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Vehicle–soil interaction: Testing, modeling, calibration and validation

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Abstract

Although many studies have been conducted on different aspects of tire–soil interaction, little work has been done focusing on the uncertainties involved such as those of the mechanical properties of soil and the interfacial properties between the tire and soil. Even less, if any, work has been done on the validation of *stochastic* tire–soil interaction models using rigorous statistical methods. In this paper, a statistical framework, along with new vehicle–soil interaction test data, is used to build a stochastic metamodel from a simple physically-based tire–soil interaction model, to calibrate model parameters with uncertainties, to predict model responses with uncertainties, and to validate the models using four validation metrics: one local metric that measures the differences between test and model at each instant of time, and three global metrics that measure these differences but over the entire time period of vehicle motion. Results in using the metrics indicate that the models performed well.

Keywords: Tire; Sand; Drawbar pull; Torque; Validation metrics; Calibration; Bayesian; Metamodel; Stochastic; Gaussian process

1. Introduction

Tire–soil interaction has been studied extensively over the years [1,2] with several hundred papers in the Journal of Terramechanics alone. As a naturally-occurring material, there is a significant amount of uncertainties for soil in material properties, as well as in interfacial properties between soil and tire; this calls for a stochastic rather than a deterministic approach [3] with the latter the dominant approach in literature. Many of the past studies involved the use of soil bins as a more controlled environment for tire–soil interaction, but the uncertainties due to the differences between soil-bin type of environment and the more realistic and challenging field environment are seldom quantified. The need, however, has not gone unnoticed [4]. In addition, although basic statistics have been used for tire–soil interaction in the past for comparison between tests and models, rigorous validation of *stochastic* models using statistical validation metrics [5] has never been attempted, to the best of authors' knowledge.

Recently, applying flexible statistical frameworks [6,7], the calibration of model parameters, the prediction using calibrated stochastic models, and validation using models and test data, have been conducted systematically for the indentation of snow [8], and tire–snow interaction [9] using the test data obtained on natural snowy terrain reported in [10]. Although snow and soil are entirely different in formation, composition, microstructure, and material properties, they do share features at the continuum mechanics level. For example, the mechanical responses of snow and soil have been modeled by pressure-sensitive plasticity models such as the Drucker–Prager [11,12], and the critical state models [13,14]. Also, the plasticity-based snow indentation model [15] used a cavity-expansion theory that was developed for pressure-sensitive materials, and applied extensively to soils [16]. Phenomenologically, the main difference between snow and most soils of interest is that the former is of finite depth.

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It is the purpose of this paper to address the uncertainties of tire–soil interaction by using deterministic physically-based models, stochastic metamodels, and newly acquired field test data for the calibration and validation of the models. The paper is organized as follows. Section 2 describes the soil material model, pressure–sinkage model, tire–soil interaction model and shear-stress shear-displacement model. Section 3 describes statistical models and methods that include the Gaussian process metamodel, calibration model, and validation metrics. Section 4 discusses test procedures for vehicle–soil interaction as well as soil properties. Results are presented in Section 5 including tests, calibration, prediction and validation. The paper closes with discussion and conclusions in Section 6.

2. Vehicle–soil interaction

2.1. Soil material model

A simple Drucker–Prager yield criterion is used to model soil:

$$\bar{\sigma} - p \tan\beta - p_d = 0 \tag{1}$$

where $p = -\frac{\sigma_{kk}}{3} = -\frac{\sigma_{ij}\delta_{ij}}{3}$ is the pressure, δ_{ij} is the Kronecker delta; $i, j = 1, \ldots, 3$. $\bar{\sigma}$ is the von Mises equivalent stress, β is the friction angle, and p_d is the cohesion. The hardening of soil uses a simplified Drucker–Prager yield criterion with a cap such that Eq. (1) is modified as:

$$\bar{\sigma} - p_a \tan\beta - p_d = 0 \tag{2}$$

where p_a is considered as a material parameter and expressed as:

$$p_a = c_1 \epsilon^p \tag{3}$$

where $\epsilon^p = \epsilon^p_{kk} = 3\epsilon^p_v$ is related to the volumetric plastic strain ϵ^p_v, c_1 is a constant.

Drucker–Prager yield criterion is a 3-D extension of the Mohr–Coulomb yield criterion. The parameters of these two yield criteria can be related using the following approximate relationship:

$$\tan\phi = \frac{\tan\beta}{3\sqrt{3}}, \quad c = \frac{p_d}{\sqrt{3}} \tag{4}$$

where ϕ and c are the friction angle and cohesion for the Mohr–Coulomb yield criterion, respectively.

2.2. Soil pressure–sinkage model

The snow indentation model in [15], relating indentation pressure to indentation displacement (sinkage), was developed using the Drucker–Prager plasticity theory discussed in the previous section, unlike the commonly used Bekker's pressure–sinkage relationship which is purely empirical. The model categorizes the pressure–sinkage (or more precisely, the pressure–strain) relationship in three zones. Zone I is a linear elastic region. Zone II is a strain-hardening region where the pressure-bulb developed under the indenter has not reached the bottom of the snow cover. Zone III starts when the pressure-bulb has reached the bottom of the snow cover. As discussed in [15], since soil is usually modeled as a domain with semi-infinite depth, the snow indentation model could be used for soil as well using the first two zones only. Adapting the snow indentation model for soil, there are three material constants: p_d, β, and c_1 (cf. Eqs. (2) and (3)).

2.3. Tire–soil interaction model

For tire–soil interaction, shown in Fig. 1, we use the traditional rigid-wheel model commonly used for sand [13] since it is much softer than the tire such that deformation of the tire can be neglected. This corresponds to the situation that the maximum ground pressure developed at tire–sand interface is less than the contact pressure [1] between a tire and the rigid ground. It should be noted that this contact pressure is close to the inflation pressure of the tire, e.g., see Fig. 2 in [17]. These equations are well known and are included for presentation and completeness purposes.

The sinkage of tire, or deformation of soil, z at a typical point, angle θ, on the tire–soil interface is related to the exit angle θ_0 by:

$$z(\theta) = r(\cos\theta - \cos\theta_0) \tag{5}$$

where r is the tire radius.

The vertical force F_z acting on the tire can be related to the normal stress (σ_n) and shear stress (τ) at the interface by:

$$F_z = br\left[\int_0^{\theta_0} \sigma_n(\theta)\cos\theta\, d\theta + \int_0^{\theta_0} \tau(\theta)\sin\theta\, d\theta\right] \tag{6}$$

where b is the width of the contact patch of the tire. The applied torque (M_y) is defined as:

$$M_y = r^2 b \int_0^{\theta_0} \tau(\theta)d\theta \tag{7}$$

The motion resistance (R_x), always positive, is defined as:

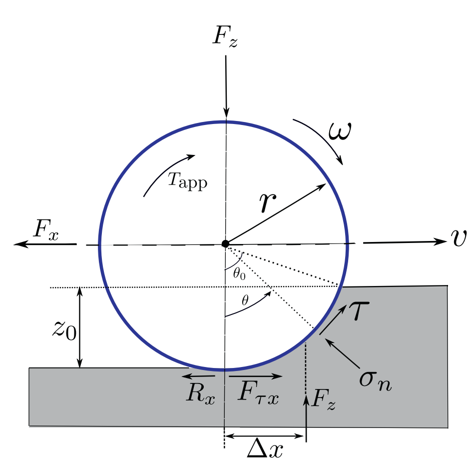

Fig. 1. Schematic of tire–soil interaction.