Parameter Identification for Planetary Soil Based on a Decoupled Analytical Wheel-Soil Interaction Terramechanics Model

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Abstract—Identifying planetary soil parameters is not only an important scientific goal, but also necessary for exploration rover to optimize its control strategy and realize high-fidelity simulation. An improved wheel-soil interaction mechanics model is introduced, and it is then simplified by linearizing the normal stress and shearing stress to derive closed-form analytical equations. Eight unknown soil parameters are divided into three groups. The highly complicated coupled equations, each of which includes all the unknown soil parameters, are then decoupled. Each decoupled equation contains one or two groups of soil parameters, making it feasible to make a step-by-step identification of all the unknown parameters that characterize the soil. Wheel-soil interaction experiments were performed for six kinds of wheels with different dimensions and wheel lugs on simulated planetary soil. Soil parameters are identified with the measured data to validate the method, which are then used to predict wheel-soil interaction forces and torque, with a less than 10% margin of error. The improved model, decoupled analytical model, and soil-characterizing method can play important roles in the development of both the planetary exploration rovers and the terrestrial vehicles.

I. INTRODUCTION

Scientists have long been interested in the soil mechanics properties of planetary rovers, both to improve our scientific knowledge of the geological properties of planetary soil and to provide engineering knowledge required to perform planetary surface exploration or future settlement activities.

During the lunar exploration missions carried out in the 1970s, the U.S.A. and the former Soviet Union brought soil samples back to the earth and conducted research on their properties [1]. Due to a lack of samples obtained from a return mission, the more recent exploration of Mars and the moon has required soil research to be conducted remotely. Compared to the research on samples that have been brought back, the in-situ research on soil mechanics properties is low in cost, and it can conveniently be conducted at any time or place with little influence on the original mechanical properties of the soil.

Viking Lander performed soil experiments by scraping the soil to dig trenches with a surface sampling arm. The internal cohesion and friction angles of different types of soils (drift, crusty and cloddy) were estimated [2]. W. Hong developed a system for estimating soil properties in-situ using a manipulator arm, including soil mechanics modeling and estimation techniques [3]. Researchers from the Sojourner rover team conducted experiments by driving one wheel on the rover while keeping the other wheels stationary. The soil appeared to show little or no cohesion, and the friction angles were found to be between 32° and 41° [4]. Mechanical experiments were also performed during NASA Mars Exploration Rover Missions [5]. The Spirit and Opportunity rovers researched the soil properties of Meridiani Planum [6] and Gusev Crater [7], respectively, by excavating the subsurface soil with wheels for in-situ observation, studying the rock mechanical properties with a rock abrasion tool and analyzing the wheel track patterns, depths, and wheel slippage dynamics during traverses.

Wheel-soil interaction terramechanics models consist of not only the internal cohesion and friction angle of the soil but also many other parameters such as the cohesive modulus, friction modulus, and sinkage exponent, which can express the pressure bearing capability of soil [8]. This makes it possible to characterize planetary soil more comprehensively by estimating soil parameters according to the forces and moments that act upon the wheel. In addition, for future rover-based exploration missions conducted on more challenging terrains, such as the MSL and ExoMars missions for exploring Mars and the SELENE and Chang’e lunar rover plans, the rover must know the variations in soil parameters in time to optimize its control and planning strategy. This enables it to maximize wheel traction or minimize power consumption [9] as well as update the parameters for rover simulation on Earth, a boon to the successful achievement of scientific goals. Two important issues, however, must first be resolved in regard to wheel-soil interaction mechanics based parameter identification. One issue is the development of a high-fidelity wheel-soil interaction terramechanics model for planetary rovers. The other issue is to simplify the relevant complex coupled nonlinear integrated equations in order to obtain simple closed-form equations.

The classical terramechanics models for terrestrial vehicles are usually used for planetary rovers [8], [10], [11]. K.
Iagnemma et al. linearized the Wong-Reece normal stress equation and Janosi shearing stress equation in order to obtain a closed-form formula, and then, they applied a linear least-squares estimator in order to estimate the internal cohesion and friction angle online by setting the shearing deformation modulus to a typical value [12]. This method is used to estimate the terrain for planetary rovers so that they can adapt their control strategies and maximize effectiveness [13]. S. Hutangkabodee et al. developed a method to identify the internal friction angle, shearing deformation modulus, and lumped pressure sinkage coefficient (cohesive sinkage modulus and frictional sinkage modulus), while the internal cohesion was fixed to 3 Kpa. The composite Simpson’s rule was employed to obtain an approximated form model [14].

The fidelity of wheel-soil interaction models can determine the precision of parameter identification. An improved model for calculating the interaction mechanics was developed that took into account the slip-sinkage and lug effect, which gave considerable precision to the prediction of both the mechanics and the entire sinkage of the wheel [15], a subject that is introduced in Section II. Section III deduces a decoupled closed-form analytical formula, which is then used to predict eight soil parameters in Section IV. Section V describes the purpose of simplification [16].

II. WHEEL-SOIL INTERACTION MECHANICS MODEL

A. General model for lugged planetary wheel

Planetary rovers are usually installed with lugs of a certain height to improve their tractive ability in deformable soil. Fig. 1 shows a diagram of lugged wheel-soil interaction mechanics [12], where $z$ is the wheel sinkage; $\theta_1$, the entrance angle at which the wheel begins to contact the soil; $\theta_2$, the exit angle at which the wheel looses contact with the soil; $\theta_m$, the angle of maximum stress; $\theta'_m$, the angle where the soil begins to deform; $W$, the vertical load of the wheel; $DP$, the resistance provided by forward movement, which is equal to the drawbar pull; $T$, the driving torque of the motor; $r$, the wheel radius; $h$, the height of the lugs; $v$, the vehicle velocity; and $\omega$, the angular velocity of the wheel. The soil interacts with the wheel in the form of continuous normal stress $\sigma$ and shearing stress $\tau$, which are divided into a forward part $(\sigma_1, \tau_1)$ and a rear part $(\sigma_2, \tau_2)$.

For a steadily moving wheel, force balance equations can be expressed by integrating the stresses as follows:

$$W = b\int_{0}^{\theta_2} \left[ \sigma_2(\theta) \cos \theta + \tau_2(\theta) \sin \theta \right] d\theta + \int_{\theta_2}^{\theta_1} \left[ \sigma_1(\theta) \cos \theta + \tau_1(\theta) \sin \theta \right] d\theta$$

$$DP = b\int_{0}^{\theta_2} \left[ \tau_2(\theta) \cos \theta - r \sigma_2(\theta) \sin \theta \right] d\theta + \int_{\theta_2}^{\theta_1} \left[ \tau_1(\theta) \cos \theta - r \sigma_1(\theta) \sin \theta \right] d\theta$$

$$T = r^2b\int_{0}^{\theta_2} \tau_2^2(\theta)d\theta + \int_{\theta_2}^{\theta_1} \tau_1^2(\theta)d\theta$$

where $b$ is the width of the wheel, $r$, is the equivalent shearing radius, i.e., the average radius where the shearing between the moving soil adhered to the wheel and static soil takes place:

$$r = r + \lambda h \quad (0 \leq \lambda \leq 1)$$

The lug coefficient $\lambda$, in (2) is related to the internal friction angle of the soil and the number of lugs, and it is set to 0.5 for the purpose of simplification [16].

B. Normal stress and shearing stress distribution

Let $s$ denote the slip ratio, an important state variable of wheel soil interaction. It is defined with $r_1$, [16]:

$$s = \begin{cases} (r_1 \omega - v) / r_1 \omega & (r_1 \omega \geq v, 0 \leq s \leq 1) \\ (r_1 \omega - v) / v & (r_1 \omega < v, -1 \leq s < 0) \end{cases}$$

The normal stress equation is improved on the basis of the Wong-Reece model [15]:

$$\sigma_1(\theta) = \left( \frac{k_1}{b} + k_s \right) r^N \left( \cos \theta - \cos \theta_1 \right)^N \left( \theta_m \leq \theta \leq \theta_1 \right)$$

$$\sigma_2(\theta) = \left( \frac{k_2}{b} + k_s \right) r^N \left( \cos \theta - \frac{\theta - \theta_m}{\theta_m - \theta_2} \left( \theta_1 - \theta_m \right) \right) \cos \theta_1^N \left( \theta_2 \leq \theta \leq \theta_m \right)$$

where $k_1$ is the cohesive modulus of the soil, $k_s$ is the frictional modulus, and $N$ is the improved soil sinkage exponent. $N$ is the linear function of the slip ratio:

$$N = n_0 + n_1s$$

where $n_0$ and $n_1$ are coefficients for calculating $N$. Equation (5) is deduced to change the constant sinkage exponent $n$ with the slip ratio to predict all sinkage of the wheel, including severe slip sinkage [17], which cannot be reflected well by the conventional model. The sinkage exponent $N$ is an increasing function of the slip ratio, while the normal stress is a decreasing function of $N$. Therefore, the entrance angle and sinkage increase as the slip ratio increases. The linearized method is effective in predicting wheel sinkage.

Angles $\theta_1$, $\theta_2$, and $\theta_m$ are functions of wheel sinkage $z$ and coefficients $c_1$, $c_2$, and $c_3$:

$$\theta_1 = \cos \left( \frac{r - z}{r} \right)$$

$$\theta_m = (c_1 + c_2z) \theta_1$$
\( \theta_2 = c_1 \theta_1 \)  

The leaving angle \( \theta_2 \) is usually simplified as zero, as is the parameter \( c_1 \).

The Janosi equation for calculating shearing stress was also improved [15]:

\[
\tau(\theta) = \left[ c + \sigma(\theta) \tan \phi \right] \times \left[ 1 - \exp \left( -r_1 \left( \theta' - \theta \right) \right) (1 - s) \sin \left( \theta' - \sin \theta \right) / k \right] / k
\]

where \( c \) is the cohesion of the soil, \( \phi \) is the internal friction angle, and \( k \) is the shearing deformation modulus.

\[
\theta' = \frac{(r - z)}{L}
\]

\[
R_j = \begin{cases} r + h & (0 \leq s \leq s_j) \\ r + h(s_j - s)/(s_j - s_{j1}) & (s_{j1} < s < s_{j2}) \\ r & (s_{j2} \leq s \leq 1) \end{cases}
\]

If the entrance angle is \( \theta_1 \) and wheel sinkage is small (indicated by a slip ratio less than approximately 0.15), soil displacement can be considered as starting from angle \( \theta'_1 \) calculated by the maximum radius \( r + h \) (as shown in Fig. 1). If wheel sinkage is great, the next lug cannot contact the soil immediately after the former one completely enters the soil. The interaction between lug and soil is quite a complex process. The radius \( R_j \) for calculating \( \theta'_j \) is deduced in order to approximate the effect of that process. Transitional slip ratios \( s_{j1} \) and \( s_{j2} \) are adopted because wheel sinkage is related to the slip ratio [15]. If the slip ratio is larger than 0.5, the influence of wheel lugs on the starting angle of soil deformation can be ignored. According to the above analysis, the parameters \( s_{j1} \) and \( s_{j2} \) are 0.15 and 0.5 respectively.

Equations (5) and (10) contribute most to the improvement of the model, as they reflect wheel slip-sinkage phenomena and the lug effect quite well. More details can be found in [15].

Apart from \( \lambda_a \), \( c_1 \), \( s_{j1} \), and \( s_{j2} \), which have been determined, there remain nine unknown soil parameters: \( c_1 \), \( c_2 \), \( k_a \), \( k_m \), \( n_1 \), \( c \), \( \varphi \), and \( k \).

III. DECOUPLED ANALYTICAL MODEL DERIVATION

A. Model Analysis

The wheel-soil interaction model in (1) includes three equations. Given \( s \) and \( \theta_1 \), \( W \), \( DP \) and \( T \) can be calculated if the soil parameters are known. Figure 2 shows the process. Inversely, if \( W \), \( DP \), \( T \), and \( \theta_1 \) of different slip ratios are measured, it is possible to identify the unknown soil parameters by means of the data fitting method. However, the equations are highly coupled, and each of them contains all the unknown parameters. It is not feasible, therefore, to identify these nine parameters simultaneously by means of the measured data, due to the complexity and high nonlinearity of the model, which can easily lead to local convergence.

Let \( K_a = k_a/b + K_m \) denote the wheel-soil interaction sinkage exponent, i.e., the lumped pressure-sinkage coefficient in [14]. For a wheel of a certain width \( b \), the parameter \( K_m \) will therefore replace \( k_a \) and \( k_m \), which are not feasible and don’t need to be separately identified. The parameters can be divided into three groups:

\[ P_1 = \{ c_1, c_2 \}, P_0 = \{ K_a, n_0, n_1 \}, P_m = \{ c, \varphi, k \}, \]

which are directly related to angles of \( \theta_1 \) and \( \theta_2 \), normal stress and shearing stress, respectively.

\[
\begin{align*}
\sigma & = \sigma_1 + \sigma_2 \\
\tau & = \tau_1 + \tau_2
\end{align*}
\]

Fig. 2 Diagram of coupled wheel-soil interaction mechanics model

If the equations can be decoupled to separate the variables of three groups, it will become easier, and feasible, to identify all the unknown parameters.

B. Stress Simplification

Let \( \sigma_m \) denote the maximum normal stress, and \( \tau_m \) denote the maximum shearing stress:

\[
\sigma_m = K_s r^N \left( \cos \theta_m - \cos \theta_1 \right)^N
\]

\[
\tau_m = \left( c + \sigma_m \tan \phi \right) \times \left[ 1 - \exp \left( -r_1 \left( \theta'_m - \theta_1 \right) \right) (1 - s) \sin \left( \theta'_m - \sin \theta_1 \right) / k \right] / k
\]

The normal stress and shearing stress can be simplified by means of the linearized method [12]:

\[
\begin{align*}
\sigma_1(\theta) & \approx \frac{\sigma_1^1(\theta)}{\theta_1 - \theta_2} = \frac{\sigma_m(\theta_1 - \theta_2)}{(\theta_1 - \theta_m)} \quad (\theta_m \leq \theta \leq \theta_1) \\
\sigma_2(\theta) & \approx \frac{\sigma_2^1(\theta)}{\theta_1 - \theta_2} = \frac{\sigma_m(\theta_1 - \theta_2)}{(\theta_1 - \theta_m)} \quad (\theta_2 \leq \theta < \theta_1) \\
\tau_1(\theta) & \approx \frac{\tau_1^1(\theta)}{\theta_1 - \theta_2} = \frac{\tau_m(\theta_1 - \theta_2)}{(\theta_1 - \theta_m)} \quad (\theta_m \leq \theta \leq \theta_1) \\
\tau_2(\theta) & \approx \frac{\tau_2^1(\theta)}{\theta_1 - \theta_2} = \frac{\tau_m(\theta_1 - \theta_2)}{(\theta_1 - \theta_m)} \quad (\theta_2 \leq \theta < \theta_1)
\end{align*}
\]

The literature [12] has verified the linearized method for soils with a sinkage exponent in the range of 0.5 to 1.6. Soil exponent sinkage influences the simplification error. Six kinds of wheels (Section V) with wheel-soil interaction exponent coefficients \( n_0 \) and \( n_1 \) [15] close to the identified value (Section VI) are used to check the error. Three groups of typical values are selected: \( \theta_1 = 35^\circ, s = 0.4; \theta_1 = 25^\circ, s = 0.2; \theta_1 = 15^\circ, s = 0 \), which are comparable to the experimental results of wheel-soil interaction presented in Section V. The results of calculations show that the maximum relative error is larger for a lower slip ratio because the sinkage exponent is smaller. The maximum simplification error for both normal stress and shearing stress is approximately 15%.

C. Closed-form analytical equations

By substituting (14) and (15) for (1) and integrating the equations, one arrives at:

\[
\begin{bmatrix}
W \\
DP \\
T
\end{bmatrix} =
\begin{bmatrix}
A & B & 0 \\
-B & A & r \\
0 & r & C
\end{bmatrix}
\begin{bmatrix}
X \\
Y \\
Z
\end{bmatrix}
\]

where

\[
A = \frac{\cos \theta_m - \cos \theta_1}{\theta_m - \theta_2} + \frac{\cos \theta_m - \cos \theta_1}{\theta_1 - \theta_m}, \quad X = r b \sigma_m
\]

\[
B = \frac{\sin \theta_m - \sin \theta_1}{\theta_m - \theta_2} + \frac{\sin \theta_m - \sin \theta_1}{\theta_1 - \theta_m}, \quad Y = r b \tau_m
\]

\[
C = \frac{\theta_1 - \theta_m}{2}
\]

\( A, B \) and, \( C \) are functions of entrance angle \( \theta_1 \) and parameters of \( P_1, X \) is related to parameters of \( P_1 \) and \( P_0 \), while
Y is related to all parameters. It is clear that $W$, $DP$, and $T$ are functions of all the soil parameters.

**D. Decoupling of equations**

According to (16),

$$X = (W - BY) / A = (AY - DP) / B$$

$$Y = T(r, C)$$

By substituting (17) and (18) into (16), one obtains:

$$DP = AY - B = \frac{A^2 + B^2}{r_c AC} - \frac{B}{A}$$

$$W = AX + BT / (r_c C) = r_b AC \sigma_m + BT / (r_c C)$$

According to (20),

$$\sigma_m = W / (rbAC - BT / (r_c AC))$$

Let $D = 1 - \exp(\cdot)$, $T(r_c C)$. Substitute $Y = r_b \sigma_m$.

$$T = r_c CD[b + (W / (rA)) / BT / (r_c AC)] tan \phi$$

The explicit formulation of $T$ is:

$$T = r_c CD[b + W tan \phi(rA)] (1 + r, BD tan \phi / (rA))$$

Equations (19), (20) and (23) are decoupled equations. $DP$ is the function of the parameters in $P_1$; $W$ is the function of the parameters in $P_1$, while $T$ is the function of the parameters in $P_1$.

**IV. PARAMETER IDENTIFICATION METHOD**

**A. Identifying $c_1$ and $c_2$**

According to (19), $DP$ is the function of $W$, $T$, $\theta$, $s$, and $t$, the unknown parameters $c_1$ and $c_2$, $c_1$ and $c_2$ can be identified if the other parameters have been measured, as shown in Fig. 3.

**B. Identifying $K_s$, $n_0$ and $n_1$**

According to (12) and (20),

$$F_n = r_b AC \left[ r_c n_0 \cos \theta_m - \cos \theta_0 \right] + BT / (r_c C)$$

As shown in Fig. 4, three parameters $K_s$, $n_0$, and $n_1$ can be identified according to the measured $\theta_1$, $W$, $T$, $s$, and $c_1$, $c_2$.

**C. Identifying $c$, $\phi$ and $k$**

By substituting the values of $D$ in (23), one obtains:

$$r_c CD[b + W tan \phi(rA)] (1 - \exp(\cdot))$$

$$\theta = \frac{\theta'_0 - \theta'_0}{(s)(\sin \theta'_0)}$$

As shown in Fig. 5, parameters $c$, $\phi$, and $k$ can be identified with the measured $\theta_1$, $W$, $T$, and $s$ with (25).

**D. Parameter identification implementation**

The least square method is adopted to identify the soil parameters with the lsqcurvefit function of Matlab. Let $x$ denote the vector of identified parameters, $xdata$ denote the input data, $ydata$ denote the measured $DP$, $W$, and $T$, $m$ denote the length of $xdata$ and $ydata$, and $F_n$ denote the function of (19), (24) and (25) respectively. The identifying process seeks to find the vector $x$ that best fits (26):

$$\min \frac{1}{2} \| F(\mathbf{x}, xdata) - ydata \|^2 = \frac{1}{2} \sum_{i=1}^{m} [F(x, xdata) - ydata]^2$$

**V. EXPERIMENTAL STUDY OF WHEEL-SOIL INTERACTION**

**A. Experimental equipment and materials**

Figure 6 shows the wheel-soil interaction testbed that was used to perform the experiments. The testbed consists of three motors and various related sensors. The driving motor can cause the wheel to move forward; the carriage motor is used together with a conveyance belt to imitate the influence of the vehicle body on the wheel and to create various slip ratios; and the steering motor is used for research into steering. Wheel sinkage $z$ is measured by a high precision sliding resistance displacement sensor; $T$, $DP$ and $W$ can be measured with a torque sensor and F/T sensor.

The design of the experimental wheels was based upon those in recent planetary rovers (Fig. 7). Six types of cylindri-
The literature shows that the mechanical properties of dry loose sand are similar to those of planetary soil, so that such sand is usually employed as planetary soil simulant. The simulant used in this study was made from soft sand after removal of impurities, sieving, ventilating and drying. The experimental slip ratios were 0, (0.05), 0.1, 0.2, 0.3, 0.4, (0.5), and 0.6. The slip ratios were calculated with $\lambda = 1$, and the values were amended with the shearing radius $r_s$ [16]. The vertical wheel load was approximately 80 N. All the setting values were comparable to those of planetary rovers.

C. Results

Hundreds of raw data could be obtained for a single test. The measured data fluctuate periodically in correspondence with the entrance and exit of the wheel lugs. The results of the experiment show that the mean values of several tests are almost the same, regardless of fluctuations in the data. The wheel interacted with the soil to achieve a steady state after it was kept running for several seconds. The steady data were used in order to calculate the mean values of $z$, $DP$, $W$ and $T$ after filtering. The entrance angles were then calculated with the wheel sinkage. The curves of $\theta_1$, $DP$, $W$, and $T$ versus slip ratio were obtained for the 6 kinds of wheels used.

VI. EXPERIMENTAL VERIFICATION

A. Parameter identification result and discussion

Experimental data were used to identify the soil parameters. Table II shows the results (the unit of $K_c$ is Kpa/m$^3$) and Table III shows the data fitting error and calculation time.

The data fitting result of Wh11 is plotted in Fig. 7 (M1). The relative data fitting error values for $DP$, $W$ and $T$ are smaller than 4.13%. The computation time for fitting $DP$ and $W$ is smaller than 50 ms on a 2G Hz laptop PC, but it sometimes takes about 150 ms to fit $T$ due to the complexity of (25). The calculation time can be decreased by optimizing the codes and further simplifying (25). In any case, it can be concluded that this method is suitable for online planetary soil parameter identification.

The largest error for identified $\phi$ is only 3.1°. The error of $c$ is also very small as compared to the shearing stress; a difference of only several Kpa. Parameter $k$ has an acceptable range from 9.7 mm to 13.1 mm. Parameter $K_c$ is sensitive to the initial value and the identified result is quite close to the initial value 2500 Kpa/m$^3$, meaning that only $n_0$ and $n_1$ are sufficient for fitting the vertical load. $K_c$ could be fixed to the value of estimated soil frictional modulus $k_s$, as $k_s$ is so small as to be negligible [12]. For example, for lunar soil, $K_c$ can be set to $k_s = 820$ Kpa/m$^3$ by ignoring $k_s = 1.4$ Kpa/m$^3$ [15]. The bearing performance of soil could be quite well characterized by the identified $n_0$ and $n_1$. The range of $n_0$ and $n_1$ for the experimental planetary soil stimulant is from 0.73 (W31, $s = 0$) to 2.10 (W11, $s = 1$), from which wheel sinkage into the soil can be estimated.

Parameter $c_1$ is between 0.37 and 0.53, while $c_2$ is between -0.38 and -0.04. Their values exhibit a wide range, but the
other identified parameters are not obviously influenced by this. This means that wheel-soil interaction mechanics are not sensitive to $c_1$ and $c_2$. One can therefore assign typical values of $c_1$ and $c_2$ to the soil even if the values of $DP$ are unknown. If we let $c_1 = 0.5$ and $c_2 = 0$, the drawbar pull can be fitted with an acceptable maximum relative error of 8.57% (M2 in Fig. 7 (a)), the data fitting error or $W$ and $T$, and the identification results of the other parameters are not significantly influenced.

If a constant sinkage exponent is used instead of $N$ in (5), the identification results for Wh11 are $K_s = 14.2$ Kpa/m$^n$ and $n = 0$ (lower limit). The fitting errors of $W$ are quite large (M3 in Fig. 7 (b)). Extending the limits of $n$, the best data fitting result for $K_s$ is from 1.32 Kpa/m$^n$ (Wh11) to 2.66 Kpa/m$^n$ (Wh11), $n$ is from $-0.54$ (Wh11) to $-0.50$ (Wh31), which is far from the soil parameters. If (10) is not used, i.e., the influence of lugs on the starting angle of soil deformation is ignored, then the identified $c$ ranges from $448$ Pa (Wh12) to $3071$ Pa (Wh11), $\sigma$ from $15.7^\circ$ (Wh11) to $26.2^\circ$ (Wh12), and $k$ from 1.3 mm (Wh31) to 5.5 mm (Wh12). These results, however, are untenable, and the fitting error of $T$ reaches 10.58% (Wh31).

B. Mechanics prediction with identified parameters

The prediction of wheel-soil interaction mechanics by means of the identified parameters can be applied to rover design, control strategy optimization, and dynamics simulation.

The process for mechanics prediction is as follows. (1) Given the vertical load $W_a$ (the average value of measured $W$, 80–85N), slip ratio $s$, and the initial value of the entrance angle. (2) Calculate $\sigma_0$ and $\tau_0$ with (12) and (13). (3) Calculate $W$ with (16). (4) If $|W - W_s| > \delta$ (error tolerance), change $\theta_s$ and return to (2); or else, calculate $z$. (5) Calculate $DP$ and $T$ with (16).

Table IV shows the relative error and calculation time. The maximum relative error for $z$, $DP$ and $T$ are 1.89%, 9.09% and 4.28%, respectively. The calculation time for $z$ is less than 30 ms and that for $DP$ and $T$ is about 30 µs. These are feasible values for real-time application.

VII. CONCLUSION

The improved model is effective and superior to the original model. The closed-form analytical equations for calculating $DP$, $W$, and $T$ are suitable for real-time applications because of their high precision and short calculation time. It is possible to characterize planetary soil more comprehensively with the decoupled analytical model onboard, which can help us better understand planetary soil. The methods and results developed in this study can also be extended to terrestrial wheeled vehicles and mobile robots. Our results also suggest that a new kind of soil parameter measurement meter based on wheel-soil interaction mechanics should be developed.