A survey on approaches of soil stress determination generated through soil-tire interaction

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Abstract

Normal and shear stresses are important factors that are closely related to rolling resistance and tractive parameters, respectfully. However, the generation of soil stress beneath a driving wheel is a significant and complex phenomenon. The process of analyzing soil stress can be implemented through different methods of analytic, semi-empirical, numerical, etc. Shear stress is necessary for the provision of drawbar pull but creation of vertical stress and its propagation in soil profile can lead to soil compaction. There are also numerous parameters that affect the soil stress state and tractive parameters simultaneously. This paper provides an overlook to the various approaches adopted to analyze the aforementioned aspects that can serve functionally for the future studies in this realm.

Keywords: Terramechanics; Finite Element Method; Soil stress; Tire

1. Introduction

Vehicle performance on deformable terrain is significantly affected by the design of a vehicle power provision unit, power transmission, soil-wheel interaction condition, design and characteristics of suspension system, tires, etc., and the soil texture that the vehicle should travel over it and its state such as moisture content, compactness, cohesion, etc.

Soil volume is usually deformed under heavy loading while the vehicle is traveling over rough terrain. Reduction in soil volumetric value results in soil compaction which is a great concern from agricultural perspective but provision of a satisfactory soil deformation on the other hand is needed for a robust traction provision for the off-road vehicle propulsion. One of the most important and ongoing effects of heavy vehicle use is the compaction of soil caused by the force of rolling wheels. Compaction can be described as the act of exerting forces to a soil mass which brings about an increase in density and strength [1]. However, a considerable amount of contact pressure can bring about more rigorous friction at soil-tire interface that result in a higher shear stresses which is the most prominent index for the estimation of net tractive force created by the running gears.

The mechanical characteristic of the terrain profile under compression/tension loading that is under the vehicle tires is affected by different parameters. It is needed to gain a comprehensive knowledge of the vehicle/ground interaction from dynamics and kinetics perspective as well as the strength of material (for soil medium to provide traction/braking forces, rolling resistance and sinkage phenomenon) while the identification and modeling of the terrain characteristics and the parameters that are engaged with vehicle performance [2].

Unlike the motion of vehicle over rigid surface, when the vehicle is traveling over deformable terrain, the soil-wheel interaction treats differently, and established modeling techniques and suspension design regulations are not necessarily true. Important parameters including road roughness, soil deformation, forward speed, wheel load, and suspension characteristics can significantly affect the vehicle responses to the excitations. It is advised to adopt time domain analysis if the nonlinear characteristics and elastic-plastic behavior of the soil medium is considered. The nonlinearity becomes more significant with the increases in the vehicle weight or soil deformability [3].

An accurate investigation of vehicle dynamics in off-road conditions should explain the statistical variation of inherent system parameters, soil features, and inexact terrain mode while going afar from the deterministic approach and treating these components in a stochastic framework is a significant step forward in bringing the modeling results closer to real-life situations [4].

The fundamental model of a wheel was first formulated by Bekker in the 1960s and later further modified by others [5-9], while the developed tractive performance models were formulated on account of normal stress distributions provided under a wheel and shear stress distributions produced over the same area as the normal stress, as an indication of rolling resistance.

In a research work [10], three pressure transducers were installed on a wheel to observe the stress distribution on flat and
soft soil in the circumferential direction while it was considered that the normal force acting on a wheel edge was zero and deduced the distribution based on the quadratic approximation of three points of the wheel center, near the left edge of the wheel, and the left edge of the wheel, and the wheel center, near the right edge of the wheel, and the right edge of the wheel [11]. Fig. 1 shows the normal stress distribution in the width direction of the wheel in a uniform manner [11].

The process of analyzing soil stress can be implemented through different methods of analytic, semi-empirical, numerical, etc. Shear stress is necessary for the provision of drawbar pull but creation of vertical stress and its propagation in soil profile can lead to soil compaction. There are also numerous parameters that affect the soil stress state and tractive parameters simultaneously. This paper provides an overlook to the various approaches adopted to analyze the aforementioned aspects that can serve functionally for the future studies in this realm.

2. Semi-empirical and Theoretical Works

There are different semi-empirical parameters that have been presented to the model developed by Boussinesq to explain the condition of various surface textures. For instance, Frohlich introduced a concentration factor v to the Boussinesq equation and introducing the concentration factor v, the expressions for the vertical and radial stresses in the terrain due to a point load applied on the surface take the following forms [12]:

\[
\sigma_x = \frac{vW}{2\pi R^2} \left( \cos^2 \theta \right) = \frac{vW}{2\pi R^2} \left( 1 - \frac{x^2}{a^2} \right)
\]

\[
\sigma_y = \frac{vW}{2\pi R^2} \left( \cos^2 \theta \right) = \frac{vW}{2\pi R^2} \left( 1 - \frac{y^2}{b^2} \right)
\]

(1)

The value of v depends on the type of terrain and on its moisture content. For instance, for hard, dry soil, the value of v is 4; for farm soil with normal density and moisture content, the value of v is 5; and for wet soil, the value of v may be 6 [13].

The vertical stress exerted to the tire in contact patch is the z-oriented component of stress (σz) while the longitudinal and lateral shear stresses are represented by τx and τy (Fig. 2). To consider the equilibrium theory in the steady-state loading condition, the following equations should be satisfied [14].

\[
\int_A \tau_x(x, y) dA = 0, \quad \int_A \tau_y(x, y) dA = 0, \quad \int_A \sigma_z(x, y) dA = F_z
\]

(2)

It is important to obtain a satisfactory approximation of contact patch geometry shape and its corresponding parameters if it is aimed at developing a reliable model of normal stress. On a rigid surface, a better contact patch geometry may be better presented by an elliptic shape:

\[
\left( \frac{x}{a} \right)^k + \left( \frac{y}{b} \right)^k = 1, \quad k = 2n, \ n \in N
\]

(3)

where the number of power for the elliptic shape can be varied based on the tire type between 1 and 3. If the tire is a radial ply tire, and n=3 is used, the following stress distribution function is used [14].

The normal stress σz(x, y) may be approximated by the function [15]:

\[
\sigma_z(x, y) = \sigma_{z,\max} \left( 1 - \frac{x^2}{a^2} - \frac{y^2}{b^2} \right)
\]

(4)

where a and b indicate the dimensions of the tire contact area. In this manner, based on the equilibrium equation, the following function may be used:

\[
F_z = \int_A \sigma_z(x, y) dA = \int_A \sigma_{z,\max} \left( 1 - \frac{x^2}{a^2} - \frac{y^2}{b^2} \right) ddy
\]

(5)

By considering the equilibrium theory in the steady-state loading condition, the equations for tangential stresses have to be fulfilled. The tangential stress should be developed based on the contact patch area in both x and y directions.

The tangential stress on a tire is inward in x direction and outward in y direction. Hence, the tire tries to stretch the ground in the x-axis and compact the ground on the y-axis. Fig. 3 [14].

It is clear-cut that the force distribution on the tire print is not constant and varies by the change of tire structure, load, inflation pressure, etc. As available in the literature, the tire tangential stresses in x and y oriented directions can be presented as [16]:

\[
\tau_x(x, y) = -\tau_{x,\max} \left( \frac{x}{a} \right)^{2n} \sin \left( \frac{x}{a} \pi \right) \cos \left( \frac{y}{2b} \pi \right) \quad n \in N
\]

(6)

\[
\tau_y(x, y) = -\tau_{y,\max} \left( \frac{x}{a} \right)^{2n} \sin \left( \frac{x}{a} \pi \right) \cos \left( \frac{y}{b} \pi \right) \quad n \in N
\]

(7)

Consequently, the normal stresses for on road and soft soil in the contact patch geometry are presented in Fig. 4. The difference between the trends of figures can be attributed to the soil profile sinkage (deformation) when compared with a rigid surface where the stress distribution in the contact area is more homogenous [17].

\[
\bar{j}_0 = R \left[ (\theta_0 - \theta) - (\sin \theta_0 - \sin \theta) \right]
\]

(8)

The vertical support force acting on the wheel can be calculated from the normal stress as:

\[
w_0 = Rb \left[ \int_0^\theta \sigma_z(\theta) \cos \delta \cos \theta + \tau_{z,\max} (1 - e^{-\frac{\theta}{k}}) \sin \delta \sin \theta d\theta \right]
\]

(9)

where:
The calculation of the shear stress under the wheel is based on an empirical expression first expressed by Janosi and Hanamoto [18] and widely used:

\[
\tau_{\text{max}} (\theta) = \tau_{\text{max}} \left( 1 - e^{-\frac{\theta}{b}} \right)
\]

where \( \tau_{\text{max}} \) is the limiting shear stress and can be defined by the normal stress through the Mohr-Coulomb equation:

\[
\tau_{\text{max}} = c + \sigma_n \tan \varphi
\]

where \( c \) is soil cohesion and \( \varphi \) is the angle of shear resistance or angle of internal friction.

In this manner, the shear displacement \( j_s \) is calculated integrating the shear velocity of the terrain in contact with the wheel:

\[
j_s (\theta) = \frac{1}{\delta} \int_0^\theta \tau_{\max} (\theta) d\theta = r \left( \theta - \theta - (1 - s) \sin \theta \sin \theta \right)
\]

Combining the Janosi-Hanamoto equation, the lateral shear stress across the contact patch can be expressed as:

\[
\tau_{xy} = \left( c + \sigma_n \tan \varphi \right) \left( 1 - e^{-\frac{j_s}{K}} \right)
\]

Normal, tangential, and lateral stresses are distributed along the wheel interface. The normal stress can be derived from the pressure-sinkage equation proposed by Bekker [7].

\[
P = \left( \frac{K_c}{b} + K_s \right) Z^n
\]

where \( b \) is the smaller dimension of the loading area usually width of contact for rectangular contact area. For small sinkage; however, the length of contact may be assumed in the equation. The deformation parameters of \( k_c \) and \( k_p \) are constant and are usually acquired by sinkage plate tests. It is noteworthy that the pressure-sinkage parameter test results using rectangular plates of large aspect ratios and those of circular plates having radii equal to the widths of the rectangular plates are almost equal and this is a good reason to adopt circular plates because a lower load level is required to acquire the pressure-sinkage parameters with the same contact pressure.

However, there are two drawbacks to this equation that cannot provide a unified equation that accounts for different plate shapes and also the soil bulk density has not been considered. On this basis, a modified version of the Bekker sinkage-pressure equation, also known as Bekker-Reece equation was proposed:

\[
\sigma_n = (ck'_n + by_k') \left( \frac{z}{b} \right)^n
\]

The parameters \( k'_n \) and \( k'_y \) and exponent \( n \) are obtained through a beavemeter or a penetrometer and are important indices for this equation as they are the representative of the relationship’s trend. The exponent number typically falls within a range of 0.8 to 1.2 and close to 1. Soil cohesion value is obtained through uni-axial and tri-axial compression tests [19]. Another privilege of the Bekker-Reece equation is that in contrast to the parameters of Bekker’s pressure-sinkage equation, the parameters of the Bekker-Reece equation non-dimensional (because of the \( z/b \) term in the equation) and are independent of the units of the exponent.

\[
\sigma_{sx} (\theta) = (ck'_n + by_k') \left( \frac{R (\cos \theta - \cos \varphi)}{b} \right)^n
\]

For the region between the maximum radial stress at \( \theta_m \) and the rear contact region, the tire radial stress can be stated as:

\[
\sigma_{sx} (\theta) = (ck'_n + by_k') \left( \frac{R}{b} \right)^n \left( \cos \left( \theta - \theta - \varphi \right) \right)^n
\]

In Terramechanics’ terminology, the drawbar pull, vertical force and the torque are important terms to be calculated. The radial and tangential stresses can then be integrated across the tire contact patch and be projected along longitudinal and vertical directions to the wheel. In this manner, these soil-wheel interaction products can be presented as following:

\[
DP = Rb \left( \int_{-\theta_m}^{\theta_m} \tau_s (\theta) \cos \theta d\theta - \int_{-\theta_m}^{\theta_m} \sigma_{sx} (\theta) \sin \theta d\theta \right)
\]

In drawbar pull equation, the first term is the shear thrust and the second term addresses the compaction resistance.

\[
W = Rb \left( \int_{-\theta_m}^{\theta_m} \sigma_{sx} (\theta) \cos \theta d\theta + \int_{-\theta_m}^{\theta_m} \tau_s (\theta) \sin \theta d\theta \right)
\]

\[
T = R^2 b \int_{-\theta_m}^{\theta_m} \tau_s (\theta) d\theta
\]

where \( b \) is the contact width, and \( \tau_s \) and \( \sigma \) are the shear and normal stress components.
Figure 1. The schematic of the forces exerted to the wheel, where r is wheel radius, b is wheel width, ω is angular velocity, h is wheel rotational angle with wheel bottom defined as zero, θ_e is entry angle to soil, θ_f is departure angle from soil, σ(θ) is normal stress, τ(θ) is shear stress, F_x is traction force (i.e., drawbar pull), and F_z is vertical force [11].

Figure 2. Normal stress distribution with respect to contact length and contact width [14].

Figure 3. Tangential tire stress distribution in x-direction and y-direction [14].
3. Numerical Approach

Discrete element method (DEM) is of famous a numerical method that is used in Terramechanics mainly in the realm of sand soil texture effect and its interaction on wheel. DEM is any of a family of numerical methods for computing the motion and effect of a large number of small particles.

The main concept of discrete element methods stems from considering the soil as a system of discrete particles and models the mechanical interaction of the individual elements with adjacent elements, soil track, and the wheel.

A number of past studies have established the mathematical framework for investigating the behavior of granular materials and more importantly mechanical interaction of the soil and machine [20-23].

For steady-state simulations, wheel drawbar pull, sinkage and driving torque at a constant longitudinal velocity at different slip ratios are compared. For the transient simulations, the values for wheel sinkage and wheel torque in a digging test are evaluated over the experimental results.

Similarly, finite element method can serve as a useful method to analyze the soil-wheel interaction parameters. Finite element analysis is a computerized method for predicting how a tire or soil reacts to the forces generated at soil-tire interface.

Tire traffic over soil causes non-uniform ground pressures across the tire width and along the soil–tire contact area. In Ref. [24], the objective was to obtain in the topsoil the shape, magnitudes, distribution and transmission in depth of the ground pressures from a finite element model of soil compaction. The influence of tire inflation pressure, tire load and soil water content over the pressures propagation in the soil was analyzed. The model indicated that how low inflation pressure the tire carcass supports most of the total load and the biggest peak pressures are distributed in the tire axes when it traffics over firm soil. For high inflation pressure the incremented stiff causes that pressure is distributed with parabolic shape. In wet soil the inflation pressure does not influence on the ground pressure distribution, this depends only on the tire load. The inflation pressure and tire load changed the shape of the vertical pressures distribution on the surface of a hard dry soil, but these variables did not affect the distribution of vertical stresses in a soft wet soil or below a depth of 0.15 m [24].

An Extended Drucker-Prager method is usually used for soil forum characterization. The soil block discretization can be made with 8-node linear brick elements with reduced integration (C3D8R). The mesh density can be obtained through a convergence analysis. The mesh was more refined around the tire–soil contact area. The Drucker–Prager/Cap model was used and the obtained stresses are represented in Fig. 6.

There are also similar studies documented in the literature [25-26] that shows the Footprint for 3000N vertical load, 120kPa inflation pressure in Fig. 7.

In Ref. [26], 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 meshed structures as well as the obtained stress propagation have been presented in Figs. 8-10.

Figure 4. Normal stresses for on soft soil [14]
Figure 5. The meshed tire soil structure for FEM analysis [24].

Figure 6. Vertical stresses predicted as a function of inflation pressure and tyre load, (a) at soil surface with 25% of water content, (b) at soil surface with 30% of water content, (c) at a depth of 0.15 m with 25% of water content, and (d) at a depth of 0.15 m with 30% of water content. Black solid line, \( P_i = 100 \) kPa, \( L = 0.712 \) kN; black broken line, \( P_i = 325 \) kPa, \( L = 0.712 \) kN; grey broken line, \( P_i = 325 \) kPa, \( L = 2.35 \) kN; grey solid line, \( P_i = 10 \) kPa, \( L = 2.35 \) kN [24].

Figure 7. Footprint for 3000N vertical load, 120kPa inflation pressure [25].
Figure 8. Meshing of a) tread, b) inner layer, and c) ring [26]

Figure 9. a) Meshed soil profile and b) assembly of the tire on the soil profile [26].

Figure 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 [26].

4. Experimental Methods

In another investigation, the vertical soil reaction acting on a driven wheel was analyzed by strain gages attached to the left rear axle of a 2WD tractor driven under steady-state con-
dition on different soil surfaces, tractor operations, and combinations of static wheel load and tire inflation pressure. Furthermore, the quantifications of radial and tangential stresses on the soil–tire interface were implemented at lug’s face and leading side near the centerline of the left rear tire using spot pressure sensors. The obtained trends further confirmed that the suggested method of vertical soil reaction measurement is capable of monitoring the real-time vertical wheel load of a moving vehicle and provides a tool for further studies on vehicle dynamics and dynamic wheel–soil interaction. Furthermore, the measured distributions of soil stresses under tractor tire could provide more real insight into the soil–wheel interactions [27]. Soil stress distributions under tractor tires during propelling and tilling operations at different tire inflation pressures and soil stress distributions under tractor tires during pulling tests on firm and tilled sandy loam fields with different combinations of wheel load and tire inflation pressure and tire slips are shown in Figs. 11-12.

A new method for obtaining of soil stress-strain relationships under traffic in field experiments was investigated. Tire sinkage along with vertical motions of a point in soil volume can be measured using an optoelectronic method. In soil stress measurements, a standard stress state transducer (SST) with six strain gage type pressure transducers was used (Fig. 13) [28].

In another study, field experiments on off-road vehicle traction and wheel–soil interactions were carried out on sandy and loess soil surfaces. A 14 T, 6 × 6 military truck was used as a test vehicle, equipped with 14.00-20 10 PR tires, nominally inflated to 390 kPa. Tests were performed at nominal and reduced (down to 200 kPa) inflation pressures and at three vehicle loading levels: empty weight, loaded with 3.6 and 6.0 T mass (8000, 11,600 and 14,000 kg, respectively). Traction was measured with a load cell, attached to the rear of the test vehicle as well as to another, braking vehicle. Soil stress state was determined with the use of an SST (stress state transducer), which consists of six pressure sensors.

It was noticed that reduced inflation pressure has positive effects on traction and increased stress under wheels. Increasing wheel load resulted in increasing drawbar pull. These effects and trends were different for the two soil surfaces investigated. The soil surface deformed in two directions: vertical and longitudinal [29]. The mechanism and apparatus of the experiment as well as the obtained results are shown in Figs. 14-15.

Figure 11. Soil stress distributions under tractor tires during propelling and tilling operations at different tire inflation pressures [27]
Figure 12. Soil stress distributions under tractor tires during pulling tests on firm and tilled sandy loam fields with different combinations of wheel load and tire inflation pressure and tire slips [27].

5. Conclusions

Normal and shear stresses are important factors that are closely related to rolling resistance and tractive parameters, respectively. However, the generation of soil stress beneath a driving wheel is a significant and complex phenomenon. The process of analyzing soil stress can be implemented through different methods of analytic, semi-empirical, numerical, etc. Shear stress is necessary for the provision of drawbar pull but creation of vertical stress and its propagation in soil profile can lead to soil compaction. There are also numerous parameters that affect the soil stress state and tractive parameters simultaneously. This paper provides an overlook to the various approaches adopted to analyze the aforementioned aspects that can serve functionally for the future studies in this realm.

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