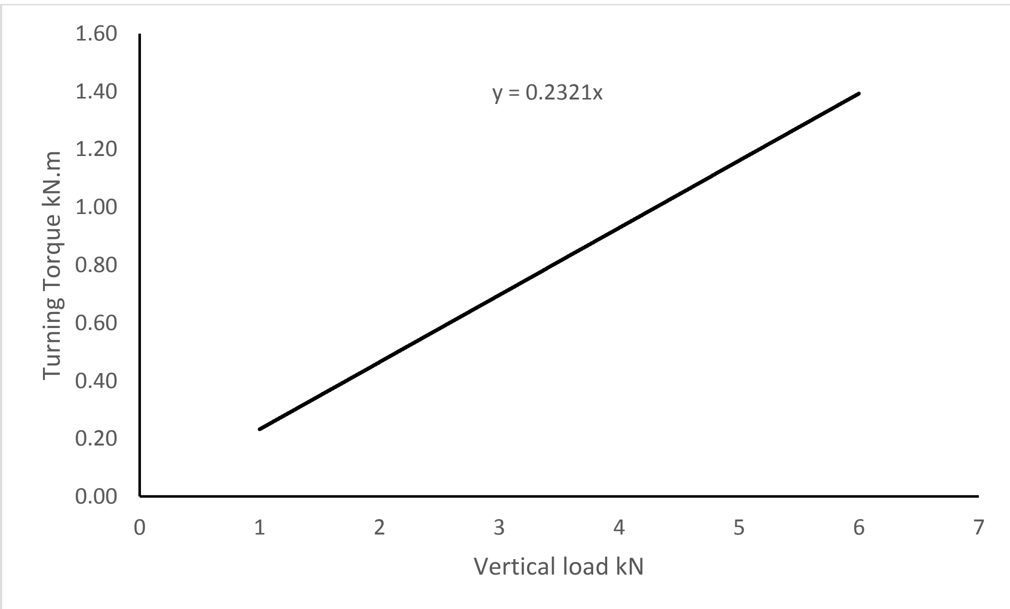


Figure 8: Vertical load versus torque of the tire

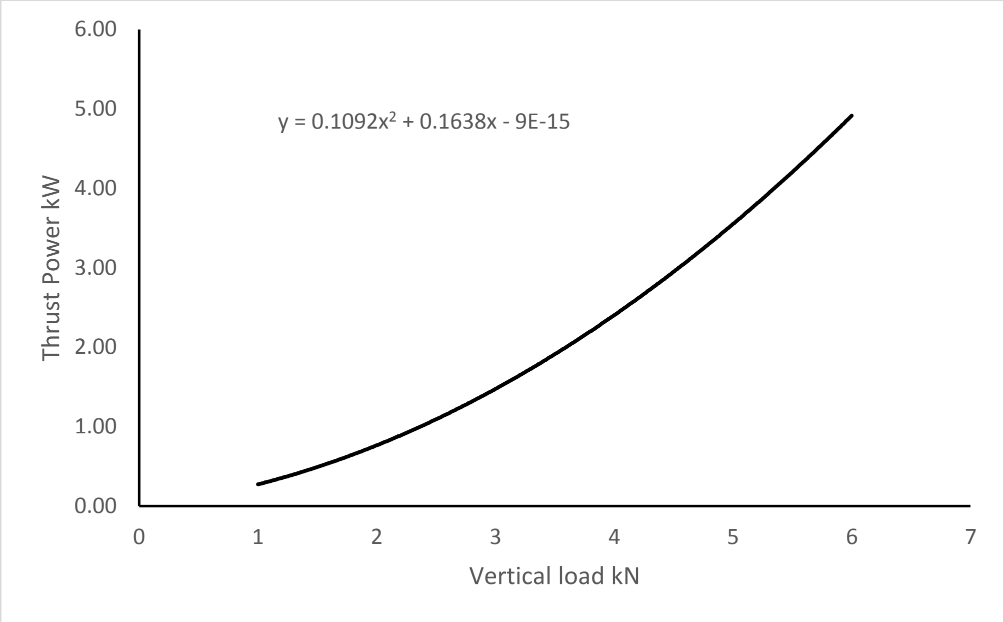


Figure 9: Vertical load versus required Thrust power

From Figures 10, 11, and 12 easily to note the effect of raising forward speed of the tire on required thrust, torque, and draft power which are very crucial variables for successful operating of tires on off-road mode. Figure 12 shows the relationship of the draft power with forward speed.

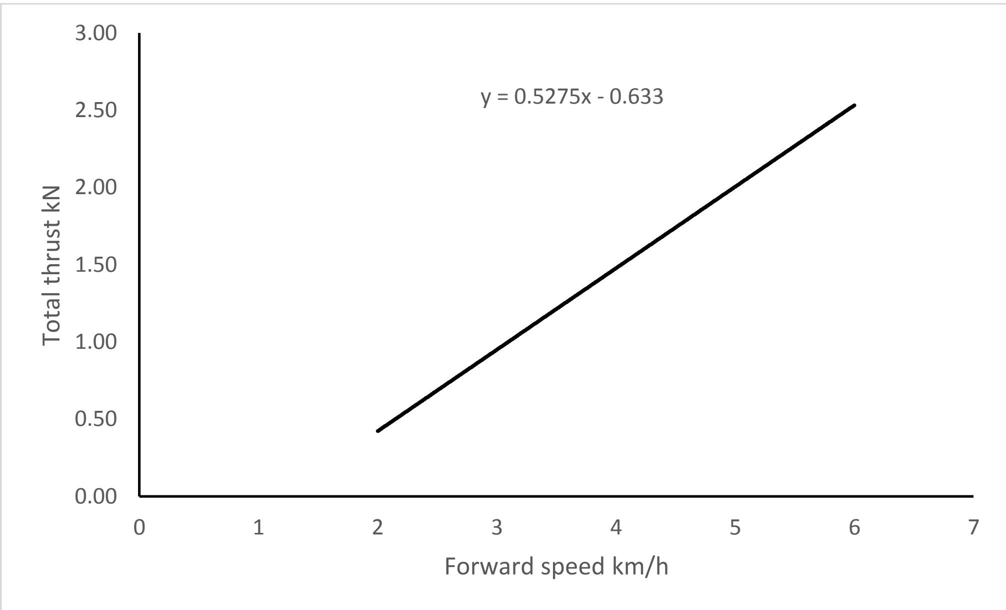


Figure 10: Forward speed versus total thrust of the tire

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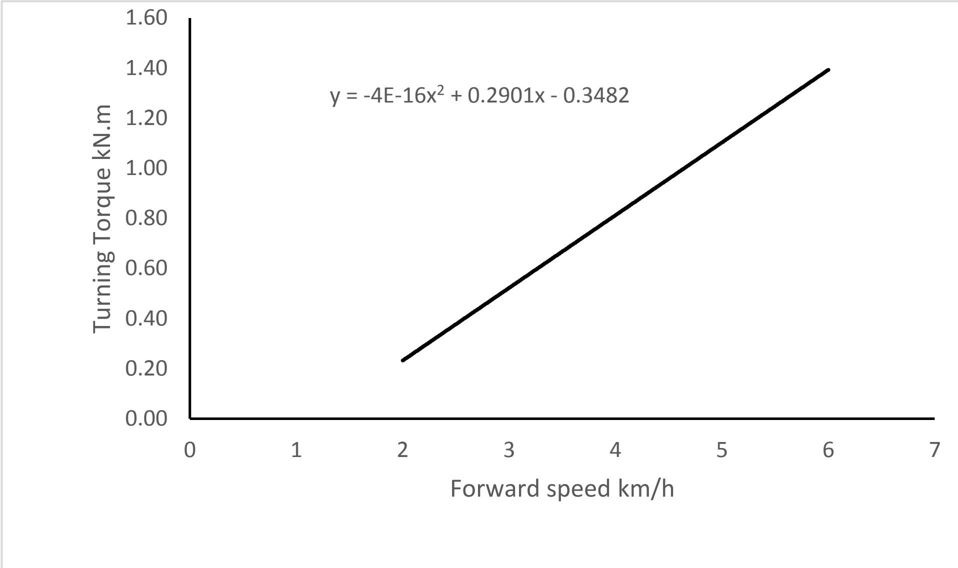

Figure 11: Forward speed versus torque of the tire.

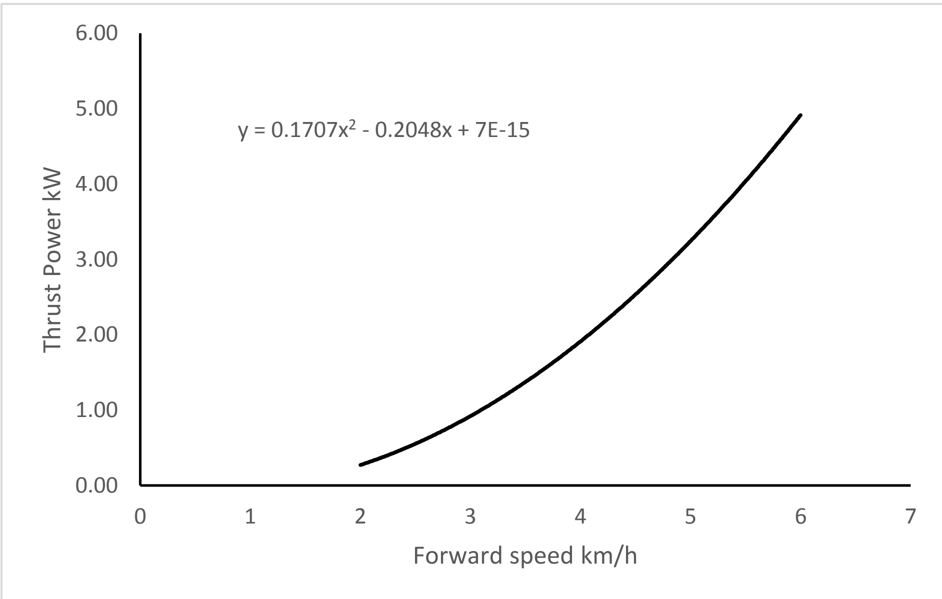

Figure 12: Forward speed versus required Thrust power

CONCLUSIONS

A three-dimensional finite element tire model is proposed for estimating the behavior of a pneumatic tire during dynamic simulations. The model was developed in ABAQUS 6.14.1 software based on the geometrical and material properties of a Michelin tire from the Tire Model Performance Test (TMPT).
Based on the results obtained in the present work, the following main summary remarks and conclusions can be drawn:

- A series of finite element computational analyses is carried out in order to investigate rolling/slip behavior of a pneumatic flotation tire in paddy field under various conditions of vertical force, rotational and forward speeds.
- The forces on a tire in the longitudinal and lateral directions due to the interaction with a paddy field were collected using a single flotation tire. A tire–soil interaction model that can be utilized for vehicle simulation was constructed from the data.

- A numerical simulation with the tire model demonstrated the ability to reproduce the trajectory and the sinkage of a four-wheel model vehicle in steady and non-steady turn experiment on a flat and soft terrain.

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