A Numerical Investigation of Deformable Soil-Tire Interaction

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***Abstract*— An accurate modeling of soil-tire interaction is necessary to determine and optimize key tire and vehicle performance parameters. In this study, soil is modeled using the Coupled Eulerian-Lagrangian (CEL) method, which is quite stable numerically for large deformation problems such as soil-tire interaction studies. The methodology for material model parameterization and setting up of numerical simulation is developed and validated against experimental data. The realistic stress data and good prediction of tire traction relative to experimental data suggest using the proposed methodology in future studies.**

Keywords: Soil constitutive material model; Soil-tire interaction; Coupled Eulerian-Lagrangian (CEL).

I. INTRODUCTION

The study of a deformable soil-tire interaction is important due to its wide applications in mining, agricultural, forestry, and military industries. Several researchers have used analytical and semi-empirical approaches to understand the complex phenomenon of traction mechanics on deformable terrain and optimize tire/vehicle performance [1]. The limitations of these studies include the oversimplification of the soil model by neglecting some of its complex factors (e.g., strain rate, moisture content, confining pressure, and/or drainage conditions) [2]. To overcome these limitations, in the past few decades, numerical methods have been used to study soil-tire interaction problems.

Various formulations of the Finite Element Method (FEM), such as Lagrangian, Arbitrary Lagrangian-Eulerian (ALE), and Coupled Eulerian-Lagrangian (CEL) have been used to model the soil-tire interaction [3-6]. These methods were able to provide a suitable alternative to analytical models because of their ability to capture the soil deformations and stresses in a more detailed manner. Additionally, meshless methods, such as Smooth Particle Hydrodynamics (SPH) and Discrete Element Method (DEM) were also employed [7][8]. Although meshless methods were able to predict the soil separation process occurring during the soil-tire interaction accurately, they have inherent stability issues. Furthermore, there is a lack of validation of these meshless methods for cohesive soil-tire interaction [9].

The main goal of this work is to investigate the numerical accuracy of tire-deformable soil interaction simulations performed based on literature data. Numerical simulations of a plain rigid tire on deformable soil (Norfolk Sandy Loam) were performed for the traction prediction. The CEL approach is used due to its numerical stability in modeling large deformation problems. The soil is modeled using an elastic-plastic constitutive material model which is parameterized using literature data. The variation of net traction with different normal loads is studied and compared with the experimental data.

The methodology of performing the soil-rigid tire interaction numerical simulation is proposed in Section 2. In Sections 3 and 4 of the paper, numerical simulation results and discussion are provided. In the last section, a summary of the study is provided with the scope of future work.

II. METHODOLOGY

The methodology of modeling rigid tire interaction with soil is based on the four steps (Figure 1). The first step is to analyze the experimental study of the rigid tire and soil [10] for the collection of traction data at different compaction, moisture content, normal load, and slip ratios.

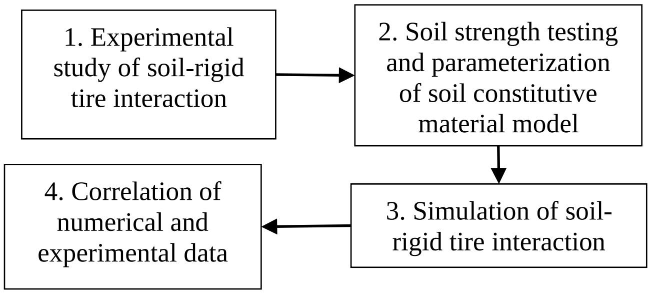


Figure 1: Soil-rigid tire interaction modeling methodology.

Based on the soil type and conditions, an appropriate soil strength test must be conducted for the parameterization of the soil constitutive material model. In the last two steps, the numerical simulation models of soil-rigid tire interaction are used to predict net traction, and the results are compared with experimental data.

A. *Experimental study of soil-rigid tire interaction*

The experimental data from a rigid tire traction test conducted on Norfolk Sandy Loam (NSL) soil is carefully analyzed [10]. In testing, a rigid tire with dimensions of 1372 mm in diameter and 305 mm in width was used. Before the test, the soil was first rotary-tilled and then leveled with the roller until the required level of compaction was achieved, which was verified with a cone penetrometer. The experiment was designed to study the effect of variation of normal load and slip ratio on the traction of rigid tire (TABLE I). After soil conditioning, the normal load was applied to the rigid tire with a longitudinal velocity of 0.15 m/s. Based on the slip ratio, angular velocity was estimated and applied to the rigid tire. The wheel force transducers were used to record the net traction value for the corresponding normal load and slip ratio.

TABLE I: SOIL-RIGID TIRE INTERACTION TEST DESIGN OF EXPERIMENTS (DOE) [10].

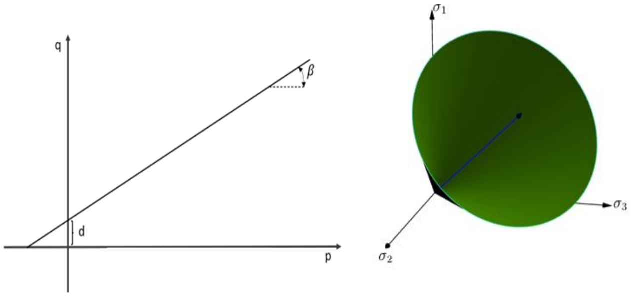
Factor	**Levels**		
	1	2	3
Normal Load	2.9 kN	5.8 kN	8.7 kN
Slip Ratio	18.5 %	-	-

B. *Soil testing and constitutive material model parameters*

The shear strength of the soil is dependent on moisture content, strain rate, confining pressure, and drainage conditions. The triaxial test is extensively used for determining the shear strength and failure envelope of soil [2]. In triaxial testing, the cylindrical soil specimen is first subjected to predetermined confining pressure and then it is sheared at a constant strain rate until failure. The triaxial testing of the NSL soil used in the soil-rigid tire interaction was done at the three confining pressures (300 kPa, 400 kPa, and 500 kPa), and the failure envelope of the soil was calculated [11]. Based on the failure envelope of the soil, parameterization of the relevant soil constitutive material model is done.

The soil constitutive material models based on the theory of plasticity are frequently used in the modeling of granular materials such as soils and rocks. The elastic-plastic material models such as Mohr-Coulomb (MC), Drucker-Prager (DP), Cap-plasticity, and Cam-Clay are used in commercial FE software such as ABAQUS and LS-Dyna. An appropriate material model must be selected based on the available testing data and the expected output of the numerical simulation. For modeling of soil-rigid tire interaction, the DP material model is used because of its ability to capture the plastic deformations occurring in soil under the tire and its easy parameterization. The yield surface of the DP material model is defined in p-q space using two plastic parameters, i.e., compressive yield stress (σ_c) and material friction angle (β) given by (1) (Figure 2). The DP material model parameters for NSL soil based on triaxial test results are provided in TABLE II.

$$F(\sigma)=q-3\sqrt{3}\alpha p-\sqrt{3}k \qquad (1)$$



a) b)

Figure 2: a) 2D DP Yield Surface b) 3D DP Yield Surface.

TABLE II**:** DP MATERIAL MODEL PARAMETERS FOR NSL SOIL [4].

Parameter	Value
Material friction angle (β) [deg]	59.41
compressive yield stress (σ_c) [MPa]	0.001
Mass density [kg/m^3]	1255
Young's Modulus [MPa]	5
Poisson's ratio	0.3

C. *Soil-rigid tire interaction numerical simulation*

For the soil-rigid tire interaction model, the soil is modeled using Eulerian elements (EC3D8R) and the rigid tire with rigid elements (S4R) in ABAQUS/Explicit (Figure 4) [12]. A void region of a height of 150 mm is also added to capture the soil. Fixed boundary conditions are applied to the sides and bottom face of the soil domain, while the top surface interacting with the rigid tire is kept free. The DP material model is assigned to the soil domain. The soil domain, rigid tire dimensions, and coefficient of friction between rigid tire and soil are defined based on literature (TABLE III) [4].

TABLE III: SOIL-RIGID TIRE INTERACTION NUMERICAL SIMULATION PARAMETERS

Parameter	Value
Rigid tire thickness	304.8 mm
Rigid tire radius	686 mm
Soil domain cross-section	4000x1500 mm
Soil domain height	500 mm
Soil mesh size	20 mm
Friction coefficient between soil and rigid tire	0.4
Applied Longitudinal velocity	150 mm/s
Applied rotational velocity (18.5 % slip rate)	0.26 rad/s

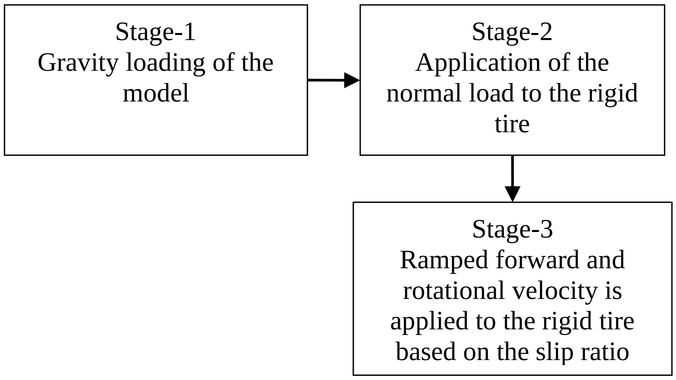
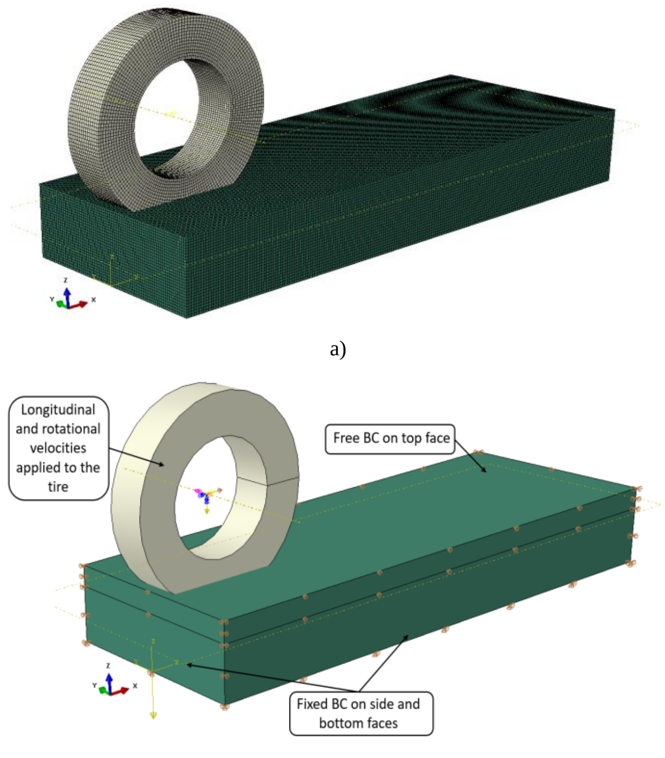


Figure 3: Soil-rigid tire interaction numerical simulation setup.



a)

b)

Figure 4: a) CEL model discretization b) CEL model BC.

The numerical simulations are set up in three stages (Figure 3). The net traction force which is the summation of normal and shear contact force is estimated from the total contact forces on the rigid tire.

III. RESULTS

The normal stress (S33) and in-plane shear stress (S13) components of the soil domain are plotted once the steady state is reached during the traction performance simulation. A formation of the normal stress bulb due to applied normal load and a soil slip plane caused by applied longitudinal and rotational velocities are observed (Figure 5).

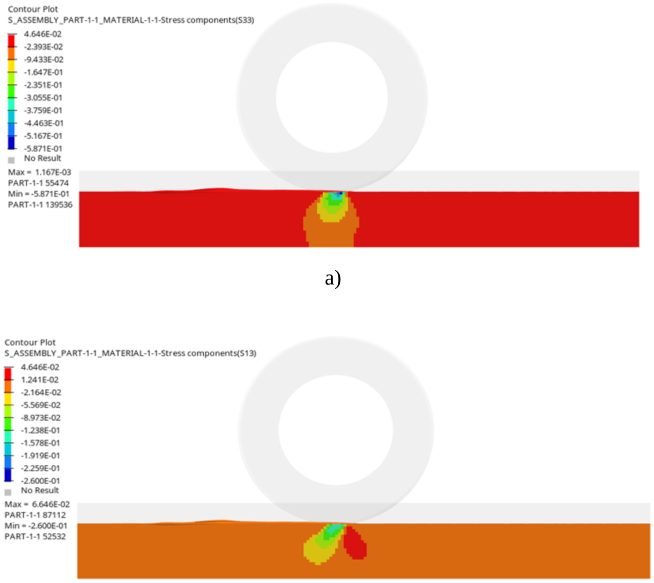


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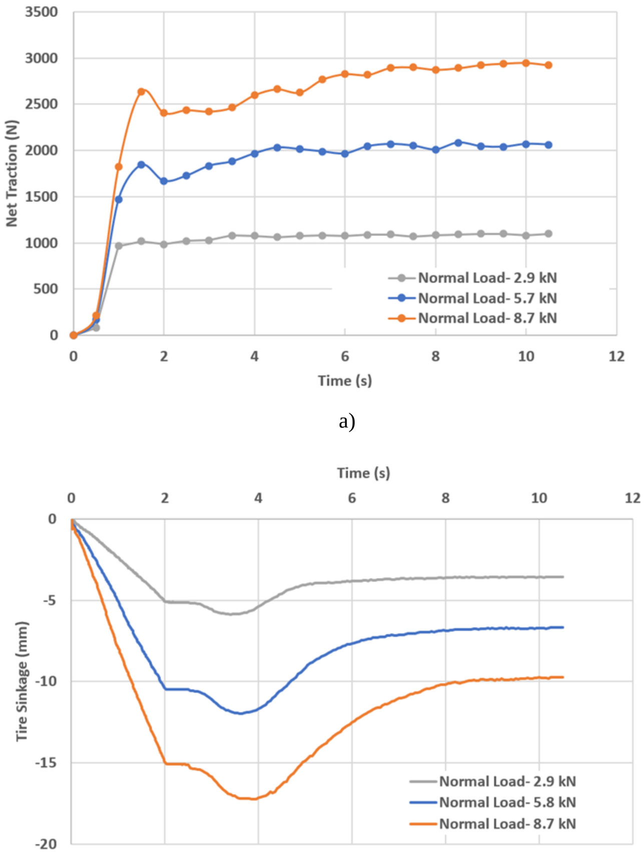
Figure 5: a) Normal stress (S33) b) in-plane shear stress (S13) (Normal load of 8.7 kN and slip rate of 18.5%).



a)

b)

Figure 6: a) Net Traction performance b) Tire Sinkage (Slip ratio-18.5%).

The unfiltered time history data of net traction and sinkage of rigid tire on soil at three different DOE normal loads is estimated from the numerical simulation runs. Based on the applied normal load, the settling time of the net traction and sinkage varies with time. Further, the net traction and sinkage increased with the increase in normal load (Figure 6).

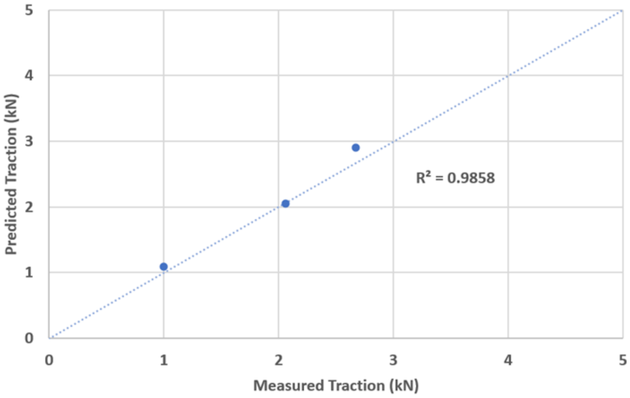


Figure 7: Traction for NSL soil: measured data vs. numerical predictions [10].

The net traction predicted by the numerical simulations is compared with the experimental results provided in the literature [10]. The predicted vs measured values for three normal loads applied at an 18.5% slip rate along with the R^2 for the rigid tire on NSL soil are presented (Figure 7).

IV. DISCUSSION

The numerical simulations are performed based on the parameterization of the soil constitutive material model using soil strength testing results and rigid tire soil interaction experimental study DOE [10]. The soil undergoes volumetric and shear deformation when the tire passes over it during the soil-tire interaction process [13]. The stress plots indicate plastic deformation and volumetric changes occurring in the soil. The volumetric deformation in the soil provides information about the compaction state of the soil and soil-tire interface contact area, which directly affect the shear strength of the soil. The stress bulb formation and stress distribution are directly dependent on the soil-tire contact area (Figure 5-a). The shear stress plot indicates the formation of the slip planes under the tire, where the soil in front of the tire provides a negative contribution to the net traction as it is resisting the movement of the tire. The soil under and at the back of the tire provides a positive contribution to the net traction as it assists in the driving process (Figure 5-b). The location of the slip plane is dependent on the applied normal load and slip ratio, shear strength of soil, and tire sinkage [8].

The variation of net traction of the rigid tire is investigated for different applied normal loads. The soil strength is pressure dependent, the increase in applied normal load increases the shear strength of the soil. Therefore, both net traction and tire sinkage increase with soil shear strength (Figure 6). In numerical simulation, the ramped longitudinal and rotational velocity is applied, therefore there is variation in the initial time duration of the simulation is observed before the net traction and tire sinkage settle down to the steady state values. The measured vs fitted curve of net traction at three different normal loads provided a good correlation with an R^2 value of 0.98.

Overall, a plain rigid tire is used at a low slip rate in this study. Therefore, additional studies are required with a more complex problem definition and extensive validation plan in terms of net traction, tire sinkage, and soil stresses to determine the accuracy of the developed methodology presented in this study for large-scale application.

V. CONCLUSIONS AND FUTURE WORK

The modeling of the soil-tire interaction process with traditional numerical methods is infeasible due to stability issues. Further, soil undergoes high plastic deformation, and the use of non-linear elastic-plastic material models is required for accurate results. The CEL approach has been successfully implemented in the simulation of non-linear dynamic problems such as soil-structure interaction. Therefore, in this study, a methodology of numerical simulation of soil-rigid tire interaction is developed using the CEL approach in Abaqus/Explicit. The numerically predicted net traction for three normal loads at a given slip rate of 18.5 % provided a good correlation with the experimental data.

The developed methodology with the CEL approach is suitable for predicting the net traction, tire sinkage, tire-soil contact area, and stress distribution in soil. These performance attributes are important for the design optimization of off-road tires based on the application and properties of terrain. However, the comparison of the relative accuracy of the CEL approach with other meshed and meshless numerical methods is still not undertaken for soil-tire interaction modeling.

The next steps are to model the soil-tire interaction with other numerical formulations used in modeling large deformation problems, such as SPH and ALE. Also, the sensitivity of the net traction to different slip rates and tire parameters will be studied.

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