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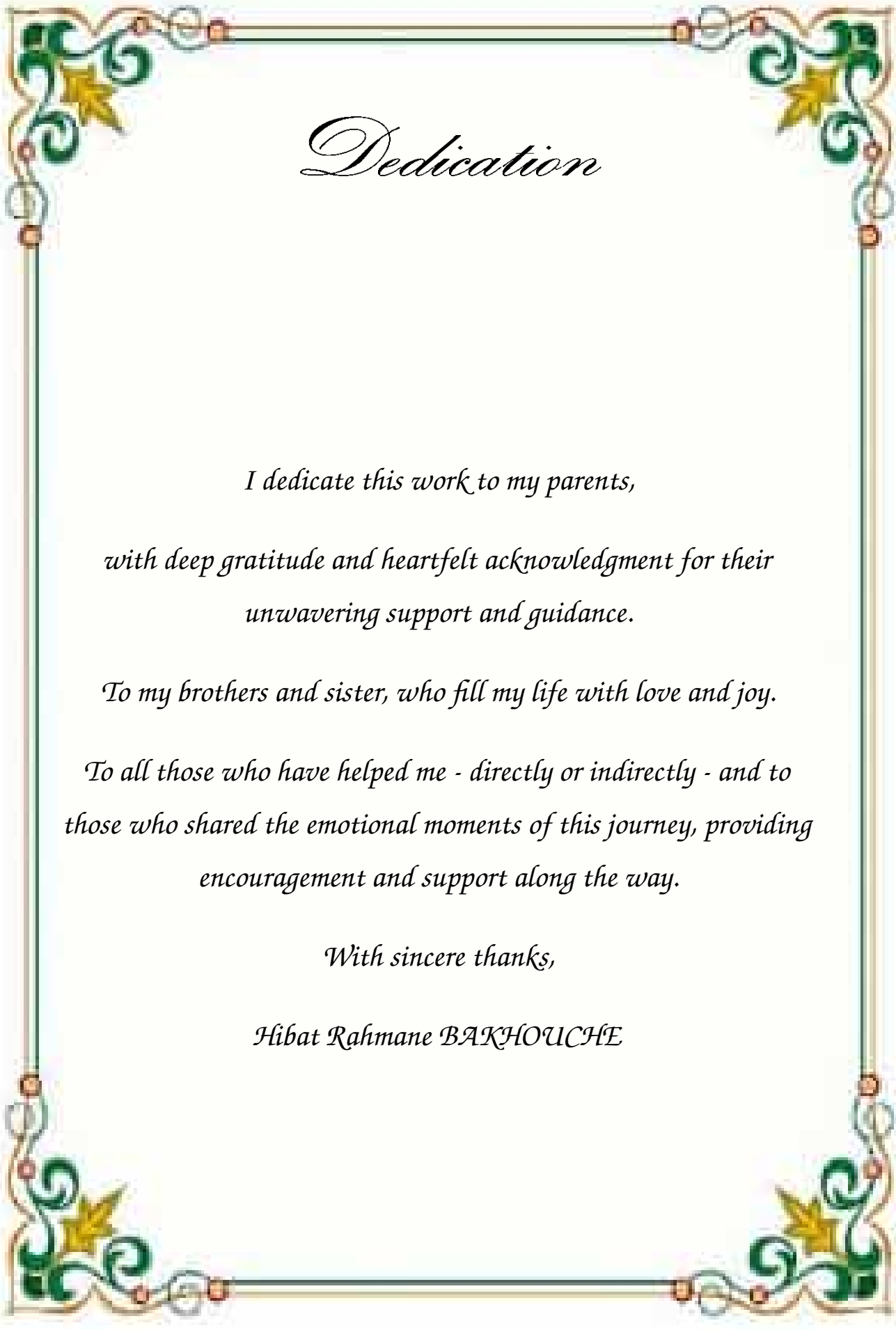
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Dedication

*I dedicate this work to my parents,
with deep gratitude and heartfelt acknowledgment for their
unwavering support and guidance.*

To my brothers and sister, who fill my life with love and joy.

*To all those who have helped me - directly or indirectly - and to
those who shared the emotional moments of this journey, providing
encouragement and support along the way.*

With sincere thanks,

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ملخص

تعتمد كفاءة عملية الحفر بشكل كبير على هندسة أداة القطع وشروط التشغيل، ولا سيما زاوية الهجوم، وعمق القطع، وسرعة الأداة. تهدف هذه الدراسة إلى تحليل تفاعل التربة-الأداة أثناء عملية الحفر من خلال مقارنة تجمع بين النمذجة العددية ثلاثية الأبعاد والتحقق التجريبي، وذلك من أجل تحديد ظروف التشغيل المثلى التي تحقق أداءً عالياً مع تقليل متطلبات الطاقة. تم اعتماد طريقة الجسيمات الملساء (*Smoothed Particle Hydrodynamics (SPH)*) في برنامج *Abaqus/Explicit* لإجراء التحليل العددي، مع استخدام نموذج موهر-كولوم لتمثيل السلوك الميكانيكي لتربة من نوع الرمل الطيني. أجريت دراسة بارامترية شملت زوايا هجوم تتراوح بين 30 و 90 درجة، وأعماق قطع تصل إلى 300 مم، وسرعات مختلفة للأداة. تم تحليل تأثير هذه المعلمات على قوى رد الفعل العمودية ($RF2$) والأفقية ($RF3$) من خلال المحاكاة العددية ومقارنتها بالنتائج التجريبية المتحصل عليها من اختبارات الحوض الترابي. أظهرت النتائج أن قوى رد الفعل تزداد بزيادة عمق القطع، كما ترتفع المقاومة العمودية بزيادة زاوية الهجوم وسرعة الأداة، في حين تتأثر المقاومة الأفقية بشكل رئيسي بسرعة الأداة. وقد بينت المقارنة بين النتائج العددية والتجريبية توافقاً جيداً، مما يؤكد موثوقية النموذج المعتمد. وأظهرت الدراسة أن زاوية هجوم مقدارها 45 درجة، وعمق قطع 100 مم، وسرعة أداة 100 مم/ثانية تمثل الإعداد الأمثل الذي يحقق توازناً فعالاً بين كفاءة الحفر.

كلمات مفتاحية: أداة الحفر، قوى رد الفعل، تفاعل التربة-الأداة، طريقة الجسيمات الملساء (*SPH*).

Abstract

Excavation efficiency is primarily governed by tool geometry and operating parameters, notably rake angle, cutting depth, and tool velocity. This study examines soil-tool interaction during excavation using a combined numerical and experimental approach to identify operating conditions that enhance performance while minimizing energy consumption. A three-dimensional numerical model was developed using the Smoothed Particle Hydrodynamics (SPH) method implemented in Abaqus/Explicit, with the Mohr-Coulomb constitutive model adopted to represent the mechanical behavior of clayey sand. Parametric simulations were conducted for rake angles ranging from 30° to 90° , cutting depths up to 300 mm, and various tool velocities. The effects of these parameters on vertical (RF2) and horizontal (RF3) reaction forces were systematically analyzed and validated through soil bin experiments. The results indicate that reaction forces increase with cutting depth, while vertical resistance generally rises with increasing rake angle and tool velocity. Horizontal resistance is mainly influenced by tool velocity, with a secondary dependence on rake angle. Numerical predictions showed good agreement with experimental measurements, confirming the reliability of the proposed modeling framework. The analysis revealed that rake angles between 30° and 45° , combined with moderate tool velocities, significantly reduce reaction forces and improve energy efficiency. Conversely, steeper rake angles and higher velocities intensify soil engagement and operational forces. The optimal excavation configuration was identified as a rake angle of 45° , a cutting depth of 100 mm, and a tool velocity of 100 mm/s, providing an effective balance between cutting efficiency and tool resistance.

Key words: *Excavation tool, Reaction forces, Soil-tool interaction, Smoothed Particle Hydrodynamics (SPH).*

Résumé

L'efficacité de l'excavation dépend fortement de la géométrie de l'outil et des paramètres opératoires, notamment l'angle d'attaque, la profondeur de coupe et la vitesse de l'outil. Cette étude analyse l'interaction sol-outil lors de l'excavation à l'aide d'une approche combinant modélisation numérique tridimensionnelle et validation expérimentale, dans le but d'identifier les conditions de fonctionnement permettant d'optimiser les performances tout en réduisant la consommation énergétique. La modélisation numérique repose sur la méthode Smoothed Particle Hydrodynamics (SPH), implémentée dans Abaqus/Explicit, associée au modèle constitutif de Mohr-Coulomb pour représenter le comportement mécanique d'un sable argileux. Une étude paramétrique a été menée en faisant varier l'angle d'attaque de 30° à 90° , la profondeur de coupe jusqu'à 300 mm et la vitesse de l'outil. L'influence de ces paramètres sur les forces de réaction verticale (RF2) et horizontale (RF3) a été analysée numériquement et comparée aux résultats expérimentaux obtenus sur banc d'essai. Les résultats montrent une augmentation des forces de réaction avec la profondeur de coupe, ainsi qu'une élévation de la résistance verticale avec l'angle d'attaque et la vitesse de l'outil. La résistance horizontale est principalement influencée par la vitesse de l'outil. Une bonne concordance entre les résultats numériques et expérimentaux a été observée, confirmant la fiabilité du modèle proposé. La configuration optimale correspond à un angle d'attaque de 45° , une profondeur de coupe de 100 mm et une vitesse de 100 mm/s, offrant un compromis efficace entre performance d'excavation et réduction des efforts.

Mots clés : *Outil d'excavation, Forces de réaction, Interaction sol-outil, Smoothed Particle Hydrodynamics (SPH).*

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List of Symbols

The number of the page in which a symbol is introduced or explained is given in parentheses.

- E_{50}^{ref} = secant stiffness at 50 % strength mobilization in a standard triaxial test
- E_{oed}^{ref} = tangent stiffness for primary oedometer loading
- E_{ur}^{ref} = unloading/reloading modulus
- P_{ref} = reference confining pressure
- ε_q^p = plastic shear strain
- C = damping matrix
- D = is the constitutive matrix
- K = stiffness matrix
- M = mass matrix
- $\ddot{x}$, $\dot{x}$, x = displacement, velocity, and acceleration vectors
- Δe = void ratio
- ΔW = energy dissipated
- $\Delta \sigma'$ = change in effective stress
- b = Contact radius
- B = foundation width
- b = radius of circular contact area
- c = soil cohesion
- c' = effective cohesion
- CI = Consistency Index
- D = damping ratio
- Dr = relative density
- E = Young's modulus
- e = void ratio
- e_{max} = loosest possible states
- e_{min} = densest possible states
- $f(\gamma)$ = stiffness degradation function
- f_{ij} = frictional force vector
- F_{ij} = normal contact force vector
- G = shear modulus
- I = moment of inertia (**page 39**)
- I = the *ith* particle (**page 40**)

- J = particle keeping touch with particle
- k = slope of the swelling (**page 51**)
- K = bulk modulus (**page 37**)
- k = spring constant (**page 42**)
- LI = Liquidity Index
- m = stress dependency exponent
- M_i = particle mass
- m_s = dry soil solids mass
- m_v = volume compressibility
- m_w = water mass
- n = tangential component
- N_c = Bearing capacity factor for cohesion
- N_q = Bearing capacity factor related to confinement
- $N\gamma$ = Bearing capacity factor due to soil weight
- P = load acting on between two particles
- P' = mean effective stress
- P_{ext} = external force vector
- p_c = preconsolidation pressure
- PI = Plasticity Index
- P_{ref} = reference confining pressure
- q = deviatoric stress (**pages 45, 54**)
- q = overburden pressure (**page 19**)
- q_a = asymptotic value of the overburden pressure q
- q_f = is the ultimate deviatoric stress
- R_f = is the failure ratio
- R_i = particle radius
- s = normal component
- u = pore water pressure
- u_a = pore air
- u_w = pore water pressures
- v_s = shear wave velocity (**page 36**)
- V_s = volume of solid particles (**page 26**)
- V_t = total volume
- V_v = ratio of the volume of voids
- w = Moisture content
- W_s = maximum strain energy stored
- x_i = displacement vector
- γ = shear strain (**pages 36, 47**)
- γ = unit weight of soil (**page 19**)
- δ_{ij} = Kronecker delta
- ε_{ij} = strain tensor
- η = damping coefficient (**page 42**)

- η = Porosity (**page 26**)
- λ = slope of the virgin compression line
- ν = Poisson's ratio
- ρ = mass density
- σ' = effective stress
- σ = total stress applied externally
- σ_1 = major principal stress at failure
- σ_3 = minor principal stress at failure
- σ_{ij} = the stress tensor and
- σ_{oct} = octahedral normal stress
- τ = shear stress at failure
- τ_{oct} = octahedral shear stress
- ϕ' = effective angle
- χ = effective stress parameter
- ω_i = rotational angle velocity vector
- $d\varepsilon_v^p$ = increment of plastic volumetric strain
- k_n = normal stiffness coefficient
- k_t = Tangential stiffness coefficient
- γ_n = normal damping coefficient
- γ_t = Tangential damping coefficient

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General Introduction

Excavation is a fundamental operation in civil, geotechnical, and mining engineering, involving the removal and displacement of soil or rock to create space for construction or extraction activities. This process is carried out using various tools and machines, whose efficiency depends on both their design and the properties of the ground. During excavation, the material undergoes deformation, failure, and flow as it is cut and displaced. Understanding the general principles of excavation is essential before analyzing the more detailed mechanisms governing soil tool interaction. Building on this general understanding of excavation processes, the present study focuses on understanding and modelling the interaction between soil and excavation tools, a process that governs excavation performance, cutting efficiency, energy consumption, and equipment durability. Soil tool interaction is highly complex because it involves large deformations, evolving failure mechanisms, and rapidly changing forces generated at the tool soil interface.

This complexity is further amplified by the natural variability of soil properties such as moisture content, density, cohesion, and composition, which cause significant differences in cutting resistance, soil flow, and stress distribution during excavation. Understanding this interaction is therefore of great importance to several engineering domains, particularly earthmoving, foundation construction, trenching, tunneling, mining, and resource extraction. In these sectors, excavation performance directly influences project cost, productivity, safety, and equipment lifespan. The global need for improved excavation modelling arises from the continuous demand for more efficient and sustainable construction processes, optimized tool geometries, reduced energy usage, and more accurate predictions of soil behavior under dynamic loading.

Accurate analysis of soil tool interaction remains a significant challenge because traditional approaches struggle to capture the large strain, nonlinear characteristics of soil deformation. Experimental investigations such as soil bin tests provide valuable insights into soil displacement and cutting forces, yet they remain limited in reproducing the full transient nature of excavation. To address these limitations, numerical methods particularly the Finite Element Method (FEM) have been widely adopted to simulate stress distribution, wear behavior, and energy demand under excavation conditions. Classical soil constitutive models, such as Mohr-Coulomb (MC)

and its enhanced versions like the Modified Mohr-Coulomb (MMC) model, play a key role in representing soil strength, dilatancy, and nonlinear deformation behavior.

However, mesh based FEM faces considerable difficulties in simulations involving large deformations, soil fragmentation, and evolving free surfaces. This has motivated the increasing use of mesh free techniques, particularly the Smoothed Particle Hydrodynamics (SPH) method, which offers a Lagrangian formulation capable of modelling discontinuities, particle separation, and large soil displacements without requiring remeshing. SPH has proven effective in replicating soil failure patterns and cutting processes, especially when combined with Mohr Coulomb type constitutive laws, showing strong agreement with experimental observations.

Given these considerations, the global goal of this study is to investigate soil tool interaction during excavation by combining experimental soil bin testing with numerical modelling using the SPH method. This integrated approach aims to evaluate the effects of key excavation parameters such as rake angle, cutting depth, and tool velocity on cutting resistance, soil failure mechanisms, energy demand, and soil flow behavior. By validating numerical simulations against laboratory data, this study enhances the reliability of SPH modelling for geotechnical excavation applications and to support the optimization of excavation tools and operational strategies. To meet these goals, the dissertation is structured into four chapters, each building progressively toward a complete and validated understanding of soil tool interaction during excavation.

The first chapter gives a broad introduction to excavation engineering and establishes its relevance in modern civil and geotechnical applications. It begins by defining excavation principles and discussing the operational context in which excavation tools are deployed, including construction, mining, and geosystems engineering. The chapter reviews the different excavation techniques mechanical cutting, hydraulic excavation, vacuum based systems, blasting, and subsurface excavation and explains how tool geometry, cutting mechanisms, penetration conditions, and ground properties jointly govern excavation performance. Special emphasis is placed on geotechnical factors such as soil structure, stratification, moisture variations, and environmental conditions that influence the mechanical response of soil during cutting. This chapter sets the conceptual groundwork for understanding why soil-tool interaction is a complex and multidisciplinary challenge.

The second chapter develops the scientific and theoretical foundation required for analyzing excavation processes. It begins with a detailed review of soil mechanics principles relevant to large deformation problems, including soil classification, index properties; shear strength parameters, compressibility, dilatancy, and rate dependent behavior. The chapter then discusses laboratory experimental methods used to determine soil properties, along with analytical and semi empirical approaches historically used to estimate cutting forces and soil tool response. A comprehensive overview of numerical modelling strategies such as the Finite Element Method (FEM), Discrete Element Method (DEM), and mesh-free approaches is provided, highlighting

their respective advantages and limitations for excavation analysis. Particular attention is given to elastoplastic constitutive models, with a focus on the Mohr-Coulomb formulation, which are widely used to describe soil failure under excavation-induced stresses. By the end of this chapter, the reader gains a complete understanding of the theoretical tools and modelling frameworks that support the numerical analysis performed later in the thesis.

The third chapter presents the numerical method and modelling strategy implemented in this study, offering a step by step description of the computational workflow used to simulate the excavation process. It begins by detailing the experimental soil bin configuration, including its geometry, boundary conditions, and material preparation. The chapter then explains how this configuration is translated into a numerical model, describing the meshing strategy, the transition from finite elements to SPH particles, and the criteria used to ensure numerical stability and accuracy. Key modelling components such as contact algorithms, tool soil interaction laws, and particle discretization are examined. Material parameters derived from laboratory tests (cohesion, friction angle, dilation angle, density, elastic modulus, and Poisson's ratio) are implemented within Mohr-Coulomb type constitutive models to reproduce realistic soil behavior. The chapter also covers the choice of particle sizes, time step considerations, and the simulation procedures used to represent different excavation scenarios. By offering detailed justification for each modelling choice, this chapter ensures transparency, reproducibility, and scientific rigor in the numerical strategy adopted.

The final chapter analyzes and compares the results obtained from both laboratory experiments and SPH-based numerical simulations. It investigates the influence of key excavation parameters namely rake angle, cutting depth, and tool velocity on cutting resistance, soil displacement patterns, and failure mechanisms. The chapter presents force evolution trends, stress distributions, soil flow profiles, and particle movement patterns to provide insight into the physical processes during excavation. A comparative evaluation between numerical predictions and experimental measurements is performed to assess the reliability, accuracy, and limitations of the SPH approach. The final discussion synthesizes the findings, highlights the advantages and drawbacks of mesh-free modelling for excavation applications, and provides recommendations for optimizing tool design, operational parameters, and future research directions in soil tool interaction modelling.

Chapter 1

Chapter 1: Fundamentals of Excavation Engineering

1.1 Introduction to Excavation Engineering

Excavation engineering forms the foundation of modern civil, mining, and environmental infrastructure development, providing the essential processes through which soil, rock, and other geomaterials are removed, shaped, and stabilized to meet structural and environmental demands. As construction activities expand in scale and complexity, the need for a thorough understanding of excavation principles, engineering mechanisms, and geotechnical interactions becomes increasingly critical.

This chapter introduces the fundamental concepts governing excavation operations, beginning with their definition, scope, and relevance within engineering practice. It then examines the major excavation processes and methods including mechanical, hydraulic, vacuum, blasting, and linear subsurface techniques highlighting how equipment selection, cutting mechanisms, and technological advancements influence field performance. The chapter also provides an overview of excavation machinery and tooling, addressing both conventional systems and emerging innovations such as hybrid equipment, automation, and machine-control technologies.

Finally, key geotechnical and environmental factors affecting excavation, including soil behavior, climate, topography, and excavation-induced ground response, are discussed to establish a comprehensive framework for understanding how ground conditions govern the planning, safety, and efficiency of excavation works. Together, these components present a cohesive foundation for the study and practice of excavation engineering

1.1.1 Definition and Scope

Excavation is defined as the controlled process of digging, removing, and relocating soil, rock, or other natural materials to achieve a required structural or topographic configuration. It represents a fundamental operation within civil, mining, and environmental engineering, forming the basis for the construction of foundations, roadways, tunnels, pipelines, and other infrastructure systems (Das [1] and Peurifoy [2]). The scope of excavation extends beyond construction, playing a critical role in environmental engineering through activities such as contaminated-site remediation, where soil removal helps prevent pollutant migration and protects groundwater resources (Kuppusamy et al. [3]).

Modern excavation is no longer view as a purely mechanical activity but rather as an interdisciplinary engineering process governed by soil mechanics, machine dynamics, and material behavior, where cutting forces, tool geometry, and soil rheology interact to determine performance and energy requirements (Lislerud [4] and Bilgin et al. [5]). With the evolution of numerical modeling, automated measurement systems, and advanced construction techniques, the scope of excavation continues to expand toward safer, more precise, and more sustainable earthwork operations (Shehab [6] and Hu et al. [7]).

1.1.2 Engineering and Geotechnical Relevance

Excavation induces substantial changes in the stress–strain state of the surrounding ground, leading to soil deformation and potential structural instability if not properly managed. For instance, the removal of overburden in deep excavations reduces confining stresses, resulting in heave, settlement, or wall deformation depending on boundary conditions (Li et al. [8]). To mitigate such risks, engineers employ geotechnical models that simulate soil-structure interaction during the excavation process.

The understanding of excavation-induced ground behavior is essential for ensuring long-term stability in underground construction. Studies by Wang et al. [9] have shown that factors such as dump height, slope gradient, and layer thickness significantly affect the stability of soil heaps in soft soil regions. These findings have informed the design of stable embankments and excavation slopes under varying environmental conditions.

1.1.3 Environmental and Operational Context

Excavation plays a central role in environmental engineering, particularly in the management and remediation of contaminated soils. Excavation-based remediation enables the physical removal of polluted strata, preventing the spread of contaminants and protecting groundwater resources from infiltration by hazardous substances (Kuppusamy et al. [3]). The integration of

bioremediation and stabilization techniques with traditional excavation methods has further enhanced environmental outcomes, allowing for sustainable management of contaminated sites.

From an infrastructural standpoint, excavation is essential for constructing transportation networks, including roads, railways, and tunnels. For example, deep tunnel excavation in urban areas requires sophisticated support systems to prevent ground deformation and building settlement (Correia et al. [10]). Excavation also supports the establishment of drainage systems, foundations, and subway corridors, all of which are integral to urban functionality and resilience. Recent research emphasizes the importance of digital monitoring and automation in excavation to improve precision and safety. Automated earthwork volume measurement systems have revolutionized construction planning by minimizing human error and enabling real-time site monitoring (Shehab [6]). Moreover, artificial ground freezing techniques, particularly in deep shaft construction, have been employed to stabilize soils and prevent water inflow during excavation (Zhelnin et al. [11]). These advancements underscore the evolving role of excavation as a technologically integrated and environmentally conscious discipline

1.2 Excavation Processes and Methods

1.2.1 Manual Excavation

Manual excavation, though labor intensive, remains relevant in small scale and sensitive operations such as archaeological digs, confined spaces, or projects requiring high precision. It typically employs tools like shovels, picks, and spades (Hwang [12]). While mechanization has largely replaced manual work in large projects, its advantages include fine control, minimal environmental disturbance, and low initial cost (Smallwood [13]). However, it presents significant challenges in terms of worker safety and limited productivity, making it unsuitable for large or deep excavations (Chudley et al. [14]).

1.2.2 Mechanical Excavation

Mechanical excavation employs heavy machinery such as excavators, bulldozers, and backhoes to remove material, making this method efficient for large scale projects and areas where manual labor is impractical. Excavators, equipped with a bucket, arm, and rotating cab, are versatile machines used for digging trenches, holes, and foundations, as well as for material handling and demolition (McCarthy and McCarthy [15]). Bulldozers, employed for clearing and grading land, feature a large flat blade at the front to push soil and debris (Peurifoy [2]). Backhoes, which combine a digging bucket on the back and a loader on the front, are suited for small to medium sized projects (Fang [16]).

1.2.2.1 Principles and Mechanisms

Mechanical excavation relies on the application of force through cutting, ripping, or breaking mechanisms to displace soil or rock. Common mechanical systems include excavators, bulldozers, scrapers, and trenchers. These machines employ a combination of static and dynamic forces to achieve material removal (Sifferlinger et al. [17]).

The efficiency of mechanical excavation is governed by tool geometry, cutting depth, velocity, and the mechanical properties of the material being excavated particularly unconfined compressive strength (UCS) and tensile strength (Tumac et al. [18]).

1.2.2.2 Equipment Classes and Field Use

Mechanical excavation encompasses several classes of equipment designed to meet varying geological conditions and project requirements, with each machine type contributing uniquely to field operations. Excavators form the core of modern earthmoving systems, offering flexibility through interchangeable attachments that allow efficient trenching, foundation preparation, and material loading across diverse soil conditions (Peurifoy [2]). Complementary machines such as loaders and backhoe loaders provide combined digging and loading capabilities, making them essential in urban and medium scale utility projects where maneuverability and operational efficiency are critical. Bulldozers, characterized by their high tractive force, are employed for clearing, grading, and cut-and-fill activities, particularly in large-scale site development and infrastructure works (Correia et al. [10]).

Specialized equipment such as trenchers ensures consistent and precise trench formation for pipelines and drainage systems, minimizing over excavation and improving productivity. In more complex geological environments, especially where hard rock is encountered, drilling equipment, mechanical cutting systems, and tunneling machinery are used to overcome high strength materials, with machine performance strongly influenced by rock and soil mechanical properties (Lislerud [4] and Bilgin et al. [5]). Effective field use depends on matching equipment characteristics to soil behavior, excavation depth, and project scale, ensuring optimal productivity while maintaining safety, reducing environmental disturbance, and minimizing energy consumption.

1.2.3 Hydraulic and Vacuum Excavation

Hydraulic and vacuum excavation are specialized non-mechanical methods widely used when precision, safety, and environmental protection are required. Vacuum excavation employs high pressure air or water to loosen soil, which is then extracted using a powerful vacuum system. This technique is inherently non destructive, making it especially suitable for excavation around sensitive underground utilities, as it significantly reduces the risk of utility damage and minimizes environmental disturbance. It is commonly applied in utility locating, potholing, and

environmental cleanup operations, where controlled soil removal is essential (Dave and Agrawal [19]).

Given that excavation activities can introduce environmental and safety hazards, vacuum excavation aligns well with best practices designed to reduce ecological impact and enhance operational safety (Veidmark [20]). Hydraulic excavation, in contrast, relies on high-pressure water or fluid streams to break down, loosen, and remove soil or rock. This method is particularly effective in mining, where hydraulic mining uses concentrated water jets to dislodge material for mineral extraction (Haga et al. [21]).

Additionally, hydraulic excavation is integral to dredging operations, allowing sediment removal from rivers, ports, and waterways to maintain navigability and water management efficiency (Bray and Cohen [22]). Together, these two methods provide flexible and efficient alternatives to traditional mechanical excavation, offering enhanced precision, safety, and environmental stewardship across a wide range of engineering applications

1.2.4 Blasting Excavation

Blasting excavation involves the controlled detonation of explosives to fracture rock masses. It remains the primary technique for large scale rock removal in mining, tunneling, and quarrying operations (Onederra et al. [23]). The method is highly efficient but requires precise design to control fragmentation, minimize vibration, and ensure safety (Sifferlinger et al. [17]).

Recent innovations in non explosive rock breaking technologies such as the Instantaneous Expansion (IE) technique, and microblasting have improved safety and reduced damage to surrounding structures. Controlled blasting designs now use digital delay detonators and blast modeling software to optimize fragment size distribution and minimize overbreak (Zhang et al. [24]).

Blasting is associated with ground vibration, fly rock hazards, and air overpressure. Current research focuses on integrating vibration monitoring systems and seismic control algorithms to ensure compliance with regulatory vibration limits (McGuire [25]). However, it requires careful planning and adherence to safety regulations to prevent accidents and environmental damage (Dowding and Siebert [26]).

1.2.5 Linear and Subsurface Excavation

Linear excavation and underground construction methods encompass techniques used for creating subsurface infrastructure such as pipelines, tunnels, and utility corridors. Trenching remains one of the primary approaches, involving narrow, deep excavations formed using chain or wheel trenchers depending on soil conditions (Fewings and Henjeweale [27]). Ensuring trench stability is critical, with sloping, shoring, and shielding systems implemented in accordance with

Occupational Safety and Health Administration (OSHA) safety guidelines, while modern laser guided equipment enhances accuracy and operational efficiency (Yadav et al. [28]).

For large scale underground works, Tunnel Boring Machines (TBMs) provide continuous, high-precision excavation through diverse geological formations, simultaneously installing tunnel linings to minimize surface disruption (Goel et al. [29]). Their deployment, however, requires extensive geological investigation and simulation due to high cost and ground sensitivity (Goel et al. [29]). Microtunneling complements these methods as a trenchless, remote-controlled technology suited for small-diameter pipelines in urban environments, offering precise installation beneath existing infrastructure with minimal surface impact (Iseley [30] and Najafi [31]).

1.2.5.1 Trenching

Trenching refers to the creation of narrow, deep excavations for pipelines, cables, and drainage systems (Fewings and Henjewe [27]). Chain trenchers and wheel trenchers are commonly used, depending on soil hardness and trench depth.

In trenching operations safety is a major concern, particularly the risk of trench wall collapse. Engineers employ sloping, shoring, and shielding systems to maintain stability, as recommended by the Occupational Safety and Health Administration (OSHA) standards (Safety, Administration, et al. [32]). Advancements such as laser guided trenchers and automated grade control systems have improved precision and reduced rework (Yadav et al. [28]).

1.2.5.2 Tunnel Boring Machines

Tunnel Boring Machines or “TBMs” represent the pinnacle of mechanical excavation technology (Figure 1.1). They are large, self contained systems capable of drilling through various geological formations while simultaneously installing tunnel lining segments (Goel et al. [29]). TBMs offer continuous excavation, high advance rates, and minimal surface disruption (Ma et al. [33]). However, their high initial cost and geological sensitivity necessitate detailed site characterization and numerical simulation before deployment (Kuang et al. [34]). They Minimize surface disruption, reduce construction time, and enhance safety.

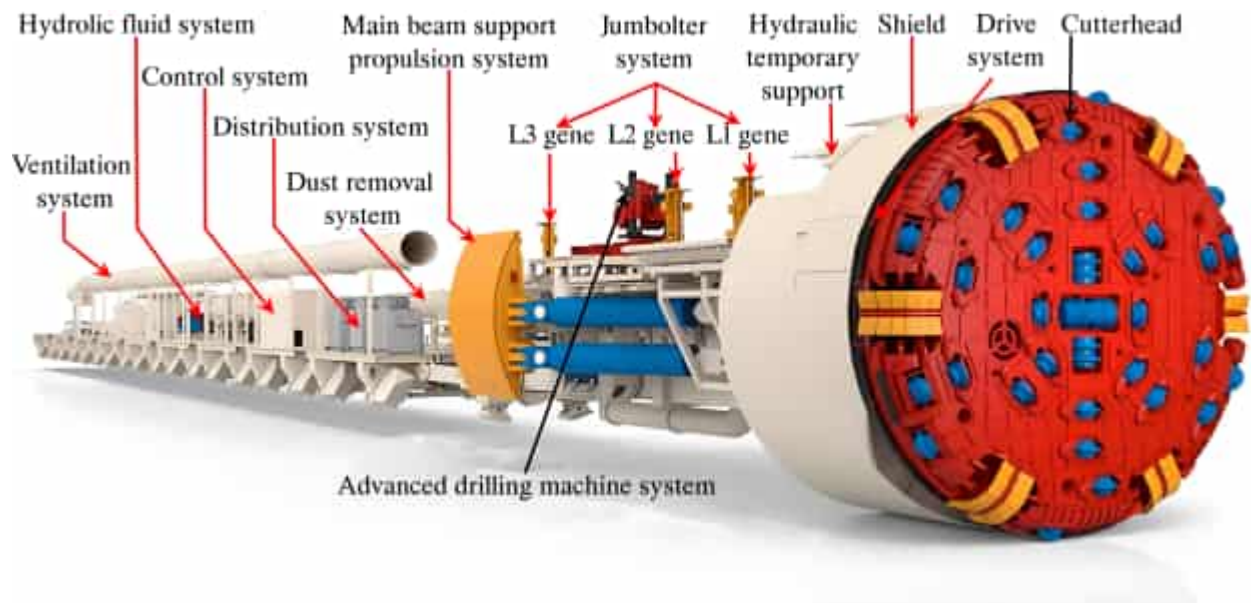


Figure 1.1: The structure of Tunnel Boring Machine Liu et al. [35].

1.2.5.3 Microtunneling

Microtunneling is a trenchless technology used for installing small diameter pipelines beneath obstacles like roads and rivers. It involves a remotely controlled, guided boring machine, minimizing surface disruption and making it suitable for urban environments (Iseley [30]). Microtunneling is ideal for sewer, water, and utility installations, offering precise and efficient underground construction (Najafi [31]).

Table 1.1: Comparative Summary of Excavation Methods and Their Applications.

Excavation Method	Typical Application	Advantages	Limitations	References
Mechanical	Urban construction, trenching	High precision, fast operation	High energy use, tool wear	Sifferlinger et al. [17]
Manual	Archaeological, small scale	Fine control, low cost	Labor intensive	Smallwood [13]
Hydraulic	Dredging, saturated soils	Suitable for loose materials	Limited in hard rock	Wang et al. [9]
Blasting	Mining, tunneling	Efficient rock breakage	Vibration and safety concerns	Sifferlinger et al. [17]
TBM	Long tunnels	High productivity	Expensive setup	Goel et al. [29]
Microtunneling	Urban pipelines	Minimal disruption	Limited diameter	Najafi [31]
Vacuum	Utility exposure	Safe and non destructive	Low penetration depth	Chen [36]

1.3 Excavation Equipment, Tooling, and Machinery

Excavation has been practiced for millennia, beginning with simple hand operated tools before progressing to mechanized and automated systems. The choice of tool remains governed by the excavation's purpose whether it involves shallow foundation digging, trenching, or rock breaking and the required precision in material removal.

1.3.1 Hand and Powered Tools

Historically, manual excavation relied predominantly on hand tools (Figure 1.2) such as shovels, spades, picks, and mattocks, which remain essential in modern projects for fine detailing and confined spaces. Shovels and spades are primarily used for loosening, lifting, and moving loose material, while picks and mattocks are suited for breaking compacted soils and small rocks. Despite their simplicity, these tools provide excellent control and tactile feedback, particularly in archaeological excavations and utility repairs (Karthikeyan et al. [37]).



Figure 1.2: Traditional agricultural and excavation hand tools shovels, spades, picks, and mattocks commonly used for small scale manual excavation and soil preparation (Thomas [38]).

The introduction of powered hand tools revolutionized small to medium scale excavation. Jackhammers, powered by compressed air or electricity, are essential for breaking concrete and rock in dense urban environments where controlled excavation is required (McGuire [25]). Similarly, power augers have simplified the process of boring holes for foundations, poles, or piles. These augers, which use spiral blades to cut through soil, enable rapid and uniform hole formation with minimal labor effort (Shurig [39]).

Basic powered tools bridge the gap between manual and fully mechanized excavation systems, providing flexibility in restricted sites and complementing larger machinery. Their portability, ease of maintenance, and cost effectiveness make them indispensable in modern field operations.

1.3.2 Heavy Machinery

As infrastructure and construction projects expanded in scope and complexity, reliance on manual methods became insufficient. This evolution necessitated the development of heavy machinery capable of handling vast material volumes, deeper excavation depths, and more challenging ground conditions.

1.3.2.1 Excavators

The excavator as presented in Figure 1.3 remains the cornerstone of modern excavation engineering. Characterized by its boom, dipper (or stick), and bucket configuration, an excavator's design allows a 360° rotation, enabling highly efficient digging, lifting, and material relocation. Depending on project requirements, excavators range from compact mini models (less than 3 tons) for urban and precision tasks to ultra large mining excavators exceeding 800

tons (Edwards and Holt [40]).



Figure 1.3: Overview of a standard hydraulic excavator used in earthmoving operations.

Modern excavators employ advanced hydraulic systems that allow precise control of force, movement, and speed.

Table 1.2: Typical specifications of excavator classes and their principal applications (Edwards and Holt [40]).

Type	Operating Weight	Typical Use	Depth Capacity
Mini Excavator	<3 tonnes	Utility works, landscaping	2-3 m
Standard Excavator	10-35 tonnes	Building foundations, roadworks	5-7 m
Large Excavator	>50 tonnes	Mining, large scale earthmoving	10-15 m

1.3.2.2 Bulldozers

Bulldozers are indispensable for clearing land, grading surfaces, and pushing large quantities of soil, sand, or rubble. Their robust steel blades typically classified as straight (S-blade), universal

(U-blade), or combination (SU-blade as in Figure 1.4) allow adaptation to diverse terrain and material conditions. Bulldozers are particularly effective in initial site preparation and large scale earthmoving operations where fine control of soil level is less critical (Ali et al. [41]). Modern models incorporate tilt and angle blade adjustments, automatic traction control, and hydrostatic transmission, which together enhance efficiency and reduce fuel consumption.



Figure 1.4: Typical track-type bulldozer equipped with SU-blade for grading and pushing material.

1.3.2.3 Backhoe Loaders

The backhoe loader represents a hybrid solution, integrating the digging capabilities of an excavator with the material handling functions of a front end loader. The backhoe arm is used for trenching, foundation excavation, or small scale demolition, while the front loader facilitates loading, grading, and backfilling (Tasevski et al. [42]). This dual functionality makes backhoe loaders (Figure 1.5) ideal for medium sized urban projects and agricultural applications.



Figure 1.5: General configuration of a backhoe loader combining a front loader unit and a rear digging arm.

1.3.2.4 Trenchers

Trenchers are specialized machines developed to excavate narrow and deep trenches for pipelines, cables, and drainage systems. Their cutting mechanisms either continuous chains or rotating wheels allow precise trench formation even in cohesive soils (Popperfuss [43]). Chain trenchers as in Figure 1.6 are best suited for deep, narrow cuts in hard ground, while wheel trenchers are optimized for shallow, wide trenches in softer soils.



Figure 1.6: Representative trencher system designed for linear excavation and trench formation.

1.3.3 Technology Enhanced Systems

The excavation industry has undergone a remarkable technological transformation over the past three decades, driven by advances in automation, digital integration, energy efficiency, and sustainability. Modern excavation equipment now incorporates intelligent control systems, environmentally friendly powertrains, and safety enhancing technologies designed to optimize performance while minimizing environmental and human risks.

These innovations are the result of combined progress in mechanical design, information technology, and mechatronics, reflecting a global shift toward smart construction and Industry 4.0 practices. The primary objectives of these developments include improved precision, productivity, safety, and environmental responsibility (Khan et al. [44]).

1.3.3.1 GPS and Machine Control

Modern excavation operations increasingly rely on the integration of GPS technology and automated machine control systems to enhance precision, efficiency, and safety. GPS-enabled systems utilize real time satellite data combined with onboard sensors to monitor and adjust the position, alignment, and slope of excavation equipment. Operators can follow preloaded digital terrain models on in-cab displays, which continuously compare the actual bucket or blade position with the desired design profile. This feedback loop allows centimeter-level accuracy in complex tasks such as foundation cutting, road grading, and trench excavation (Khan et al. [44]).

The adoption of these technologies reduces dependency on traditional surveying methods,

decreases manual grade checking, and optimizes cutting paths, which field studies report can increase productivity by up to 40 % and lower fuel consumption by 10 to 15 % (Khan et al. [44]). Figure 1.7 illustrates the integration of GPS in an excavator, highlighting the data exchange between satellite systems, a base station, and onboard sensors.

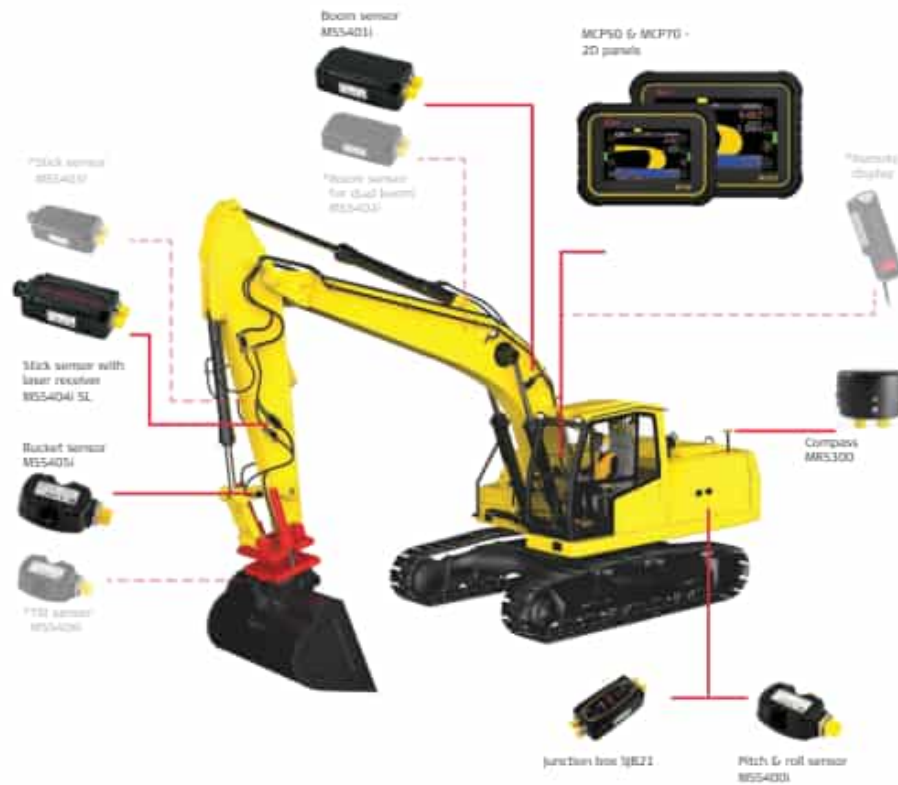


Figure 1.7: GPS-based excavation system overview. Source: Leica Geosystems AG, Product Catalogue (2025). Reproduced for academic purposes under fair use.

Autonomous excavators extend this concept by incorporating advanced navigation, perception, and robotic control systems. These machines perform real time environmental mapping and execute excavation operations with high accuracy, achieving ± 2 cm precision even under variable soil conditions (Ha et al. [45]). Autonomous systems are particularly advantageous in confined spaces, microexcavation, and tunneling, where compact adaptive machinery enhances operational safety and consistency. Robotic operation reduces human exposure to hazards such as dust, vibration, and noise while maintaining repeatable excavation quality. Figure ?? shows an example of autonomous excavators coordinated with aerial drones in a digital excavation workflow, demonstrating AI-driven integration between ground and aerial systems.

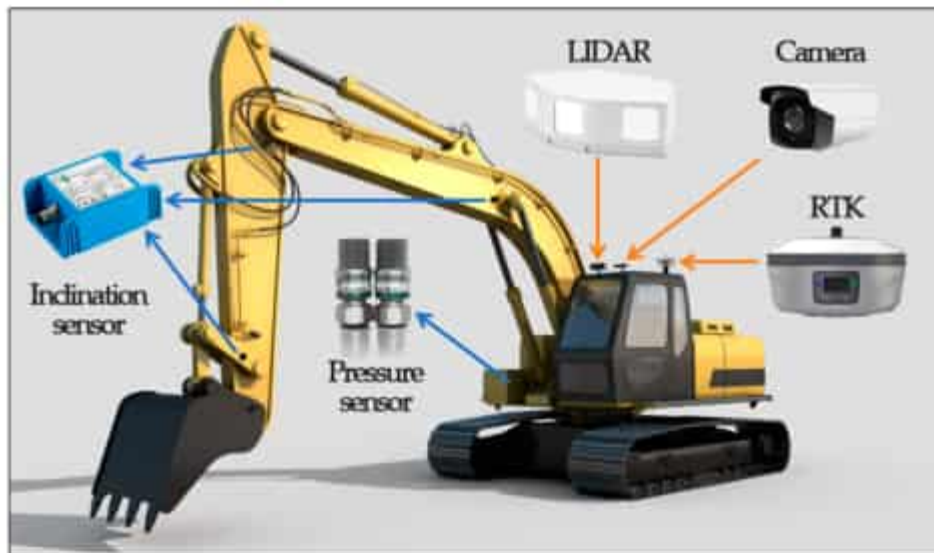


Figure 1.8: Automated excavator hardware system overview (Zhang et al. [46]).

1.3.3.2 Hybrid, Electric, and Hydraulic Systems

Increasing environmental regulations and the demand for energy-efficient machinery have driven the development of hybrid, electric, and advanced hydraulic excavators. These machines integrate conventional diesel engines, electric drives, or fully electric powertrains to reduce carbon emissions and improve operational efficiency.

Hybrid excavators utilize energy recovery systems that capture kinetic energy during swing or braking operations. This energy is stored in capacitors or batteries and reused to power auxiliary systems or assist engine output during high load operations, resulting in fuel savings of 20 to 30 % (Inoue and Yoshida [47]).

Fully electric excavators, powered exclusively by lithium-ion or solid-state batteries, are increasingly deployed in urban construction sites and tunneling projects where ventilation and emissions are critical. Hydraulic systems remain central to excavation operations due to their high power density and controllability. Modern electro-hydraulic systems are progressively replacing conventional hydraulics, enabling finer operational control, reduced energy losses, and predictive maintenance through real-time monitoring (Inoue and Yoshida [47]).

1.3.3.3 Automation, Robotics, and Teleoperation

In high-risk or contaminated environments, teleoperated systems enable remote control of machinery from safe distances. By integrating real-time video streams with haptic feedback, operators can execute excavation and construction tasks without direct exposure to hazardous zones. These systems have demonstrated effectiveness in mining, demolition, and disaster recovery operations (Huang et al. [48]).

The construction and infrastructure sector increasingly leverages robotics, automation, and digital control systems to enhance productivity, safety, and sustainability while reducing operational costs. Inspired by advancements in the mining industry, civil engineering projects such as road construction, bridge assembly, tunneling, and excavation are progressively adopting intelligent machinery with machine learning-based decision support and semi-autonomous operation capabilities (Ha et al. [45]).

Advanced systems combine teleoperation, sensor fusion, and machine intelligence to allow adaptive responses to dynamic excavation conditions. Predictive analytics and real-time decision support reduce human error, optimize task execution, and enable semi-autonomous operations even in challenging or hazardous environments. The integration of machine learning models allows the system to improve performance over time:

These technologies collectively enhance operational safety, efficiency, and precision, paving the way for fully autonomous or collaborative robotic excavation systems in civil and mining engineering applications.

1.4 Excavation Safety, Environmental Impacts, and Risk Control

1.4.1 Environmental Impacts

Excavation affects multiple environmental components including soil stability, hydrological balance, and biodiversity. These impacts vary with project scale, soil type, excavation method, and the presence of mitigation strategies. Uncontrolled excavation can cause severe erosion, sediment transport, and long term ecosystem degradation.

1.4.1.1 Erosion and Sedimentation

Soil erosion is among the most immediate consequences of excavation, particularly on sloped or unprotected sites. The removal of vegetative cover and disturbance of soil structure expose surfaces to wind and water erosion, leading to sedimentation in nearby water bodies (Lal [49]). This sedimentation can increase turbidity, reduce aquatic oxygen levels, and impair water quality downstream.

1.4.1.2 Habitat and Ecological Disturbance

Excavation activities can significantly disrupt local ecosystems and wildlife habitats through vegetation removal, noise, dust, and vibration. The scale of habitat disturbance is influenced by the excavation footprint, access roads, and spoil disposal areas (Forman and Alexander [50]).

Sensitive habitats such as wetlands and riparian zones require particular attention, as they often host endangered or migratory species.

Prior to excavation, Environmental Impact Assessments (EIAs) are typically conducted to evaluate potential ecological consequences. These assessments inform the design of mitigation measures such as buffer zones, wildlife corridors, and progressive restoration of disturbed areas emphasize that incorporating ecological planning early in the design stage can substantially reduce long term habitat fragmentation and biodiversity loss (Forman and Alexander [50]).

1.4.1.3 Air, Noise, and Vibration Emissions

The operation of heavy excavation machinery contributes to air pollution through emissions of nitrogen oxides (NO_x), carbon monoxide (CO), and particulate matter (PM_{10} and $PM_{2.5}$). In urban excavation projects, such emissions may exacerbate respiratory issues and reduce local air quality. The introduction of hybrid and electric excavators has been effective in lowering emissions by up to 30 % (Inoue and Yoshida [47]).

Noise and ground vibration from excavation and blasting can also impact nearby residents and structures. Regulatory frameworks such as the European Environmental Noise Directive (2002/49/EC) and the U.S. Federal Highway Administration (FHWA) guidelines prescribe maximum allowable noise and vibration limits. Implementing sound barriers, using low noise machinery, and scheduling noisy operations during limited time windows are effective mitigation strategies.

1.4.2 Safety Engineering

Excavation remains one of the most hazardous operations in the construction industry due to risks such as cave ins, falling objects, toxic atmospheres, and equipment related accidents. The Occupational Safety and Health Administration (Safety, Administration, et al. [32]) identifies excavation and trenching as activities with the highest fatality rates in civil works, primarily due to inadequate protective systems and unsafe practices.

1.4.2.1 Training and Protocols

Human factors remain a decisive component in excavation safety performance. Effective training programs, supervision, and safety management systems ensure that workers understand operational risks and appropriate mitigation procedures highlight that continuous education in hazard recognition and emergency response significantly reduces the frequency of accidents (Li and Poon [51]).

1.4.2.2 Ground Control and Stability

In deep or rockburst prone excavations, ground control becomes vital to maintaining stability. Advanced techniques such as shotcrete lining, fiber reinforced concrete shells, and energy absorbing rock bolts are now standard practices in tunnel support (Kuang et al. [34]). These methods not only resist static and dynamic loading but also provide flexible deformation control, enabling safe excavation in highly stressed rock masses.

1.4.2.3 Emergency Management

Comprehensive safety management extends to emergency response planning, including procedures for cave in rescue, equipment failure, and hazardous gas exposure. The presence of a designated safety officer and clearly marked evacuation routes are prerequisites for high risk excavation sites.

Supervisory personnel must ensure coordination between different contractors and maintain open communication with local emergency services. Regular safety audits and toolbox talks serve to reinforce compliance and foster a culture of continuous vigilance.

1.4.3 Sustainable Excavation

The convergence of environmental stewardship and occupational safety defines the modern approach to excavation. Sustainable excavation practices emphasize minimal disturbance, energy efficient machinery, and long term site rehabilitation, while advanced safety protocols prioritize human well being through training, monitoring, and protective engineering design.

Emerging technologies such as AI-based hazard prediction, digital twins, and IoT-connected safety sensors are expected to further enhance the integration between environmental and safety management systems. These advancements support the global shift toward zero harm and net zero carbon construction objectives, ensuring that excavation operations remain both efficient and responsible

1.5 Geotechnical and Environmental Factors Affecting Excavation

Excavation performance and stability are highly dependent on the interaction between soil characteristics, environmental factors, and geotechnical conditions. Understanding these factors is fundamental for designing safe and efficient excavation operations, optimizing equipment performance, and minimizing environmental impacts

The following sections detail the principal parameters affecting excavation: soil characteristics, environmental influences, and geotechnical considerations.

1.5.1 Soil Characteristics

Soil characteristics fundamentally determine the response of ground material to excavation forces. The mechanical resistance encountered during digging, cutting, or penetration is governed by the physical and chemical properties of the soil. These properties also influence the selection of excavation methods, equipment types, and support systems (Brady et al. [52]).

1.5.1.1 Physical Properties

The physical properties of soils such as texture, structure, porosity, density, and consistency play a pivotal role in excavation engineering.

- **Soil Texture:** Texture refers to the relative proportions of sand, silt, and clay in a soil. Coarse textured soils (sandy) are generally easier to excavate and have good drainage characteristics, while fine textured soils (clayey) exhibit higher cohesion and plasticity, making them more resistant to cutting and requiring greater excavation forces (Brady et al. [52]).
- **Soil Structure:** The structure, or the arrangement of soil particles into aggregates, affects the ease of penetration and the mechanical response under loading. Well aggregated soils exhibit better stability, while dispersed structures can lead to slumping or flow during excavation (Hillel [53]).
- **Porosity and Bulk Density:** Porosity governs the void ratio and thus the soil's ability to retain air and water. High porosity indicates loose soil, which may collapse under excavation loads, whereas high bulk density corresponds to compacted soils that resist tool penetration (Dexter [54]).
- **Consistency and Plasticity:** The Atterberg limits define soil plasticity and consistency, which are crucial in determining the deformation behavior during excavation. For instance, clays near their plastic limit exhibit ductile deformation, while those below the shrinkage limit may crack under tool loading (Das and Sivakugan [55]).

Table 1.3: Typical physical properties of soils and their impact on excavation behavior (adapted from Brady et al. [52], Hillel [53] and Dexter [54]).

Property	Definition	Influence on Excavation
Texture	Ratio of sand, silt, and clay	Determines ease of cutting and tool wear
Structure	Arrangement of soil particles	Affects slope stability and collapse potential
Porosity	Volume of voids per unit volume	Controls drainage and compressibility
Bulk density	Mass per unit volume	Governs penetration resistance
Plasticity index	Difference between liquid and plastic limits	Indicates soil workability and deformation

1.5.1.2 Chemical Properties

The chemical composition of soils influences their reactivity, cohesion, and interaction with water.

- **Soil pH:** Soil acidity or alkalinity affects the dissolution of minerals and can modify the strength of cemented soils. Optimal pH values (6 – 7.5) ensure chemical stability and reduce corrosive reactions with metallic excavation tools (Foth [56]).
- **Cation Exchange Capacity (CEC):** CEC represents the soil’s ability to retain and exchange essential cations such as Ca^{2+} , Mg^{2+} , and K^{+} . High CEC is associated with clay rich soils that tend to exhibit greater cohesion and stickiness, increasing resistance to excavation (Sparks et al. [57]).
- **Nutrient and Mineral Content:** The concentration of nutrients like nitrogen (N), phosphorus (P), and potassium (K) influences biological activity, which in turn affects soil aggregation and organic matter content (Havlin et al. [58]). Soils with high organic matter often display reduced shear strength and greater compressibility, affecting excavation slope stability.

1.5.2 Environmental Factors

Environmental conditions exert strong control over soil properties, excavation efficiency, and site stability. Variations in climate, topography, vegetation, and human interventions alter soil strength, moisture content, and erosion susceptibility.

1.5.2.1 Climate

Climate determines the rates of weathering, moisture balance, and thermal expansion of soils.

- Temperature influences the viscosity of pore water and the strength of frozen or thawed soils. High temperatures accelerate chemical weathering, while freeze thaw cycles in colder regions can weaken slopes and excavated faces (Birkeland [59]).
- Precipitation affects soil saturation and pore pressure. Heavy rainfall can trigger slope instability or reduce bearing capacity.
- Humidity influences evaporation and soil suction, which are key parameters in unsaturated soil mechanics (Brady et al. [52]).

1.5.2.2 Topography

Topography dictates surface runoff, erosion potential, and drainage patterns. On steep slopes, gravitational forces accelerate soil movement and increase excavation difficulty (Jenny [60]). In contrast, flat terrains facilitate machinery access but are prone to water accumulation and low shear strength.

Topographic analysis using digital elevation models (DEMs) helps engineers predict soil erosion zones and design effective drainage systems to stabilize excavation faces.

1.5.2.3 Vegetation

Vegetation contributes to soil stability by binding particles through root systems and enhancing organic matter. Dense plant cover reduces erosion, improves infiltration, and regulates soil temperature (Pimentel and Kounang [61]) showed that vegetation can reduce erosion rates by up to 90 % compared to bare soils.

1.5.2.4 Human Activity

Anthropogenic activities such as agriculture, construction, and mining are major drivers of soil modification. Deforestation and overgrazing degrade soil structure and increase erosion, while urbanization leads to compaction and reduced permeability (Lal [49]). Industrial pollution introduces heavy metals that alter soil chemistry and weaken particle bonding. Sustainable excavation practices require site restoration, waste management, and erosion control planning to offset these impacts.

1.5.3 Geotechnical Considerations

Geotechnical parameters govern the mechanical response of soils and directly affect excavation stability, tool performance, and structural safety. These include bearing capacity, compaction, slope stability, and permeability.

1.5.3.1 Bearing Capacity

The bearing capacity is the maximum pressure that soil can sustain without shear failure or excessive settlement. Factors such as soil density, moisture content, and stratification influence this property (Bowles and Guo [62]).

In excavation design, low bearing capacity may cause slope collapse or machinery instability. Terzaghi's classical bearing capacity equation remains widely used for preliminary design:

$$q_u = cN_c + qN_q + \frac{1}{2}(\gamma BN_\gamma) \quad (1.1)$$

where:

- c : soil cohesion (kPa);
- q : overburden pressure (kPa);
- γ : unit weight of soil (kN/m³);
- B : foundation width (m);
- N_c : bearing capacity factors for cohesion;
- N_q : bearing capacity factors due to soil weight;
- N_γ : bearing capacity factors related to confinement.

In soft or loose soils, low shear strength frequently leads to instability under loading. To address this, ground improvement techniques such as dynamic or vibro-compaction, chemical stabilization with lime or cement, or the use of deep foundations (e.g., driven or bored piles) are often applied prior to excavation. These methods enhance the effective bearing capacity and mitigate settlement or failure risks (Das and Sivakugan [55] and Budhu [63]). Such reinforcement ensures slope stability, maintains machinery balance, and supports the overall safety and durability of excavation operations.

1.5.3.2 Compaction

Compaction involves densifying soil to improve its strength and reduce compressibility. In excavation works, proper compaction of backfilled material ensures stability of slopes and retaining structures (Das and Sivakugan [55]).

1.5.3.3 Slope Stability

Slope failure is one of the most critical hazards in excavation. Stability is controlled by soil cohesion, internal friction angle, slope geometry, and groundwater conditions. Terzaghi et al. [64] emphasized that the factor of safety (FoS) must exceed 1.5 for permanent slopes and 1.3 for temporary excavations.

Stability analysis methods include the limit equilibrium, finite element, and finite difference approaches.

1.5.3.4 Drainage and Permeability

Permeability governs groundwater movement, directly affecting excavation safety and performance. Excess pore water pressure can lead to boiling, piping, or base heave in deep excavations (Cedergren [65]).

Efficient drainage systems such as subsurface drains, weep holes, and dewatering wells are essential to lower groundwater levels and maintain stability. Darcy's law provides the theoretical foundation for estimating seepage and designing drainage networks.

1.5.4 Soil Response to Excavation

Soil response to excavation is governed by changes in stress conditions, deformation behavior, and the disturbance induced by mechanical or hydraulic cutting processes. Excavation alters the in-situ stress equilibrium, leading to stress redistribution around the newly formed cavity, which may trigger localized yielding or progressive failure depending on soil type and loading history (Brady et al. [52]).

These changes often manifest as settlement, lateral displacement, or shear failure, particularly in weak or highly sensitive soils where structural integrity is easily compromised (Lal [49]). The use of heavy excavation machinery, such as power shovels and backhoe excavators, can intensify these effects by imposing dynamic loads and increasing ground vibration (Orlemann [66] and Tasevski et al. [42]).

Moreover, excavation-induced disturbance modifies soil structure, reduces density, and alters hydraulic conductivity, affecting both short-term stability and long-term geotechnical performance (Forman and Alexander [50]). Understanding these responses is essential for designing safe excavation operations, selecting appropriate support systems, and minimizing environmental and structural risks.

1.5.4.1 Stress Redistribution

Excavation inherently alters the in-situ stress state of soil by removing the confining material that previously supported the ground. This reduction in lateral stress causes a redistribution of forces within the surrounding soil mass, often inducing stress concentration zones and relaxation zones depending on excavation geometry and soil type (Brady et al. [52]).

Mechanical excavation systems such as backhoes, loaders, and trenchers intensify these effects by generating dynamic loading and vibration that modify stress paths during material removal (Tasevski et al. [42] and Orlemann [66]). Modern excavation technologies, including robotic and automated systems, have improved control of cutting forces, thereby reducing abrupt stress changes and improving safety in unstable soils (Ha et al. [45] and Huang et al. [48]). Understanding stress redistribution is therefore essential for predicting ground movement,

ensuring excavation stability, and preventing hazards such as wall collapse or surface subsidence.

1.5.4.2 Failure and Deformation Patterns

As stresses redistribute, soils may exhibit various deformation modes such as settlement, heave, shear deformation, and localized failure. Excavation-induced failures commonly include trench wall collapse, basal heave, and shear sliding, particularly in weak or saturated soils where strength is significantly reduced (Lal [49]).

Heavy machinery such as power shovels and bulldozers can further influence deformation patterns by imposing concentrated loads along excavation edges, increasing the likelihood of shear failure in sensitive soils (Orlemann [66]). For underground construction, tunnel boring machines (TBMs) modify ground deformation by applying continuous face support and controlled cutting forces, reducing the risk of collapse while still requiring detailed assessment of soil-machine interaction (Goel et al. [29]).

Numerical modeling and improved monitoring systems used in TBM operations help identify deformation patterns early, enhancing predictive capability and ensuring safer excavation performance (Goel et al. [29]).

1.5.4.3 Excavation-Induced Disturbance

Excavation inevitably disturbs the physical and mechanical properties of soils, altering density, fabric, moisture distribution, and permeability. This disturbance is amplified by high-energy mechanical tools and hydraulic systems that break soil structure and accelerate degradation processes, especially near excavation boundaries (Brady et al. [52]). Equipment such as vacuum excavation systems offer reduced disturbance by enabling non-destructive removal around sensitive utilities, aligning with safe-excavation procedures highlighted by (Dave and Agrawal [19]) and (Veidmark [20]).

In trenchless operations such as microtunneling, disturbance is minimize due to guided, closed-face excavation that maintains ground support and limits over-excavation (Iseley [30] and Najafi [31]). However, even low-disturbance methods require proper management to prevent environmental impacts such as erosion, sediment mobilization, or ecological disruption near construction zones (Forman and Alexander [50]). Effective control of excavation-induced disturbance is therefore fundamental to maintaining soil stability, protecting adjacent structures, and ensuring sustainable construction practices

1.6 Conclusion

The fundamentals of excavation engineering presented in this chapter establish the technical and scientific basis required for understanding modern earthwork operations. Excavation, whether

performed mechanically, hydraulically, or through controlled blasting and trenchless techniques, is govern by a combination of engineering principles, geotechnical behavior, and operational constraints. The chapter highlighted the diversity of excavation processes and equipment, showing how each method from trenching systems to tunnel boring machines responds to specific project demands and geological conditions.

Equally important are the geotechnical and environmental factors that influence excavation performance. Soil properties, environmental conditions, and site-specific constraints determine both the feasibility and the safety of excavation works. The discussion of soil response, including stress redistribution, deformation patterns, and excavation induced disturbances, demonstrates that earth materials continually react to human intervention, making accurate prediction and control essential for stable and efficient construction.

Overall, this chapter provides the foundational knowledge required for evaluating excavation methods, selecting appropriate equipment, and anticipating soil behavior during earthwork operations. These principles form the groundwork for the more advanced analytical and numerical studies developed in the subsequent chapters of the thesis.

Chapter 2

Chapter 2: Soil Mechanics and Modelling Approaches for Soil-Tool Interaction

2.1 Introduction

Understanding soil behavior and its interaction with excavation tools is fundamental to predicting ground response, optimizing cutting processes, and ensuring the stability of geotechnical systems. Soil, as a natural and highly heterogeneous material, exhibits complex mechanical behavior governed by its composition, structure, stress history and environmental conditions. These characteristics influence how the soil resists deformation, redistributes stresses and ultimately fails during excavation or penetration processes. As excavation methods become more mechanized and design tolerances more stringent, accurate characterization of soil behavior and robust modelling frameworks are essential for both engineering performance and safety.

This chapter establishes the theoretical basis required for modelling soil tool interaction under practical excavation conditions. It begins by outlining essential soil classification systems and index properties that dictate the physical and mechanical character of geomaterials. It then examines key aspects of soil behavior including shear strength, deformation mechanisms, volume change tendencies and dynamic properties providing the foundation for assessing how soils respond when subjected to excavation-induced stresses. The chapter further discusses the behavior of soils in the immediate vicinity of an excavation, where stress redistribution, deformation patterns and failure mechanisms govern tool forces and ground stability.

To bridge fundamental soil mechanics with practical excavation analysis, the chapter reviews available experimental, analytical and numerical approaches used to investigate soil tool interaction. Particular emphasis is placed on advanced computational techniques such as the Finite Element Method (FEM), the Discrete Element Method (DEM), and coupled

FEM-DEM formulations, which are increasingly employed to capture large deformation, nonlinear behavior and particle-scale interactions. The final sections present the constitutive models commonly adopted in excavation simulations, ranging from linear elastic and elastic-perfectly plastic frameworks to critical state and advanced hardening or hypoplastic formulations. Their assumptions, limitations and selection criteria are discussed in relation to excavation problems, ensuring a coherent link between soil mechanics theory and the modelling approaches used throughout this research

2.2 Soil Classification and Index Properties

2.2.1 Soil Types

Soil can be broadly categorized into several types based on origin, grain size, and mechanical behavior, essential for analyzing soil tool interactions, as each soil type responds distinctly to excavation forces like cutting, shearing, and compaction. Major soil groups include gravel, sand, silt, and clay, typically classified into coarse grained soils (gravel and sand) and fine grained soils as presented in Figure 2.1 (Das and Sobhan [67]; Terzaghi et al. [64]).



Figure 2.1: Soil types with particle sizes. Shown (right to left): medium gravel (9.5-mm), fine gravel (2.0-mm), medium-coarse sand (0.425 mm), silt, and clay (0.075 mm) (Samtani et al. [68]).

2.2.1.1 Gravel Soils

Gravel consists of particles larger than 2 mm in diameter, typically formed through rock weathering and fragmentation. Characterized by high permeability and excellent drainage due

to large particle sizes, gravel soils' mechanical behavior is dominated by particle interlocking rather than cohesion. This results in stable behavior under load with negligible compressibility, making gravel ideal for foundation applications (Das and Sobhan [67]). Despite offering low cutting resistance to excavation tools, the abrasive nature of gravel particles can cause significant wear on equipment (Shmulevich et al. [69]). Moreover, gravel impacts permeability in sandy soils variably depending on its content and size, influencing excavation dynamics (Joliet [70]).

2.2.1.2 Sandy Soils

Sand particles range from 0.06 to 2 mm and are inherently noncohesive; strength arises mainly from internal friction between grains. Dry, compacted sands exhibit high shear strength; however, saturation can reduce stability and trigger phenomena like liquefaction. Excavation wise, sand permits relatively easy cutting tool penetration but may collapse along excavation faces if unsupported (Perdok and Kouwenhoven [71]). The Unified Soil Classification System (USCS) differentiates well graded sands, which have broader particle size distribution and better compaction characteristics, from poorly graded sands, which tend to have lower shear resistance (Terzaghi et al. [64]). Particle shape and grading notably affect shear strength, with well graded and angular sands exhibiting higher internal friction angles than poorly graded, rounded sands (Terzaghi et al. [64]; Lambe and Whitman [72]).

2.2.1.3 Silty soils

Are composed of fine particles with diameters between 0.002 and 0.06 mm, exhibiting properties that fall between those of sand and clay. These soils have limited inherent cohesion but gain apparent strength through capillary effects when moist. Silts are highly sensitive to changes in moisture content, and when saturated, they may behave plastically and lose bearing capacity. During excavation, silty soils tend to adhere to tool surfaces, reducing cutting efficiency. Their behavior is strongly influenced by both mineral composition and moisture conditions, making classification and prediction of mechanical response challenging (Nikiforova [73]; Wang et al. [74]).

2.2.1.4 Clay soils

Consist of particles smaller than 0.002 mm and are characterized by strong plasticity and cohesion. The mechanical properties of clays depend heavily on the types of clay minerals present such as kaolinite, illite, or montmorillonite and the degree of water adsorption. Clays show high compressibility, low permeability, and significant volume changes with moisture variation. For excavation, clay offer substantial resistance to tool penetration and tend to stick to metal surfaces, influencing tool performance and increasing energy demands. Understanding

the mineralogy and structure of clays is vital for anticipating their behavior under mechanical disturbance (Terzaghi et al. [64]; Lu et al. [75]).

2.2.1.5 Organic soils

Contain high amounts of decomposed plant material, which results in low shear strength, high compressibility, and variable moisture retention. Such soils typically present unstable, spongy conditions that complicate excavation and make them generally unsuitable for construction unless stabilized or replaced (Das and Sobhan [67]). Their organic content also affects soil density and drainage patterns, producing inconsistent mechanical responses.

2.2.1.6 Composite and Mixed Soils

Natural soils often occur as composites or mixtures, such as sandy clays or silty sands, with mechanical behavior depending on the proportion of coarse and fine particles. For example, a silty sand can exhibit the drainage characteristics of sand while retaining some plasticity from the finer fraction. Proper classification of these mixed soils is critical for accurate modeling of excavation forces and deformation patterns (Das and Sobhan [67]; Terzaghi et al. [64]).

2.2.2 Physical and Index Properties of Soils

Soil parameters describe the fundamental physical and index properties that govern soil behavior under mechanical loading and environmental variations. They are essential for interpreting soil structure and soil tool interactions, especially in excavation, foundation design, and stability analysis. The parameters discussed here porosity, void ratio, relative density, moisture content, and plasticity form the basis for quantitative assessment of soil fabric, compressibility, permeability, and strength (Das and Sobhan [67]; Craig [76]; Lambe and Whitman [72]).

2.2.2.1 Porosity, Void Ratio, and Relative Density

Porosity (η) and void ratio (e) are geometric parameters describing the proportion of voids within a soil mass. Porosity is defined as the ratio of the volume of voids (V_v) to the total volume (V_t):

$$\eta = \frac{V_v}{V_t} \quad (2.1)$$

The void ratio, conversely, is the ratio of the volume of voids to the volume of solid particles (V_s):

$$\eta = \frac{V_v}{V_s} \quad (2.2)$$

Both are interrelated through the expression

$$e = \frac{\eta}{1 - \eta} \quad (2.3)$$

$$e = \frac{\eta}{1 + e} \quad (2.4)$$

These parameters influence the permeability, compressibility, and strength of the soil mass. High void ratios and porosity generally correspond to low dry densities and high compressibility, characteristics typical of loose granular or organic soils (Lambe and Whitman [72]; Mitchell and Soga [77]).

For granular soils, relative density (D_r) is a key index used to assess the degree of compaction relative to the loosest (e_{max}) and densest (e_{min}) possible states:

$$D_r = \frac{e_{max} - e}{e_{max} - e_{min}} \times 100\%$$

This parameter provides a measure of soil stiffness and shear strength. A high D_r (typically >70 %) indicates a dense state with high resistance to deformation and low compressibility, while low D_r values (<30 %) denote loose states prone to settlement and liquefaction (Terzaghi et al. [64]; Das and Sobhan [67]). Relative density also governs the dilatancy behavior of sands under shear dense sands tend to dilate, whereas loose sands contract under loading, significantly affecting their stress strain response (Bolton [78]).

2.2.2.2 Moisture Content

Moisture content, or water content (w), quantifies the proportion of water within the soil mass and is defined as:

$$w = \frac{m_w}{m_s} \times 100\% \quad (2.5)$$

where m_w is the mass of water and m_s the mass of dry soil solids. Moisture content is a fundamental control variable in both cohesive and cohesionless soils, influencing effective stress, shear strength, and compressibility.

In unsaturated soils, changes in moisture content directly affect matric suction, leading to variations in shear strength and stiffness (Fredlund and Rahardjo [79]). High moisture contents in fine grained soils, particularly clays, lead to reduced strength and increased plasticity due to expansion of the diffuse double layer around clay particles (Mitchell and Soga [77]). Conversely, a decrease in moisture results in shrinkage, increased suction, and hardening behavior.

In excavation contexts, moisture content significantly affects soil tool interaction. For instance, in over-wet conditions, clays adhere to metal surfaces and increase cutting resistance,

while dry soils tend to fragment and produce higher abrasive wear (Shmulevich et al. [69]; Wang et al. [74]).

2.2.2.3 Plasticity and Consistency

Plasticity and consistency parameters are used to describe the deformation characteristics of fine grained soils as their water content changes. The Atterberg limits, introduced by (Atterberg [80]) and standardized by (Casagrande [81]), define critical thresholds separating different states of soil consistency:

- **Liquid Limit (LL):** the water content at which soil changes from plastic to liquid behavior.
- **Plastic Limit (PL):** the lowest water content at which the soil remains plastic and can be molded without cracking.
- **Shrinkage Limit (SL):** the water content below which further drying does not result in volume reduction.

The Plasticity Index (PI), calculated as ($PI = LL - PL$), provides a numerical measure of the range of plastic behavior. High PI values indicate highly plastic and compressible soils, typical of montmorillonitic clays, whereas low PI values correspond to less plastic, more stable soils like kaolinites (Das and Sobhan [67]; Holtz et al. [82]).

The Consistency Index (CI) and Liquidity Index (LI) are additional measures relating in-situ water content (w) to the Atterberg limits:

$$CI = \frac{LL - w}{PI} \quad (2.6)$$

$$LI = \frac{w - PL}{PI} \quad (2.7)$$

A CI near 1 indicates a stiff or semi-solid state, while LI values greater than 1 correspond to a fluid like state. These indices are essential for evaluating the mechanical condition of cohesive soils in the field, influencing predictions of settlement, stability, and workability during excavation (Craig [76]; Head [83]). Plasticity also affects soil tool interaction mechanics, as more plastic soils exhibit higher adhesion and remolding resistance during excavation operations (Nikiforova [73]; Lu et al. [75]).

2.2.2.4 Clay Minerals and Fines Influence

The plastic behavior of soils is strongly influenced by the presence and nature of fines, particularly clay minerals. These fine particles determine how a soil reacts to changes in water content, affecting its workability, strength, and volume stability. Soils containing a high proportion of

clay generally exhibit greater plasticity because of the surface properties of clay minerals, which allow them to attract and hold water molecules through adsorption and capillary forces. This capacity gives clay rich soils their distinctive cohesion and deformability (Mitchell and Soga [77]; Das and Sobhan [67]).

The type of clay mineral plays a decisive role in governing soil plasticity. For example, montmorillonite, a highly active clay, is known for its strong affinity for water and its ability to swell considerably when wet, leading to pronounced changes in volume and strength. In contrast, kaolinite, with a lower specific surface area and weaker interlayer bonding, shows only moderate plasticity and limited expansion. Illite typically exhibits intermediate behavior between these two extremes (Mitchell [84]). The relative activity of a clay can be expressed through Skempton's activity ratio, which relates the plasticity index to the clay fraction and serves as an indicator of the swelling potential of fine grained soils (Skempton [85]).

As the amount of fines increases within a soil mass, its mechanical behavior gradually shifts from granular to cohesive. Well graded sands mixed with a small percentage of fines may still behave predominantly as frictional materials, but as the fine content exceeds a critical threshold, cohesion begins to dominate, reducing permeability and increasing plasticity (Wroth and Wood [86]; Holtz et al. [87]). The water content also exerts a major influence: high plasticity clays possess a wide range between the liquid and plastic limits, reflecting their sensitivity to moisture variation (Terzaghi et al. [64]).

2.3 Mechanical Behavior of Soils

2.3.1 Shear Strength

The shear strength of soil represents its capacity to resist deformation or failure under the action of applied shear stress. It defines the maximum shear stress that a soil can sustain before yielding, and this limiting condition may be expressed either in terms of shear stress itself or as a function of principal stresses. Shear strength is one of the most critical parameters governing soil stability, directly influencing the design and performance of earthworks, foundations, and excavation systems (Liu and Evett [88]). The overall shear resistance of a soil mass arises from three fundamental mechanisms:

- **Structural resistance**, resulting from the interlocking of soil particles;
- **Frictional resistance**, generated by sliding between individual grains;
- **Cohesion or adhesion**, which develops between particle surfaces, particularly in fine grained soils.

In cohesionless soils such as sands and gravels, shear strength depends primarily on intergranular friction and particle arrangement. Conversely, in cohesive soils such as clays,

the total resistance is governed by both frictional and cohesive components that stem from electrochemical bonding and capillary forces between clay particles (Matsui and San [89]).

Several external and internal factors influence soil shear strength, including loading conditions, degree of compaction, stress history, and moisture content, all of which modify the soil's microstructure and, consequently, its resistance to deformation. During shearing, soils often exhibit dilatancy, a phenomenon where the volume changes due to particle rearrangement. Dense soils tend to expand during shearing as grains roll over one another, whereas loose soils tend to contract as particles realign and fill existing voids (Massoudi [90]).

This contrast in volumetric behavior leads to distinct stress strain responses. Dense soils usually display a pronounced peak strength followed by softening, reflecting strain localization and potential failure, while loose soils generally show continuous strain hardening without a post peak decline (Lade [91]). The relative density and confining stress thus play a decisive role in defining the mechanical response and stability of soil structures.

Shear strength primarily arises from interparticle contact forces, which are enhanced by normal stress acting within the soil mass. An increase in normal stress enlarges the contact area between particles, thereby improving the soil's ability to resist shear deformation. Mechanisms that strengthen these interparticle bonds such as improved compaction or cementation directly enhance the soil's shearing resistance (Phoon [92]).

2.3.1.1 Effective Stress Theory

The concept of effective stress lies at the core of soil mechanics and controls both deformation and shear strength of geomaterials. Introduced by (Terzaghi et al. [64]), the principle states that the mechanical behavior of a saturated soil mass is not governed by the total stress alone but by the portion of that stress transmitted through the soil skeleton. The classical expression of this relationship is given as

$$\sigma' = \sigma - u \quad (2.8)$$

where σ' is the effective stress, σ is the total stress applied externally, and u is the pore water pressure within the soil. This principle has provided a fundamental framework for understanding consolidation, shear strength, and stability phenomena in geotechnical engineering. When pore pressure increases such as under rapid loading or saturated undrained conditions the effective stress decreases, leading to reduced shear strength and potential instability. Conversely, dissipation of pore pressure or the presence of negative pore water pressure (suction) increases the effective stress and enhances soil strength (Craig [76]; Das and Sobhan [67]).

In practical terms, the effective stress represents the portion of total stress carried by interparticle contact forces, which govern the soil's ability to resist deformation. For fully saturated soils, Terzaghi's simple relationship suffices; however, for unsaturated soils, this

formulation becomes incomplete because two fluid phases air and water coexist in the pores (Bishop et al. [93]) extended the effective stress concept to unsaturated conditions by incorporating an effective stress parameter (χ) which varies between 0 (dry) and 1 (saturated). The modified equation is expressed as:

$$\sigma' = (\sigma + u_a) + \chi(u_a - u_w) \quad (2.9)$$

where u_a and u_w are the pore air and pore water pressures, respectively, and $(u_a - u_w)$ represents the matric suction. The parameter χ depends on the degree of saturation and the soil water characteristic curve, as later formalized by (Fredlund and Morgenstern [94]). This formulation allows for a more realistic assessment of the stress state in partially saturated soils, where suction contributes to apparent cohesion and increased shear strength. The relationship between effective stress and shear strength can be directly expressed through the Mohr-Coulomb failure criterion:

$$\tau = c' + \sigma' \tan \phi' \quad (2.10)$$

where τ is the shear stress at failure, c' is the effective cohesion, and ϕ' is the effective angle of internal friction. Here, the effective stress σ' replaces the total stress in determining the soil's shear resistance, indicating that only the stress transmitted through the soil skeleton contributes to strength. Variations in pore pressure, therefore, have a direct impact on the mobilized shear strength. Under drained conditions, pore pressures dissipate and the soil deforms gradually, while under undrained conditions, excess pore pressure builds up, reducing effective stress and potentially triggering failure. This distinction is fundamental in interpreting the results of laboratory tests such as triaxial compression, direct shear, and consolidation experiments (Lambe and Whitman [72]; Phoon [92]).

Pore pressure effects are especially significant in dynamic or excavation environments. Rapid excavation in saturated soils, for example, can induce undrained loading conditions, leading to a temporary reduction in effective stress and potential face instability. In contrast, slower excavation allows pore pressure dissipation and more stable conditions. In unsaturated soils, matric suction enhances interparticle attraction, improving slope stability and reducing deformation during excavation (Lu [95]). Thus, accurate modeling of soil tool interaction requires coupling between mechanical and hydraulic fields to account for variations in effective stress and pore pressure distribution. Numerical tools such as *Abaqus* or *PLAXIS* implement effective stress formulations to simulate these coupled hydro-mechanical behaviors realistically.

2.3.1.2 Laboratory Testing

Soil shear strength is soil resistance to deformation by applied external shear forces, for example, during soil cutting process with different tillage tools. Shear failure occurs when shear forces exceed a maximum limit called yield strength. However, shear failure can also occur under

compression load, for example, under tyres, which makes soil as bulk material behaves differently than metals under compression load (McKyes [96]). Different methods are use to measure the soil shear strength.

- **The direct shear test** is one of the most widely used laboratory procedures for determining soil shear strength (Figure 2.2), in which a sample is placed in a shear box and a normal stress is applied before shearing along a predetermined plane. (Saada and Townsend [97]) identify it as a practical and efficient device, particularly useful for many designers, though they caution that stress distribution in the box and sample geometry changes can introduce limitations. Its simplicity and cost effectiveness encourage widespread use, but it offers limited control of drainage or pore pressure conditions, making it less reliable for fully saturated clays or detailed stress path analyses.



Figure 2.2: Direct shear test apparatus (Pant et al. [98]).

- **The triaxial compression test**, by contrast, allows much greater control of confining pressure, drainage conditions, and stress path, making it a standard reference for strength and deformation behaviour (Figure 2.3). (Sowers [99]) emphasises that triaxial tests can replicate a variety of field like conditions (e.g., consolidated drained, consolidated undrained) and generate detailed stress strain data, including volumetric changes and pore pressure responses. Comparison studies, such as (Yin et al. [100]) on grouted clays, highlight that triaxial tests yield more reliable shear strength parameters than direct shear tests for certain conditions, owing to their better control of specimen saturation and stress state.



Figure 2.3: Triaxial test equipment (Nandanwar and Chen [101]).

- **The vane shear test** is principally used for fine grained, cohesive soils and undrained strength assessment (Figure 2.4), offering rapid and minimally disruptive measurements of shear strength in the laboratory or in-situ. (Goughnour and Sallberg [102]) reported that the laboratory vane test provides values of undrained shear strength that closely correspond to those obtained from triaxial compression under comparable water content, provided the rotation rate and sample disturbance are carefully controlled. (Bachmann et al. [103]) further demonstrate that vane shear test data often correlate with field penetrometer results for weak soils, though the method does not directly provide stress strain curves or effective stress parameters.

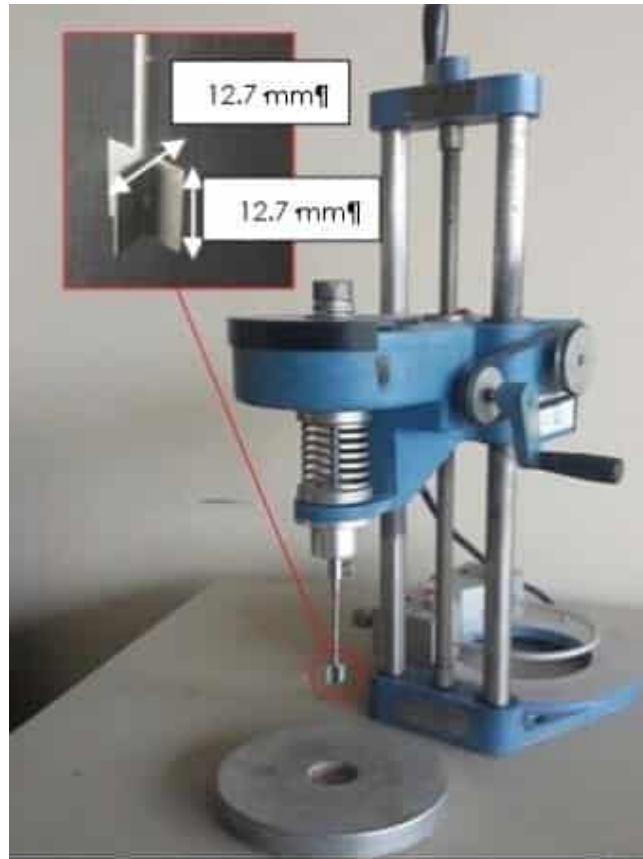


Figure 2.4: Laboratory vane shear apparatus (Rosman and Chan [104]).

2.3.2 Deformation and Volume Change

The deformation and volume change behavior of soils form the cornerstone of geotechnical engineering analysis, influencing the performance of foundations, slopes, embankments, and underground structures. Unlike idealized solid materials, soils are multiphase systems composed of solid particles, water, and air, whose interactions govern their mechanical response to applied stresses. When subjected to loading or unloading, soils may deform through particle rearrangement, sliding, compression of voids, and changes in pore water pressure, leading to both recoverable (elastic) and permanent (plastic or viscoplastic) strains. These processes also involve changes in volume that depend on the soil's structure, density, and degree of saturation. Volume change behavior whether compressive in saturated clays or dilative in dense sands directly affects settlements, lateral movements, and overall stability of geotechnical systems. Understanding these mechanisms is therefore essential for predicting soil response under static and dynamic loading and for developing reliable constitutive models used in advanced numerical simulations (Terzaghi [105]; Lambe and Whitman [72]; Mitchell and Soga [77]).

2.3.2.1 Elastic, Plastic, and Viscoplastic Behavior

Soil deformation may be classified into three conceptual regimes: elastic, plastic and viscoplastic. Elastic deformation is the recoverable strain under unloading: when the load is removed, the soil returns (approximately) to its original configuration. In soil behaviour, this is valid only for very small strain levels (e.g., shear strains below $\sim 10^{-4}$) and allows the use of stiffness parameters such as Young's modulus and Poisson's ratio (Craig [76]).

Plastic deformation represents irreversible strain that persists after unloading, resulting from particle rearrangement, yield of the soil skeleton or permanent fabric change. Traditional elastic-plastic constitutive models (such as Modified Cam-Clay) aim to describe this regime. Viscoplastic deformation, furthermore, accounts for time dependent, rate sensitive behaviour such as creep under constant load or strain. For soft clays, organic soils or long term loading conditions, the rate of permanent strain becomes significant, so pure elastic-plastic models may underestimate deformation (Islam and Gnanendran [106]). Recognising which deformation regime dominates is vital for the appropriate design of foundations, embankments and excavation support systems.

2.3.2.2 Compressibility and Consolidation under Static Loading

Compressibility refers to a soil's tendency to undergo volume reduction under applied load. Terzaghi's one dimensional consolidation theory remains foundational: when a saturated soil is subjected to a load increment, excess pore water pressure develops and dissipates over time, transferring load to the soil skeleton and causing settlement (Craig [76]). A commonly used expression for the change in void ratio Δ_e is:

$$\Delta_e = -m_v \times \Delta\sigma' \quad (2.11)$$

where m_v is the volume compressibility and $\Delta\sigma'$ is the change in effective stress. Primary consolidation is followed by secondary compression (creep) under constant stress. The magnitude and rate of volume change govern settlement behaviour of foundations and other geotechnical structures.

2.3.2.3 Swelling and Shrinkage in Expansive and Unsaturated Soils

Expansive soils typically rich in clay minerals such as montmorillonite exhibit significant swelling when wetted and shrinkage when dried. In unsaturated soils, changes in suction and water content drive volume change: reduction in suction during wetting allows rearrangement and volume increase; conversely, suction rise during drying causes volume decrease (Budhu [107]). The soil water characteristic curve (SWCC) links suction, water content and volumetric behaviour (see Figure 2.5). These cyclic volumetric changes can lead to heave, cracking of slabs

or settlement when drying occurs, and must therefore be incorporated into the design of shallow foundations, pavements and seasonal exposure structures.

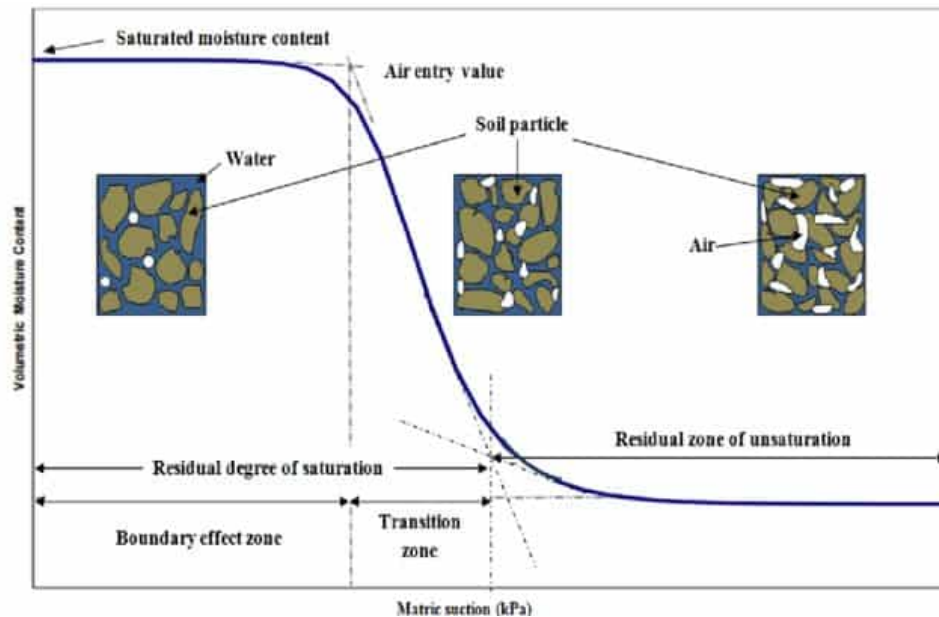


Figure 2.5: Typical soil water characteristic curve (SWCC) showing zones of desaturation (Azmi et al. [108]).

2.3.2.4 Collapse Behavior in Loose and Partially Saturated Soils

Certain geomaterials such as loess, loosely packed sands or weakly cemented soils may experience sudden volume reduction (collapse) upon wetting under load, even without an applied increase in stress. These soils are metastable: their structure is supported by suction or bonding, and when that support is lost (e.g., through infiltration) the void ratio may reduce rapidly and strength degrade (Verruijt [109]). Designers must assess collapse potential and consider ground improvement or controlled infiltration to mitigate risk of large settlements.

2.3.3 Dynamic Properties

The dynamic behavior of soils is a critical aspect of geotechnical engineering, especially for applications involving vibrations, seismic loading, or cyclic machine foundations. Understanding how soils respond dynamically under cyclic and transient stresses is essential for predicting deformation, wave propagation, and energy dissipation characteristics in the ground. The key dynamic properties that govern this behavior include the shear modulus (G), damping ratio (D), and the parameters describing wave propagation in soils.

2.3.3.1 Shear Modulus

The shear modulus (G), also known as the modulus of rigidity, defines the relationship between shear stress and shear strain within the elastic range of soil behavior. It is expressed as:

$$G = \frac{\tau}{\gamma} \quad (2.12)$$

Where τ is the shear stress and γ is the shear strain. At very small strains (typically $<10^{-4}$), soils behave almost elastically, and the modulus is referred to as the small strain shear modulus G_{max} . This modulus is directly related to the shear wave velocity (V_s) and the mass density (ρ) of the soil by the equation (Kramer [110]; Hardin and Richart Jr [111]):

$$G_{max} = \rho \times V_s^2 \quad (2.13)$$

As the strain amplitude increases, the soil structure undergoes particle rearrangement and slippage, leading to a reduction in stiffness. The degradation of shear modulus with increasing strain is a key feature of soil nonlinearity and is typically represented by the normalized modulus reduction curve G_{max} versus shear strain (Seed [112]). Empirical models and laboratory cyclic triaxial or resonant column tests are commonly used to establish these relationships.

2.3.3.2 Damping

The damping ratio (D) quantifies the energy dissipated per loading cycle as hysteretic or viscous damping during cyclic loading. In soils, energy loss results mainly from interparticle friction, viscous resistance of pore fluid, and rearrangement of soil structure. The damping ratio is defined as:

$$D = \frac{1}{4\pi} \times \frac{\Delta W}{W_s} \quad (2.14)$$

where ΔW is the energy dissipated per loading cycle and W_s is the maximum strain energy stored in the system (Seed [112]).

At small strains, soils exhibit low damping ratios (typically 1-3 %), while at larger strains ($>10^{-3}$), damping increases significantly due to progressive structural rearrangement and plastic deformation (Ishihara [113]). Laboratory cyclic triaxial and resonant column tests are used to determine both the shear modulus degradation and damping ratio variation with strain. These properties are essential for dynamic site response analysis, earthquake engineering, and vibration control in structures.

2.3.3.3 Wave Propagation

Reflect within the ground. The two primary wave types of interest are compressional (P-waves) and shear (S-waves), characterized by their velocities:

$$V_P = \sqrt{\frac{K + \frac{4}{3}G}{\rho}} \quad (2.15)$$

$$V_S = \sqrt{\frac{G}{\rho}} \quad (2.16)$$

where K is the bulk modulus, G is the shear modulus, and ρ is the soil density (Richart et al. [114]; Kramer [110]). Since most geotechnical structures are affected primarily by shear deformation, the shear wave velocity (V_s) is widely used as an index of soil stiffness and is fundamental in seismic site classification, dynamic settlement, and earthquake response analyses (Hardin and Drnevich [115]).

The attenuation of waves as they propagate is influenced by soil type, density, saturation, and damping properties. Fine grained soils, for example, tend to exhibit higher attenuation due to viscous damping, while coarse grained soils allow faster wave transmission. Understanding wave propagation behavior aids in predicting ground motion amplification and designing structures resilient to dynamic loading.

2.4 Modelling and Simulation of Soil–Tool Interaction

2.4.1 Experimental Approaches

Experimental investigations of soil tool interaction provide indispensable physical data about the behaviour of soil when subjected to tool penetration, cutting, or excavation. Both laboratory based and field based experiments contribute complementary insights. In laboratory settings, soil-bin rigs or soil boxes allow a tool (e.g., a blade, tine, or bucket tooth) to traverse a prepared soil mass under controlled conditions. Resistive forces (such as draft or cutting forces), soil deformation and displacement fields, and penetration depth may be quantitatively measured via load cells, displacement sensors, high speed imaging, or tracers embedded in the soil. For example, (Yong et al. [116]) investigated the interaction between very narrow tines and soil bins during penetration and recorded resistances and soil failure mechanisms.

In the field, larger scale tests replicate realistic boundary conditions including natural soil heterogeneity, scale effects, tool geometry variation and operational parameters (tool speed, rake angle, depth of cut). These tests often provide the baseline for validating numerical models of tool-soil interaction.

Nevertheless, the experimental approach poses several challenges. First, the cost, time and

logistical effort required to set up soil-bin tests or field trials are considerable; for example, (Drwish [117]) highlights that experimental studies provide valuable information, but they are expensive, time consuming, and limited to certain cutting speeds and depths.

Second, scaling issues arise: laboratory rig dimensions, tool size, soil layering and boundary conditions may differ significantly from real excavation conditions, thereby limiting generalisability. Third, soil is inherently heterogeneous and its mechanical properties (bulk density, moisture content, structure, anisotropy) (Pandey et al. [118]). vary spatially and temporally, introducing reproducibility and uncertainty issues in experiments. Fourth, instrumentation to measure internal soil stresses, particle movements and three dimensional deformations remains complex and expensive. As a result, experimental data sets often cover only a limited range of tool-soil combinations, depths and speeds, which may restrict the ability to explore wide parametric domains (Karmakar [119]).

Because of these limitations, the exclusive reliance on experiments is increasingly inadequate when research aims to cover broad parametric variation (tool geometry, soil type, speed, depth), extreme conditions or repeatable design optimisation. This recognition has promoted the adoption of numerical modelling techniques as a robust complement.

2.4.2 Analytical Approaches

Analytical methods, while insightful, cannot fully capture the nonlinearities of soil deformation and failure under excavation (Ng and Lings [120]). Hence, numerical methods notably the Finite Element Method (FEM), Discrete Element Method (DEM), and Coupled FEM-DEM have become indispensable tools for modeling soil tool interaction (Lysych [121]). These approaches solve the governing equilibrium, compatibility, and constitutive equations iteratively, enabling detailed stress and deformation fields to be computed under realistic loading and boundary conditions.

2.4.2.1 Finite Element Method (FEM)

The Finite Element Method treats the soil as a continuum, subdivided into discrete elements connected by nodes. The governing equation of motion in matrix form is expressed as:

$$[M]\{\ddot{x}\} + [C]\{\dot{x}\} + [K]\{x\} = P_{\{ext\}} \quad (2.17)$$

where:

- $[M]$ = mass matrix,
- $[C]$ = damping matrix,
- $[K]$ = stiffness matrix,

- $\{\ddot{x}\}, \{\dot{x}\}, \{x\}$ = displacement, velocity, and acceleration vectors,
- $P_{\{ext\}}$ = external force vector.

The stress-strain relationship within each element is governed by the constitutive law:

$$\{\sigma\} = [D] \times \{\epsilon\} \quad (2.18)$$

Where $[D]$ is the constitutive matrix that defines the soil's elastic or elasto-plastic response. In soil tool modeling, FEM is widely used to analyze:

- Stress distribution beneath and around cutting blades.
- Deformation zones and soil flow patterns.
- Reaction forces acting on the tool during cutting and penetration.

Dynamic FEM simulations often employ Updated Lagrangian formulations, which account for mesh deformation and nonlinear kinematics. To overcome mesh distortion, modern techniques such as the Arbitrary Lagrangian-Eulerian (ALE) formulation and Smoothed Particle hydrodynamics (SPH) have been introduced. These methods decouple mesh movement from material flow, allowing accurate tracking of large displacements and soil separation during excavation (Zhang et al. [122]; Urban et al. [123]).

The FEM approach, implemented in software such as ABAQUS, PLAXIS, and ANSYS, provides high accuracy in stress prediction and is particularly suited to coupled thermo-mechanical or hydro-mechanical problems (Superczyńska et al. [124]). However, its limitation lies in handling discontinuous behavior such as soil fragmentation or particle separation where continuum assumptions break down.

2.4.2.2 Discrete Element Method (DEM)

In contrast to FEM, the Discrete Element Method represents soil as a collection of interacting particles that obey Newton's laws of motion. This method is inherently suited for granular materials and can simulate discontinuities, particle rearrangements, and soil tool interaction (Murray [125]).

For a particle i , the translational and rotational motions are expressed as:

$$m_i \frac{d^2 x_i}{dt^2} = \sum_{j=1}^n F_{ij} + m_i g \quad (2.19)$$

$$I \frac{d\omega_i}{dt} = \sum_{j=1}^n \mathbf{r}_i \cdot \mathbf{f}_{ij} \quad (2.20)$$

Where:

- m_i = particle mass (kg)

- x_i = displacement vector of the i_{th} particle (m)
- I = moment of inertia (N.m)
- ω_i = rotational angle velocity vector of the i_{th} particle, (rad/s)
- F_{ij} = normal contact force vector on the i_{th} particle, exerted by the j_{th} particle that keeps touch with the i_{th} particle (N)
- f_{ij} = frictional force vector between the i_{th} particle and j_{th} particle (N)
- r_i = particle radius (m)
- i = the i_{th} particle
- j = particle keeping touch with the i_{th} particle

The method assumes that disturbances propagate only between directly contacting particles during a single time step. Therefore, each particle's motion is computed independently, without solving large systems of simultaneous equations (Tanaka [126]).

Using the explicit Euler finite difference scheme, the known external and contact forces, together with the resulting moments, are used to compute particle accelerations, which are then integrated over discrete time steps to determine velocities and displacements. This iterative process, applied to every particle, enables the Discrete Element Method (DEM) to reproduce the complete dynamic evolution of granular materials. Within this framework, unbalanced forces and moments are continuously updated, ensuring accurate representation of both translational and rotational particle motions during interaction and collision (Cundall and Strack [127]; Tsuji et al. [128]).

To evaluate the contact forces, In order to obtain the contact forces, the force displacement relationship is indispensable. Here, the force displacement relationship between two particles is assumed separately for normal and tangential components by the model using two rigid spheres shown in Figure 2.6, a spring, and a dashpot.

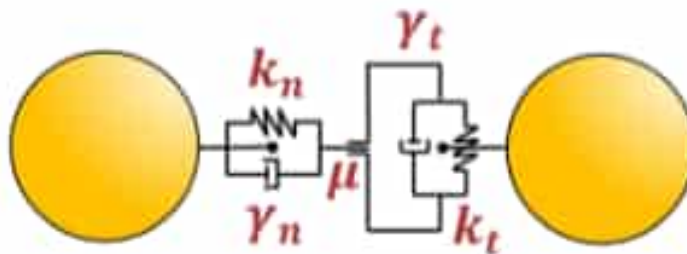


Figure 2.6: Normal and tangential forces Hertz-Mindlin model (Dhaouadi et al. [129]).

where:

- k_t : tangential stiffness coefficient.
- γ_t : tangential damping coefficient.
- k_n : normal stiffness coefficient.
- γ_n : normal damping coefficient.

In order to take account of the friction between spheres, a slider element used for tangential force (Mindlin and Deresiewicz [130]). Spring coefficient obtained as a function of the displacement as follows:

$$k_n = \frac{4b}{3\pi} \left(\frac{1}{\sigma_i + \sigma_j} \right) \quad (2.21)$$

where:

$$\sigma_i = \frac{1 - \nu_i^2}{E_i \pi} \quad (2.22)$$

$$\sigma_j = \frac{1 - \nu_j^2}{E_j \pi} \quad (2.23)$$

and

$$b = \sqrt[3]{\frac{3}{4} \left(\frac{1 - \nu_i^2}{E_i} + \frac{1 - \nu_j^2}{E_j} \right) \frac{r_i \times r_j}{r_i + r_j} P} \quad (2.24)$$

where E_i , E_j , ν_i , ν_j , r_i , r_j respectively represents Young's modulus, Poisson's ratios, and Radii of particles i and j , and b is the contact radius.

This force displacement formulation enables DEM to simulate realistic contact mechanics, incorporating normal restitution, energy dissipation, and frictional slip. Such modeling capability allows DEM to capture complex soil behaviors, including particle rearrangement, interlocking, and flow patterns under dynamic or quasi-static conditions (Brilliantov et al. [131]; Luding [132]).

The spring coefficient and damping coefficient in the tangential direction are determined by inferring that the following relationship holds (Tanaka [126]):

$$K_s = K_n s \quad (2.25)$$

$$\eta_s = \eta_n \sqrt{s} \quad (2.26)$$

where:

$$s = \frac{G}{E} = \frac{1}{2(1 + \nu)} \quad (2.27)$$

with:

- ν : Poisson's ratio
- P : load acting on between two particles (N)
- G : shear modulus (Pa)
- E : Young's modulus (Pa)
- b : radius of circular contact area (mm)

- K : spring constant, (N/m)
- s : normal component
- n : tangential component
- η : damping coefficient of dashpot (N.s/m)

DEM provides microscopic insights into force chains, particle rotation, and local failure mechanisms that are not accessible in continuum formulations (Cundall and Strack [127]; Coetzee [133]). Modern DEM tools such as EDEM and Particle Flow Code (PFC3D) have enabled detailed 3D modeling of soil flow around excavation tools and prediction of cutting resistance under various conditions. The main limitation remains computational cost, as millions of particles may be required for realistic soil representation.

2.4.2.3 Coupled FEM-DEM Approaches

The Coupled FEM-DEM method combines the strengths of both techniques: the accuracy of continuum modeling in the FEM domain and the flexibility of particle interactions in the DEM domain (Ucgul et al. [134]). In this approach, the soil tool interface is modeled dynamically, ensuring mutual transfer of forces and displacements between the FEM and DEM regions.

This hybrid framework captures the transition from continuous deformation modeled by FEM to discrete failure and separation handled by DEM. It is particularly effective for simulating soil cutting, trenching, and impact processes where both continuum and discontinuum behavior coexist (Nezami et al. [135]; Mohammadnejad et al. [136]).

Coupled codes such as LS-DYNA, EDEM and Abaqus, have demonstrated superior capability in modeling realistic soil flow, stress distribution, and tool wear mechanisms (Rajendran et al. [137]). Despite higher computational demands, these models offer the most comprehensive simulation of excavation processes.

2.5 Constitutive Models Used in Excavation Simulation

Over the past decades, the development of constitutive soil models has evolved significantly, reflecting advances in experimental techniques and computational power. Figure 3.4 illustrates the chronological evolution of constitutive modeling approaches used in geomechanics research from 1970 to 2002. Early models were predominantly based on linear and non-linear elasticity, providing simplified representations of soil stiffness and deformation.

However, as understanding of soil behavior deepened, elasto-plastic and elasto-visco-plastic formulations gained prominence, allowing for more realistic descriptions of irreversible deformation, creep, and time dependent effects. The Figure 2.7 highlights this paradigm shift, demonstrating a clear trend toward physically enriched models that better capture the complex, path dependent response of soils under various loading conditions (Schanz et al. [138]; Mařín [139]).

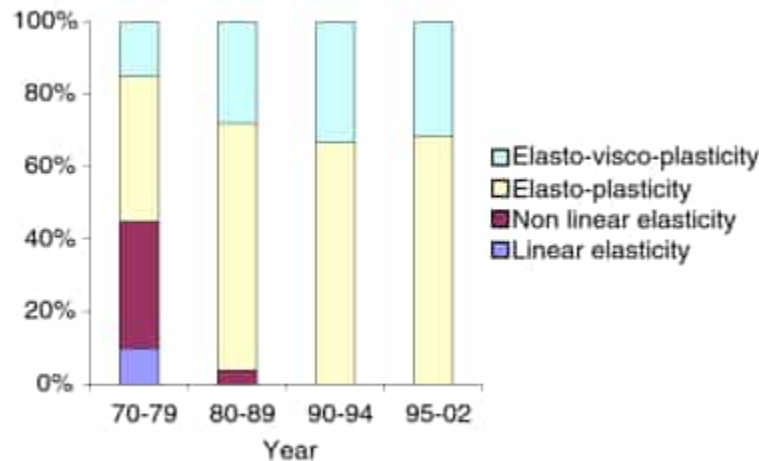


Figure 2.7: Evolution of the type of constitutive model used in numerical models for soft soil over the past 30 years (Ti et al. [140]).

Constitutive models describe how soils respond to applied stresses, linking experimental behavior with numerical prediction in geotechnical analysis. Depending on their complexity, these models range from simple linear-elastic perfectly plastic laws to advanced formulations accounting for nonlinear, cyclic, and anisotropic effects (Chen et al. [141]; Wood [142]). The Mohr-Coulomb model remains widely used due to its simplicity and reliance on a few measurable parameters; however, it cannot capture stress dependent stiffness or strain hardening. More sophisticated models such as Drucker-Prager, Modified Cam Clay (MCC), and Hardening Soil (HS) incorporate stress path dependency and plastic hardening, providing greater accuracy in predicting soil deformation and failure (Schofield and Wroth [143]; Schanz et al. [138]).

Figure 2.8 represents several representative yield surfaces in the octahedral stress space, including the Von Mises, Mohr-Coulomb, Drucker-Prager, Willam-Warnke, and Ottosen criteria. These surfaces define the combinations of stress invariants leading to yielding or plastic flow. Classical criteria such as Mohr-Coulomb and Drucker-Prager exhibit linear boundaries, whereas advanced models account for nonlinearity and intermediate principal stress effects, enhancing their applicability to complex soil and rock conditions (William and Warnke [144]; Ottosen [145]).

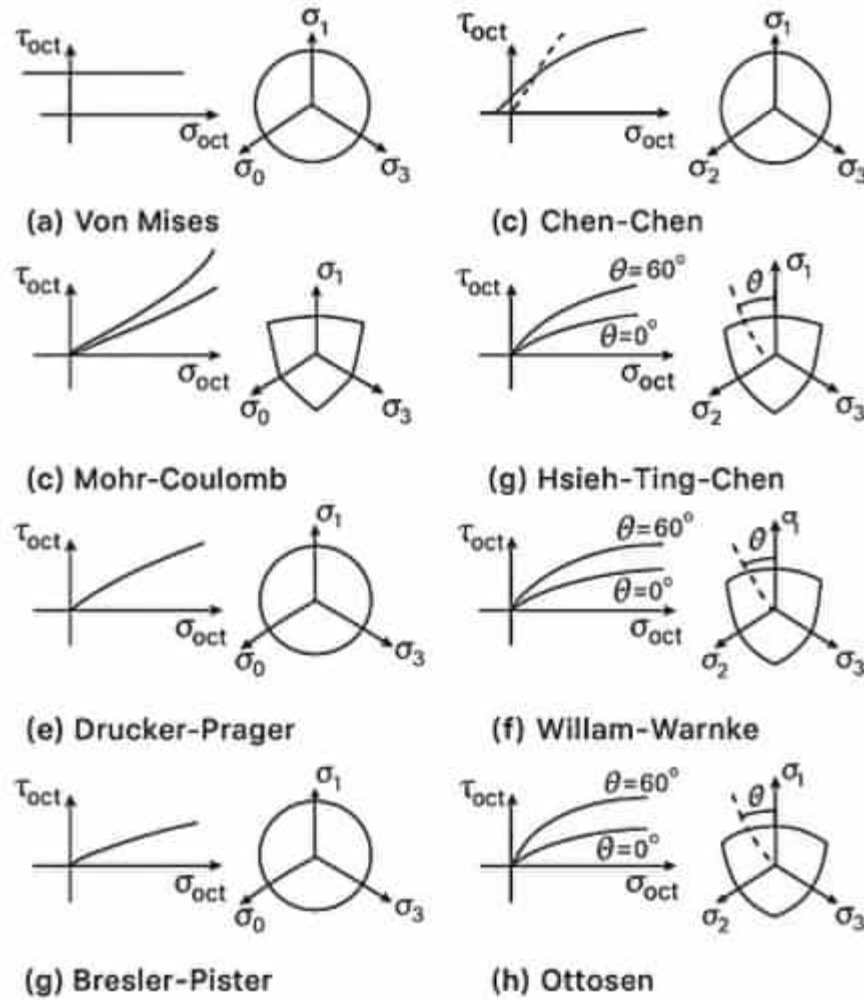


Figure 2.8: Failure models (Ti et al. [140]).

2.5.1 Basic Concepts

When modelling the mechanical interaction of a soil and an excavation tool, understanding the underlying constitutive behavior of the soil is essential. In other words, how the soil skeleton deforms, yields, and rearranges under stress must be captured in order for numerical simulations to be meaningful and realistic.

At the outset, one must recall the basic stress-strain relationship. Under small strain levels, soils often respond approximately elastically incremental stress produces incremental strain, and the structure of the skeleton remains undisturbed. But as loading proceeds, strains increase and the soil enters the large strain domain, wherein particle rearrangement, plastic yielding, volume changes and irreversible deformations occur. The distinction between “small” and “large” strain regimes is not rigidly defined in all cases, but is critical in practice because many constitutive models change behavior for example the stiffness degradation once a threshold strain is surpassed (Herle [146]). In the full picture of soil response, three classes of deformation

should be highlighted.

- **Elastic deformation** is reversible: when loading is removed the soil returns to its prior configuration (neglecting any creep or time dependent effects).
- **Plastic deformation** is irreversible: once yield has been reached, further strain remains after removal of stress.
- **Viscous deformation** may occur in clays or under sustained loads, wherein strain accumulates gradually even at constant stress. Modern constitutive modelling acknowledges that soils may simultaneously exhibit elastic stiffness, plastic yield and viscous creep behaviour.

To characterise the soil state, key state variables are employed:

- **The mean effective stress**, typically denoted p' , representing the average compressive stress carried by the soil skeleton.
- **The deviatoric stress**, denoted q , capturing the difference between major and minor principal stresses and therefore the shear component of loading.
- **The void ratio**, which describes the current void space in the soil skeleton and thus its density/packing state, and which plays a central role in volume change and stiffness behavior (Lade [147]).

These three variables, in many elasto-plastic constitutive frameworks, become part of the so-called “stress-state” description of soil (Lade [147]). From experimental work and field observations certain “fingerprints” of soil behavior emerge. For example:

1. **dilatancy**: dense granular soils tend to expand (increase in volume) when sheared, whereas loose soils may contract.
2. **Anisotropy**: the soil fabric (particle orientation, bonding, consolidation history) influences stiffness and strength differently in different directions.
3. **Strain hardening/softening**: many clays and silts, when sheared beyond yield, either increase their resistance (hardening) or reduce it (softening) depending on the initial structure, over consolidation ratio or bonding. These phenomena must be captured when selecting and calibrating constitutive models (Ng et al. [148]).

2.5.2 Linear Elastic Models

As the simplest representation of soil behavior one may adopt the linear elastic model. In this model the soil is assumed to respond in a reversible, proportionate manner to applied stress increments: Hooke’s law applies, and two material parameters suffice the Young’s modulus E and Poisson’s ratio ν . Explicitly, the stress-strain relationship may be written in isotropic elasticity as (Barber [149]):

$$\sigma_{ij} = \frac{E}{1 + \nu}(\varepsilon_{ij} + \frac{\nu}{1 - 2\nu}\delta_{ij}\varepsilon_{kk}) \quad (2.28)$$

where ε_{ij} is the strain tensor, σ_{ij} the stress tensor and δ_{ij} : Kronecker delta, equal to 1 when $i = j$, and 0 when $i \neq j$.

This model is attractive because of its simplicity and the small number of parameters required. It is well suited to small strain problems and the initial loading stage of an experiment or simulation, when the soil is still within its elastic domain and volume changes and irreversible deformations are limited. In computational practice (including finite element modelling of excavations), linear elasticity may serve as the first approximation or as part of the “initial condition” behaviour before yield or plasticity takes over (Lade [147]).

However, the limitations of the linear elastic model must be emphasised. Real soils seldom behave purely elastically under moderate to large shear: they undergo plastic deformation, meaning the model cannot capture permanent strains following unloading. Moreover, soils often exhibit volume changes under shear (dilatancy or contraction), which elasticity alone cannot represent, because linear elastic models assume no permanent volumetric change unless there is a change in mean stress. Additionally, in real soils stiffness is stress level dependent (the modulus increases with confining pressure) and nonlinear even at small strains, again linear elasticity does not account for stress dependency or stiffness degradation (Ti et al. [140]).

2.5.3 Elastic-Perfectly Plastic Models

In geotechnical engineering, elastic-perfectly plastic constitutive models are fundamental tools for describing the stress-strain behavior of geomaterials such as soils and rocks. These models idealize material response as linear elastic up to a defined yield point, followed by plastic deformation without hardening. While simplified, this assumption captures many key features of soil behavior under monotonic or quasi-static loading and provides an efficient and stable basis for finite element analyses (Chen et al. [141]; Potts et al. [150]; Wood [142]).

Elastic-perfectly plastic models provide the theoretical foundation for a wide variety of soil constitutive frameworks, including Mohr-Coulomb, Drucker-Prager, and Cam-Clay formulations (Chen et al. [151]). The following subsections focus on the two most widely implemented forms in engineering software and research applications.

2.5.3.1 Mohr-Coulomb

The Mohr-Coulomb (MC) model is the classical elasto-plastic model used in geotechnical simulations and represents one of the earliest attempts to quantify soil failure through stress invariants (Figure 2.9). The nonlinear shear strength envelope of soils can be represented through the mobilized values of cohesion (c) and internal friction angle (φ), which vary with

the stress level. Accordingly, the general nonlinear failure criterion can be formulated as:

$$F = f(c, \varphi) = \tau - c + \sigma \tan(\varphi) = 0 \quad (2.29)$$

where τ denotes the shear stress and σ represents the normal stress. considering the general principle effective stress state, the nonlinear Mohr-Coulomb criteria can be expressed as:

$$\sigma_1 = \sigma_3 \left(\frac{1 + \sin \varphi}{1 - \sin \varphi} \right) + 2c \frac{\cos \varphi}{1 - \sin \varphi} \quad (2.30)$$

where σ_1, σ_3 are major and minor principal stresses respectively. For the deformation analysis, the strain within each computational layer is determined from the stress-strain relationship, incorporating the soil's elastic parameters (Wang et al. [152]), as follows:

$$\varepsilon = \frac{\sigma_1 - \sigma_3}{E} = \frac{\sigma_1 - \sigma_3}{2G(1 + \nu)} \quad (2.31)$$

where E is the Young's modulus of the soil, G is the shear modulus and ν is the Poisson's ratio. The corresponding shear strain (γ) in each layer can be estimated by:

$$\gamma = (1 + \nu)\varepsilon \quad (2.32)$$

For each computed shear strain level, the normalized shear modulus ratio (G/G_{max}) corresponding to the linear elastic range (typically for $\gamma < 10^{-4}$ and the damping ratio (D) are determined using the modulus reduction and damping curves, respectively:

$$\left(\frac{G}{G_{max}} \right) = f(\gamma) \quad (2.33)$$

where G is the current shear modulus at a given strain level and $f(\gamma)$ is an empirical function describing stiffness degradation. The damping ratio is given by:

$$D = \frac{1}{4\pi} \left(\frac{W_D}{W_s} \right) \quad (2.34)$$

where W_D energy dissipated in one complete loading cycle (area enclosed by the hysteresis loop), W_s maximum strain energy stored during the cycle.

These relationships characterize the nonlinear and hysteretic behavior of soil under cyclic loading, typically derived from empirical laboratory data such as resonant column or cyclic triaxial tests. This iterative procedure allows accurate characterization of soil stiffness degradation and energy dissipation under varying levels of cyclic or dynamic loading, which is essential in the analysis of ground response, slope stability, and soil-structure interaction problems (Seed [112]; Vucetic and Dobry [153]; Kramer and Stewart [154]; Idriss and Boulanger [155]).

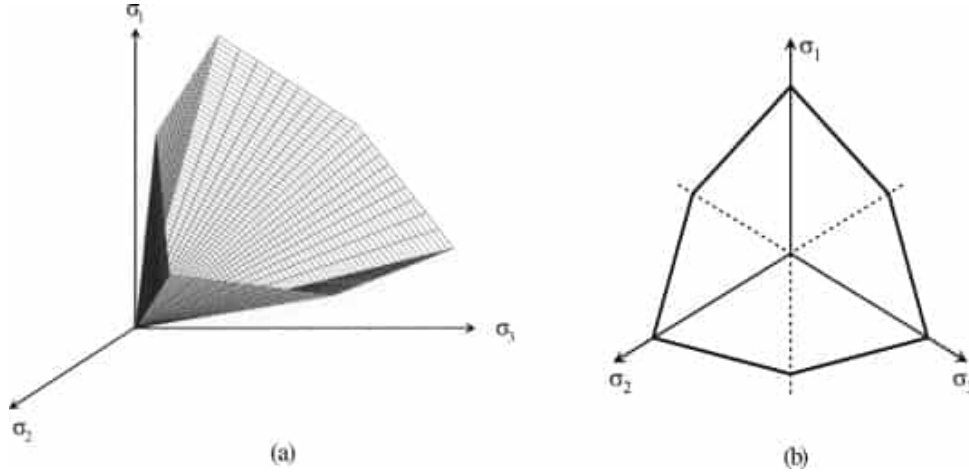


Figure 2.9: Mohr-Coulomb yield surface in principal stress space (Abbo et al. [156]).

2.5.3.2 Drucker-Prager

To address the geometric discontinuities of the Mohr-Coulomb yield surface, Drucker and Prager introduced a smooth conical approximation that enhances numerical stability and convergence in three-dimensional finite element analyses (Alejano and Bobet [157]) as shown in Figure 2.10. This approach, known as the Drucker-Prager failure criterion, serves as a generalized and continuous form of the Mohr-Coulomb model for soil behavior. It is expressed as:

$$\sqrt{J_2} = \lambda I'_1 + k \quad (2.35)$$

where λ and k are material constants derived from cohesion c and internal friction angle ϕ , can be determined :

$$\lambda = \frac{2 \sin \phi}{\sqrt{3}(3 - \sin \phi)} \quad (2.36)$$

$$k = \frac{6c \cos \phi}{\sqrt{3}(3 - \sin \phi)} \quad (2.37)$$

J_2 is the second invariant of the stress deviator tensor, and I'_1 is the first invariant of the stress tensor, and are defined as follows:

$$I'_1 = \sigma'_1 + \sigma'_2 + \sigma'_3 \quad (2.38)$$

$$J_2 = \frac{1}{6} [(\sigma'_1 - \sigma'_2)^2 + (\sigma'_1 - \sigma'_3)^2 + (\sigma'_3 - \sigma'_2)^2] \quad (2.39)$$

σ'_1 , σ'_2 , and σ'_3 are the principal effective stresses.

The criterion, when expressed in terms of octahedral shear stress τ_{oct} , and octahedral normal stress, σ'_{oct} , takes the form:

$$\tau_{oct} = \sqrt{\frac{2}{3}} (3\lambda\sigma'_{oct} + k) \quad (2.40)$$

where:

$$\sigma'_{oct} = \frac{1}{3} \times I'_1 \quad (2.41)$$

and

$$\sigma'_{oct} = \sqrt{\frac{2}{3} \times J_2} \quad (2.42)$$

The Drucker Prager criterion can thus be considered as a particular case of Nadai's criterion that states that the mechanical strength of brittle materials takes the form $\tau_{oct} = f(\sigma'_{oct})$, where f is a monotonically increasing function. It can be also considered as an extension of the Von Mises failure criterion, which is recovered when $\lambda = 0$ (Alejano and Bobet [157]).

This smooth representation of the yield surface significantly enhances numerical stability during plastic integration and makes the model well suited for rock mechanics, cemented soils, and frozen ground applications (Yu [158]; Sheng et al. [159]; Sloan [160]). The DP model is often implemented in two variations:

1. **The inscribed version**, which fits inside the Mohr-Coulomb hexagon, underestimates shear strength but ensures safety.
2. **The circumscribed version**, which overestimates strength slightly but matches average performance.

Although less accurate in capturing the sharp yield corners of frictional soils, the Drucker-Prager criterion provides a valuable computational compromise, particularly in three-dimensional stress conditions where smoothness ensures convergence. It also supports the implementation of isotropic hardening or viscoplastic extensions for rate-dependent soil behavior (Yu [158]; Borja [161]).

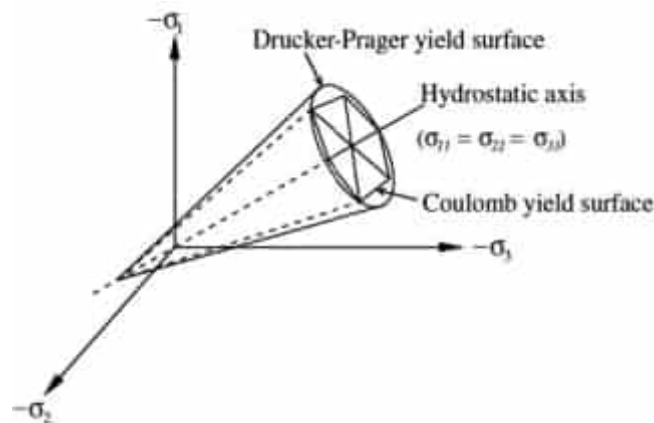


Figure 2.10: Comparison between Mohr-Coulomb and Drucker-Prager yield surfaces (Khatibinia et al. [162]).

The Figure 2.11 highlights how the Drucker-Prager model provides a smooth approximation of the Mohr-Coulomb envelope, improving computational convergence while slightly modifying shear strength prediction.

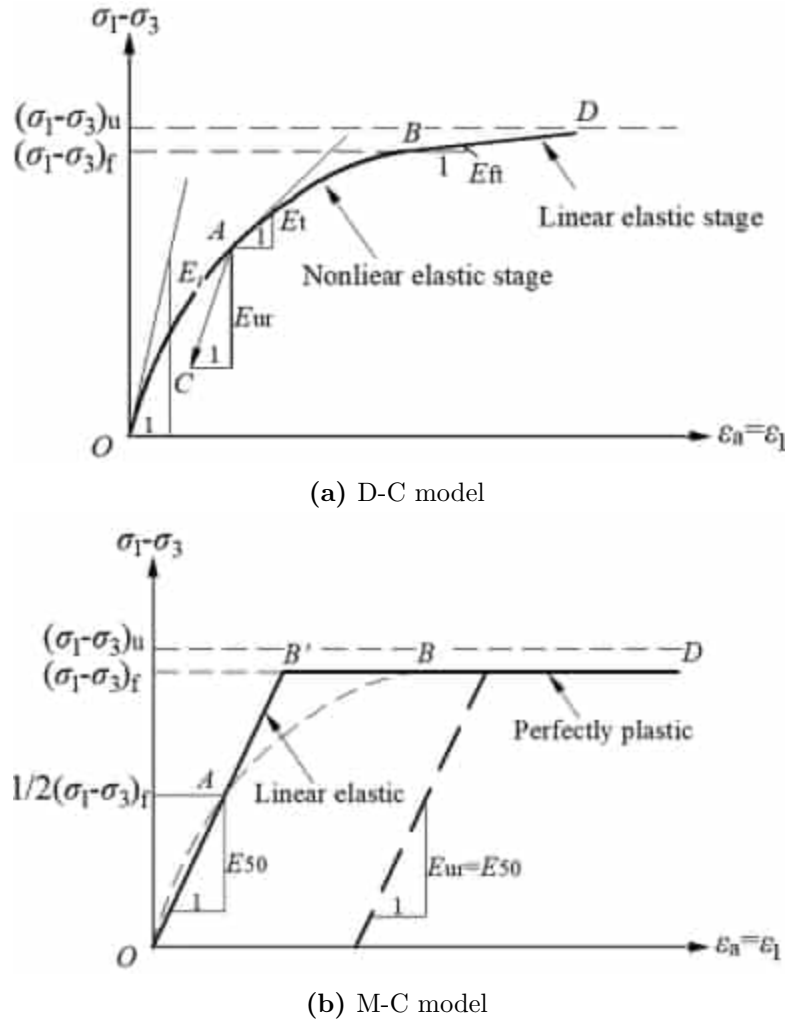


Figure 2.11: Stress-strain relationships (Xu et al. [163]).

2.5.4 Critical State Models

2.5.4.1 Cam-Clay

The Cam-Clay (CC) model, initially formulated by (Roscoe and Burland [164]), is a foundational constitutive model within the framework of critical state soil mechanics. It was developed to describe the behavior of normally consolidated and lightly over consolidated clays under triaxial stress conditions. The CC model characterizes soil as an elasto-plastic material governed by a yield surface that expands isotropically with plastic volumetric strain, reflecting the hardening behavior of clays.

Mathematically, the yield function for the Cam-Clay model is expressed as:

$$F = q + Mp' \ln(p - p_c') = 0 \quad (2.43)$$

where p is the mean effective stress, q is the deviatoric stress, p_c is the preconsolidation pressure representing the isotropic hardening variable, and M is the slope of the critical state line in the

q-p plane. The CC model assumes associated plastic flow, with the plastic volumetric strain increment proportional to the derivative of the yield function with respect to mean stress. This framework allows the model to simulate volumetric contraction under loading and volumetric expansion upon unloading, capturing essential features of clay behavior such as consolidation and critical state attainment (Schofield and Wroth [143]).

Despite its elegance, the CC model exhibits certain limitations, particularly in its prediction of stress-strain nonlinearity at low strains and in overconsolidated soils. Its assumptions of isotropic hardening and associated flow can lead to inaccuracies in modeling the anisotropic response and strain-softening behavior observed in natural clays. Nonetheless, the model remains widely used due to its simplicity, sound theoretical basis, and clear physical interpretation (Wood [142]).

2.5.4.2 Modified Cam–Clay

The Modified Cam-Clay (MCC) model was subsequently developed to address the limitations of the original Cam-Clay formulation and to improve numerical stability in finite element analyses (Roscoe and Burland [164], Schofield and Wroth [143]). The MCC model retains the critical state framework but replaces the elliptical yield surface of the original CC model with a logarithmic-type function in the ppp-qqq space, providing better representation of the stress path during isotropic and deviatoric loading. Its yield function is typically expressed as:

$$f(p, q, p_c) = q^2 + M^2 p(p - p_c) = 0 \quad (2.44)$$

With the main distinction that the hardening law is defined through the volumetric plastic strain increment:

$$dp_c = \frac{p_c}{\lambda - k} d\varepsilon_v^p \quad (2.45)$$

where λ is the slope of the virgin compression line, k is the slope of the swelling/recompression line, and $d\varepsilon_v^p$ is the increment of plastic volumetric strain. This formulation enables the MCC model to capture both the compression and shear behavior of clays more accurately than the original CC model.

The MCC model has been extensively validated against laboratory triaxial tests, showing improved predictions of stress-strain curves, volumetric changes, and pore pressure evolution under undrained and drained conditions. Its associated flow rule ensures consistency in plastic deformation calculations, and the model is widely implemented in advanced numerical simulation software for geotechnical engineering applications, including the analysis of excavation, foundation, and slope stability problems (Zienkiewicz and Taylor [165]).

Figure 2.12 illustrates the yield surfaces of the Cam Clay (CC) and Modified Cam Clay (MCC) models in the p-q stress space, along with the Critical State Line (CSL). The CC model

is represented by the smaller, red yield curve, while the MCC model expands the yield surface to account for volumetric hardening under isotropic compression. The Figure 2.12 highlights the evolution of the MCC yield curve toward the critical state, where soil continues to deform without further changes in stress or void ratio.

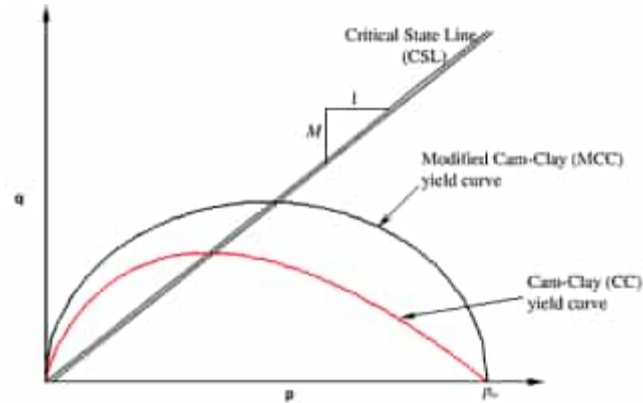


Figure 2.12: Cam-clay and Modified cam-clay model yield surface (Liu et al. [166]).

2.5.5 Advanced Models

2.5.5.1 Hardening Soil Model

The Hardening Soil (HS) model and its extension to small-strain stiffness (HSsmall) represent advanced constitutive frameworks in geotechnical engineering, introduced by Schanz, Vermeer and Bonnier among others (2019) to overcome limitations of simpler elasto-plastic formulations (Schanz et al., 2019). The HS model incorporates both shear and volumetric hardening, distinguishing between virgin loading and unloading/reloading paths with different stiffness moduli, and accounts for stress dependent stiffness to capture the non-linear behaviour of soils (Schanz et al. [138]; Briaud [167]).

- **Fundamental Concept:** The HSM is formulated within the framework of multi-surface plasticity, distinguishing between two principal hardening mechanisms:
 1. **Deviatoric (shear) hardening**, which governs irreversible strains under triaxial shear.
 2. **Volumetric (cap) hardening**, which governs plastic strains under isotropic or oedometer compression.

This dual mechanism enables the model to describe both yielding in shear and the compression behavior observed in oedometer tests. The stress-strain relationship under primary loading follows a hyperbolic law, first proposed by (Kondner [168]), where stiffness decreases with increasing stress level until reaching the Mohr-Coulomb parameters, ultimate

friction angle (φ) and cohesion (c), are used in the definition of q_a as following

$$q_a = \frac{q_f}{R_f} \quad (2.46)$$

$$q_f = (c \cot \varphi + \sigma_1) \frac{2 \sin \varphi}{1 - \sin \varphi} \quad (2.47)$$

Where R_f is the failure ratio (less than 1.0 with a default value 0.9), q_f is the ultimate deviatoric stress, c is the cohesion, φ is the friction angle, and σ_1 is the confining stress (Schanz et al. [138]).

- **Stress-Dependent Stiffness:** The model defines three independent stiffness moduli each stress dependent to represent different loading conditions:

$$E_{50} = E_{50}^{ref} \left(\frac{c \cos \varphi + \sigma_1 \sin \varphi}{c \cos \varphi + P_{ref} \sin \varphi} \right)^m \quad (2.48)$$

$$E_{oed} = E_{oed}^{ref} \left(\frac{c \cos \varphi + \sigma_1 \sin \varphi}{c \cos \varphi + P_{ref} \sin \varphi} \right)^m \quad (2.49)$$

$$E_{ur} = E_{ur}^{ref} \left(\frac{c \cos \varphi + \sigma_1 \sin \varphi}{c \cos \varphi + P_{ref} \sin \varphi} \right)^m \quad (2.50)$$

where:

- E_{50}^{ref} : is the secant stiffness at 50 % strength mobilization in a standard triaxial test,
- E_{oed}^{ref} : is the tangent stiffness for primary oedometer loading,
- E_{ur}^{ref} : is the unloading/reloading modulus,
- P_{ref} : is the reference confining pressure (typically 100 kPa)
- σ_1 : minor principal effective stress,
- c and φ : effective cohesion and friction angle,
- m is the stress dependency exponent ($0.5 < m < 1.0$).

This formulation allows realistic stress-level dependency of stiffness, a major improvement over linear-elastic assumptions in traditional models (Brinkgreve and Vermeer [169]).

- **Yield and Hardening Functions:** In triaxial stress space, the deviatoric yield function takes the form:

$$F_s = \frac{q}{E_i(1 - q/q_a)} - \frac{q}{E_{ur}} - \varepsilon_q^p = 0 \quad (2.51)$$

where q is the deviatoric stress, q_a is the asymptotic value of q , and ε_q^p is the plastic shear strain.

The model employs a multi-surface yield criterion where both deviatoric (shear) and

volumetric (cap) yield surfaces evolve in size according to accumulated plastic strains, thereby representing shear and volumetric hardening respectively (Schanz et al. [138]). Unloading-reloading stiffness is significantly higher than virgin loading stiffness, reflecting the commonly observed soil behaviour under cyclic or repeated loadings (Obrzud [170]). From an application viewpoint, HS and HSsmall are well suited for scenarios involving medium to dense sands and stiff clays where both shear and volumetric hardening are significant, and the differentiation between virgin loading and reload/unload behaviour is non-negligible (Briaud [167]). Their ability to reflect stress dependent stiffness, differing loading paths, and history effects makes them highly applicable in numerical simulations (finite-element modelling) of soil-structure interaction, deep excavations and large deformation problems.

However, these models are not without limitations: despite their enhanced fidelity, they still typically assume isotropic hardening and often adopt an associative flow rule (which may not represent dilatancy or anisotropy adequately); parameter calibration is more complex than in simpler models (Mohr-Coulomb) and may require extensive laboratory data (Obrzud [170]). Furthermore, while HSsmall improves small-strain response, the cyclic behaviour modelling remains less detailed than fully cyclic-specific models.

2.5.5.2 Hypoplasticity and Bounding Surface Theories

The bounding surface plasticity and hypoplasticity models constitute high fidelity constitutive frameworks designed to capture complex soil behaviour under cyclic, dynamic, or path dependent loading. The bounding surface concept was first introduced by (Dafalias and Popov [171]) and further developed by (Dafalias [172]), providing a mechanism by which plastic deformation is triggered even within the yield surface, with the plastic modulus varying according to the distance between the current stress state and a specified bounding surface (Dafalias [172]; Dafalias and Popov [171]; Gudehus [173]) and (Mašín [139]) further extended the hypoplasticity theory, which dispenses with the classical elastic-plastic split and instead defines a unified stress-strain rate relation capable of capturing path dependent, cyclic and rate effects (Gudehus [173]; Mašín [139]).

In the bounding surface framework, two surfaces are defined in stress space: the current yield (loading) surface and the bounding surface which represents the ultimate stress state. The proximity of the current stress point to the bounding surface controls the plastic modulus; as loading progresses and the stress point approaches the bounding surface, the plastic modulus decreases, and plastic strains increase. This mapping rule enables a smooth transition from elastic to plastic states and allows for accumulation of plastic deformation under repeated cycles, a phenomenon not well represented by classical yield surface models (Dafalias [172]; Rahimi

[174]).

Hypoplastic models, in contrast, present a direct tensor rate relation between stress rate and strain rate (plus state variables such as void ratio) without explicit decomposition into elastic and plastic parts. They are particularly adept at modeling gradual stiffness degradation, cyclic loading, strain-rate effects, and path dependence in soils (Mašín [139]). For instance, (Mašín [139]) presented a hypoplastic constitutive model for clays which improved undrained response predictions and accounted for over consolidation effects. (Gudehus [173]) introduced a comprehensive hypoplastic model for granular materials, while laid foundations of hypoplasticity (Kolymbas [175]).

These advanced models are especially relevant when simulation scenarios involve cyclic loading (such as seismic loading, traffic-induced vibrations), dynamic excavation, and soil fatigue. The bounding surface approach can represent load cycles even when the stress state remains inside the classical yield surface. Hypo-plastic models excel when a continuous constitutive response is desired especially when incremental stiffness changes, unloading/reloading hysteresis, and strain accumulation over many cycles are important.

However, adoption of bounding surface or hypoplastic models comes with challenges. Calibration is demanding: many more material parameters are required (mapping rules, bounding surface size, hypoplastic coefficients), and extensive laboratory cyclic tests are often necessary. Computational implementation is more intensive and may require advanced numerical techniques (e.g., implicit integration) for stability. Moreover, for soils with strong anisotropy, structural features or fabric effects, further model extensions may be needed (Ghobadi et al. [176]).

2.5.6 Comparative Assessment and Model Selection

In geotechnical numerical simulation of soil structure interaction such as for excavation, tunnelling or retention support the choice of constitutive soil model must strike a balance between complexity, parameter availability, predictive capability, and suitability to the soil type at hand. Below is a comparative discussion of these aspects, followed by the justification for adopting the Mohr-Coulomb model (MC) in the present work.

2.5.6.1 Complexity and Parameterization

- The MC model is a classic linear-elastic / perfectly-plastic framework defined by few parameters, typically Young's modulus E , Poisson's ratio ν , cohesion c , friction angle φ , and often dilatancy angle ψ (Yosef et al. [177]). Its lower complexity means fewer calibration tests and fast numerical implementation. However, this simplicity comes at the cost of neglecting many important soil behaviours: non-linear stiffness, stress dependency, cyclic loading effects, stiffness degradation, and strain hardening / softening.

- On the other end of the spectrum, more advanced constitutive frameworks for example the Hardening Soil model (HS) including stress dependence of stiffness, multiple yield surfaces and cap surfaces provide significantly improved predictive capacity for deformation and failure behavior of real soils. That increased fidelity is paid for by: a larger number of input parameters requiring specialized laboratory or in-situ tests; more complex calibration; and typically, greater computational effort.
- For example, a field study of deep excavation in stratified soils compared MC versus HS: the HS model reproduced wall deflections and deformation profiles with errors under 12 %, whereas MC significantly overestimated displacements (Wani and Showkat [178]).
- In summary:
 - **MC:** simple, widely used, few parameters, but limited in representing realistic soil deformation behavior, especially under unloading reloading, cyclic effects, or high stress paths.
 - **HS (and similar advanced models):** more realistic, good for serviceability and advanced loading cases, but require more data, more calibration, and higher computational load.

2.5.6.2 Justification for Mohr–Coulomb Selection

Given the context of this research namely simulation of soils under excavation tool interaction (bucket tooth vs soil) within a *PhD* framework the decision is justified as follows:

1. The soil under study is a clay (rather than a clean sand) and the focus is on the mechanical interaction between a tool (bucket tooth) and the soil rather than extremely complex service level cyclic behaviour or long term settlement of a large structure. Thus, the loading path, while dynamic in excavation terms, is reasonably bounded and does not necessarily involve long sequences of loading/unloading cycles or large consolidation history.
2. The available laboratory data for the site may not extend to the full battery of tests required to calibrate an advanced constitutive model with confidence for example small strain stiffness degradation, cyclic repetition, stress dependent modulus. Under such constraints the simpler MC model allows a credible first approximation.
3. From a practical standpoint, the MC model provides a good balance between simplicity and accuracy it allows straightforward parameter input (cohesion, friction angle) typical for clays, ease of implementation in finite element / finite difference frameworks, and faster computational turnaround important in early *Ph.D* research when multiple simulations must be run.
4. Accepting its limitations, the MC model still captures the essential shear failure behaviour (cohesion and friction) of clays under the low to moderate shear loads expected in the bucket tooth interaction scenario. Provided that the results are interpreted with awareness

of the model's simplifications (and potentially bounded by sensitivity analyses), the MC model is considered appropriate.

2.6 Conclusion

This chapter established the geotechnical foundations required to understand and simulate soil tool interaction with scientific rigor. It began with the classification and index properties of soils, which govern their mechanical and hydraulic behavior and frame the expected response during excavation. The discussion of shear strength, deformation, volume change, and dynamic properties highlighted the fundamental mechanisms controlling soil stability and soil failure, particularly under changing stress paths imposed by excavation activities. The chapter then examined soil behavior in excavation environments, emphasis stress redistribution, deformation and failure modes, and the role of constitutive behavior in governing ground response.

A review of available modelling strategies including experimental, analytical, and numerical approaches demonstrated the progression from classical laboratory techniques to advanced computational frameworks capable of capturing large deformations, nonlinearity, and particle-scale processes. Among these, the finite element method, discrete element method, and coupled FEM-DEM strategies were identify as the most relevant for modern excavation research. Finally, an assessment of constitutive models showed the diversity of available formulations, ranging from simple elastic-perfectly plastic representations to advanced hardening, critical state, and hypoplastic models. Their comparative evaluation underscored the need to balance realism, numerical stability, and parameter availability, providing justification for the selection of the Mohr-Coulomb model in subsequent chapters of this thesis

Chapter 3

Chapter 3: Experimental Characterization and Numerical Modelling of Soil-Tool Interaction

3.1 Introduction

This chapter outlines the numerical methodology used to model soil tool interaction in Abaqus/Explicit through the Smoothed Particle Hydrodynamics (SPH) technique. Excavation involves large deformations and material separation, which often lead to numerical instability in traditional mesh-based finite element approaches. By contrast, SPH treats the soil as a particle assembly that deforms freely, making it well suited for simulating cutting and earth-moving processes.

The chapter first describes the geometric and mechanical representation of both the soil domain and the excavation tool. The soil is initially meshed with hexahedral elements and subsequently converted into SPH particles for dynamic analysis, while the tool is defined as a rigid body. The modelling procedure includes the selection of particle size and total particle number, the application of boundary conditions, and the definition of contact algorithms necessary for capturing soil tool interaction.

To ensure reliable material characterization, the laboratory tests used to identify soil parameters are also present. The direct shear box test provides the cohesion and internal friction angle required to define the soil's shear strength. The soil bin test is introduced as the controlled excavation experiment that will later serve for model validation in the following chapter.

Material parameters for both soil and tool are then detailed. The soil properties such as density, elastic constants, shear strength parameters, dilation angle, and contact friction are implemented using the Mohr-Coulomb elastoplastic model, a commonly adopted constitutive law for frictional cohesive geomaterials. Tool characteristics such as geometry, stiffness, mass, and interaction properties are also specified to complete the numerical setup.

This chapter concludes by presenting the overall workflow for constructing the soil tool interaction model in Abaqus, including geometry preparation, meshing, SPH conversion, material assignment, and definition of the interaction parameters

3.2 Excavation tool

Excavator bucket teeth in the mining sector are typically manufactured from robust alloy steels to withstand demanding operating conditions. Despite their strength, these teeth are highly exposed to abrasive forces, making them susceptible to damage and wear during service. To improve durability, hard-facing with wear-resistant materials is often applied, extending service life under abrasive environments. Nevertheless, even hard alloys may show insufficient resistance over prolonged use, which has led to growing interest in surface coatings as a practical solution for enhancing wear performance.

3.2.1 Why CAT K130?

In this study, the CAT K130 Penetration Plus bucket tooth Figure 3.1 was deliberately selected to model realistic soil tool interactions under aggressive excavation scenarios. Its low-profile leading edge is optimized for penetrating soft, dense or compacted soils, and its self-sharpening wear geometry ensures consistent penetration performance as the tip wears. The steel alloy and heat treatment confer excellent toughness, allowing the tooth to withstand both abrasive wear and impact without premature failure. The K-series twist-on retention system, paired with a vertical retainer, guarantees secure fixation throughout repeated loading cycles, eliminating extraneous movement that might confound force and displacement measurements. Because the K130 configuration is widely used in industry, using it in this research enhances the practical relevance and reproducibility of the results, enabling the findings to inform both academic understanding and real-world tool-selection strategies in excavation engineering.



Figure 3.1: Real (CAT K130) bucket tooth.

3.2.2 Three Dimensional Geometric Model

In this study, a three-dimensional model of a bucket tooth was constructed using SOLIDWORKS 2022. The model reproduces the real geometry of a CAT K130 (reference 220-9133) tooth, which is a commonly used component in medium-sized excavation systems. The digital reconstruction aimed to ensure geometric fidelity to the industrial part so that the subsequent numerical analyses accurately reflect in-service mechanical behavior.

Figure 3.2 illustrates the generated CAD model, including multiple orthogonal and isometric views that capture the overall morphology of the component. The model comprises detailed features such as the tapered penetration tip, load-bearing shoulders, and the socket interface that connects the tooth to the adaptor shank. These features are essential to correctly represent stress concentrations and contact interactions during soil tool engagement.

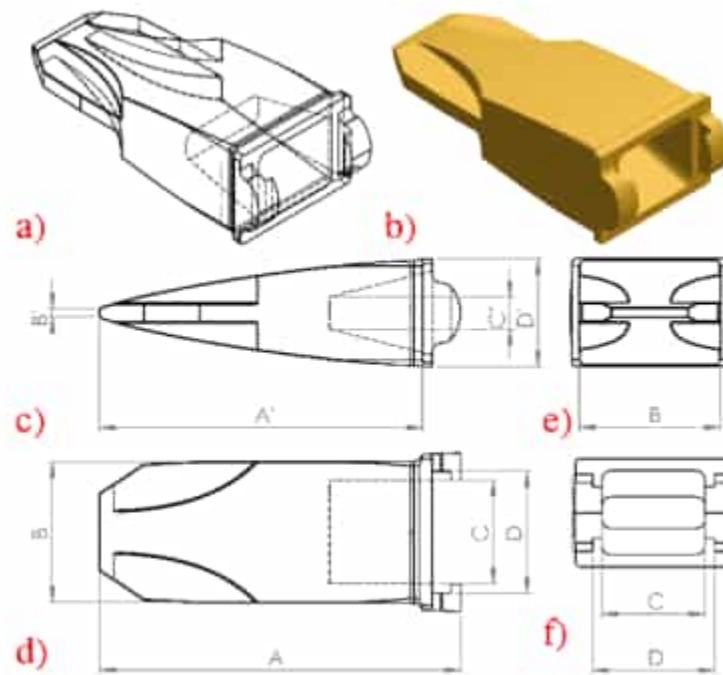


Figure 3.2: Three-dimensional model of the (CAT K130) bucket tooth generated in SOLIDWORKS 2022 for use in excavation tool simulations: a, b) 3D view, c) Side view, d) Top view, e) Front view, f) Back view.

The principal geometrical dimensions extracted from the physical component and implemented in the model are summarized in Table 3.1. Dimensions A , B , C , and D correspond to the global length and sectional widths of the tooth, while A' , B' , C' , and D' characterize the socket and internal mounting geometry. These parameters were used directly in the meshing and boundary-condition definitions of the numerical simulation.

Table 3.1: Geometrical dimensions of the CAT K130 bucket tooth used in the excavation tool simulations (mm).

A	B	C	D	A'	B'	C'	D'
386	150	110	130	346	10	34	115

3.2.3 Material Properties of the Bucket Tooth

The bucket tooth is manufactured from EN X200Cr12, a high-carbon, high-chromium martensitic steel commonly employed in abrasive wear environments. The mechanical properties of this alloy were incorporated into the numerical model to define the elastic-plastic behavior of the tool under excavation loading.

Table 3.2 presents the material parameters used in the simulations. The material exhibits a high elastic modulus (207 GPa), substantial yield strength (976 MPa), and significant tensile strength (1400 MPa), reflecting its suitability for severe contact and impact conditions. The

hardness of 48-52 HRC ensures resistance to abrasive soil-particle interactions, whereas a mass density of 7700 kg.m^{-3} allows realistic estimation of inertia and gravitational effects. The nominal weight of the manufactured tooth is approximately 20 kg.

Table 3.2: Mechanical properties of the CAT K130 bucket tooth material considered in the numerical model.

Material	EN: X200Cr12
Elastic Modulus (MPa)	207000
Mass Density (kg.m^{-3})	7700
Poisson's ratio	0.3
Yield Strength (MPa)	976
Hardness (HRC)	48-52
Weight (kg)	20
Tensile strength (MPa)	1400
Shock (J)	20

3.2.4 Integration in the Numerical Simulation

The geometric model and material properties described above were directly imported into the finite element environment used for excavation tool analysis. The geometry provided the boundary surfaces for soil tool interaction, while the material dataset controlled the elastic, plastic, and failure responses. These parameters ensured that the numerical model realistically represented the operational behavior of the CAT K130 tooth under typical excavation conditions.

3.3 Soil

This section presents the geotechnical characterization and numerical representation of the clayey sand used in this study. A series of laboratory investigations including mineralogical analysis and mechanical testing were carried out to quantify the soil's physical, chemical, and strength-related properties. These results were subsequently incorporated into the numerical modeling framework to simulate soil-tool interaction under large deformation conditions.

3.3.1 Mineralogical Composition

A representative clayey sand sample was collected and subjected to mineralogical characterization to establish its physico-chemical profile. X-ray Diffraction (XRD) analysis was performed on two subsamples to determine the oxide composition and identify the predominant mineral phases.

Prior to analysis, the soil was oven-dried at 105 °C for 24 hours, gently crushed to break down aggregates without altering the mineral structure, and sieved through a 2 mm mesh. Powdered specimens were then prepared using the backloading technique to ensure homogeneous packing and minimize preferred orientation effects.

The XRD measurements employed a standard diffractometer with $Cu - K\alpha$ radiation, operating at 40 kV and 30 mA. Diffraction patterns were collected over a 2θ range of 5° to 70° with a step size of 0.02°. The oxide phases were quantified using Rietveld refinement.

The resulting composition illustrates in Table 3.3 revealed that the soil is predominantly composed of silica (SiO_2) at approximately 52.5 %, indicating a significant quartz content. Alumina (Al_2O_3) and iron oxide (Fe_2O_3) were present at around 15.9 % and 7 %, respectively, suggesting the presence of clay minerals and iron-bearing minerals. The relatively low levels of sulfates (SO_3) and chlorides (Cl) indicate minimal presence of these compounds.

Table 3.3: Chemical composition of clayey sand soil.

Element	Sample 1 (%)	Sample 2 (%)
SiO_2	52.7	52.4
Al_2O_3	15.9	15.9
Fe_2O_3	7.01	7.05
SO_3	0.008	0.008
Cl	0.04	0.035
CaO	6.28	6.21
MgO	2.68	2.84
Na_2O	0.43	0.45
K_2O	2.17	2.28

These findings characterize the soil as a clayey sand, which combines both sandy and clay components. This composition influences the soil's physical properties, such as permeability, plasticity, and overall mechanical behavior

3.3.2 Direct Shear Testing

To determine the shear strength parameters for numerical modeling, consolidated drained direct shear tests were performed using a Casagrande-type shear box apparatus (Figure 3.3). This apparatus, standard in geotechnical engineering, enables controlled shearing along a predefined horizontal failure plane, allowing accurate determination of soil shear resistance.



Figure 3.3: Direct shear test apparatus used for determining shear strength parameters of the clayey sand.

3.3.2.1 Soil Material

The tested material is a clayey sand, selected to represent soil conditions commonly encountered in geotechnical and excavation applications. Prior to testing, the soil was air dried, homogenized, and prepared at a controlled water content. The material was carefully handled to ensure uniformity and repeatability among all tested specimens.

3.3.2.2 Sample Preparation

Before each test, the shear box components were cleaned and properly assembled. The soil specimen was placed into the shear box in successive layers, with each layer gently compacted to achieve a uniform density throughout the specimen. The final specimen dimensions corresponded to the internal dimensions of the shear box.

A porous plate and a rigid loading cap were positioned on top of the specimen to ensure uniform distribution of the applied normal stress. Care was taken to align the upper and lower halves of the shear box prior to loading.

3.3.2.3 Application of Normal Load

After specimen preparation, a predetermined normal stress was applied vertically using the loading system. Several normal stress levels were selected to define the shear strength envelope of the soil. Once the normal load was applied, the specimen was allowed to consolidate, and

vertical deformation was monitored until stabilization was observed.

3.3.2.4 Shearing Procedure

Following consolidation, the shear test was initiated by applying a horizontal displacement to the lower half of the shear box at a constant shear rate. The shearing process was continued until the soil reached peak shear resistance or until a sufficiently large horizontal displacement was achieved.

During the test, the following parameters were continuously recorded:

- Shear force,
- Horizontal displacement,
- Vertical displacement.

These measurements allowed the evaluation of shear stress development and volumetric behavior during shearing.

3.3.2.5 Repetition of Tests

To ensure the reliability and reproducibility of the experimental results, the direct shear test was repeated three times for each applied normal stress level. Each repetition was conducted using a freshly prepared specimen under identical testing conditions. The reported results are based on the average values obtained from the three tests.

3.3.3 Measured Properties

Following completion of the shearing phase, the recorded force-displacement data were processed to obtain the corresponding shear stress-strain relationships under each applied normal stress. The peak shear strength was identified at the maximum shear resistance, while the post-peak branch was used to evaluate the residual state. These results enabled the construction of Mohr-Coulomb failure envelopes, from which the essential shear strength parameters cohesion and internal friction angle were derived. In addition, complementary elastic properties required for numerical modeling were determined to provide a complete geotechnical characterization of the tested clayey sand. The resulting mechanical parameters are summarized in Table [3.4](#).

Table 3.4: Mechanical properties of the clayey sand soil determined from Casagrande shear test.

Mechanical properties	Soil
Elastic Modulus (MPa)	28 (Das and Sobhan [67])
Mass density ($kg.m^{-3}$)	1790
Poisson's ratio	0.32 (Terzaghi et al. [64])
Cohesion (KPa)	8
Internal friction angle (ϕ)	30°
Dilatancy angle (ψ)	0° (Potts et al. [150])
Water content (%)	15.84

3.3.4 Numerical Soil Modelling

The numerical modeling of the soil domain was conducted using Abaqus/Explicit, which is well suited for high-strain, high velocity processes such as excavation, cutting, and soil flow. The modeling framework was designed to ensure realistic replication of the excavation mechanism, including contact, large deformation, and material failure. The following subsections describe the modeling sequence adopted in the simulation pipeline.

1. Geometry and Part Definition:

The soil was modeled as a deformable three-dimensional block with dimensions of $700mm \times 400mm \times 500mm$ (see Figure 3.4), selected to eliminate boundary interference with the tool-induced stress fields. The excavation tool was defined as a rigid analytical surface to ensure numerical stability and minimize computation time, as its deformation was negligible compared with the soil.

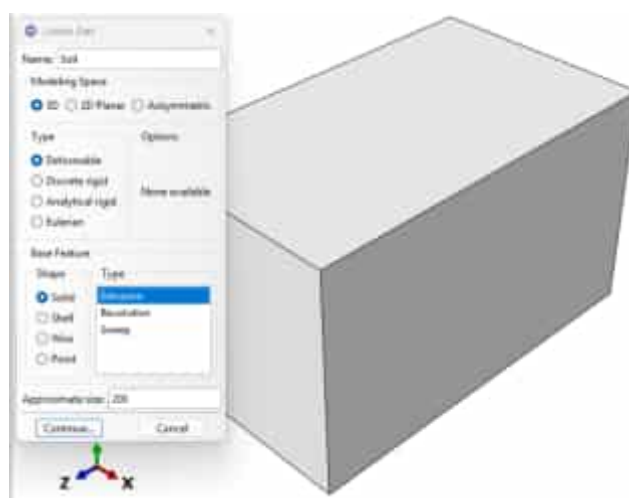


Figure 3.4: Part geometry

2. Material properties:

The mechanical properties (Figure 3.5) determined experimentally (Table 3.4) were incorporated into the Abaqus material definitions. The soil's elastic behavior was modeled using a Young's modulus of 28 MPa and Poisson's ratio of 0.32. The Mohr-Coulomb plasticity model was implemented to capture yielding, frictional resistance, and volumetric response during shearing. Cohesion (8 kPa), friction angle (30°), and dilatancy angle (0°) were assigned to define the shear strength envelope.

The excavation tool was assigned a linear elastic material with high stiffness values to replicate rigid behavior.

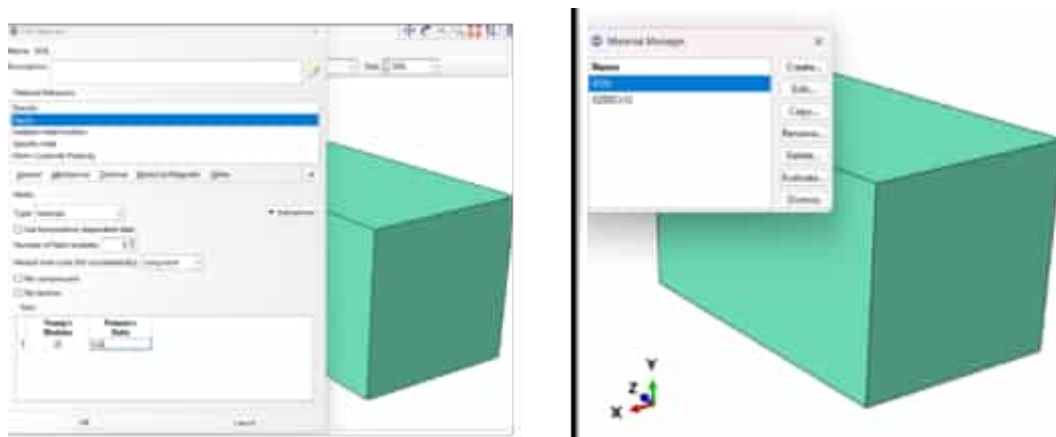


Figure 3.5: Implementation of soil and tool material properties in Abaqus.

3. Section Assignment:

Each part was linked to its respective material model through section assignments (Figure 3.6). This ensured correct interpretation of mechanical behavior during the explicit analysis.

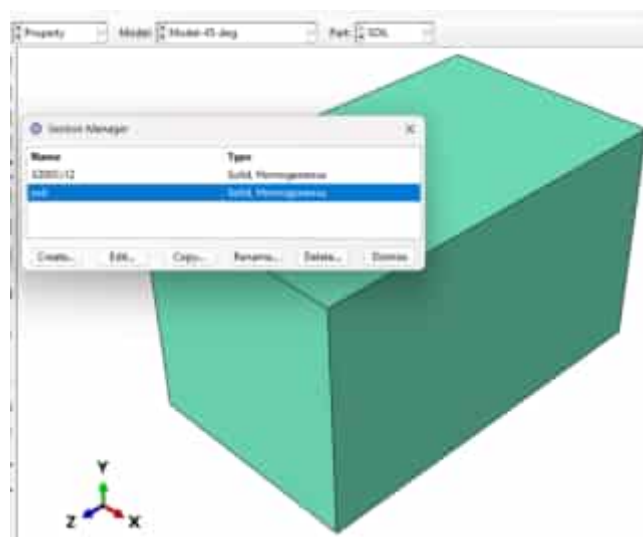


Figure 3.6: Section assignment of the soil and tool components, linking each part to its corresponding material model.

4. Assembly:

The soil and tool parts then positioned in the global coordinate system to recreate the initial configuration of the excavation process. Proper alignment between the cutting edge of the tool and the soil surface ensured during this stage (see Figure 3.7).

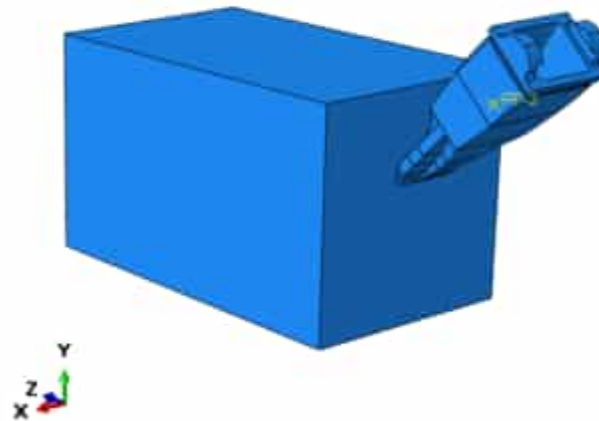


Figure 3.7: Soil and Bucket tooth assembly.

5. Interaction and Contact Modeling:

Tool-soil interaction was modeled using surface-to-surface contact with a frictional formulation (Figure 3.8). The mechanical contact parameters were selected to reflect observed shear resistance and were calibrated from laboratory evidence and relevant literature on soils.

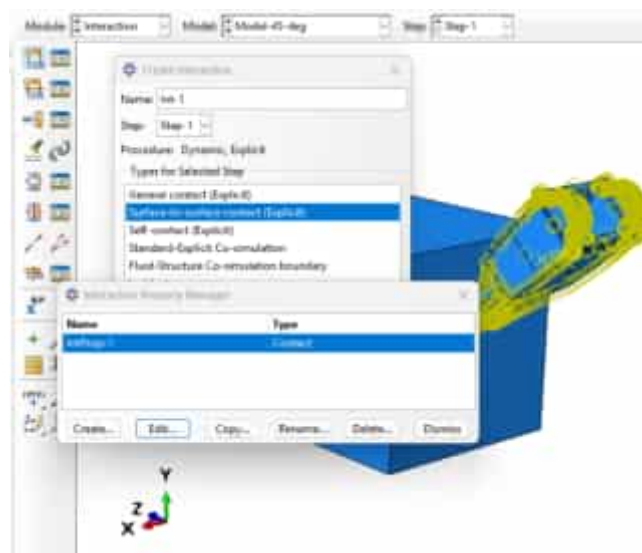


Figure 3.8: Definition of contact in Abaqus/Explicit of an interaction between the excavation tool and the soil domain.

6. Boundary Conditions:

The soil bin is constrained along its base and lateral faces to prevent rigid-body motion and ensure realistic confinement, while the tool is control through a reference point (RP) that governs its prescribed displacement and loading path during excavation (see Figure 3.9) :

- The bottom face of the soil block was fully fixed in all translational and rotational degrees of freedom.
- The two vertical lateral faces were constrained against displacement normal to their plane to emulate lateral confinement.
- The top surface was left free to deform.
- The tool was driven with a constant velocity in the Z-direction, with all other motions restricted.

These constraints ensured numerical stability and realistic soil response during large deformation.

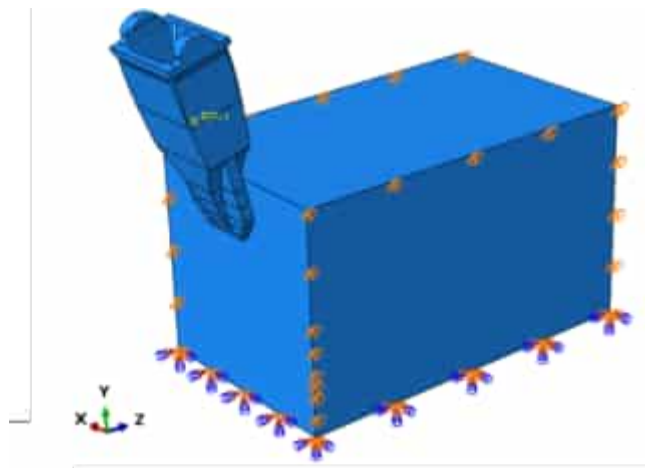


Figure 3.9: Boundary conditions applied to the soil domain and excavation tool.

7. Step Definition:

The analysis was conducted using Abaqus/Explicit in a two-stage sequence. A preliminary step established initial conditions, followed by a dynamic explicit step of 1 second during which the tool penetrated and sheared the soil (Figure 3.10). The explicit solution scheme was selected due to its robustness in handling contact, large deformation, and nonlinearity.

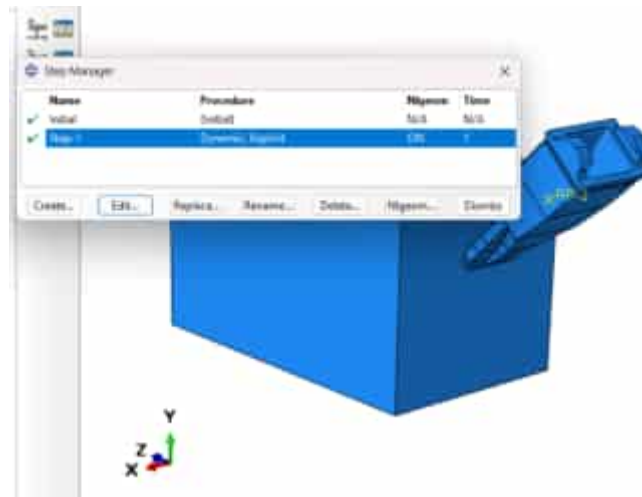


Figure 3.10: Step creation in Abaqus/Explicit.

8. Mesh Generation:

The soil bin domain was first discretized using hexahedral reduced-integration elements (C3D8R) to ensure a uniform and structured representation of the soil volume prior to particle conversion. During the initial step of the Abaqus/Explicit analysis, this finite element mesh transformed into a Smoothed Particle Hydrodynamics (SPH) representation, enabling large deformation modeling suitable for soil tool interaction. The generated SPH particle file was subsequently imported into the Part module to construct the final SPH-based soil model used in the simulation (Figure 3.11). The resulting discretization produced a total of $N = 8,960,000$ particles, providing a sufficiently refined particle density to accurately capture soil failure, flow, and cutting mechanisms throughout the excavation process.

In addition to the soil domain, the excavation tool was mesh independently to ensure accurate geometric and contact representation. The tool mesh consisted of 239,695 C3D10 quadratic tetrahedral elements and 345,333 nodes (Figure 3.12). offering high geometric fidelity required to model detailed tool-soil interaction and stress transfer during excavation.

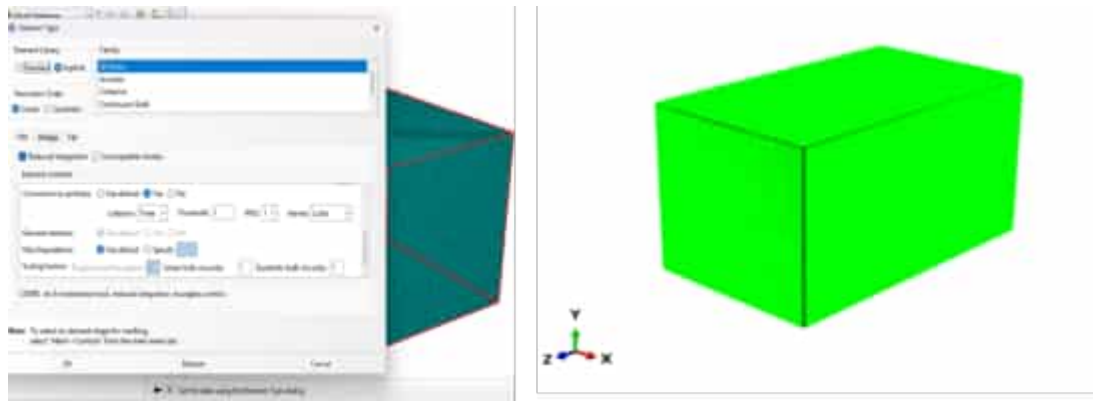


Figure 3.11: Mesh generation and SPH particle conversion for the soil domain.

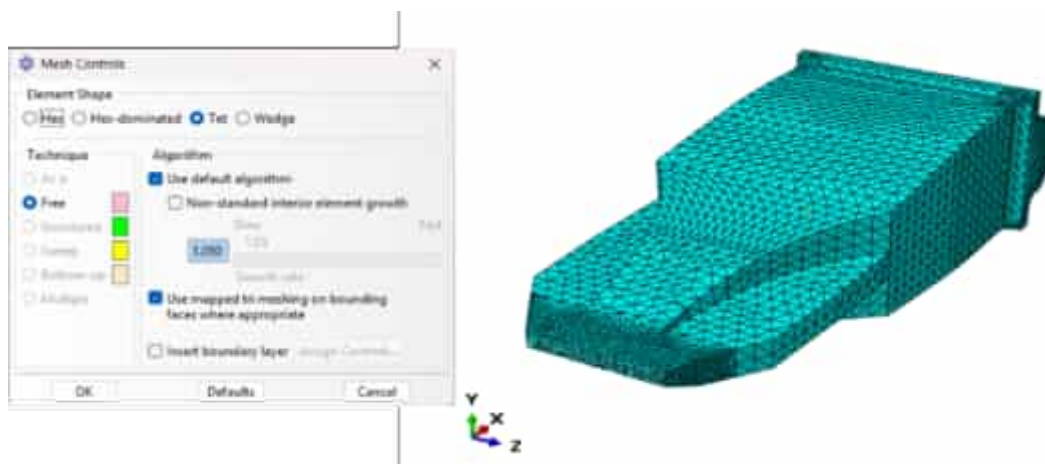


Figure 3.12: Mesh generation of the bucket tooth using tetrahedral elements (C3D10).

3.4 Numerical Model Description

3.4.1 Soil Modeling

Accurate representation of soil mechanical behavior is essential for predicting excavation forces, deformation patterns, and soil tool interaction mechanisms. A wide range of constitutive models has been developed to describe the nonlinear stress-strain response of geomaterials under various loading paths. Advanced critical-state models, such as Modified Cam-Clay, provide robust descriptions of volumetric behavior under complex stress histories (Cassiani et al., 2017). Likewise, the Hardened Soil (HS) and Hardened Soil Small-Strain (HSS) models incorporate stress-dependent stiffness and small-strain behavior to enhance predictions of deformation and settlement.

Despite the availability of these sophisticated formulations, the Mohr-Coulomb (MC) model remains one of the most widely applied constitutive laws in geotechnical analysis. Its popularity is attributed to its conceptual simplicity, computational efficiency, and the ease with which its

parameters (cohesion (c), internal friction angle (φ), and elastic stiffnesses) can be derived from standard laboratory or in situ tests (Liang & He, 2014; Tian & Zheng, 2023). Comparisons with more advanced models often reveal that differences in global performance indicators, such as safety factors and cutting forces, remain relatively small, further supporting its practical application.

Coulomb initially proposed a linear shear failure criterion expressed as:

$$\tau = c + \sigma \times \tan \varphi \quad (3.1)$$

where τ shear strength acting on the failure plane (MPa), σ normal stress on the failure plane with tensile stress considered positive (MPa), c - cohesion of the soil or rock (MPa), φ - internal friction angle ($^\circ$).

Mohr later generalized this concept into a full three-dimensional representation of stress failure, resulting in the Mohr-Coulomb yield criterion, commonly expressed in terms of the major and minor principal stresses ($\sigma_1 \leq \sigma_2 \leq \sigma_3$) as:

$$\sigma_1 = \frac{1}{2} (\sigma_1 + \sigma_3) - \frac{1}{2} (\sigma_1 - \sigma_3) \times \sin \varphi \quad (3.2)$$

where: σ_1 - major principal stress at failure (MPa), σ_3 - minor principal stress at failure (MPa).

This formulation defines the stress state at failure as a function of shear strength parameters (c , φ) and serves as the basis for the MC yield surface illustrated in Figure 3.13. The model assumes elastic-perfectly plastic behavior and implements a non-associated flow rule for frictional materials (Ti et al., 2009). Numerous experimental studies confirm its ability to capture the primary failure mechanisms of soils and rocks under a wide range of loading scenarios (Robert, 2017; Xiang & Zi-Hang, 2017).

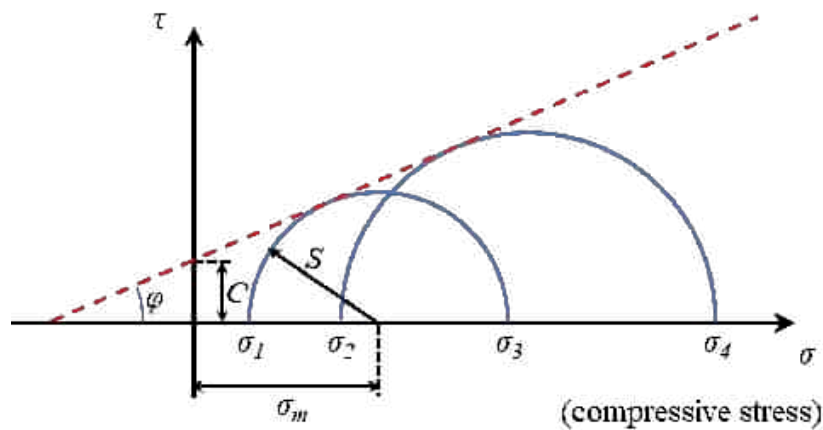


Figure 3.13: Schematic of the Mohr-Coulomb yield surface in principal stress space (Zaid et al., 2020).

3.4.2 Boundary and Initial Conditions

The excavation model was developed in Abaqus/Explicit, with the bucket tooth discretized using 10-node quadratic tetrahedral elements (C3D10). This element type is well-suited for complex geometries and ensures accurate representation of stress gradients near the cutting edge. The final tooth mesh included 239,695 elements and 345,333 nodes. The soil domain was initially meshed using reduced-integration hexahedral elements (C3D8R), resulting in 108,800 elements and 115,989 nodes.

Boundary conditions were imposed to reproduce realistic experimental confinement (Figure 3.14). The bottom boundary of the soil container was fully constrained in all degrees of freedom to simulate rigid support. Lateral boundaries (left and right faces) were restricted in horizontal displacement (X and Y directions), preventing outward soil movement while allowing vertical deformation. The remaining faces top, front, and back were left free to enable natural soil flow during excavation.

A constant translational velocity in the Z-direction was applied to the reference point of the rigid tooth, while rotation and lateral translations were fixed. This loading approach reflects typical excavation motion and follows procedures established in previous soil tool interaction research (Abo-elnor et al., 2004).

The simulation was executed in two stages:

1. An initial step defining boundary conditions and establishing equilibrium.
2. A dynamic explicit step of 1 second duration, capturing the transient response of soil under cutting.

These settings have been validated in earlier numerical excavation studies (Armin et al., 2014; Godwin & O'Dogherty, 2007) and ensure stable computation under large deformations.

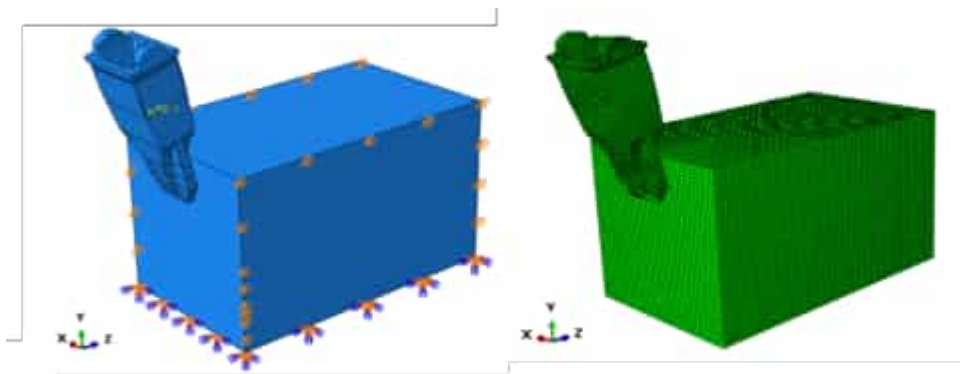


Figure 3.14: Finite element meshing and boundary conditions applied in the soil tool interaction model: a) boundary constraints, b) soil and tool mesh before excavation.

A workflow diagram summarizing the complete numerical and experimental methodology is provided in Figure 3.15 highlighting the model development, data acquisition, and validation sequence.

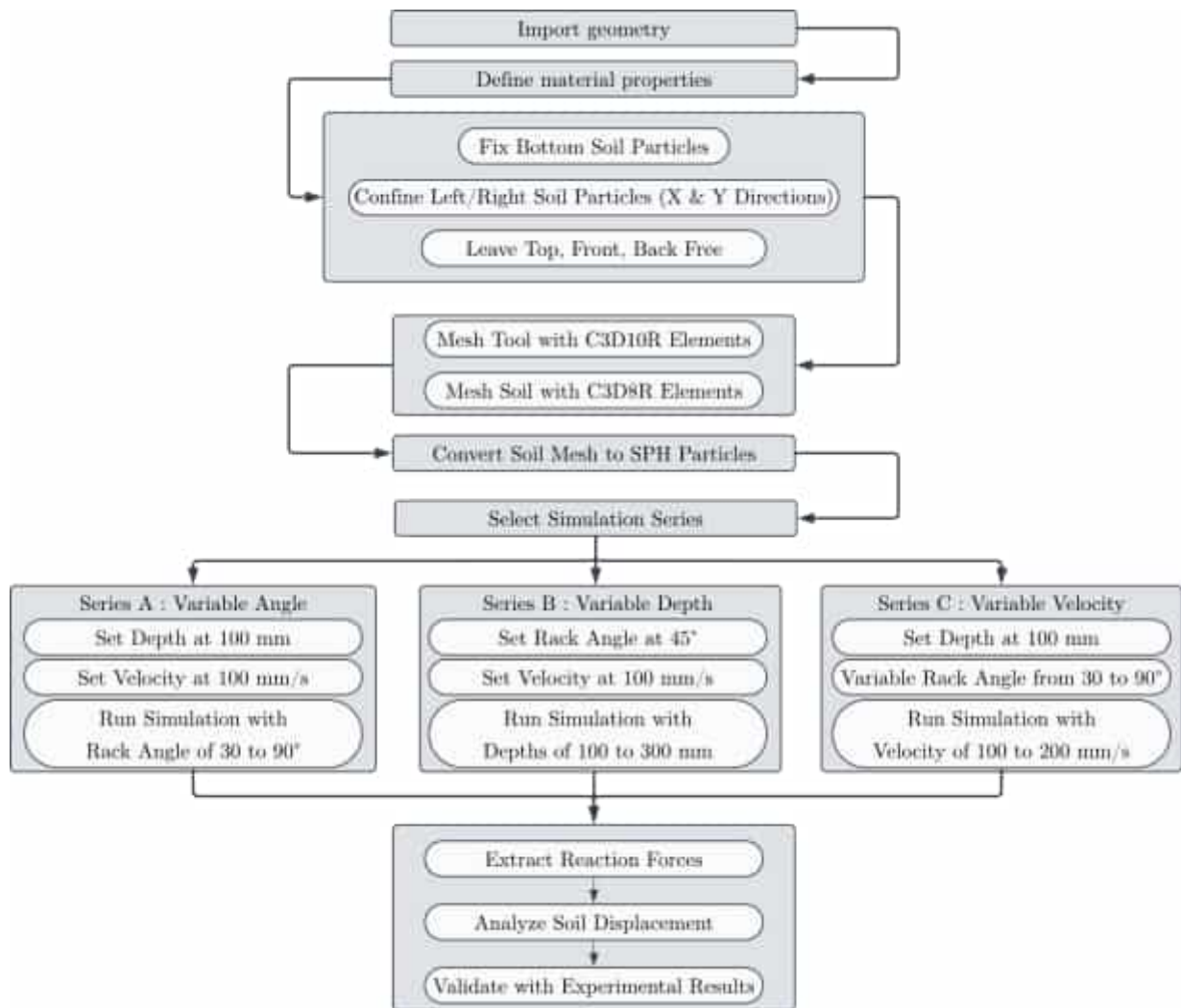


Figure 3.15: Simulation and experimental validation workflow diagram.

3.4.3 SPH Formulation and Interaction Laws

Smoothed Particle Hydrodynamics (SPH) is a mesh-free numerical method increasingly used in geomechanics to simulate large deformations, soil rupture, and complex material flow. Unlike mesh dependent methods such as FEM or granular approaches such as DEM, SPH treats the continuum as interacting particles governed by smoothing kernels, allowing natural modeling of separation, free surfaces, and post-failure soil movement (Bui et al., 2008; Ucgul et al., 2018). This makes it particularly suitable for excavation problems, where accurate reproduction of soil flow, heave, and rollover beneath the cutting tool is essential (Monaghan, 1992).

In this study, a three-dimensional soil-tool interaction model was developed in Abaqus/Explicit (Figure 3.16). The soil domain was defined using SPH particles, each carrying mass, momentum, and stress tensors, while the bucket tooth was represented as a rigid analytical body. Particle interactions were computed through the built-in SPH kernel functions, with neighbor lists updated automatically during the simulation. The governing conservation equations were

solved using an explicit Lagrangian integration scheme, enabling stable representation of highly nonlinear soil motion.

The numerical model consisted of two primary components:

- A rigid Caterpillar K130 bucket tooth, represented as an analytical rigid body.
- A clayey sand soil domain modeled using SPH particles.

Reported soil bin dimensions in the literature vary according to tool geometry and study objectives, ranging from $300 \times 300 \times 100\text{mm}$ (Tagar et al., 2015) to $900 \times 900 \times 700\text{mm}$ (Ibrahmi et al., 2014). To ensure adequate boundary clearance and reproduce the experimental setup, a soil bin of $700 \times 400 \times 500\text{mm}$ was adopted. The same geometry, soil parameters, and boundary constraints were used for both experimental and numerical stages, allowing direct comparison of cutting forces and soil displacement fields.

The bucket tooth was driven at a constant forward velocity of 100 mm/s in the Z-direction, with the cutting angle γ fixed during each test (Abo-Elnor et al., 2004). Two parametric studies were performed:

1. Rake angle variation at constant depth (100 mm): $\gamma = 30^\circ, 45^\circ, 60^\circ, 75^\circ$, and 90° .
2. Penetration depth variation at constant rake angle (45°): $d = 100, 150, 200, 250, 300$ mm.

The selection of $\gamma = 45^\circ$ as the fixed angle for the second series was based on initial results indicating the lowest reaction forces at this configuration.

This SPH-based methodology provides a robust framework for analyzing soil failure mechanisms, reaction forces, and tool kinematics with high resolution under conditions of extreme deformation.

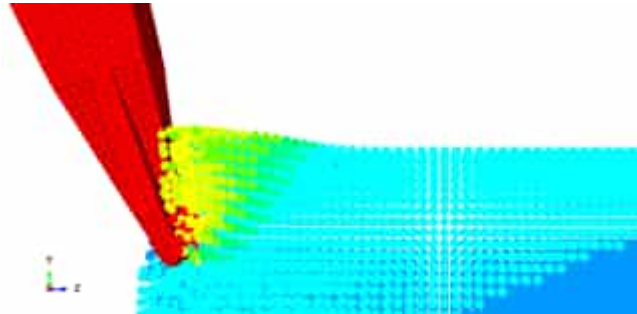


Figure 3.16: Visualization of SPH particle response during excavation, illustrating the interaction between the bucket tooth and clayey sand.

3.5 Experimental Investigation

This section presents the experimental work conducted to investigate soil tool interaction mechanisms using a controlled soil bin testing facility. The experimental tests were designed to quantify the effects of tool rake angle and cutting depth on excavation forces in clayey sand. Controlled laboratory conditions were employed to ensure repeatability, minimize environmental variability, and support subsequent numerical model validation.

3.5.1 Soil bin test machine

the soil bin test machine is a well-established experimental platform in both geotechnical and agricultural engineering research for studying soil tool interactions under repeatable and controlled conditions. It provides a reliable means to measure soil reaction forces, observe soil deformation patterns, and evaluate the influence of soil properties, tool geometry, and operating parameters on excavation performance. Unlike field experimentation, the soil bin environment ensures consistent boundary conditions, homogeneous soil preparation, and the ability to systematically modify experimental inputs, which are essential for parameter sensitivity analysis and numerical model calibration.

A typical soil bin system consists of three fundamental subsystems: the soil container, the tool carriage, and the data acquisition and control unit.

Soil Bin Container

The soil bin employed for this research is a large, rigid, rectangular container designed to maintain stable boundary conditions and prevent lateral soil displacement during testing. These bins are commonly constructed using steel or reinforced composite materials to ensure structural integrity under repeated loading. Various configurations exist, including modular designs for variable soil volumes, transparent sidewalls for visual inspection, and integrated conditioning systems for compaction or moisture control. The bin used in this study provided adequate dimensions and depth to avoid wall effects and to ensure the development of representative soil failure mechanisms.

Tool Carriage Mechanism

The tool carriage is a precision-controlled mechanical system responsible for driving the tool through the soil at prescribed kinematic conditions. The carriage generally consists of linear actuation rails or a gantry framework powered by servo motors or hydraulic actuators. These enable accurate control of tool velocity, cutting depth, and rake (attack) angle. In advanced systems, the carriage operates under programmable motion control, ensuring constant cutting speed and smooth tool penetration throughout the test run.

Force Measurement and Instrumentation

Accurate measurement of soil reaction forces is achieved through high resolution load cells or strain-gauge-based transducers attached to the tool mount or carriage. These sensors record draft (horizontal), penetration (vertical), and in some setups, lateral forces. Modern soil bin systems

may also incorporate soil displacement sensors, digital imaging systems, or laser profilometers to capture soil deformation patterns and failure zones. The measurement system is coordinated through a central data acquisition unit, enabling synchronized recording of force responses, tool motion parameters, and environmental conditions.

Data Acquisition and Control

A dedicated control system integrates motion control, sensor feedback, and data logging. It allows automated test execution, real-time monitoring, and storage of high-frequency measurements for post-processing. This high-fidelity experimental environment supports detailed evaluation of excavation processes and is widely used for validating computational models such as FEM- or SPH-based simulations. The combination of mechanical precision, accurate force sensing, and flexible configuration makes soil bin test machines indispensable for both scientific research and engineering design optimization.

3.5.2 Experimental setup and testing procedure

The experimental program was conducted at the Soil Bin Testing Facility, which is specifically designed for laboratory investigation of soil tool interaction phenomena. A schematic representation of the facility and its instrumentation is provided in Figure 3.17. The soil bin dimensions were 5000 mm in length, 3000 mm in width, and 1600 mm in depth, providing adequate soil volume to replicate realistic excavation conditions while ensuring consistent test boundaries.

Tool Configuration

The cutting tool used in this study was a steel bucket tooth mounted on a rigid tool holder capable of adjusting the rake angle. Five rake angles were investigated: 30°, 45°, 60°, 75°, and 90°. The tool assembly was attached to a horizontally translating carriage operating at a constant speed of 100 mm/s, ensuring uniform cutting velocity across all tests. The cutting depth was adjustable, and five values were selected: 100 mm, 150 mm, 200 mm, 250 mm, and 300 mm, to examine the influence of penetration depth on excavation forces.

Soil Preparation

The soil employed in all tests was classified as clayey sand. Its geotechnical and mechanical properties are summarized in Table 3.4. Before each test, the soil bed was carefully prepared to achieve uniform density and moisture content. Soil preparation included systematic mixing,

controlled compaction, and surface leveling. These steps were performed to ensure repeatable initial conditions, minimize heterogeneity, and maintain the integrity of the experimental comparisons across different test configurations.

Testing Procedure

For each test run, the tool was positioned at the designated rake angle and cutting depth before initiating horizontal motion (Figure 3.17). The carriage then translated the tool across the full length of the bin, allowing steady-state excavation conditions to develop before force measurements were recorded. The forces exerted on the tool were continuously monitored using calibrated load cells that measured the horizontal draft force and the vertical penetration force. Data were recorded at a sampling frequency of 50 Hz through a computer-based acquisition system, generating detailed force-time histories for each test.

To ensure statistical reliability, each combination of rake angle and cutting depth was tested three times. The force responses from these repetitions were averaged to reduce random variability and improve the robustness of the experimental dataset. The collected data served as a basis for analyzing the influence of tool geometry and operating conditions on excavation mechanics and for validating the numerical simulation models presented in subsequent sections.

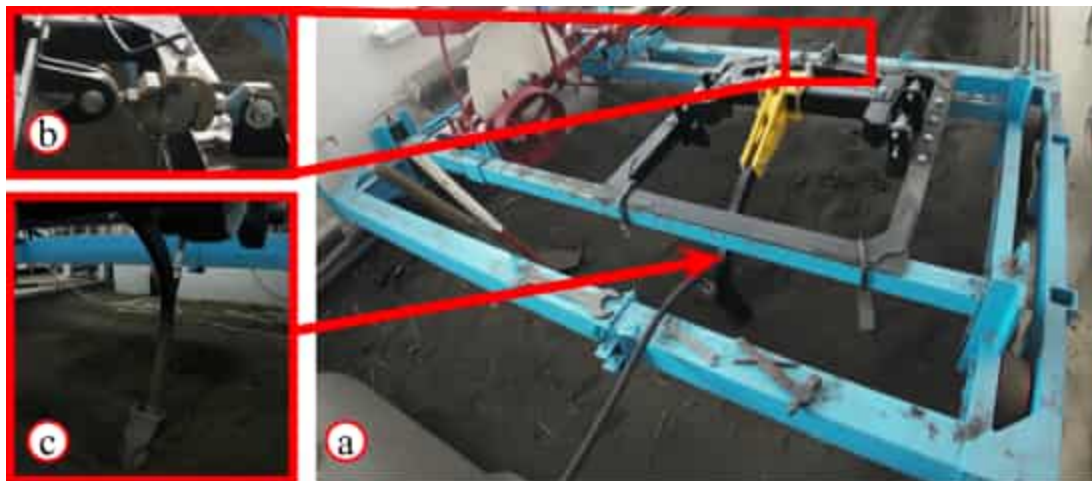


Figure 3.17: a) Soil bin testing facility, b) Load cell instrumentation, c) Rigid mounting of cutting tool.

3.6 Conclusion

This chapter outlined the numerical methodology used to model soil tool interaction with the SPH approach in Abaqus/Explicit. The modelling steps geometry definition, meshing, SPH conversion, and contact and boundary condition setup were present to establish a stable

framework capable of handling large deformations typical of excavation processes.

The direct shear box test provided the soil's shear strength parameters, while the soil-bin test introduced the excavation conditions that will later be used to assess the model's performance. All necessary soil and tool parameters were define, with soil behavior implemented using the Mohr-Coulomb elastoplastic model.

As this chapter focused solely on methodology, no simulation results were included. The modelling framework developed here serves as the foundation for the analyses and validation presented in the next chapter.

Chapter 4

Chapter 4: Analysis and Validation of Soil Tool Interaction Modelling

4.1 Introduction

This chapter presents a comprehensive analysis of the soil tool interaction based on the experimental and numerical investigations conducted in this study. The primary focus is placed on evaluating the effects of rake angle, cutting depth, and tool velocity on the vertical and horizontal reaction forces experienced by the excavation tool. Detailed comparisons between simulation results and experimental measurements are provided to assess the accuracy of the numerical model and its capability to replicate real-world soil behavior under different operating conditions.

The discussion emphasizes the observed trends in reaction forces as a function of varying tool parameters, highlighting the mechanical responses of the soil during excavation. The comparison with experimental data demonstrates a generally good agreement, confirming the reliability of the simulation methodology for predicting both vertical and horizontal forces. Particular attention is given to identifying conditions that minimize soil resistance while maintaining efficient cutting performance. The findings presented herein provide critical insights into optimal excavation parameters and serve as a basis for the interpretation of the subsequent results in terms of both tool performance and soil response.

4.2 Reaction Forces and Displacement Fields

Reaction forces and displacement trends were systematically evaluated for varying rake angles ($30^\circ - 90^\circ$), penetration depths (100 mm to 300 mm) and tool velocity (50 mm/s to 200 mm/s). Figure 4.1 to Figure 4.18 illustrate the close agreement between numerical predictions and experimental measurements for both vertical (RF2) and horizontal (RF3) forces.

1. **Rake Angle:** Vertical forces remained negative across all angles, with the minimum magnitude observed at 45° , indicating reduced downward resistance. At higher rake angles ($75^\circ - 90^\circ$), vertical forces increased to approximately -500 N due to greater soil compaction. Horizontal forces increased steadily with rake angle, exceeding 900 N at steeper angles, reflecting higher draft resistance as soil accumulated in front of the tool. These trends confirm that intermediate rake angles, particularly 45° , provide optimal cutting conditions by balancing efficiency with reduced soil resistance.
2. **Depth:** With the rake angle fixed at 45° , vertical forces transitioned from negative at shallow depths ($100\text{--}150$ mm) to positive at greater depths (200 to 300 mm), reflecting the increased uplift resistance with deeper penetration. Horizontal forces rose proportionally with depth, ranging from ~ 500 N at 100 mm to nearly 1500 N at 300 mm. The simulation slightly overestimated the forces at deeper cuts; however, the overall trends were consistent with experimental results, confirming the model's predictive capability.
3. **Velocity:** With the cutting depth fixed at 100 mm, a series of simulations was performed in which the cutting velocity was varied between 50 mm/s, 100 mm/s, and 200 mm/s for all rake angles (30° , 45° , 60° , 75° , and 90°). The results revealed a clear and systematic influence of velocity on the reaction forces. As the cutting velocity increased, the vertical reaction force (RF2) tended to decrease, reflecting a reduction in downward resistance due to the shorter interaction time and the more dynamic nature of soil flow beneath the tool. Conversely, the horizontal reaction force (RF3) increased with higher velocities, indicating enhanced forward resistance and greater soil accumulation in front of the cutting edge under rapid loading conditions.

4.3 Results and Discussion

4.3.1 Effect of Rake Angle

The results in Figure 4.1 show the variation of reaction forces with tool displacement at different rake angles for a constant depth of 100 mm. The vertical force decreases continuously, starting close to zero and becoming more negative as displacement increases. At rake angles of 30° , 45° , and 60° , the values converge, while at 75° and 90° , the vertical forces reach nearly -500 N, indicating stronger downward resistance from the soil. This trend confirms that soil reaction intensifies with displacement as tool-soil interaction develops.

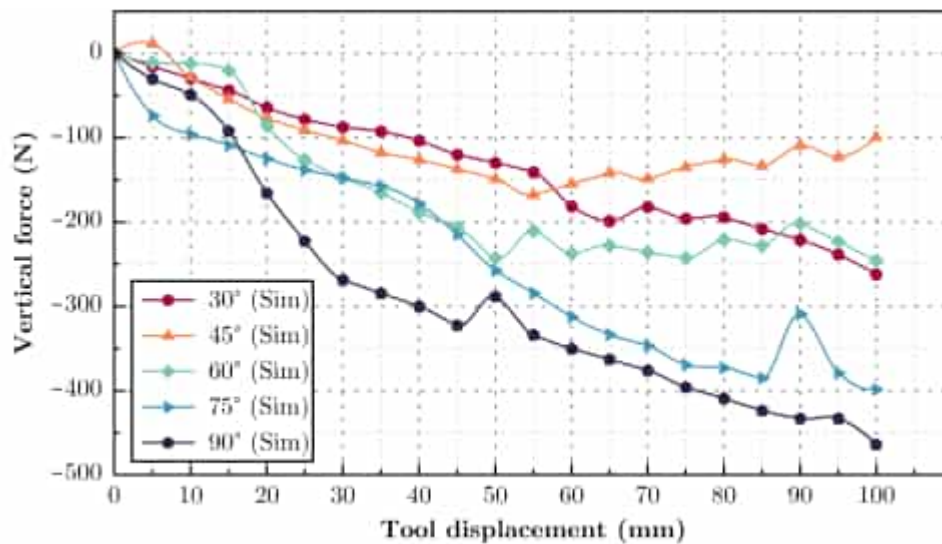


Figure 4.1: Influence of rake angle on soil vertical force (RF2) variation at a cutting depth of 100 mm.

Figure 4.2 shows that the horizontal force increases steadily with displacement. At 30° and 45°, draft forces remain lower, while at 75° and 90° they rise significantly, exceeding 900 N. This indicates that forward soil resistance grows with tool advancement and is amplified at higher rake angles due to greater compaction and soil accumulation. These findings are consistent with soil cutting mechanics, where penetration is easier at the start but resistance grows as cutting progresses, in line with reported results (Cheng et al., 2019).

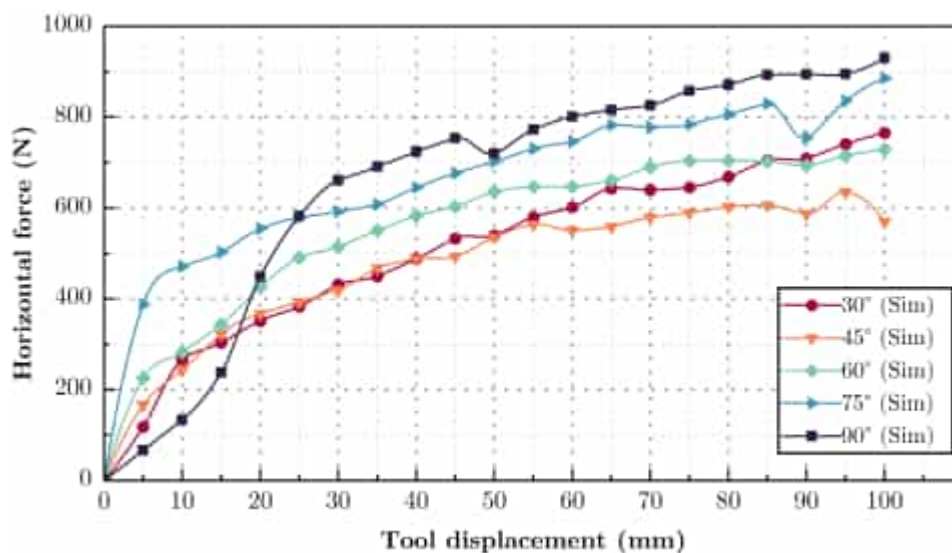


Figure 4.2: Influence of rake angle on soil horizontal force (RF3). variation at a cutting depth of 100 mm.

The variation of maximum reaction forces with rake angle summarized in Figure 4.3. The vertical force (RF2) remains negative at all rake angles, with the smallest magnitude observed at 45° and decreases to nearly -500 N at 90°. This shows that intermediate rake angles reduce

downward soil resistance, while higher angles intensify it due to increased soil pressure on the tool.

Conversely, the horizontal force (RF3) decreases slightly up to 45° then increases steadily, reaching its maximum at 90° . This indicates that draft resistance rises at steeper angles. These findings demonstrate that intermediate rake angles provide more favorable cutting conditions by minimizing both vertical and horizontal resistance.

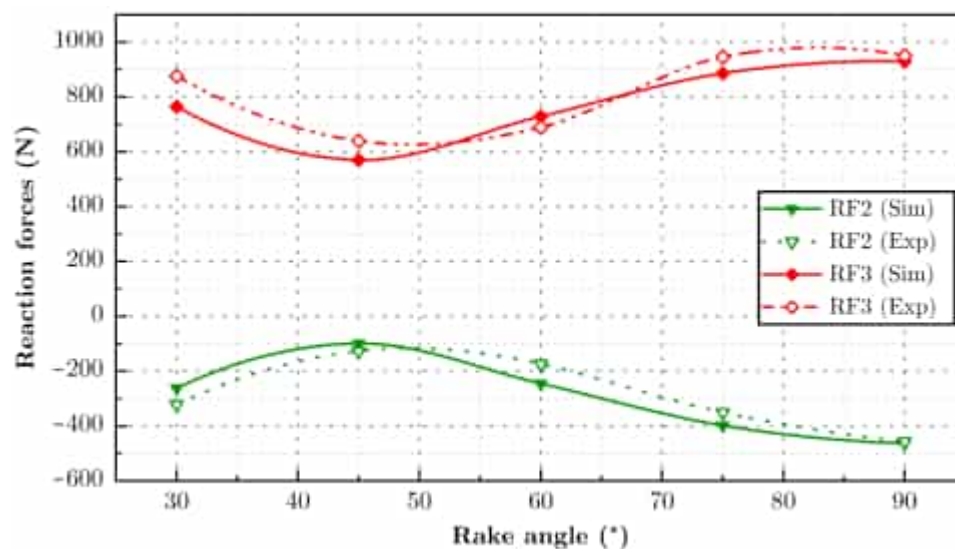


Figure 4.3: Maximum vertical (RF2) and horizontal (RF3) reaction forces as functions of rake angle.

Figure 4.4 presents the variation of the draft (horizontal) reaction force with tool displacement for the 45° rake angle at a cutting depth of 100 mm, comparing simulated and experimental results. The draft force increases sharply at the onset of penetration, rising from approximately 0 N at 0 mm displacement to nearly 250 N at 10 mm, reflecting the rapid mobilization of soil shear resistance during initial tool entry. As the tool advances, the force continues to grow steadily, reaching around 350 to 400 N at 20 mm, 480 to 520 N at 40 mm, and stabilizing near 550 to 600 N between 60 and 80 mm.

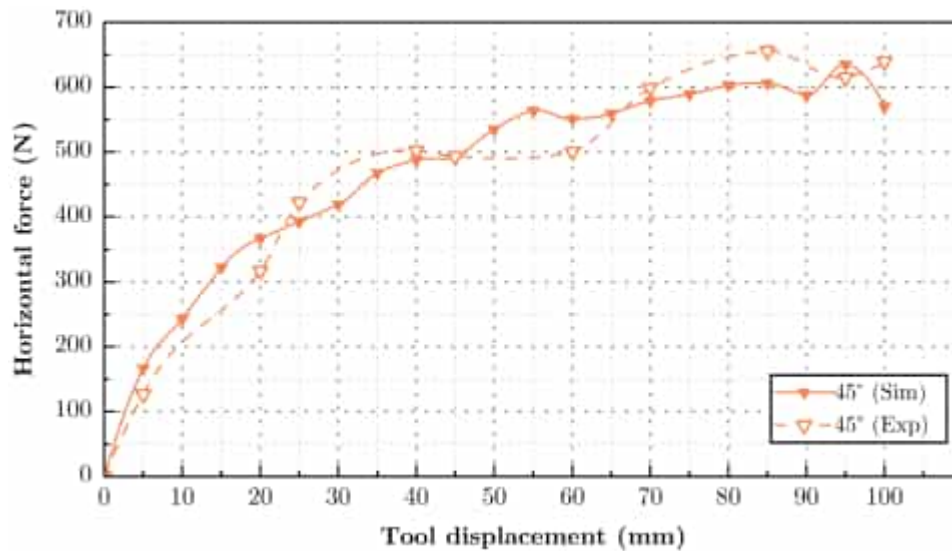


Figure 4.4: Numerical and experimental comparison of vertical force at 45° rake angle and 100 mm cutting depth

Both curves exhibit similar trends, indicating consistent development of a stable soil failure wedge ahead of the cutting edge. In the final phase of motion (80 to 110 mm), the draft force reaches its maximum approximately 620-650 N in both simulation and experiment with small oscillations that are typical of soil stick-slip behavior in cohesive materials. Overall, the simulation reproduces the experimental pattern with good agreement, confirming its capacity to capture the progressive increase and subsequent stabilization of horizontal excavation resistance.

Figure 4.5 illustrates the evolution of the vertical reaction force acting on the tool for the same 45° rake angle, again comparing simulated and experimental data. At the start of cutting, the vertical force fluctuates near 0 to 20 N within the first 10 mm, indicating minor upward or downward disturbance as the soil begins to fail and accumulate in front of the cutting edge. As displacement increases, the vertical force gradually becomes negative reaching approximately -80 to -120 N around 30 mm, and approaching nearly -150 to -200 N between 50 and 70 mm which demonstrates that the soil is exerting a net upward reaction on the tool.

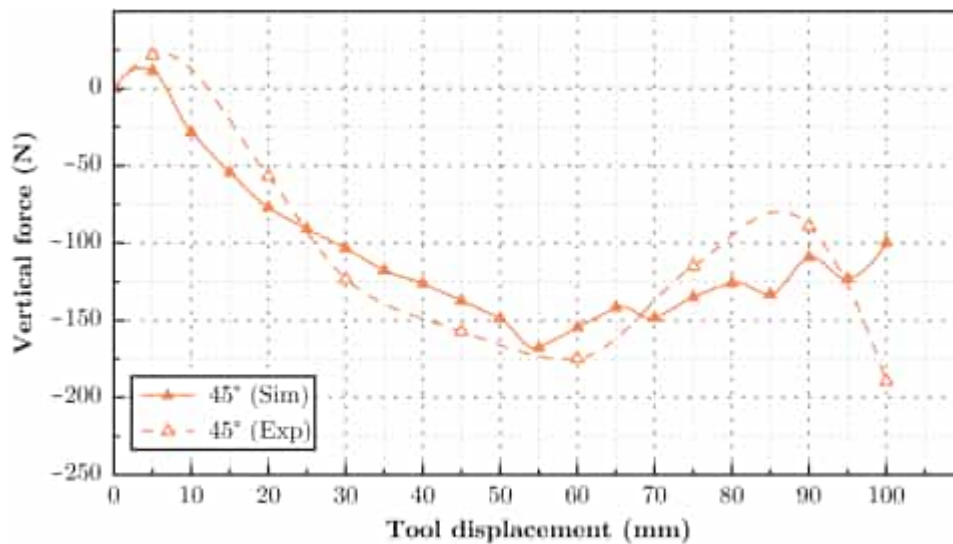


Figure 4.5: Numerical and experimental comparison of horizontal force at 45° rake angle and 100 mm cutting depth.

This uplift is characteristic of moderate rake angles where the sheared soil wedge redirects part of the resistance vertically. Beyond 70 mm, both simulation and experimental curves show small oscillations around -150 to -180 N, reflecting periodic rearrangement of the compacted soil and intermittent adhesion-slip effects on the tool surface.

Despite localized differences, the numerical results closely follow the experimental measurements, confirming that the model captures the typical vertical reaction patterns associated with cohesive soil cutting.

4.3.2 Effect of Cutting Depth

In this section, the rake angle is fixed at 45°, identified previously as the optimum value due to higher displacement (greater than 100 mm) and lower reaction forces compared with other angles. Figure 4.6 presents the vertical (RF2) and horizontal (RF3) reaction forces obtained from simulation results. The vertical force is negative at shallow depths of 100 mm and 150 mm, while at greater depths (200-300 mm) it becomes positive and increases in magnitude, indicating that uplift resistance grows significantly with penetration depth.

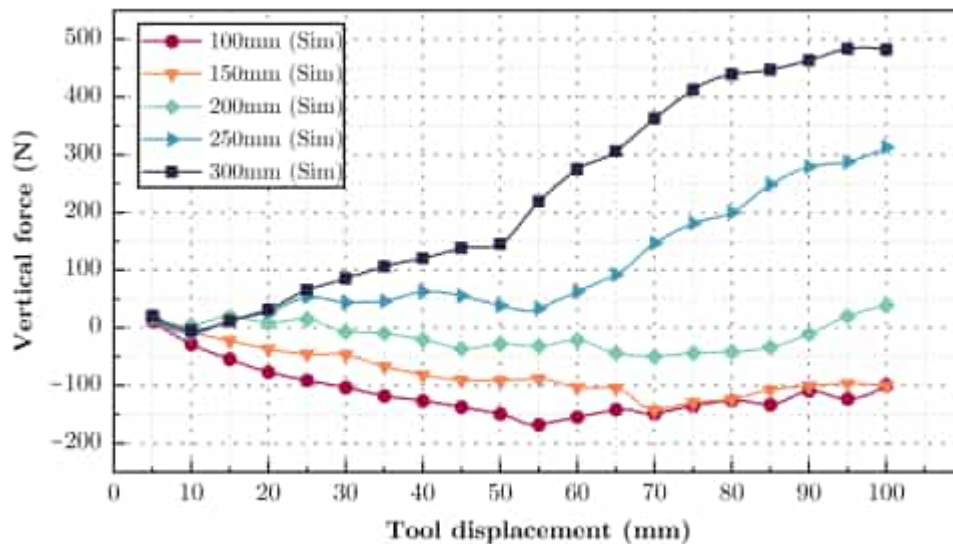


Figure 4.6: Effect of cutting depth (100–300 mm) on vertical force (RF2) at a 45° rake angle.

In Figure 4.7, the horizontal force rises progressively with displacement for all depths, with maximum values ranging from about 500 N at 100 mm to nearly 1500 N at 300 mm.

The effect of depth on maximum reaction forces is shown in Figure 4.6 and Figure 4.7, with deeper penetration producing progressively higher vertical and horizontal forces. Quantitatively, the horizontal force (RF3) rises steadily with depth, reaching approximately 1102 N at 200 mm, 1150.4 N at 250 mm, and 1156.05 N at 300 mm. Similarly, the vertical force (RF2) increases gradually, attaining a maximum of 481.99 N at 300 mm.

results follow the same trend, confirming that excavation depth strongly influences soil resistance. These findings also demonstrate the ability of the numerical model to reproduce soil tool interaction behavior.

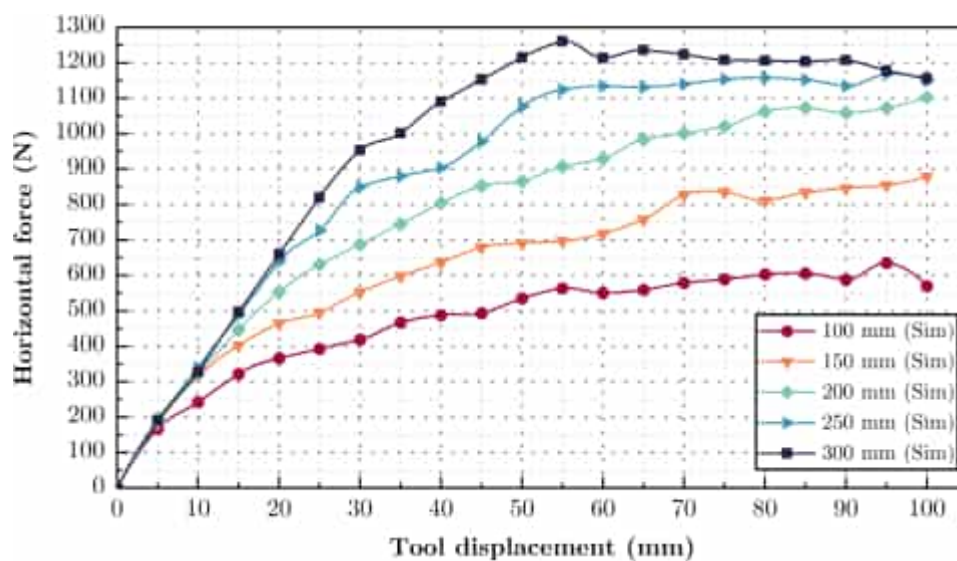


Figure 4.7: Effect of cutting depth (100–300 mm) on horizontal force (RF3) at a 45° rake angle.

In Figure 4.8 the comparison of RF2 and RF3 across rake angles (30° – 90°) demonstrates

that the numerical model effectively captures the overall behavior of both vertical and horizontal forces, though with differing accuracy. For RF3 (draft force), the simulation closely matches the experimental values at all rake angles, indicating that the model reliably represents shear failure, soil cutting, and interface friction. For RF2 (vertical reaction), the simulation reproduces the negative force trend as rake angle increases, but under predicts the magnitude at lower angles (30° and 45°).

The discrepancy narrows at higher angles (75° and 90°), suggesting that the model performs better when the tool geometry induces more concentrated soil deformation. These results validate the model's strength in predicting horizontal resistance while also highlighting that vertical force predictions remain sensitive to soil heave and local detachment, particularly at shallow rake angles.

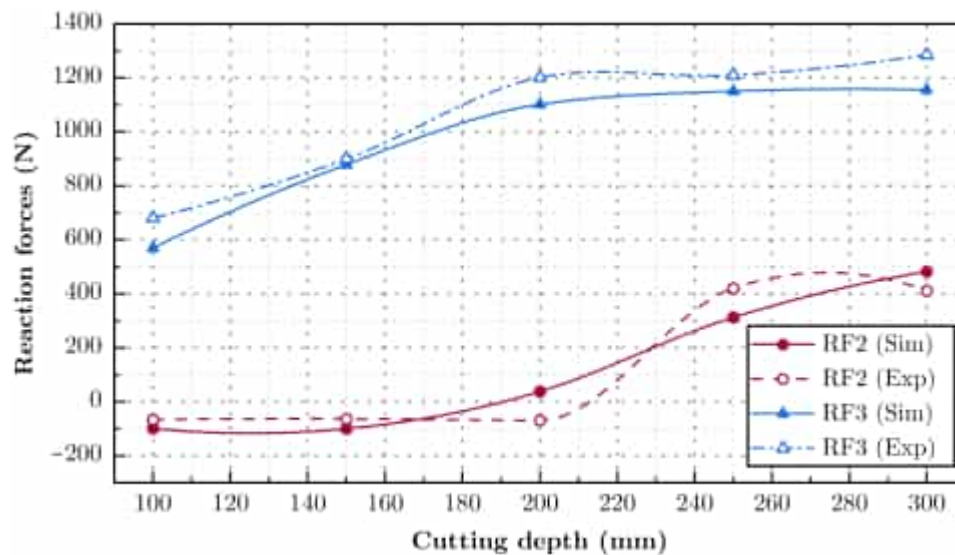


Figure 4.8: Numerical and experimental comparison of vertical (RF2) and horizontal (RF3) reaction forces at cutting depths of 100–300 mm (45° rake angle).

Figure 4.9 shows that the vertical reaction on the tool evolves from a small positive value at the start of motion to a pronounced upward reaction (negative vertical) as displacement increases. From the plotted curve at the chosen 100 mm depth, the vertical force rises briefly to about +25–35 N within the first ≈ 5 to 10 mm (surface disturbance), then declines to roughly –60 N at ≈ 20 mm, and about –120 to –140 N at a depth of 40 to 60 mm. The simulation reaches a minimum around –160 to –170 N in the mid range of displacement before partially recovering to about –100 to –120 N at 100 mm.

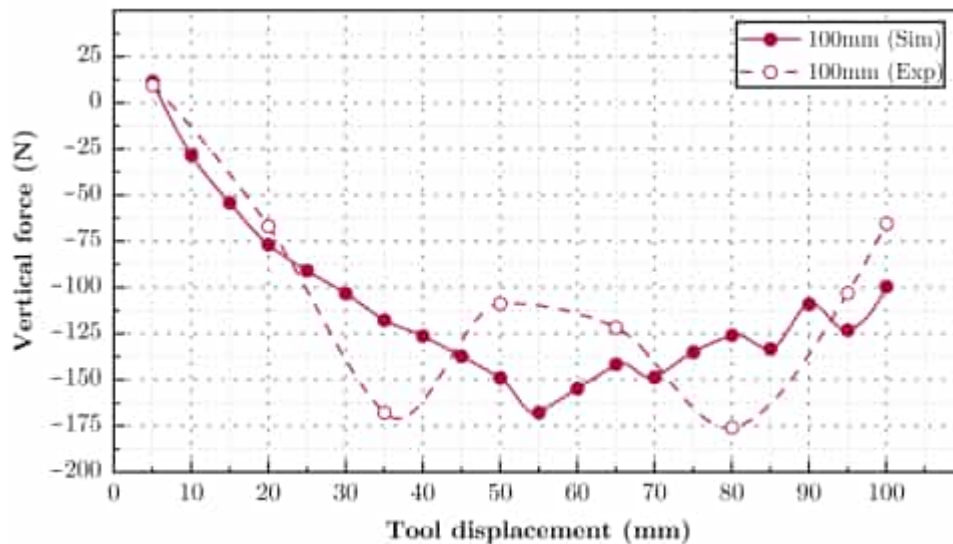


Figure 4.9: Comparison of simulated and experimental vertical force (RF2) at a cutting depth of 100 mm.

The experimental markers follow the same general trend (positive near the first 10 mm, then negative and approaching -100 to -160 N), but individual experimental points deviate from the simulation by roughly 10 to 40 N at several positions. This behaviour initial small downward/upward disturbances followed by sustained uplift is typical for moderate rake angles where the developing failure wedge redirects part of the resistance vertically, producing net uplift on the tool.

Figure 4.10 presents the horizontal (draft) resistance versus tool displacement for the 45° rake; the curve chosen for validation at 100 mm depth shows a rapid mobilization of horizontal force followed by a progressive rise to a plateau and a late peak. Numerically, the draft force increases from about 0 N at 0 mm to roughly 120-140 N by 10 mm, then to ≈ 300 -350 N at 20-40 mm, and continues to climb to about 500-600 N between 60 and 80 mm. The maximum horizontal resistance in both simulation and experiment is observed near the end of the travel, at roughly 620-700 N around 90-100 mm, with small oscillations superimposed.

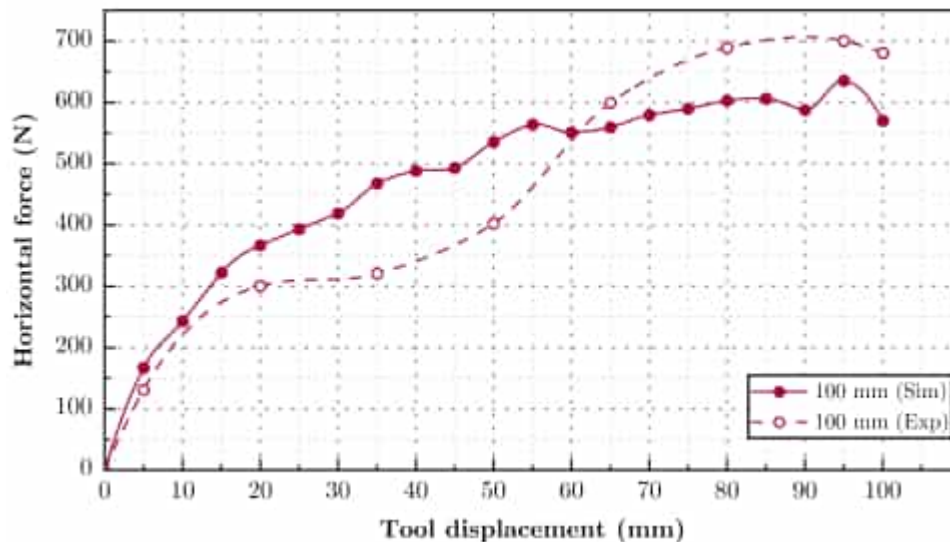


Figure 4.10: Comparison of simulated and experimental horizontal force (RF3) at a cutting depth of 100 mm.

Experimental data points are close to these values (for example, experimental markers near 20, 40, 60 and 80 mm fall near ~ 300 N, ~ 400 -450 N, ~ 550 -600 N, and ~ 680 -700 N, respectively), producing residual errors in the range of tens of newtons but no systematic bias. The simulation captures both the magnitude and trend of the draft resistance at the validated

4.3.3 Effect of Excavation Velocity

4.3.3.1 Velocity 50 mm/s

- **Vertical Reaction Force**

At a cutting velocity of 50 mm/s, Figure 4.11 shows that the vertical reaction force (RF2) exhibits a consistent increase in magnitude with rising rake angle, transitioning from mild uplift at low angles to severe upward resistance at steep configurations.

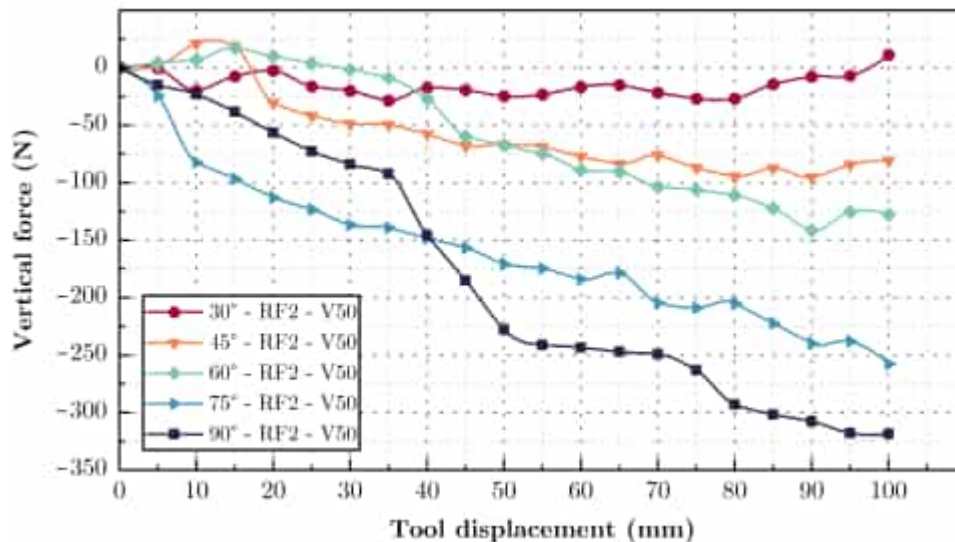


Figure 4.11: Variation of vertical force (RF2) with tool displacement at different rake angles (30° – 90°) at velocity of 50 mm/s.

For 30° , RF2 remains relatively small, fluctuating between approximately -0.5 N and -28 N, indicating limited upward soil movement. Increasing the angle to 45° amplifies the uplift noticeably, with RF2 decreasing steadily to around -80.6 N at full penetration. This trend intensifies at 60° , where the force reaches nearly -141 N, reflecting more pronounced upward redirection of soil. The uplift becomes substantial at 75° , exceeding -239 N, driven by large soil accumulation against the tool face. The steepest angle, 90° , produces the highest uplift forces, culminating at approximately -318 N at 100 mm displacement, confirming that perpendicular cutting maximizes vertical destabilizing loads due to dominant upward soil flow.

Overall, RF2 increases in magnitude as the rake angle steepens, demonstrating a strong geometric influence on soil heave and vertical tool loading.

- **Horizontal Reaction force**

The draft force (RF3) at 50 mm/s shows in Figure 4.12 a clear and progressive increase with both displacement and rake angle, driven by the higher energy required to shear and displace soil as the tool steepens. At 30° , RF3 rises smoothly from 58.9 N to 540.5 N, reflecting efficient cutting with minimal compaction in front of the tool.

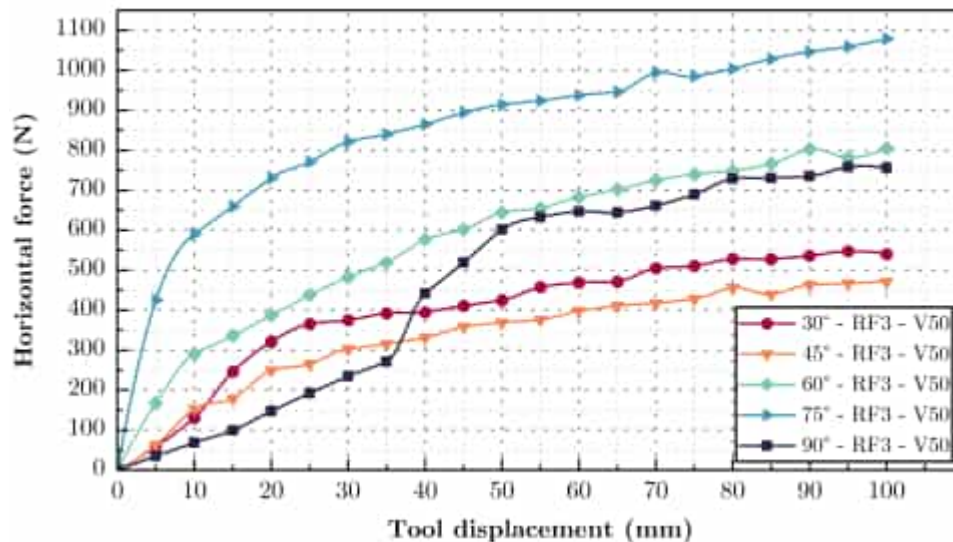


Figure 4.12: Variation of horizontal force (RF3) with tool displacement at different rake angles ($30^\circ - 90^\circ$) at velocity of 50 mm/s.

At 45° , the force remains moderate, increasing from 62.8 N to 471.4 N, slightly lower than the 30° case due to favorable soil flow along the tool face. At 60° , RF3 grows substantially, reaching 805.5 N, as deeper soil engagement increases the horizontal cutting resistance. For 75° , the force becomes considerably higher, exceeding 1079 N, indicating significant soil buildup and high shear demand. The 90° orientation maintains large draft forces throughout the penetration, culminating near 756 N, as the tool pushes soil primarily through compression rather than sliding.

Collectively, RF3 curves demonstrate that higher rake angles dramatically elevate cutting resistance, with the 75° configuration exhibiting the highest energy demand at this velocity.

4.3.3.2 Velocity 100 mm/s

- **Vertical Reaction force**

Figure 4.13 presents the vertical reaction force RF2 exhibits predominantly negative values for all rake angles, indicating that the vertical component of soil resistance acts opposite to the designated positive vertical axis (commonly downward on the tool). The magnitude of RF2 increases in absolute terms with displacement, reflecting the progressive build up of normal pressure on the tool surface as the soil is displaced vertically. Among all tested rake angles, the 45° configuration again shows the smallest vertical reaction, reaching only about -99 N at 100 mm. This lower vertical load suggests more favorable soil flow around the tool and reduced normal stress concentration on the cutting face. By contrast, steep rake angles such as 75° and 90° exhibit markedly higher vertical resistance, with RF2 values of -398 N and -464 N respectively at maximum penetration.

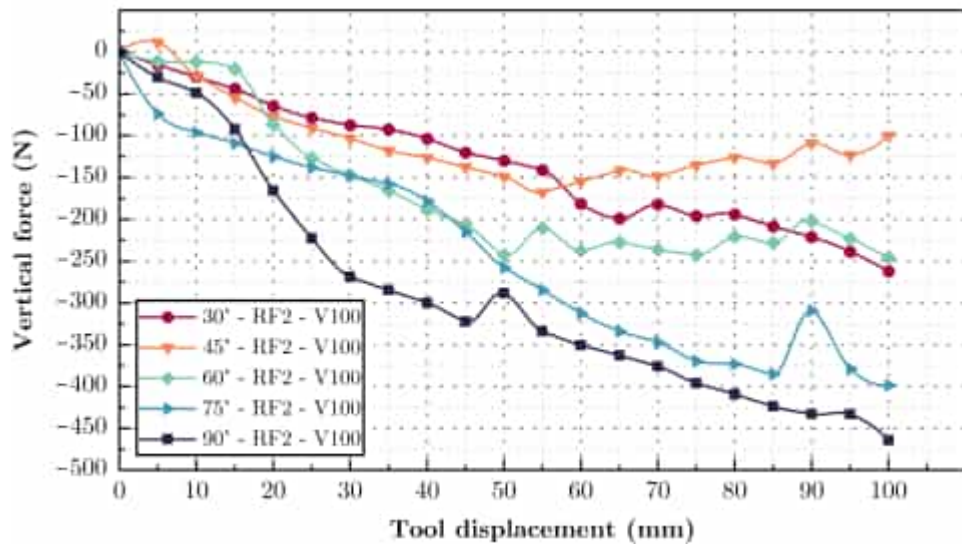


Figure 4.13: Variation of vertical force (RF2) with tool displacement at different rake angles ($30^\circ - 90^\circ$) at velocity of 100 mm/s.

These results indicate that increasing the rake angle intensifies the vertical confinement and compaction of soil against the tool, thereby amplifying the normal loading and mechanical stress imposed on the system. Consequently, a 45° rake angle minimizes vertical resistance and reduces the structural loading transmitted to the tool during excavation.

- **Horizontal Reaction force** The horizontal reaction force RF3 shows in Figure 4.14, which represents the draft force required to advance the tool through the soil, shows a consistent increasing trend with tool displacement for all rake angles, reflecting the growing resistance as more soil is mobilized ahead of the cutting edge. At a velocity of 100 mm/s, the results clearly indicate that the rake angle significantly influences the magnitude of the draft force.

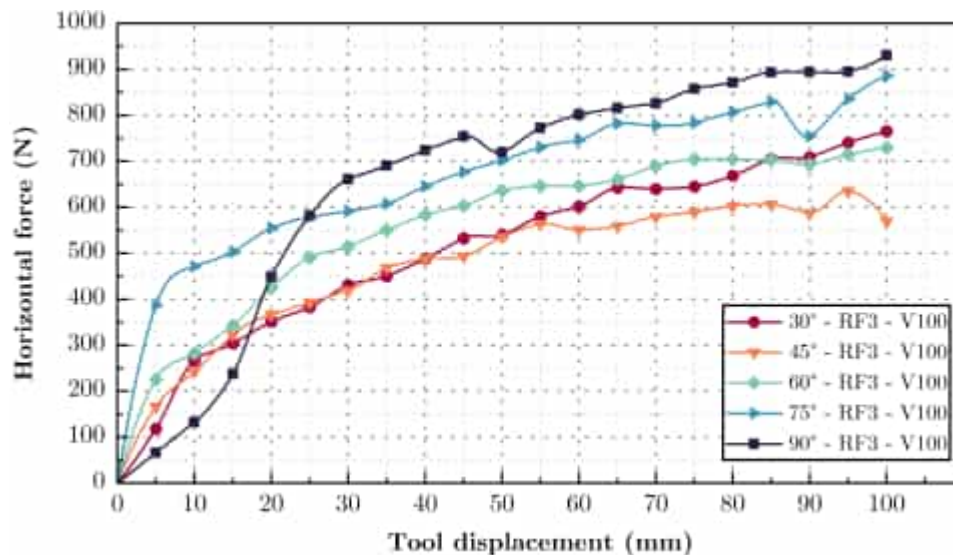


Figure 4.14: Variation of horizontal force (RF3) with tool displacement at different rake angles ($30^\circ - 90^\circ$) at velocity of 100 mm/s.

The 45° configuration consistently exhibits the lowest RF3 values throughout the penetration process, reaching approximately 570 N at 100 mm, suggesting that this angle provides the most efficient cutting geometry by reducing soil tool friction and the extent of soil upward flow. In contrast, higher rake angles, especially 75° and 90° , generate substantially larger draft forces, exceeding 886 N and 930 N respectively at full displacement.

These elevated RF3 values reflect increased passive resistance and reduced soil separation efficiency at steep angles, leading to greater energy demand and higher operating cost. The results confirm that 45° constitutes the optimal rake angle for minimizing horizontal resistance during excavation at this velocity

4.3.3.3 Velocity 200 mm/s

- **Vertical Reaction force)**

For the vertical reaction force RF2 under 200 mm/s, Figure 4.15 represents the data shows predominantly negative values (indicating a downward reaction assuming the positive vertical axis is upward), whose magnitude also depends strongly on rake angle and displacement. At 30° , RF2 starts near *zero* but becomes increasingly negative, reaching about -177 N near 60 mm before fluctuating slightly. At 45° , the vertical reaction becomes more negative more steadily, reaching approximately -378 N at 100 mm, while the 60° rake generates a similar downward load around -118 N initially but deepens to -244 N for larger penetration. For 75° and 90° , the vertical force becomes even more substantial (in magnitude): about -250 N at 75° and reaching -603 N at 90° for displacements around 100 mm.

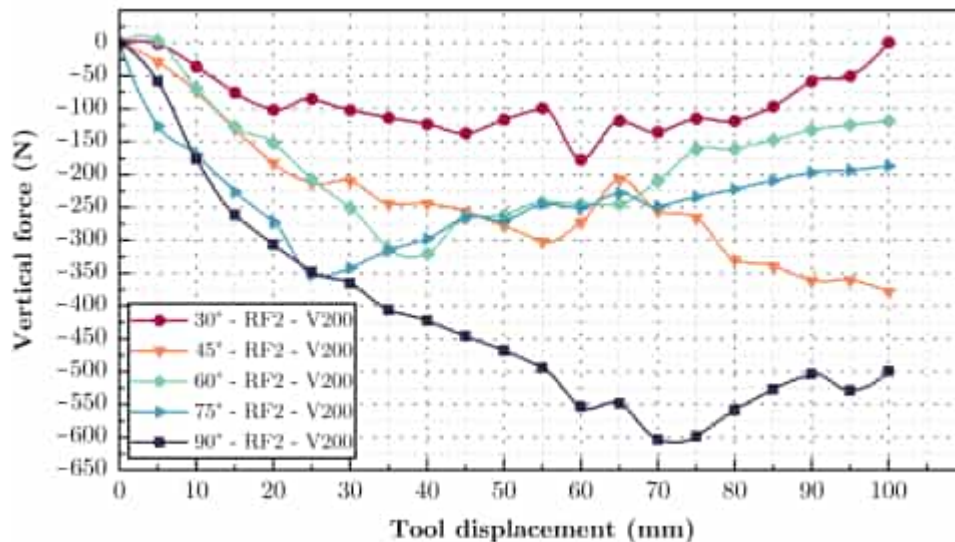


Figure 4.15: Variation of vertical force (RF2) with tool displacement at different rake angles ($30^\circ - 90^\circ$) at velocity of 200mm/s.

These trends suggest that steeper rake angles amplify the normal soil tool compressive load, likely due to increased soil compaction and reduced ability for soil to flow upward along the rake face. This increased vertical load could exacerbate tool wear and risk structural stress under dynamic motion.

- **Horizontal Reaction force**

Figure 4.16 illustrates that the horizontal reaction force RF3 (draft force) exhibits a strong increase with both displacement and rake angle at a tool velocity of 200 mm/s, reflecting significantly greater resistance at higher rake values. For a 30° rake, the draft force rises quickly to approximately 1044 N at 100 mm displacement. As the rake angle increases, the maximum RF3 also increases: 45° produces around 1063 N, 60° yields 1139 N, 75° goes up to 1180 N, and the steepest rake of 90° reaches about 1090 N.

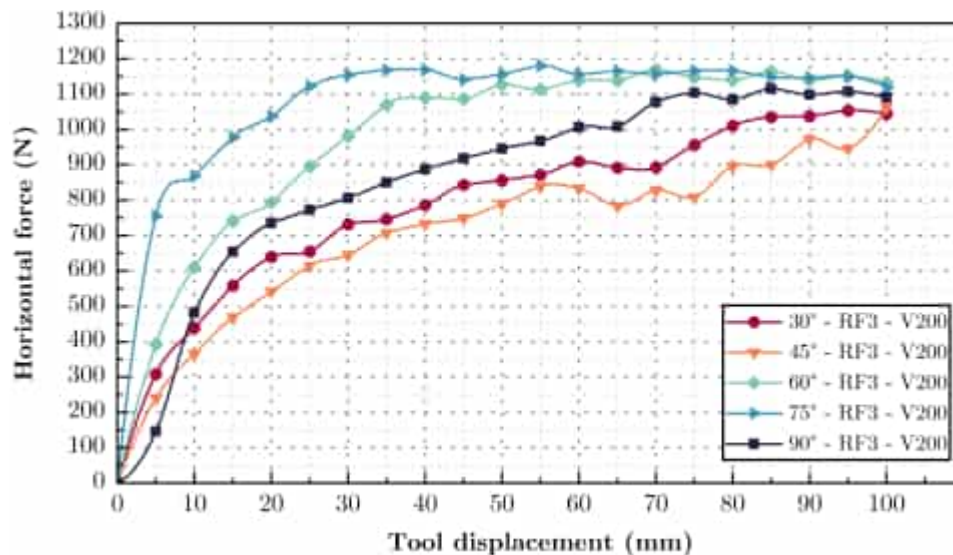


Figure 4.16: Variation of horizontal force (RF3) with tool displacement at different rake angles ($30^\circ - 90^\circ$) at velocity of 200 mm/s.

This trend indicates that more positive rake (steeper) angles lead to a larger soil tool interaction area, increasing horizontal resistance. The particularly sharp rise from 30° to 75° suggests reduced soil separation efficiency and enhanced passive resistance due to more aggressive plowing rather than cutting.

Such behavior implies a trade off: while higher rake angles can geometrically facilitate chip flow, at this high velocity they also generate substantially higher draft forces, which may increase energy demand and machine load.

4.3.4 Cutting depth variation (comparison with experimental results)

4.3.4.1 Effect of Velocity on Vertical Reaction Force

The vertical reaction force (RF2) illustrates in Figure 4.17 exhibits a pronounced sensitivity to both rake angle and tool velocity. At low velocities (50 mm/s), RF2 is slightly positive at shallow rake angles (30°), indicating a minor lifting effect, and becomes increasingly negative as the rake angle increases, reaching maximum downward forces at 90° (simulation: -318.41 N; experiment: -299.41 N). Increasing velocity amplifies downward forces at high rake angles, with the largest values observed at 90° and 200 mm/s (simulation: -499.50 N; experiment: -502.50 N).

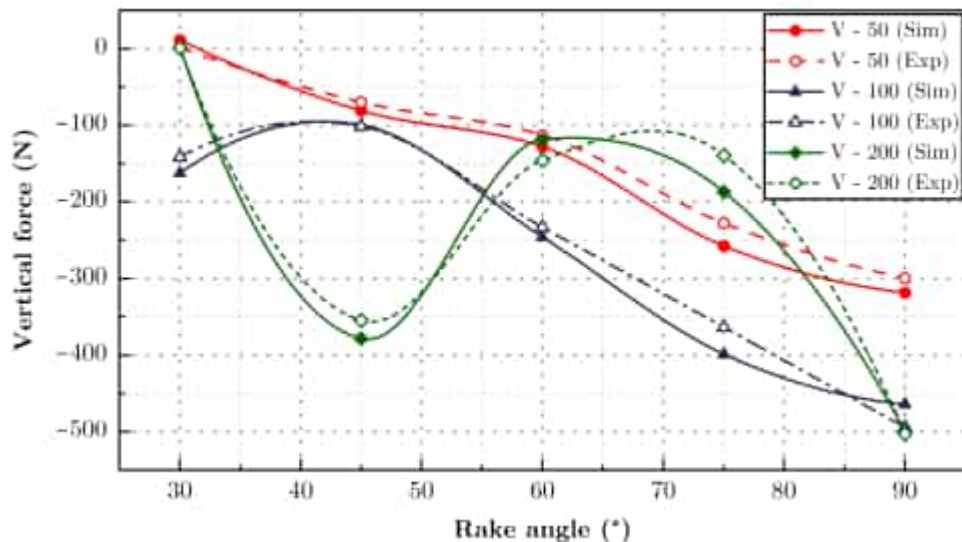


Figure 4.17: Compares vertical reaction forces (RF2) obtained from numerical simulation with the corresponding experimental measurements.

At shallow rake angles and high velocity, RF2 briefly attains small positive values, suggesting dynamic lifting effects likely caused by soil inertia. Overall, the simulations reproduce the general trends and magnitudes observed experimentally, with minor deviations at intermediate angles and velocities attributable to soil heterogeneity and simplifications in the numerical model. These results indicate that shallower rake angles ($30^{\circ} - 45^{\circ}$) at moderate velocities reduce vertical resistance, while steep angles ($75^{\circ} - 90^{\circ}$) at high velocities maximize soil engagement but impose higher vertical loads on the tool.

4.3.4.2 Effect of Velocity on Draft Force

Figure 4.18 shows that the horizontal reaction force (RF3) also demonstrates clear dependence on rake angle and velocity. At low velocity (50 mm/s), RF3 increases with rake angle, peaking around 75° (simulation: 1079.39 N; experiment: 1003.39 N), and slightly decreasing at 90° . As velocity increases, RF3 rises substantially across all rake angles, with the most pronounced values observed at steep angles and high speeds (e.g., simulation at 200 mm/s, 1132 N at 60° ; experiment: 1203 N at 75°), reflecting enhanced forward soil resistance due to dynamic effects. Simulation results align well with experimental measurements, reproducing the overall trends and peak magnitudes, although small discrepancies exist at intermediate angles and higher velocities.

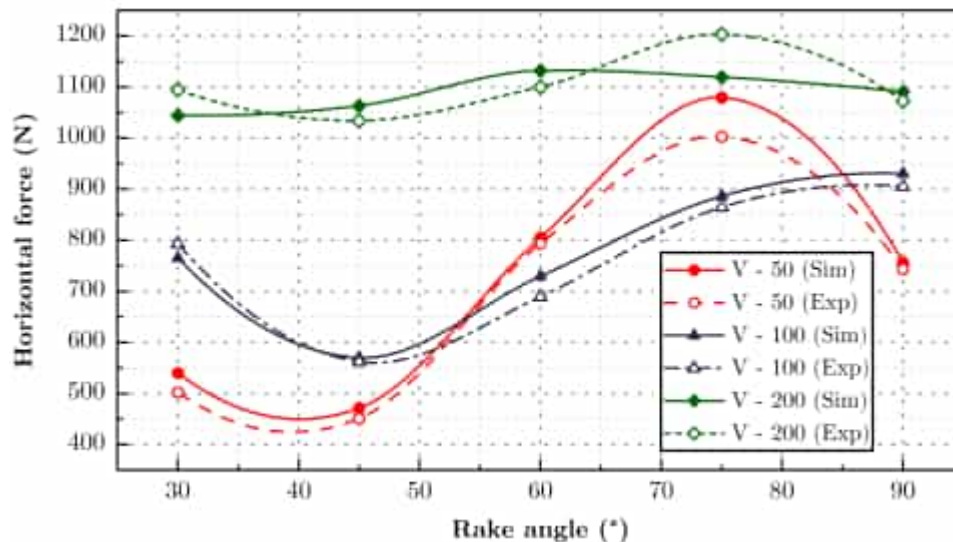


Figure 4.18: Numerical and experimental comparison of horizontal reaction force (RF3).

These findings indicate that horizontal resistance is minimized at shallow rake angles ($30^\circ - 45^\circ$) and moderate velocities, facilitating energy-efficient operation, whereas steep rake angles combined with high velocities increase forward resistance and soil engagement, which may be advantageous for intensive excavation tasks but require higher operational forces.

4.3.4.3 Comparison between velocities

As the tool velocity rises from 50 to 200 mm/s, both the draft force (RF3) and the vertical reaction force (RF2) show clear sensitivity to speed, albeit with different trends in magnitude and roughness. At the slowest speed (50 mm/s), RF3 values for all rake angles are relatively modest (ranging from roughly 36 N to just over 1,000 N as rake increases), reflecting limited inertial or dynamic resistance but still showing the dominant effect of rake geometry. When velocity is increased to 100 mm/s, RF3 generally increases for each rake angle, but the lowest draft force remains at 45° , indicating that this rake angle optimizes cutting efficiency by minimizing horizontal resistance. At the highest speed (200 mm/s), the draft force dramatically escalates, particularly for steep rake angles: RF3 peaks at over 1,100 N at 60° and 75° rake, showing that dynamic loading and soil plowing effects amplify significantly at high advance velocities.

In parallel, the vertical reaction RF2 also intensifies with increasing speed and rake, but with more complex behavior. At 50 mm/s, RF2 remains relatively low (in magnitude) even for higher rake angles (-317 N at 90°), suggesting modest compressive normal loading. Increasing the speed to 100 mm/s leads to deeper negative vertical reactions, especially at extreme rake angles (75° and 90°), though the 45° configuration still produces the smallest RF2, indicating a favorable balance of vertical loading. When the velocity moves to 200 mm/s, vertical forces become substantial: the 90° rake produces RF2 near -600 N, while 75° also yields a very large downward reaction. This progression implies that higher speeds intensify the normal stress on

the tool, especially at steep rake angles, likely due to increased compaction, frictional contact, and more aggressive soil plowing under dynamic conditions.

4.3.5 The Adequate Excavation Velocity and Rake Angle

Across the parametric study, the configuration that minimizes both horizontal resistance and vertical loading is a rake angle of 45° operated at a moderate velocity, with 50 mm/s providing the lowest absolute forces and 100 mm/s representing an acceptable compromise when productivity must be increased. At 45° and 50 mm/s the draft force (RF3) and the vertical reaction (RF2) remain substantially lower and evolve more smoothly with displacement than for shallower or steeper rake angles, indicating efficient soil separation, reduced ploughing, and lower normal stress concentration on the cutting face; this condition therefore minimizes energy demand, diminishes tool wear, and reduces structural loading. If higher advance rates are required for throughput, 45° at 100 mm/s retains the lowest draft among tested angles while incurring only moderate increases in vertical load, making it the preferred compromise between productivity and mechanical efficiency. By contrast, velocities near 200 mm/s, particularly combined with steep rakes ($\geq 75^\circ$), produce pronounced increases in RF3 and RF2 due to dynamic ploughing and compaction effects and should be avoided when the objective is to minimize force and extend tool life.

4.4 Comparison Between Experimental and Numerical Results

4.4.1 Soil-Tool Interaction Behavior

The SPH based simulations provided detailed insights into the dynamic behavior of soil during excavation. The model captured the full evolution of soil flow, displacement fields, and reaction forces as the bucket tooth progressed through the clayey sand medium. Visualization of the soil domain revealed the development of shear zones and localized deformation patterns around the tool edge, consistent with the soil failure mechanisms observed in the soil-bin test.

As the tool advanced, soil heave was clearly observed in front of the cutting edge, with particle displacement indicating the formation of a plastic zone extending from the tool tip into the surrounding soil. The simulations demonstrated how soil is displaced both vertically and horizontally, with the magnitude and direction of flow dependent on the rake angle, cutting depth and tool velocity. At intermediate rake angles ($30^\circ - 60^\circ$), soil tended to flow smoothly along the tool face, producing moderate heave and minimal resistance, whereas at steeper angles ($75^\circ - 90^\circ$), soil accumulation in front of the tool led to higher compaction and increased vertical

and horizontal reaction forces.

In addition to the effects of rake angle and depth, the simulations revealed a clear sensitivity of the soil response to variations in cutting velocity. Increasing the velocity led to a reduction in the vertical reaction force RF2, attributed to the shortened time available for the development of vertical stresses under rapid loading conditions. Conversely, the horizontal reaction force RF3 increased with higher velocity, driven by intensified forward soil displacement and higher draft resistance under dynamic conditions.

The FEM outputs also provided continuous time resolved reaction force curves, capturing both the initial transient phase of cutting and the subsequent steady state behavior. Vertical forces (RF2) were initially negative at shallow depths, reflecting downward resistance, and increased with displacement, eventually becoming positive at greater depths due to soil uplift and heave effects. Horizontal forces (RF3) increased steadily throughout the cutting process, reflecting the progressive accumulation of soil in front of the tool. The simulation successfully reproduced the characteristic trends of soil tool interaction: initial ease of penetration, followed by increasing resistance as the tool advances and soil flow reaches equilibrium. These patterns were in excellent agreement with experimental measurements, validating the physical realism of the FE model.

4.4.2 Model Accuracy and Comparative Evaluation

The Table 4.1 summarizes the predictive capability of the numerical model under three key operating conditions: depth variation, rake angle variation, and velocity variation. The metrics used MAPE and R^2 provide complementary insight into the model's accuracy and its ability to reproduce the experimental trends. Overall, the results indicate that the numerical model captures the essential behavior of soil tool interaction, although its performance varies depending on the loading condition and the force component considered.

4.4.2.1 Depth Variation (100 – 300 mm)

For depth variation, the horizontal reaction force (RF3) exhibits low error (MAPE $\approx 8.76\%$) and a strong correlation ($R^2 \approx 0.85$), indicating that the model reliably predicts cutting resistance as penetration depth increases. Conversely, the vertical reaction force (RF2) shows higher deviation (MAPE $\approx 61.76\%$) despite a good correlation ($R^2 \approx 0.89$). This behavior reflects the well-known difficulty of accurately modeling soil heave, upward displacement, and detachment mechanisms, which strongly influence vertical forces. Thus, while depth-dependent RF3 responses are captured effectively, RF2 remains more sensitive to local soil disturbances and requires additional model refinement.

4.4.2.2 Rake Angle Variation ($30^\circ - 90^\circ$)

When rake angle varies, both force components show moderate predictive accuracy but with contrasting patterns. The model reproduces the trend of RF2 with reasonable reliability (MAPE $\approx 19.25\%$, $R^2 \approx 0.836$), suggesting that the changes in vertical loading due to tool orientation are well represented. For RF3, the model achieves acceptable but weaker correlation ($R^2 \approx 0.733$), even though the error remains low (MAPE $\approx 7.95\%$). This indicates that while the magnitude of draft forces is predicted accurately, the detailed evolution of horizontal resistance with rake angle is more complex, likely due to changes in soil flow direction, shear band formation, and tool-soil interface dynamics.

4.4.2.3 Velocity Variation (50 – 200 mm/s)

Velocity variation produces the largest contrast between RF2 and RF3 behavior. The horizontal force (RF3) shows excellent agreement between simulation and experiment (MAPE $\approx 3.84\%$ and $R^2 \approx 0.97$). This confirms that draft force increases with velocity in a predictable manner dominated by shear failure and rate-dependent interface friction mechanisms that the numerical model handles very well. In contrast, RF2 exhibits very strong correlation ($R^2 \approx 0.979$) but a high error level (MAPE $\approx 78.78\%$). This combination suggests that the model captures the overall shape and trend of the RF2 curve with velocity, but struggles to match the exact force magnitude. Vertical forces are influenced by transient soil heave, compaction waves, and rapid deformation patterns that intensify at higher speeds, making them inherently more difficult to simulate with precision.

Table 4.1 quantitative comparison between simulated and experimental reaction forces obtained under different operating conditions. RF2 corresponds to the vertical reaction force and RF3 to the horizontal reaction force. The mean absolute percentage error (MAPE) expresses the average deviation between predicted and measured values, while the coefficient of determination (R^2) measures the strength of the correlation. Depth variation refers to tests performed at different penetration depths, and rake angle variation refers to tests at different tool rake angles.

Table 4.1: Accuracy assessment of numerical predictions relative to experimental results for vertical and horizontal reaction forces, based on MAPE (%) and R^2 , under different operating conditions.

Operating condition	Force component	MAPE(%)	R^2	Comment
Depth variation (100–300 mm)	RF2: Vertical reaction force	61.76	0.890	Strong correlation but higher deviation due to soil heave and detachment effects
	RF3: Horizontal reaction force	8.76	0.850	Low error and stable correlation; accurate prediction of draft forces
Rake angle variation (30–90°)	RF2: Vertical reaction force	19.25	0.836	Consistent trend captured with moderate deviation
	RF3: Horizontal reaction force	7.95	0.733	Acceptable agreement; force evolution well reproduced
Velocity variation (50–200 mm/s)	RF2: Vertical reaction force	78.78	0.979	Very strong correlation but high deviation due to rate-dependent soil heave and vertical oscillations
	RF3: Horizontal reaction force	3.84	0.970	Excellent accuracy; draft force variation with velocity is very well captured

4.4.2.4 Global Evaluation

Taken together, the results show that the model performs consistently better for RF3 (draft force) across all conditions, with low error and high correlation in most cases. RF3 is governed primarily by shear resistance, a mechanism that is reliably represented by the chosen constitutive model and the numerical formulation. On the other hand, RF2 is more challenging due to its dependence on three-dimensional soil movement, heave, and localized detachment, which are sensitive to mesh density, contact algorithms, and material softening behavior.

The model therefore demonstrates robust predictive capability for horizontal loading and good trend level accuracy for vertical loading, while identifying key areas particularly high

Note: The coefficient of determination (R^2) in Table 4.1 measures the agreement between predicted and experimental results. It ranges from 0 to 1, with values near 1 indicating strong correlation and high model accuracy. In soil tool interaction studies, $R^2 > 0.8$ denotes excellent agreement, while $0.6 \leq R^2 \leq 0.80$ indicates good consistency suitable for engineering use.

velocity vertical reactions where further refinement of soil constitutive parameters or damping schemes may improve quantitative agreement.

4.5 Conclusion

The influence of rake angle, cutting depth, and tool velocity on the vertical (RF2) and horizontal (RF3) reaction forces was systematically analyzed through both experimental testing and numerical simulation. The results demonstrated clear trends: vertical resistance generally increased with rake angle and tool velocity, while horizontal resistance rose with both velocity and, to a lesser extent, rake angle. Comparisons between experimental and simulation data showed good agreement, confirming the reliability and predictive capability of the numerical model.

The findings highlight that shallower rake angles ($30^\circ - 45^\circ$) at moderate velocities reduce both vertical and horizontal forces, suggesting conditions for energy-efficient excavation. Conversely, steep rake angles ($75^\circ - 90^\circ$) combined with higher velocities maximize soil engagement, leading to higher operational forces but potentially more effective cutting. Based on the analysis, the optimal excavation parameters are identified as a rake angle of 45° , a cutting depth of 100 mm, and a tool velocity of 100 mm/s, which together provide a balance between soil engagement, tool resistance, and operational efficiency.

This chapter confirms that the developed simulation methodology can accurately replicate experimental observations, providing a robust tool for optimizing excavation parameters and guiding the design of soil tool interactions.

General Conclusion

This thesis addressed the challenging problem of soil tool interaction in excavation processes, a phenomenon governed by highly nonlinear soil behavior, large deformations, and complex failure mechanisms at the interface between soil and excavation tools. Understanding and accurately predicting these interactions is essential for improving excavation efficiency, reducing energy consumption, and enhancing tool durability in civil, geotechnical, and mining engineering applications. Given the limitations of conventional experimental and numerical approaches, this research tried to develop a more realistic and reliable framework for modeling excavation processes under representative operating conditions.

To meet this goal, a combined experimental and numerical methods was adopted. Laboratory tests, including direct shear and soil bin experiments, provided essential data for characterizing soil behavior and validating numerical predictions. On this basis, a Smoothed Particle Hydrodynamics (SPH) modeling framework coupled with a Mohr-Coulomb constitutive law was developed to simulate soil tool interaction. Unlike traditional mesh based finite element approaches, the SPH method proved effective in capturing large soil deformations, material separation, and soil flow without numerical instability or remeshing requirements. Using a real scale excavation tool, rather than simplified geometries, further enhanced the practical relevance and realism of the simulations.

The numerical results showed strong agreement with experimental measurements, especially in terms of vertical and horizontal reaction forces, confirming the robustness and predictive capability of the proposed SPH based model. Parametric analyses showed excavation forces are influenced by tool rake angle, cutting depth, and tool velocity. The study identified an ideal operating configuration characterized by a rake angle of 45° , a cutting depth of 100 mm, and a tool velocity of 100 mm/s, that offers a favorable compromise between excavation efficiency and energy consumption. These findings underline the critical role of tool geometry and operating parameters in controlling excavation performance.

Beyond methodological validation, this research provides valuable insights for the design and optimization of excavation tools. The results highlight the importance of incorporating realistic tool geometries, including teeth and curvature, to better replicate field conditions and improve predictive accuracy. The proposed framework therefore represents a practical tool for engineers

seeking to optimize excavation operations for specific soil types and working conditions.

Recommendations

Based on the findings of this study, several recommendations can be proposed for future research. including systematic optimization of tool geometry, investigation of multi tooth and adjustable tools, and extension of the model to account for more factors such as soil moisture variability and field scale validation. Overall, this thesis shows the integration of experimental testing with SPH based numerical modeling is a powerful and reliable approach for analyzing soil tool interaction, contributing to More efficient, cost effective, and sustainable excavation and earthmoving practices.

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