

Article

An Analytical Modeling Framework for Martian Soil—Sampling Scoop Interaction with Numerical Validation

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Abstract

Accurate prediction of excavation forces is critical for the design reliability and operational safety of Mars surface sampling systems. This study establishes an analytical modeling framework to describe the excavation mechanics of Martian soil, focusing on the formation mechanism and evolution of resistance. Soil deformation and failure processes are qualitatively identified using particle image velocimetry (PIV) and discrete element method (DEM) simulations. Based on limit equilibrium theory, the passive earth pressure is derived, and the scoop is divided into seven force-bearing regions for three-dimensional force decomposition. The analytical model is validated against multibody dynamics–discrete element method (MBD–DEM) co-simulation. The results indicate that excavation resistance exhibits a distinct single-peak evolution, maximizing near the maximum excavation depth. Notably, the inner bottom surface and cutting edge dominate resistance during penetration, contributing approximately 56% and 30% of the total force, respectively. The resistance mechanism transitions after soil emergence due to the gravitational effect of retained soil. Consequently, this framework provides a physically interpretable and quantitatively validated approach for force prediction, offering theoretical support for sampling scoop design and optimization in future Mars missions.

Keywords: soil excavation; sampler; soil–tool interaction model; MBD–DEM co-simulation; model adaptability analysis

1. Introduction

Mars surface sampling requires reliable prediction of excavation resistance to support the design and operation of sampling scoops. However, existing excavation force models are often insufficient to describe the formation mechanism and evolution of resistance during scoop excavation. Therefore, an analytical modeling framework that can explicitly characterize excavation resistance based on physical principles is highly needed.

The goal of the soil–tool interaction model is to mathematically represent the resistive forces exerted by the soil on the tool during excavation tasks, based on soil parameters, tool parameters, soil–tool interaction parameters, and experimental conditions. Such

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models can be applied in areas such as design optimization, force prediction, simulation control, inversion of soil physical property parameters, control strategy optimization, improvement of sampling efficiency, and optimization of energy reserves [1]. Different approaches have been used in the literature to estimate excavation forces and torques, including analytical models and empirical models derived from experiments or discrete element method (DEM) simulations [2–5]. The limitations of analytical models lie in their inability to handle heterogeneous or more complex terrain structures, as well as their lack of accuracy in analyzing different tool geometries. Empirical models, on the other hand, often require the physical environment and specific scenarios to be faithfully replicated [6]. There is a lack of a unified theoretical foundation among different excavation models, which are mostly based on empirical formulas and methods, resulting in uncertainties in the prediction outcomes.

The excavation models can be categorized into two-dimensional cutting models and three-dimensional (3-D) models [1,7]. For modeling cutting with a blade, commonly used models include the Osman model [8], Gill and Vanden Berg model [9], Swick and Perumpral model [10], and McKyes model [11]. The 3D models take into account the influence of the sides and the bottom—the addition of these components transforms a blade into a bucket, introducing additional forces that must be considered. Representative 3D models include the Hemami model [12] and the Balovnev model [13]. The Phoenix lander applied the Balovnev model to estimate the cohesion of Martian soil in the vicinity of the lander [14]. These models are generally distinguished based on the types of excavation forces involved, such as frictional force, inertial force, adhesive force, cohesion force, and so on. Blouin reviewed various models related to penetration, cutting, and excavation tasks, and analyzed the different forces involved in the excavation process. The author pointed out the lack of general consistency between modeling and analysis in current approaches, which hinders the development of effective analytical models for excavation processes [1]. Under the context of lunar excavation, Wilkinson conducted a quantitative analysis of six excavation models, investigating the effects of soil properties such as cohesion, friction, soil–tool adhesion, and soil density. The study also examined the influence of excavation depth, gravity, and additional forces. Different excavation models yielded varying results, highlighting the need for in situ testing to determine soil parameters that are compatible with the selected models [7]. Xi conducted soil cutting experiments to validate six excavation models. The results showed that the Swick and Perumpral model and the McKyes model were able to predict the horizontal and vertical excavation forces with relatively high accuracy [15].

Catanoso used the discrete element method to determine the forces and torques acting on the lander's scoop during the sample acquisition process [16]. Xi validated the application of 3D DEM in modeling lunar soil excavation by comparing simulation outcomes with experimental data, showing that the method effectively captures soil failure mechanisms and key parameter influences, thus proving its potential for extended studies under lunar environmental conditions [17]. Xue developed a simple apparatus to measure excavation torque in regolith simulant and found that factors such as penetration angle, bulk density, and the presence of gravels significantly affect torque, highlighting the importance of monitoring torque spikes during excavation to prevent operational risks [18]. Abdeldayem developed and validated an elasto-plastic DEM model with stress-dependent cohesion to simulate cohesion-frictional soil–blade interactions, demonstrating good predictive accuracy for soil reaction forces and deformation across various blade geometries, supporting its potential for digital twin development in earthmoving operations [19]. Narayanan developed and validated a bucket design methodology for construction equipment using both analytical models and DEM simulations, demonstrating strong correlation between the two approaches and emphasizing the importance of soil properties

and bucket geometry in optimizing excavation performance [20]. Although numerous excavation models have been developed using analytical, empirical, and DEM-based approaches, inconsistencies in physical assumptions and force formulations limit their general applicability.

This study develops an analytical soil–tool interaction model for a Mars sampling scoop, aiming to describe the formation mechanism and evolution characteristics of excavation resistance based on physical principles. The model is constructed using limit equilibrium theory and force decomposition, and its validity is verified through experimental observation and numerical simulation. To support force validation, an EDEM–RecurDyn co-simulation approach is employed, enabling quantitative evaluation of the forces acting on different regions of the sampling scoop during excavation. Rather than relying solely on empirical descriptions, the proposed framework provides a physically interpretable basis for excavation force prediction and offers guidance for sampling scoop structural optimization and soil–tool interaction model development in future Mars surface sampling missions.

2. Modeling Conditions and Validation Framework

2.1. Geometric Definition of the Sampling Scoop and Test Configuration

Figure 1a presents the structural dimensions of the sampling scoop, which has an effective volume of 145 cm³. Figure 1b illustrates the experimental configuration for the excavation test, in which the sampling scoop is mounted at the end of a robotic arm (BORUNTE 0805A, BORUNTE ROBOT CO., LTD., Dongguan, China) to execute a predefined excavation trajectory. A soil bin filled with simulated Martian regolith is positioned beneath the setup to provide controlled boundary conditions for the excavation process.

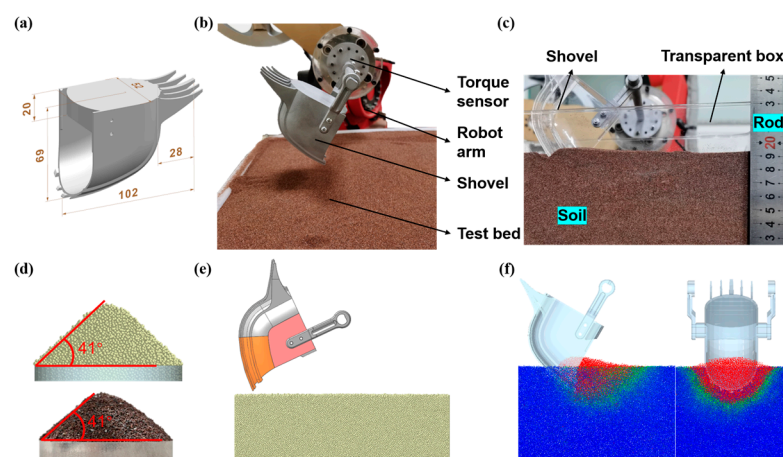


Figure 1. Overview of the sampling scoop experimental and simulation setup: (a) structural dimensions of the sampling scoop; (b) experimental setup for excavation tests, including the robotic arm and soil bin filled with simulated Mars soil; (c) transparent acrylic soil bin and half-section scoop configuration for visualizing soil disturbance; (d) angle of repose calibration test for soil parameter determination in DEM simulations; (e) schematic of the DEM–MBD co-simulation environment established in EDEM (Version 2022, Altair Engineering Inc., Troy, MI, USA) and RecurDyn (Version 2023, FunctionBay, Inc., Seongnam, South Korea); (f) soil disturbance results obtained from the DEM simulation for comparison with experimental observations.

To enable direct measurement of the interaction forces between the sampling scoop and the regolith, a six-axis force/torque sensor is integrated between the sampling scoop and the robotic arm end-effector. The sensor records three orthogonal force components and three moment components throughout the excavation process, providing time-

resolved force/torque data that are later used for validation of the analytical force model. The employed sensor is XJC-6F-D80-H28-A (Shenzhen XJC Sensor Technology Co., Ltd., Shenzhen, China). The sensor rated output (sensitivity) is 0.5–1.0 mV/V for the force channels and 0.7–1.5 mV/V for the moment channels, with nonlinearity $\leq 0.5\%$ F.S. and repeatability $\leq 0.1\%$ F.S.

To investigate soil disturbance and failure mechanisms induced by the sampling scoop, the opaque soil bin is replaced with a transparent acrylic container, as shown in Figure 1c. In this configuration, the sampling scoop is redesigned with a half-section geometry and positioned adjacent to the transparent wall of the soil bin, allowing the soil deformation and failure processes to be visually observed. The excavation process is recorded using a high-resolution camera (Canon EOS R50, Canon Inc., Tokyo, Japan) in 4K UHD (3840×2160 pixels) at up to 30 fps (29.97/25/23.98 fps). The 4K video is generated via 6K oversampling and recorded without cropping. The captured image sequences are analyzed frame by frame with the PIVlab toolbox in MATLAB (Version R2020b, MathWorks, Natick, MA, USA) to characterize the kinematic features of soil disturbance [21]. It is emphasized that these observations are introduced to qualitatively identify the failure patterns and deformation regions associated with the excavation process, rather than to derive quantitative force results.

2.2. Numerical Configuration for Force Validation

Discrete element method (DEM) simulations were further conducted to analyze the distribution of excavation forces and the soil dynamic response during digging. In EDEM 2022, a soil environment consistent with the physical tests was established to ensure the accuracy of the simulation data, as shown in Figure 1d for the angle of repose calibration test. The parameters included particle size distribution (150–180 μm), bulk density (1.48 g/cm^3), and angle of repose (41°). To ensure a valid comparison, the simulation was performed under the same operating conditions as the ground tests, maintaining identical soil properties and a consistent excavation depth of 3 cm. In addition, the simulations and experiments were conducted under a 1 g gravitational environment, which ensures that the calibrated soil parameters (obtained/validated under terrestrial gravity) remain consistent and reliable for model verification. Furthermore, we carried out a series of comparative simulation analyses under different gravity levels (including Martian gravity) to examine the corresponding trends in excavation resistance, thereby demonstrating that the proposed model can both (i) be validated under Earth gravity and (ii) be readily applied for analysis under Martian gravity by replacing the gravity term accordingly.

Figure 1e illustrates the schematic of the DEM–MBD co-simulation, while Figure 1f presents the soil disturbance obtained from the simulation, which can be further compared with the results in Figure 1c. As shown in Figure 2, the sampling scoop was divided into eight parts in RecurDyn 2023, and corresponding wall files were generated for each part. These were then coupled with the EDEM 2022 software to create the simulation environment illustrated in Figure 1e. The excavation forces acting on different parts of the sampling scoop obtained from the simulation provide detailed reference data for the construction of the soil–tool interaction model.

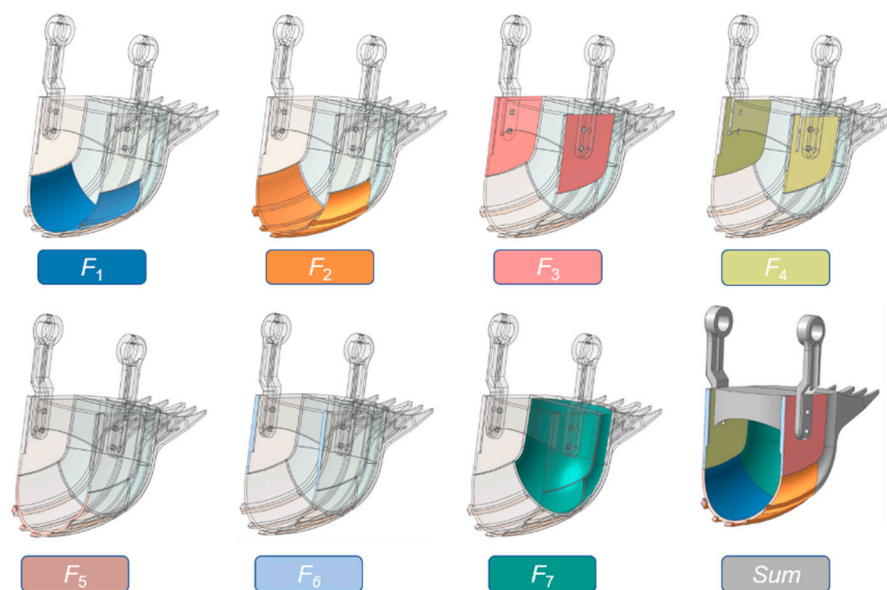
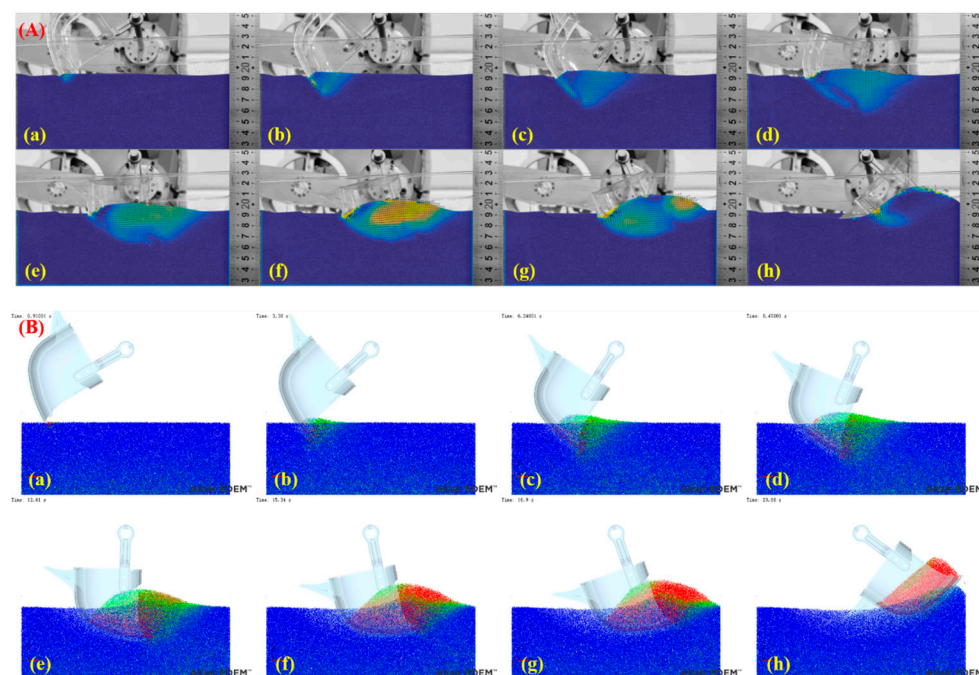


Figure 2. Regional distribution of component forces acting on the sampling tool.

3. Analytical Modeling of Excavation Forces for Scoop Tool

3.1. Analysis of Excavation Process

Figure 3A shows the PIV analysis results. As illustrated in Figure 3A(a–d), the soil disturbance and deformation increase as the tool penetrates deeper. When the tool reaches the maximum sampling depth, the soil deformation reaches its peak. During the digging process, the boundary between the moving soil and the stationary soil is clearly visible; this boundary corresponds to the failure surface in passive earth pressure theory. The EDEM 2022 analysis results shown in Figure 3B confirm this phenomenon, indicating that the EDEM 2022 simulation accurately reproduces the same soil environment as the physical experiment.



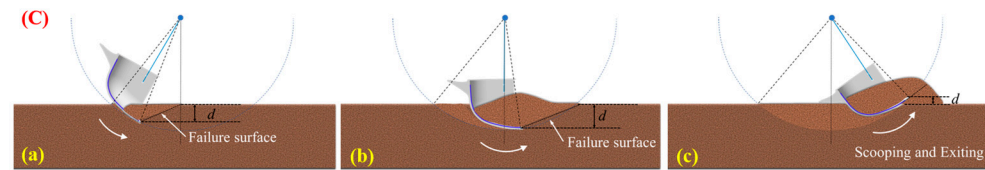


Figure 3. Soil bin test and DEM simulation of scoop excavation test. (A) and (B) are the visual comparison between test and simulation in the process of digging. (A(a–h)) The result of PIV analysis. (B(a–h)) The result of DEM analysis. (C) illustrates the division of the excavation process into three stages: (a) soil penetration, (b) cutting and pushing, and (c) soil scooping.

As shown in Figure 3A,B, the excavation process exhibits distinct stage characteristics. Accordingly, Figure 3C divides the process into three stages: soil penetration, cutting and pushing, and soil scooping.

The relationship between the forces and angles during the excavation process is analyzed based on the idealized half-sectional configuration of the sampling scoop shown in Figure 4a. The sampling scoop moves along the arc trajectory S–A–B–C–D–E, constituting a complete excavation cycle. The segment from S (Start) to A represents the idle stroke (or approach phase), during which the scoop is not in contact with the soil. The arc A–D corresponds to the excavation phase, encompassing the entire process from soil entry to soil exit. Based on the excavation mechanics, this phase is subdivided into three sub-stages:

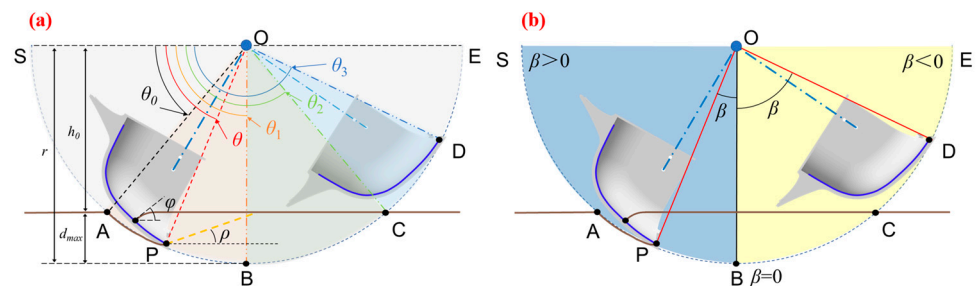


Figure 4. Angular Division of Excavation Stages. (a) Angular division of the three excavation stages. (b) Definition of the excavation angle in the model.

Arc A–B corresponds to the soil penetration stage, with an angular range of $\theta \in (\theta_0, \theta_1)$;

Arc B–C corresponds to the cutting and pushing stage, with an angular range of $\theta \in (\theta_1, \theta_2)$;

Arc C–D corresponds to the soil scooping stage, with an angular range of $\theta \in (\theta_2, \theta_3)$. Upon completion of sampling, the scoop is lifted from point D to E (End) to return to its initial position, thereby concluding the operation.

As shown in Figure 4a, the excavation angle θ ($0^\circ \leq \theta \leq 180^\circ$) describes the absolute angular displacement of the bucket relative to its starting position, representing the overall progress of the excavation operation. However, a transition in the physical mechanism occurs during the process: as the bucket passes its lowest point, both the loading conditions and the direction of motion relative to the gravitational field undergo a change. Therefore, to accurately calculate the passive earth pressure, an effective mechanical angle β , referenced to the gravitational vertical, is introduced. As illustrated in Figure 4b, a positive β ($\beta > 0$) corresponds to the soil penetration stage ($\theta \leq 90^\circ$), while a negative β ($\beta < 0$) corresponds to the cutting–pushing and soil scooping stages ($\theta \geq 90^\circ$). The zero point is defined at the lowest point of the excavation trajectory (aligned with the gravitational

vertical). The geometric mapping relationship between the excavation angle θ and the effective mechanical angle β is defined as follows:

$$\beta = \pi/2 - \theta \quad (1)$$

3.2. Forces Acting on the Idealized Failure Wedge

Based on the initial phase of the cutting and pushing stage illustrated in Figure 5, an analysis of the excavation resistance exerted by the soil on the sampling scoop is conducted. The excavation resistance is primarily composed of the following components [22]:

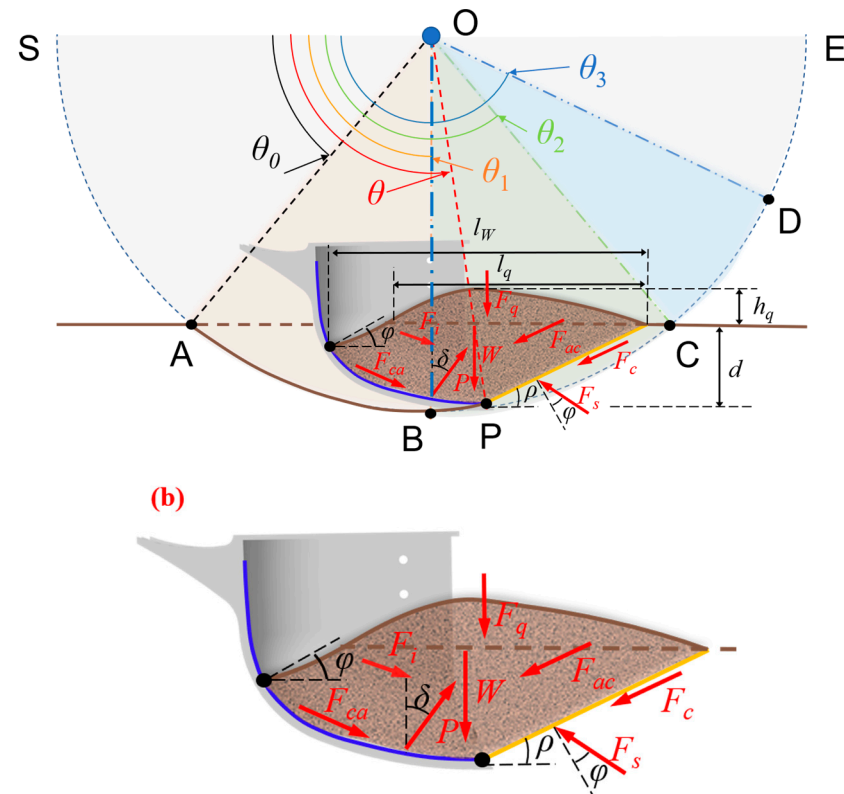


Figure 5. Forces acting on the idealized failure wedge. (a) Global View of the Geometric Model. (b) Close-up of Force Analysis.

The inertial force F_{ac} resisting the acceleration of the tool;
 The force F_q induced by the surcharge load q ;
 The frictional force F_s ;
 The cohesion force F_c ;
 The adhesion force F_{ca} ;
 The weight of the soil W within the scoop;
 The shear force F_i resisting movement on the internal surfaces of the side walls of the sampler.

With the exception of gravity, which acts vertically downwards, both the magnitude and direction of the other components of the excavation force F vary continuously during the digging motion. While the magnitude of these components does not directly depend on the scoop itself, their direction changes in accordance with the orientation of the scoop; that is, they rotate as the scoop rotates.

In this section, the two-dimensional force analysis is performed within the x-z plane of the global coordinate system. Consequently, the horizontal x-axis in this section corresponds to the global x-axis, while the vertical y-axis corresponds to the global z-axis. The

reference values for the parameters used in the analytical model are summarized in Table 1. Furthermore, the specific force components and process parameters defining the excavation resistance model are detailed in Table 2.

The position angle of the scoop tip is defined as:

$$\beta_{tip} = \beta = \pi/2 - \theta \quad (2)$$

Once the height of the rotation axis h_0 is determined, the maximum excavation depth is given by:

$$d_{max} = r - h_0 \quad (3)$$

The instantaneous excavation depth is expressed as:

$$d = r \cos \beta - h_0 \quad (4)$$

Since the sampling scoop exerts no force during the no-load approach phase ($\theta \in (0, \theta_0)$), a step function or piecewise function is introduced into the model to define the effective depth:

$$d(\theta) = \max(0, r \cos(\pi/2 - \theta) - h_0) \quad (5)$$

Based on the geometric parameters of the sampling scoop, the entry and exit points of excavation are determined by the height of the rotation axis above the ground, h_0 . From the geometric relationships, the maximum soil contact boundary angle, β_{surf} , can be expressed as:

$$\beta_{surf} = \arccos(h_0/r) \quad (6)$$

Consequently, the range of the effective mechanical angle β is a closed interval symmetric with respect to the gravity vertical:

$$\beta \in [-\beta_{surf}, \beta_{surf}] \quad (7)$$

While inertial effects are often negligible in quasi-static equilibrium models, they become significant under dynamic conditions where the failure wedge is accelerated to the tool's velocity. As the sampling scoop advances at a velocity v , the stationary soil is accelerated, generating a resistance force due to inertia. This is modeled as a body force acting parallel to the failure plane. Adopting the method proposed by Swick and Perumpral [10], the inertial effect is defined as an equivalent 'acceleration pressure' per unit volume. This value is then multiplied by the corresponding geometric projection area to derive the total equivalent inertial force F_{ac} .

$$F_{ac} = \gamma w d v^2 \sin \beta / \sin(\beta + \rho) \quad (8)$$

This equation represents a semi-empirical formulation. Fundamentally, it defines the soil inertial force as a function of tool width w , tool excavation depth d , tool velocity v , soil specific mass γ , the effective mechanical angle β , tool geometric parameters and the failure surface angle ρ . By assuming this force acts parallel to the failure surface, the formulation modifies the static model to account for dynamic conditions.

As shown in Figure 5, the soil heap formed above surface AC can be simplified as a cone. F_q represents the force exerted by the surcharge load q on a surface of length l_q and width w_q . The calculation formulas for q and F_q are given as follows:

$$q = \gamma g V_q / S_q = \frac{1}{3} \gamma g h_q w_q l_q / w_q l_q = \frac{1}{3} \gamma g h_q \quad (9)$$

$$F_q = q S_q = \gamma g V_q = \frac{1}{3} \gamma g h_q w_q l_q \quad (10)$$

Frictional Force F_s : This represents the frictional force on the failure surface, which varies with the failure surface angle ρ . It can be decomposed into two components: F_{sp} , acting parallel to the failure surface, and F_{sn} , acting perpendicular to the failure surface. F_s acts as a reaction force generated by the soil wedge under a state of force equilibrium. Its magnitude is determined by the equilibrium of other forces acting on the wedge, and it serves as an intermediate variable that is eliminated in the final solution:

$$F_{sp} = F_s \sin \varphi \quad (11)$$

$$F_{sn} = F_s \cos \varphi \quad (12)$$

The cohesion force F_c represents the cohesion force acting along the failure surface:

$$F_c = c w d / \sin \rho \quad (13)$$

The adhesion force F_{ca} represents the interaction between the soil and the curved inner surface of the sampling scoop. It originates from the adhesion stress c_a at the soil–tool interface. Considering the complex geometry of the scoop's bottom, the total force is derived by integrating the differential force acting on each element.

$$F_{cax} = c_a w \int_{\beta_s}^{\beta_e} r \cos \beta d\beta \quad (14)$$

$$F_{cay} = c_a w \int_{\beta_s}^{\beta_e} r \sin \beta d\beta \quad (15)$$

Weight of the soil within the scoop, W : This represents the weight of the soil wedge. The expression for the weight W is given by:

$$W = \gamma g w r \int_{\beta_s}^{\beta_e} (r \cos \beta - h_0) d\beta \quad (16)$$

$$\beta_s = \max(\beta_{tip}, -\beta_{surf}) \quad (17)$$

$$\beta_e = \beta_{surf} \quad (18)$$

F_i represents the shear force between the inner surface of the sampler's side wall and the soil, acting on the soil–tool interface. It is composed of the adhesive and frictional forces between the soil and the tool. The shear stress $\tau_{ca}(r, \alpha)$, derived from the friction and adhesion between the soil and the side wall, is expressed as:

$$\tau_{ca}(r, \alpha) = \tau_{ca, \max} (1 - e^{-\frac{j}{k_a}}) \quad (19)$$

where $\tau_{ca, \max}$ is the maximum shear stress; j represents the shear displacement at an angle α and distance r from the rotation axis; and k_a is the shear deformation modulus characterizing the soil–tool interaction. Their expressions are given respectively by:

$$\tau_{ca, \max} = c_a + \sigma \tan \delta \quad (20)$$

$$j = r(\alpha - \beta) \quad (21)$$

$$\sigma = K_0 (r \cos \alpha - h_0) \rho g \quad (22)$$

$$K_0 = 1 - \sin \varphi \quad (23)$$

where σ denotes the horizontal normal stress, and K_0 is the coefficient of earth pressure at rest. The latter is an empirical formula derived by Jaky in 1944 based on the regression analysis of sand sample test data [23].

The inner surface is treated as a collection of differential area elements. The differential force acting on each element is the product of the shear stress and the element's area.

The total force is obtained by vectorially integrating these differential forces over the surface. As the sampler rotates into the soil, the shear force F_i varies with the angle. The integration yields:

$$F_{ix} = 2 \int_{r_{i1}}^{r_{i2}} \int_{\beta_{i1}}^{\beta_{i2}} \tau_{ca}(r, \beta) r \cos \beta d\beta dr \quad (24)$$

$$F_{iy} = 2 \int_{r_{i1}}^{r_{i2}} \int_{\beta_{i1}}^{\beta_{i2}} \tau_{ca}(r, \beta) r \sin \beta d\beta dr \quad (25)$$

$$\beta_{i1} = \max(\beta_{tip}, -\beta_{surf}) \quad (26)$$

$$\beta_{i2} = \min(\beta_{tail}, \beta_{surf}) \quad (27)$$

$$r_{i1} = h_0 / \cos \beta \quad (28)$$

$$r_{i2} = r \quad (29)$$

$$\beta_{tail} = \beta_{tip} + l/r \quad (30)$$

Radial integration is employed to delimit the radial scope of force interaction on the sampling scoop at a given rotation angle. Here, the lower limit of radial integration, r_{i1} , and the upper limit, r_{i2} , correspond to the inner boundary and the physical outer boundary of the loaded region, respectively. The upper limit r_{i2} is determined by the rotation radius of the scoop, characterizing the effective area where the radially extending side wall contacts the soil and generates force. Meanwhile, angular integration describes the range of contact angles between the scoop wall and the soil; the corresponding rotation angles β_{i1} and β_{i2} define the angular interval in which the side wall contributes to the force.

Passive earth pressure P : The passive earth pressure P is derived from the force equilibrium of the idealized failure wedge as shown in Figure 5. By summing the forces in the horizontal and vertical directions, we obtain:

$$P \sin(\beta + \delta) = -(F_{cax} + F_{ix}) + F_{sn} \sin \rho + (F_{sp} + F_{ac} + F_c) \cos \rho \quad (31)$$

$$P \cos(\beta + \delta) = W + F_q + (F_{cay} + F_{iy}) - F_{sn} \cos \rho + (F_{sp} + F_{ac} + F_c) \sin \rho \quad (32)$$

Combining the above equations yields:

$$P = \left((W + F_q + F_{cay} + F_{iy}) \sin(\varphi + \rho) - (F_{cax} + F_{ix}) \cos(\varphi + \rho) + (F_c + F_{ac}) \cos \varphi \right) / \sin(\beta + \delta + \varphi + \rho) \quad (33)$$

In the above equation, the failure surface angle ρ is an unknown variable, which is determined by minimizing the passive earth pressure P . According to the research by Swick and Perumpral [10], passive failure corresponds to the state where the soil wedge resistance reaches its minimum. Therefore, the value of ρ that yields the minimum P should be selected. Generally, it is taken as $\pi/4 + \varphi/2$.

During the computation, numerical singularities arise in the passive earth pressure expression when the geometric parameter sum approaches a flat angle, mathematically expressed as $\beta + \delta + \varphi + \rho \rightarrow \pi$. This causes the sine denominator in the force formulation to vanish, leading the predicted resistance to diverge. Physically, this geometric limit indicates a violation of the conditions required for shear wedge formation. As the scoop approaches the soil surface, the idealized soil wedge disintegrates, rendering the classical passive pressure theory inapplicable. Therefore, a strict geometric restriction is applied, limiting the use of the passive earth pressure formulation to the main, compression-dominated excavation phase where $\beta + \delta + \varphi + \rho < \pi$. To address the transition into the exit phase, a data-driven smoothing technique is applied. The physical rationale is that once the scoop exits the soil, the primary source of resistance shifts from the active soil cutting process to the residual weight of the collected soil carried by the scoop. Because the exit

phase is not the primary region of interest for evaluating excavation cutting performance, a continuous smoothing function is utilized simply to bridge the peak theoretical resistance and the final residual soil weight. This transitional treatment effectively eliminates non-physical numerical artifacts and ensures the continuity of the force curve. By doing so, the smoothed model prioritizes engineering utility, providing a robust and practically acceptable estimation of the resistance evolution across distinct physical stages without overcomplicating the non-critical exit phase.

Table 1. Model Parameter Reference Table.

Symbol	Definition	Unit	Value
Tool			
w	Tool width	m	0.052
l	Tool length	m	0.05
t	Tool thickness	m	0.0015
Soil			
c	Cohesion	kPa	0–3.5
φ	Internal friction angle	°	20–50
γ	Soil specific mass	kg/m ³	$1-3 \times 10^3$
Tool-Soil			
δ	External friction angle	°	0–50
c_a	adhesion	kPa	0–5
Test			
h_0	Height of rotation axis above ground	m	0.04–0.1
r	Excavation radius	m	0.1
θ	Excavation angle	°	0–180
β	Effective mechanical angle	°	$\beta = \pi/2 - \theta$
d	Tool excavation depth	m	0–0.05
ω	Tool excavation angular velocity	°/s	1–10
ρ	Failure surface angle	°	$\pi/4 + \varphi/2$
q	Surcharge load	kg/m ²	0–100
K_0	Coefficient of earth pressure at rest	-	$1 - \sin\varphi$
Gravity			
g	Earth gravity	m/s ²	9.81
	Mars gravity	m/s ²	3.71

3.3. Forces and Moments Acting on Sampler

Figure 6 illustrates the schematic of forces acting on the various components of the sampler. Each force vector comprises components in the x , y , and z directions. The resultant force is decomposed into a radial force F_r and a vertical force F_z . Specifically, F_r represents the vector sum of F_x and F_y , while the total force F is the resultant of F_r and F_z .

As illustrated in Figure 7, this study divides the sampling scoop into seven regions based on the locations of the acting forces: the force F_1 acting on the inner bottom surface of the scoop; the force F_2 acting on the outer bottom surface; the force F_3 acting on the outer surface of the sidewalls and the force F_4 acting on the inner surface of the sidewalls; the force F_5 acting on the leading edge and the force F_6 acting on the side edge; and the force F_7 acting on the inner rear surface of the scoop.

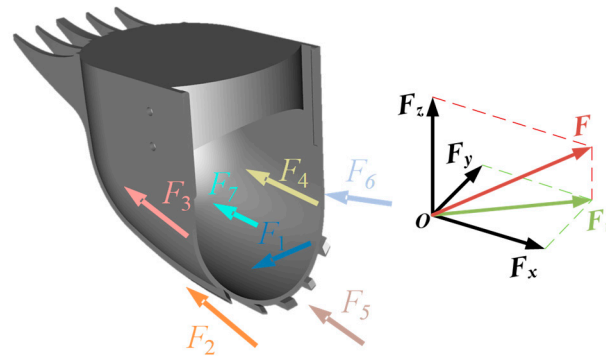


Figure 6. The distribution of the force acting on the sampler.

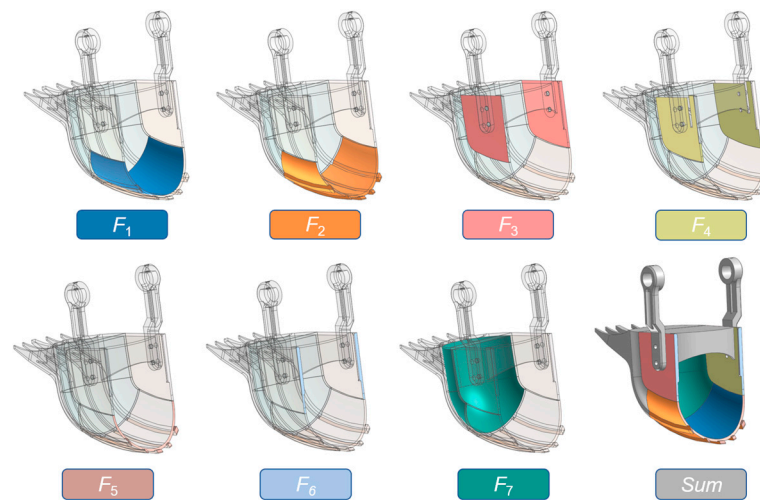


Figure 7. Division of the force area acting on the sampler.

F_1 represents the most critical force during the excavation process. As the scoop performs forward rotational cutting, the soil ahead of the scoop undergoes shear failure, forming a failure wedge. The force exerted to drive the movement of this wedge can be represented by the passive earth pressure P .

$$F_{1x} = P \cos\left(\frac{\pi}{2} - \beta - \delta\right) \quad (34)$$

$$F_{1z} = P \sin\left(\frac{\pi}{2} - \beta - \delta\right) \quad (35)$$

$$M_{F_1} = rP \sin \delta \quad (36)$$

F_2 acts on the outer bottom surface of the sampling scoop and is calculated from shear and normal stresses. The shear stress is influenced by friction and adhesion: the frictional force primarily originates from the normal pressure between the scoop's outer surface and the soil, while the adhesive force arises from the adhesive action of the soil.

$$F_{2x} = w(r+t) \left(\int_{\beta_s}^{\beta_{oc}} \tau_{oc}(\beta) \cos \beta d\beta - \int_{\beta_s}^{\beta_{oc}} \sigma_{oc}(\beta) \sin \beta d\beta \right) \quad (37)$$

$$F_{2z} = w(r+t) \left(\int_{\beta_s}^{\beta_{oc}} \tau_{oc}(\beta) \sin \beta d\beta - \int_{\beta_s}^{\beta_{oc}} \sigma_{oc}(\beta) \cos \beta d\beta \right) \quad (38)$$

$$M_{F_2} = w(r+t)^2 \int_{\beta_s}^{\beta_{oc}} \tau_{oc}(\beta) d\beta \quad (39)$$

The expressions for shear stress and normal stress are:

$$\tau_{oc}(\beta) = (c_a + \sigma_{oc}(\beta) \tan \varphi)(1 - \exp^{-j/k_a}) \quad (40)$$

$$\sigma_{oc}(\beta) = K_0 \rho g((r+t) \cos \beta - h_0) \quad (41)$$

β_{oc} is the effective contact cutoff angle between the outer surface and the soil:

$$\beta_{oc} = \beta_{tip} + k_{oc} \cdot [\min(\beta_{tail}, \beta_{surf}) - \beta_{tip}] \quad (42)$$

A contact correction coefficient, k_{oc} ($0 \leq k_{oc} \leq 1$), is introduced to describe the effective shear contact interval between the outer wall and the soil.

The force F_3 , acting on the outer surface of the scoop sidewalls, is governed collectively by the normal stress distribution of the soil within the corresponding sidewall region and the interface friction. Its calculation method is analogous to the solution for F_i .

$$F_{3x} = 2 \int_{r_{o1}}^{r_{o2}} \int_{\beta_{o1}}^{\beta_{o2}} \eta_s \tau_{ca}(r, \beta) r \cos \beta d\beta dr \quad (43)$$

$$F_{3z} = 2 \int_{r_{o1}}^{r_{o2}} \int_{\beta_{o1}}^{\beta_{o2}} \eta_s \tau_{ca}(r, \beta) r \sin \beta d\beta dr \quad (44)$$

$$M_{F_3} = 2 \int_{r_{o1}}^{r_{o2}} \int_{\beta_{o1}}^{\beta_{o2}} \eta_s r^2 \tau_{ca}(r, \beta) d\beta dr \quad (45)$$

$$\beta_{o1} = \max(\beta_{tip}, -\beta_{surf}) \quad (46)$$

$$\beta_{o2} = \min(\beta_{tail}, \beta_{surf}) \quad (47)$$

$$r_{o1} = h_0 / \cos \beta \quad (48)$$

$$r_{o2} = r + t \quad (49)$$

An effective contact coefficient, η_s , is introduced to characterize the effective extent to which the sidewalls participate in the shearing process.

Regarding the force F_4 acting on the inner surface of the scoop sidewalls:

$$F_{4x} = 2 \int_{r_{o1}}^{r_{o2}} \int_{\beta_{o1}}^{\beta_{o2}} \eta_s \tau_{ca}(r, \beta) r \cos \beta d\beta dr \quad (50)$$

$$F_{4z} = 2 \int_{r_{o1}}^{r_{o2}} \int_{\beta_{o1}}^{\beta_{o2}} \eta_s \tau_{ca}(r, \beta) r \sin \beta d\beta dr \quad (51)$$

$$M_{F_4} = 2 \int_{r_{o1}}^{r_{o2}} \int_{\beta_{o1}}^{\beta_{o2}} \eta_s r^2 \tau_{ca}(r, \beta) d\beta dr \quad (52)$$

Force F_5 Acting on the Leading Edge: The bottom cutting edge of the scoop possesses a finite thickness. Consequently, as the scoop rotates and penetrates the soil, the bottom edge surface (the thickness face) must compress and displace the soil. By modeling the cutting edge as a narrow rectangular plate penetrating the soil in the tangential direction, this force can be calculated using the Bekker pressure-sinkage model:

$$\sigma_{ec} = \left(\frac{k_c}{t} + k_\phi \right) (r \cos \beta - h_0)^n \quad (53)$$

$$F_{5x} = wt \left(\frac{k_c}{t} + k_\phi \right) (r \cos \beta - h_0)^n \cos(\beta + \delta) \quad (54)$$

$$F_{5z} = wt \left(\frac{k_c}{t} + k_\phi \right) (r \cos \beta - h_0)^n \sin(\beta + \delta) \quad (55)$$

$$M_{F_5} = wtr \left(\frac{k_c}{t} + k_\phi \right) (r \cos \beta - h_0)^n \cos(\delta) \quad (56)$$

Force F_6 Acting on the Sidewall Edge: As the side plate penetrates the soil, its edge (specifically, the thickness face) must compress and displace the soil. This force represents the bearing resistance generated by the ‘blunt’ edge. By modeling the side edge as a narrow plate pressing into the soil, the force is calculated using the Bekker pressure-sinkage model based on geometric relationships.

$$F_{6x} = 2 \int_{r_{e1}}^{r_{e2}} t \left(\frac{k_c}{t} + k_\phi \right) (r \cos(\beta) - h_0)^n \cos(\delta + \beta) dr \quad (57)$$

$$F_{6z} = 2 \int_{r_{e1}}^{r_{e2}} t \left(\frac{k_c}{t_s} + k_\phi \right) (r \cos(\beta) - h_0)^n \sin(\delta + \beta) dr \quad (58)$$

$$M_{F_6} = 2 \int_{r_{e1}}^{r_{e2}} t \left(\frac{k_c}{t_s} + k_\phi \right) r (r \cos(\beta) - h_0)^n \cos(\delta) dr \quad (59)$$

$$r_{e1} = h_0 / \cos(\beta) \quad (60)$$

The primary contribution to F_7 is attributed to the support force for the accumulated soil weight. The effective component of the soil weight is calculated as a function of the scoop’s rotation angle.

$$F_{7x} = \gamma g w r \cos \beta \int_{\beta_s}^{\beta_e} (r \cos \beta - h_0) d\beta \cdot \lambda(\beta) \quad (61)$$

$$F_{7y} = \gamma g w r \sin \beta \int_{\beta_s}^{\beta_e} (r \cos \beta - h_0) d\beta \cdot \lambda(\beta) \quad (62)$$

$$M_7 = \gamma g w r^2 \int_{\beta_s}^{\beta_e} (r \cos \beta - h_0) d\beta \cdot \lambda(\beta) \quad (63)$$

The backplate support force F_7 is not directly equivalent to the accumulated soil weight; rather, it is subject to the dual influence of the scoop’s attitude and the characteristics of the granular medium. The model introduces a gravity projection transfer function, $\lambda(\beta)$, to describe the dynamic hysteresis process as the center of gravitational support shifts from the scoop bottom to the backplate:

$$\lambda(\beta) = \begin{cases} 0, & \beta > \beta_{lag} \\ \sin \left(\frac{\pi}{2} \cdot \frac{\beta_{lag} - \beta}{\beta_{lag} - \beta_{end}} \right), & \beta_{end} \leq \beta \leq \beta_{lag} \\ 1, & \beta < \beta_{end} \end{cases} \quad (64)$$

Physically, this implies that during the initial excavation phase ($\beta > \beta_{lag}$), the soil mass is primarily borne by the bottom plate, resulting in minimal force on the backplate. As the scoop rotates upward, the soil slides toward the backplate under the influence of gravity. The sinusoidal function smoothly models this load transfer process. Here, β_{lag} represents the lag angle at which the backplate begins to sustain load, and β_{end} denotes the terminal angle corresponding to the scoop being inverted or fully loaded.

The values of the horizontal force F_x , the vertical force F_y , and the moment M acting on the sampler are given by:

$$F_x = F_{1x} + F_{2x} + F_{3x} + F_{4x} + F_{5x} + F_{6x} + F_{7x} \quad (65)$$

$$F_y = F_{1y} + F_{2y} + F_{3y} + F_{4y} + F_{5y} + F_{6y} + F_{7y} \quad (66)$$

$$F_z = F_{1z} + F_{2z} + F_{3z} + F_{4z} + F_{5z} + F_{6z} + F_{7z} \quad (67)$$

$$M = M_{F_1} + M_{F_2} + M_{F_3} + M_{F_4} + M_{F_5} + M_{F_6} + M_{F_7} \quad (68)$$

Table 2. Forces and process parameters in the excavation resistance model.

Symbol	Definition	Symbol	Definition
F_{ac}	Passive earth pressure	β_{tip}	Angular position of the scoop tip
F_q	Radial force	β_{surf}	Surface boundary angle
F_s	Vertical force	β_{tail}	Theoretical scoop-tail angle
F_c	Forward force	β_{lag}	Lag angle when the back plate starts to bear load
F_{ca}	Lateral force	β_{end}	Terminal angle at full scoop engagement
W	Weight of soil inside the scoop	β_s	$\beta_s = \max(\beta_{tip}, -\beta_{surf})$
F_i	Shear force on the inner surface of the side-wall	β_e	$\beta_e = \beta_{surf}$
P	Passive earth pressure	β_{oc}	Effective contact cut-off angle on the outer surface
F_r	Radial force	β_{i1}	$\beta_{i1} = \max(\beta_{tip}, -\beta_{surf})$
F_z	Vertical force	β_{i2}	$\beta_{i2} = \min(\beta_{tail}, \beta_{surf})$
F_x	Forward force	r_{i1}	$r_{i1} = h_0 / \cos \beta$
F_y	Lateral force	r_{i2}	$r_{i2} = r$
F_1	Force acting on the inner bottom surface of the scoop	β_{o1}	$\beta_{o1} = \max(\beta_{tip}, -\beta_{surf})$
F_2	Force acting on the outer bottom surface of the scoop	β_{o2}	$\beta_{o2} = \min(\beta_{tail}, \beta_{surf})$
F_3	Force acting on the outer surface of the scoop sidewall	r_{o1}	$r_{o1} = h_0 / \cos \beta$
F_4	Force acting on the inner surface of the scoop sidewall	r_{o2}	$r_{o2} = r + t$
F_5	Force acting on the front cutting edge	r_{e1}	Radius at the intersection of the side plate and the soil surface
F_6	Force acting on the sidewall edge	r_{e2}	Outermost edge of the side plate
F_7	Force acting on the inner rear surface of the scoop	η_s	Effective contact coefficient
F_{sum}	Resultant force acting on the scoop	V_q	Soil wedge volume
M	Resultant moment about the scoop rotation axis	S_q	Area of the soil heap
$\tau_{ca}(r, \alpha)$	Shear stress	h_q	Height of the soil heap
$\tau_{ca, max}$	Maximum shear stress	w_q	Width of the soil heap
$\tau_{oc}(\beta)$	Outer-surface shear stress	l_q	Length of the soil heap
$\sigma_{oc}(\beta)$	Outer-surface normal stress	k_{oc}	Contact correction coefficient for the outer bottom surface
σ_{ec}	Normal stress at the front cutting edge	k_c	Soil cohesion modulus
j	Shear displacement	k_ϕ	Soil friction modulus
k_a	Shear deformation modulus	n	Sinkage exponent
σ	Normal stress	d_{max}	Maximum excavation depth
τ	Shear stress	k_{oc}	Contact correction coefficient

4. Results and Model Validation

4.1. Analysis of Excavation Response

As illustrated in Figure 8, the excavation resistance exhibits a distinct phasic trend with respect to the excavation angle. Correlating this with the three typical stages defined in Figure 4a, the penetration and cutting stage (AB) corresponds to the ascending interval of the resistance curve. During this phase, as the sampling scoop gradually penetrates the soil, the resistance increases, reaching its peak at the point of maximum penetration depth (Point B). Subsequently, in the excavation and pushing stage (BC), the resistance gradually decreases as the scoop moves upward and the interaction between the scoop body and

the soil weakens. Finally, in the breakout and sampling stage (CD), the resistance curve plateaus and maintains a stable level. This residual resistance is primarily attributed to the gravity of the collected soil, as the scoop has effectively ceased contact with the surrounding soil mass.

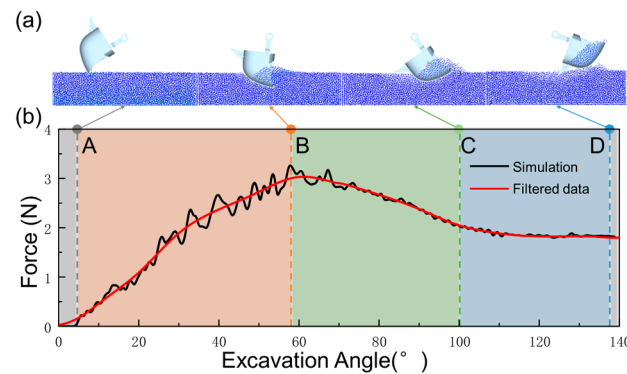


Figure 8. Variation in excavation resistance with time in different stages. In (a), the four subfigures correspond to the simulation positions A–D indicated in (b). A–D represent the corresponding positions along arc AD in Figure 4a. The three shaded regions denote the excavation stages: AB, soil penetration (orange); BC, cutting–pushing (green); and CD, soil scooping (blue).

Building on the stage-wise interpretation in Figure 8, we further conducted comparative simulations under 1 g and 0.38 g (Martian gravity level) to assess the gravity effect on excavation loads (Figure 9). The results show that, at the same excavation depth, the resistance level under 0.38 g is consistently lower than that under 1 g, with a more evident discrepancy around the peak region. Meanwhile, increasing the excavation depth from 2 cm to 4 cm shifts the resistance profile upward, leading to markedly higher peak and residual/plateau resistance. Notably, the reduction in resistance with decreasing gravity does not scale strictly linearly with g , indicating that the excavation resistance is influenced not only by gravity-related effects (e.g., soil self-weight and overburden-related contributions) but also by gravity-insensitive contributions associated with shear and tool–soil interface friction/adhesion. These observations indicate that the proposed model can be calibrated and validated under 1 g, and can be applied to the load prediction and response analysis under Martian gravity by substituting g and the regolith parameters.

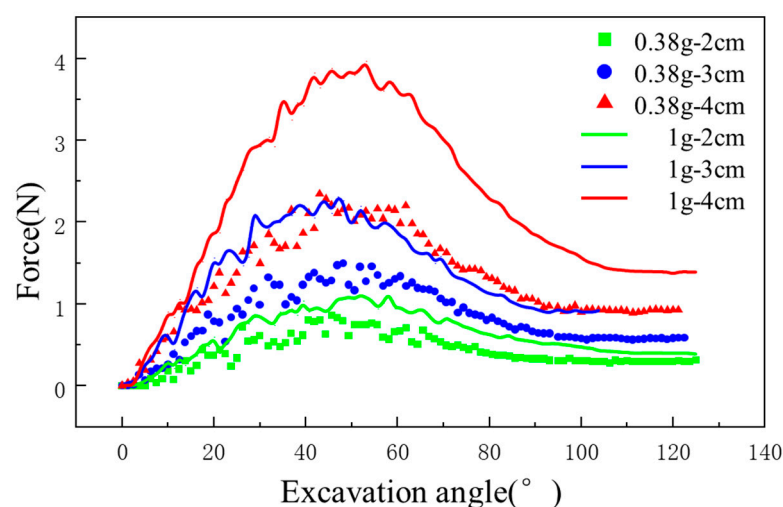


Figure 9. Comparative analysis of excavation resistance under Martian and Earth gravity conditions.

4.2. Analysis of Influencing Factors of the Excavation Model

As shown in Figure 10, the physical characteristics of the influencing factors during the excavation process are analyzed from two perspectives: process evolution and parameter sensitivity. The results indicate that the soil wedge weight W , cohesion force F_c and adhesion force F_{ca} play dominant roles in the formation of the passive earth pressure P .

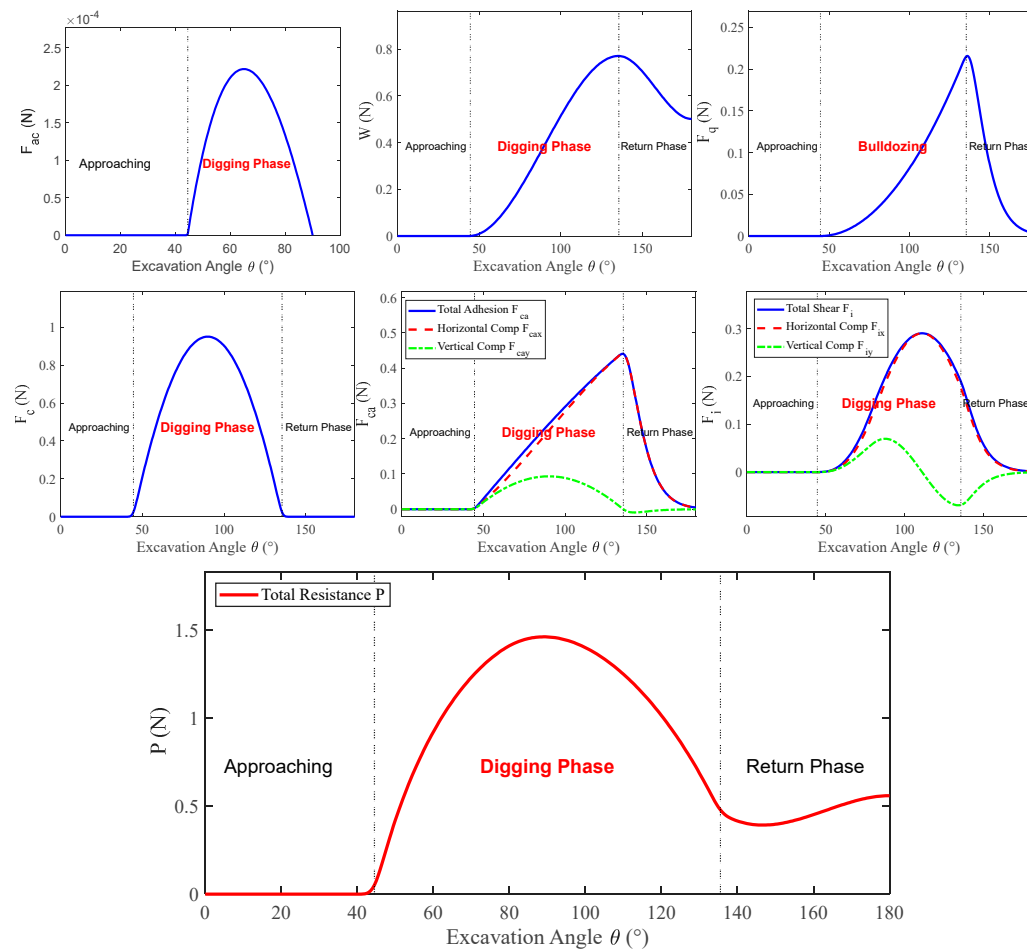


Figure 10. Variation in model influencing factors with excavation angle θ .

With the progression of the excavation angle θ , the individual force components exhibit distinct stage-dependent evolution characteristics. The soil wedge weight W increases monotonically with excavation depth and stabilizes after excavation is completed, forming the fundamental component of the passive earth pressure. During the soil-lifting and return phase, as no further cutting occurs, P is mainly governed by the self-weight of the soil wedge.

The cohesion force F_c shows an approximately parabolic distribution with respect to the excavation angle, reaching its peak at the maximum excavation depth, and is therefore one of the key dominant contributors to the passive earth pressure during the digging phase. The shear force F_i follows a trend similar to that of the cohesion force, and the superposition of these two components significantly amplifies the peak excavation resistance.

The adhesion force F_{ca} is primarily controlled by the evolution of the contact area between the soil and the inner bottom surface of the bucket. It increases progressively during the digging phase as the contact area expands. After soil emergence, the adhesion force, together with the soil wedge weight, becomes the main contributor to the resistance during the return phase, providing a sustained load on the system.

Overall, the passive earth pressure P reaches its maximum when the excavation depth is at its largest. Its formation mechanism can be interpreted as the combined effect of the continuous accumulation of soil wedge weight and the coupled enhancement of cohesion and shear effects. During the return phase, the resistance gradually transitions to a stable form dominated by soil self-weight and adhesion effects.

4.3. Simulation Validation of Model Reliability

Figure 11i shows that the excavation force–angle curves obtained from the theoretical model, DEM simulations, and ground tests share a general agreement in their primary evolution trends and peak force characteristics. As the excavation angle θ increases, all three results demonstrate a similar single-peak behavior, with the excavation force rising rapidly during the penetration and cutting stages, reaching its maximum near the maximum excavation depth, and subsequently decreasing during the exit stage. The resistance forces acting on different regions of the sampling scoop are decomposed into their radial components (F_x), vertical components (F_y), and the corresponding resultant forces, following the force definition illustrated in Figures 6 and 7.

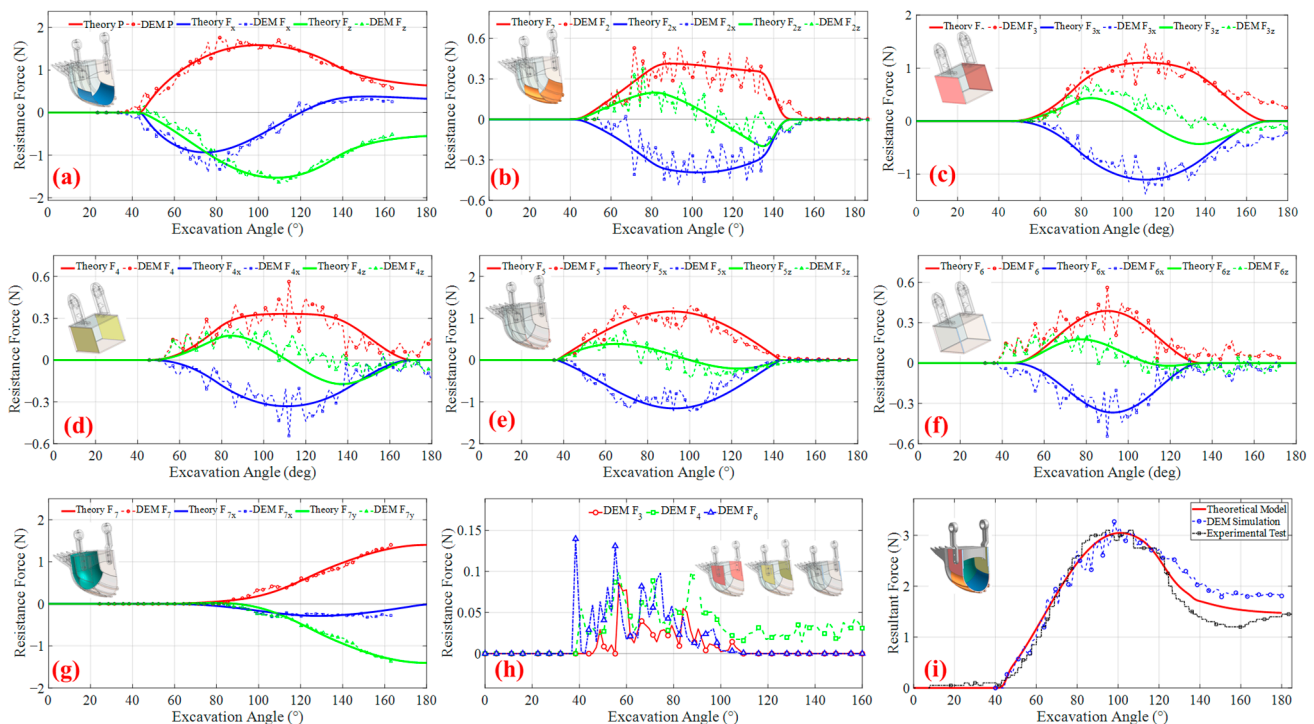


Figure 11. Force analysis of the sampling scoop during the excavation process. (a) Evolution of force F_1 on the inner bottom surface. (b) Evolution of force F_2 on the outer bottom surface. (c) Qualitative analysis of force F_3 (simplified rectangular scoop). (d) Qualitative analysis of force F_4 (simplified rectangular scoop). (e) Evolution of leading-edge force F_5 . (f) Qualitative analysis of force F_6 (simplified rectangular scoop). (g) Evolution of force F_7 on the inner rear surface. (h) Comparison of minor force components (F_3 , F_4 , and F_6) on the original scoop. (i) Comparative analysis of resultant force among theory, simulation, and experiment.

It should be noted that, due to the geometric characteristics of the original sampling scoop, the effective contact regions associated with F_3 , F_4 , and F_6 are extremely limited at the considered sampling depth of 3 cm. Consequently, these force components remain very small in magnitude (all below 0.2 N) and exhibit relatively large numerical fluctuations in the MBD-DEM results. To avoid misinterpretation caused by numerical noise, these components are not included in the quantitative contribution analysis. Instead, they

are qualitatively examined using a geometrically simplified rectangular scoop that enlarges the effective contact areas while preserving the underlying force mechanisms (Figure 11c,d,f). This comparison focuses on force evolution trends and governing mechanisms rather than absolute force magnitudes.

Under the same excavation conditions, the force components F_1 , F_5 , F_7 , and F_2 exhibit comparable orders of magnitude and can therefore be directly analyzed. Among them, F_1 , acting on the inner bottom surface of the sampling scoop, provides the dominant contribution during the penetration and cutting stages. Based on the relative magnitudes of the resultant force curves in Figure 11a and their averaged values over the effective excavation interval, F_1 accounts for approximately 56% of the total excavation resistance during the digging phase. This dominant contribution reflects the combined effects of soil accumulation, expansion of the contact area, and sustained normal loading from the soil wedge. The leading-edge force F_5 displays a pronounced peak during the main excavation stage. Although its peak magnitude is generally lower than that of F_1 , Figure 11e indicates that F_5 contributes approximately 30% of the excavation resistance during penetration and cutting, making it the second most influential force component. F_5 plays a critical role in governing the onset and evolution of excavation resistance, as it directly corresponds to soil shearing and failure at the cutting interface.

In contrast, the force component F_2 , acting on the outer bottom surface of the scoop, remains relatively small throughout the excavation process. From the force amplitudes shown in Figure 11b, its contribution is limited to approximately 11% of the total excavation resistance during the digging stage. This force mainly arises from localized soil extrusion and friction effects outside the scoop and does not dominate the excavation mechanics under the considered operating conditions.

The force F_7 , acting on the inner rear surface of the sampling scoop, exhibits a distinctly stage-dependent behavior. As shown in Figure 11g, its contribution is limited during the penetration and cutting stages but increases markedly after soil emergence. During the soil lifting and return phase, F_7 becomes one of the dominant contributors to the excavation resistance, primarily driven by the gravitational effects of the retained soil mass. Since this force component does not participate in the formation mechanism of excavation resistance during the digging phase, it is excluded from the quantitative contribution analysis of the excavation stage.

As shown in Figure 11h, by comparison, the remaining force components F_3 , F_4 , and F_6 are at least one order of magnitude smaller under the same operating condition and thus act as secondary factors. Their influence on the resultant excavation force is limited, and they primarily affect local force redistribution rather than the global resistance characteristics.

The resultant excavation force, obtained by vector summation of all force components, exhibits a distinct single-peak evolution with respect to the excavation angle, with the maximum resistance occurring near the maximum excavation depth. The theoretical model captures both the overall evolution trend and the peak location of the MBD-DEM simulation results with good agreement. Minor discrepancies observed near the peak region are mainly attributed to transient particle rearrangement and local force fluctuations inherent to the MBD-DEM.

5. Discussion

To address the limitations of existing models in terms of geometric representation, force-component interpretability, and verification rigor, the proposed modelling framework contributes the following novelties:

- (1) Structure-resolved force decomposition and enhanced interpretability. Many existing studies validate excavation models only at the level of the resultant force/torque, making it difficult to mechanistically verify the rationality of load contributions from different structural faces. This limits the interpretability of such models for structural optimization and load-path analysis. In this work, the sampling scoop is explicitly considered, and the total excavation resistance is decomposed into seven physically interpretable components associated with different structural surfaces (denoted as F_1 – F_7). Analytical expressions for each component are derived within a unified soil-wedge failure and interface friction framework. As a result, the model provides not only the resultant force/torque but also the quantitative contributions of the structure-resolved components, which directly supports design optimization and load-path interpretation.
- (2) Component-wise verification enabled by DEM–MBD coupling. Unlike conventional validations that compare only the resultant resistance, we further integrate DEM–MBD coupled simulations. Under the same operating conditions and kinematics as the ground tests, the contact reactions on individual scoop surfaces are extracted and compared component-by-component with the theoretical predictions of F_1 – F_7 , forming a closed-loop verification at the force-component level (while still validating the resultant force/torque). This strategy provides more direct evidence for the physical meaning and correctness of the modelling assumptions and decomposition, and offers traceable and quantifiable load information for subsequent structural parameter optimization.
- (3) Identification of a critical load component: F_5 should not be neglected. The component-wise comparison indicates that the force acting on the cutting-edge/front rim, F_5 , contributes approximately 30% of the total resistance. In some existing formulations, this contribution is either neglected or lumped into other terms. Our results demonstrate that F_5 is a non-negligible component, particularly during the penetration–cutting phase where cutting-edge interaction dominates. Neglecting F_5 can underestimate the peak resistance and its evolution, thereby affecting strength design and operating-condition identification.
- (4) Introduction of F_7 to describe late-stage excavation response. To explain the load evolution in the late stage of excavation (lifting–breakout), we introduce and formulate the F_7 component to represent the interaction associated with the rear structural surface and the soil/collected material. This provides a theoretical basis for interpreting the residual/plateau response during breakout and improves the completeness and stage-wise applicability of the model across the entire excavation process.

While the proposed soil–tool interaction model and the corresponding experimental validations provide valuable insights into the excavation mechanics of the sampling scoop, several limitations must be acknowledged. First, the current theoretical and experimental framework relies on the assumption of a homogeneous soil environment with a uniform hardness. It does not account for the presence of hard inclusions, such as buried rocks, gravel, or varying soil strata, which are prevalent in actual planetary environments and can introduce significant non-linearities and localized resistance spikes during the excavation process. Second, as highlighted in the discussion, the numerical model exhibits certain mathematical instabilities under extreme deformation or specific boundary conditions, which slightly limits its predictive capability for complex, non-standard excavation trajectories. Finally, the scalability of the obtained results requires further investigation.

6. Conclusions

This study establishes an analytical soil–tool interaction model for a Mars sampling scoop to describe the formation and evolution of excavation resistance. From the soil-

mechanics perspective, excavation resistance is governed by the development of a failure soil wedge, and the passive earth pressure is primarily composed of soil wedge weight, cohesion, adhesion, and shear effects. The resistance exhibits a distinct single-peak characteristic, with the peak occurring near the maximum excavation depth, where the coupled action of cohesion and shear significantly amplifies the load.

From the tool-interaction perspective, the passive earth pressure is mainly borne by the inner bottom surface of the sampling scoop, corresponding to the force component F_1 . During the penetration and cutting stages, F_1 constitutes the dominant portion of the excavation resistance, contributing approximately 56% of the total load, while the cutting-edge force F_5 contributes approximately 30% and governs the soil cutting and failure process. During the retraction stage, the resistance is primarily associated with the gravitational effect of the retained soil, reflected by the increase in the rear inner surface force, whereas other force components remain secondary.

Validation using MBD–DEM co-simulation shows good agreement with the analytical model in terms of resistance trends, peak location, and stage-dependent force evolution. The proposed modeling framework provides a physically interpretable and quantitatively supported basis for excavation force prediction and offers theoretical guidance for sampling scoop design and excavation performance optimization in future Mars surface sampling missions.

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References

1. Blouin, S.; Hemami, A.; Lipsett, M. Review of Resistive Force Models for Earthmoving Processes. *J. Aerosp. Eng.* **2001**, *14*, 102–111. [https://doi.org/10.1061/\(ASCE\)0893-1321\(2001\)14:3\(102\)](https://doi.org/10.1061/(ASCE)0893-1321(2001)14:3(102)).
2. Jin, S.; Cao, H.; Deng, X.; Zheng, Y.; Xue, L.; Zou, M. Establishment of Lunar Soil Excavation Model and Experimental Simulation Study. *Aerospace* **2025**, *12*, 315. <https://doi.org/10.3390/aerospace12040315>.
3. Li, Z.; Sun, W.; Wang, H.; Wang, J.; Simionescu, P.A. Study on the Process of Soil Clod Removal and Potato Damage in the Front Harvesting Device of Potato Combine Harvester. *Agriculture* **2024**, *14*, 1947. <https://doi.org/10.3390/agriculture14111947>.
4. Zhu, Y.; Wang, W.; Xu, Z.; Chen, J.; Zhang, J. Hydro-Mechanical Numerical Analysis of a Double-Wall Deep Excavation in a Multi-Aquifer Strata Considering Soil–Structure Interaction. *Buildings* **2025**, *15*, 989. <https://doi.org/10.3390/buildings15060989>.
5. Sedara, A.; Zeng, Z.; Digman, M.; Timm, A. Optimization of Liquid Manure Injector Designs for Cover Crop Systems Using Discrete Element Modeling and Soil Bin Evaluation. *AgriEngineering* **2025**, *7*, 404. <https://doi.org/10.3390/agriengineering7120404>.
6. Salem, T.N.; Elmahdy, M.S.; Katunský, D.; Dolníková, E.; El Ela, A.A. Numerical Investigation of Seismic Soil–Structure–Excavation Interaction in Sand. *Buildings* **2025**, *15*, 3732.

7. Wilkinson, A.; DeGennaro, A. Digging and pushing lunar regolith: Classical soil mechanics and the forces needed for excavation and traction. *J. Terramech.* **2007**, *44*, 133–152. <https://doi.org/10.1016/j.jterra.2006.09.001>.
8. Osman, M.S. The mechanics of soil cutting blades. *J. Agric. Eng. Res.* **1964**, *9*, 313–328.
9. Gill, W.R.; Berg, G.E.V. Soil dynamics in tillage and traction. In *Agriculture handbook*; US Department of Agriculture: Washington, DC, USA, 1967. Available online: <https://access.onlinelibrary.wiley.com/doi/10.2136/sssaj1968.03615995003200030005x> (accessed on 3 February 2026).
10. Swick, W.C.; Perumpral, J.V. A model for predicting soil-tool interaction. *J. Terramech.* **1988**, *25*, 43–56. [https://doi.org/10.1016/0022-4898\(88\)90061-4](https://doi.org/10.1016/0022-4898(88)90061-4).
11. McKyes, E. *Soil Cutting and Tillage*; Elsevier: Amsterdam, The Netherlands, 1985.
12. Hemami, A.; Goulet, S.; Aubertin, M. Resistance of particulate media to excavation: Application to bucket loading. *Int. J. Surf. Min. Reclam. Environ.* **1994**, *8*, 125–129. <https://doi.org/10.1080/09208119408964772>.
13. Balovnev, V.I.; Datta, P.; Pandit, V.S. *New Methods for Calculating Resistance to Cutting of Soil*; Amerind Publishing Private Limited: New Delhi, India, 1983.
14. Shaw, A.; Arvidson, R.E.; Bonitz, R.; Carsten, J.; Keller, H.U.; Lemmon, M.T.; Mellon, M.T.; Robinson, M.; Trebi-Ollennu, A. Phoenix soil physical properties investigation. *J. Geophys. Res. Planets* **2009**, *114*, E1 <https://doi.org/10.1029/2009JE003455>.
15. Xi, B.; Jiang, M.; Cui, L.; Liu, J.; Lei, H. Experimental verification on analytical models of lunar excavation. *J. Terramech.* **2019**, *83*, 1–13. <https://doi.org/10.1016/j.jterra.2019.01.002>.
16. Catanoso, D.; Stucky, T.; Case, J.; Rogg, A. Analysis of Sample Acquisition Dynamics Using Discrete Element Method. In Proceedings of the 2020 IEEE Aerospace Conference, Big Sky, MT, USA, 7–14 March 2020; pp. 1–11.
17. Xi, B.; Jiang, M.; Cui, L. 3D DEM analysis of soil excavation test on lunar regolith simulant. *Granul. Matter* **2020**, *23*, 1. <https://doi.org/10.1007/s10035-020-01070-6>.
18. Xue, L.; Chen, B.; Zhao, Z.; Dang, Z.; Zou, M. Experimental Study of Torque Using a Small Scoop on the Lunar Surface. *Int. J. Aerosp. Eng.* **2016**, *2016*, 8035456. <https://doi.org/10.1155/2016/8035456>.
19. Abdeldayem, M.A.A.; Tekeste, M.Z. Simulation of cohesive-frictional artificial soil-to-blade interactions using an elasto-plastic discrete element model with stress-dependent cohesion. *J. Terramech.* **2025**, *117*, 101029. <https://doi.org/10.1016/j.jterra.2024.101029>.
20. Narayanan, A.; Bhojne, S. *Construction Equipment's Bucket Design Based on Soil-Tool Interaction-Analytical and DEM Approach*; SAE International: Warrendale, PA, USA, 2017.
21. Mori, D.; Ishigami, G. Excavation model of soil sampling device based on particle image velocimetry. *J. Terramech.* **2015**, *62*, 19–29. <https://doi.org/10.1016/j.jterra.2015.02.001>.
22. Olmedo, N.A.; Barczyk, M.; Lipsett, M.G. An improved terramechanics model for a robotic soil surface sampler. *J. Terramech.* **2020**, *91*, 257–271. <https://doi.org/10.1016/j.jterra.2020.07.003>.
23. Jaky, J. The coefficient of earth pressure at rest. *J. Soc. Hung. Archit. Eng.* **1944**, *78*, 355–358.

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