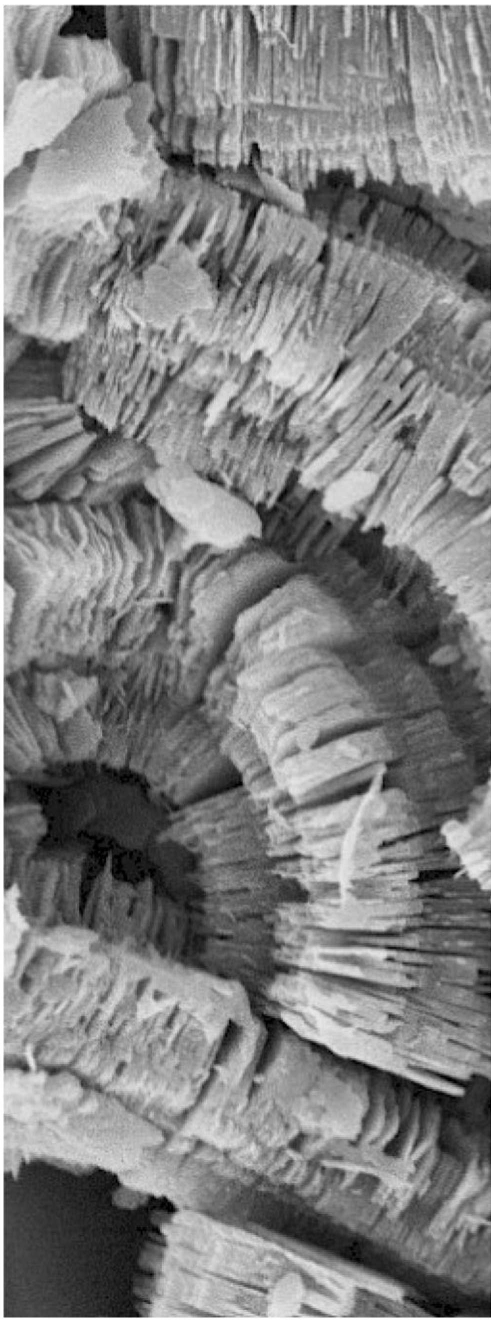
Evaluating the use of constants in a theoretical clay-cutting model



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Evaluating the use of constants in a theoretical clay-cutting model

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Summary
The aim of this thesis is to assess the reliability and accuracy of Miedema's clay-cutting model by critically examining its underlying assumptions and investigating potential discrepancies. The research questions revolve around identifying the inconsistencies in nomenclature, evaluating the chosen strain rate value, assessing adjustments made to shear rate formulation, exploring the relationship between shear angle and the strengthening factor, and lastly investigating a suitable design for a cutting rig for studying clay's mechanical properties. To address these research questions, a comprehensive methodology has been employed. The study begins with a critical analysis of Miedema's model, comparing it with the findings of Hatamura and Chijiiwa to identify discrepancies in nomenclature and clarify definitions. Next, data from Hatamura and Chijiiwa's experiments are used to calculate strain and strain rate, providing insights into the accuracy of Miedema's chosen strain rate value.
The findings of this comparative study ultimately aim to contribute to the development of more accurate cutting models for the dredging sector. As a result, the thesis enhances the reliability of Miedema's clay-cutting model. The insights gained from this research have implications for the broader understanding of clay-cutting processes in dredging.

Abstract
The primary objective of this study is to evaluate the accuracy of Miedema's model for clay cutting. The results reveal several critical issues and discrepancies within Miedema's theory. The nomenclature used by Miedema lacks clarity and deviates from the definitions provided by Hatamura and Chijiiwa. The assumption of a constant strain rate of 0.03 1/s, derived from Hatamura and Chijiiwa, is found to be inaccurate. Instead, the calculated strain rate values align with those reported by the Japanese researchers, indicating a need for reassessment.
Furthermore, the study highlights the contrasting definitions of the strengthening factor between Wismer and Luth's original formulation and Miedema's modified expression. The calculated values deviate significantly, indicating the necessity for a comprehensive reevaluation of the calculation of the strengthening factor and its relationship to the strain rate in clay cutting models. Moreover, the investigation reveals that the shear angle significantly influences the strengthening factor, contrary to Miedema's assertion of limited dependence. Modifying the shear angle results in corresponding changes in the strengthening factor, emphasizing the importance of considering the shear angle in clay cutting models.
In conclusion, this study exposes limitations and discrepancies within Miedema's cutting theory for clay. The assumptions of constant values, unclear nomenclature, and inconsistencies in strain rate and strengthening factor calculations undermine the accuracy of the model. These findings call for further research and refinement of Miedema's theory, considering specific clay characteristics and behaviors, to develop more accurate and reliable clay-cutting models.

Acknowledgments
I am grateful to Damen Dredging Equipment, specifically to Frank Bosman for giving me the invaluable opportunity to immerse myself in the PhD project led by Mark Winkelman. This experience has allowed me to gain a deeper understanding of the field of research and its incredible potential. I would like to express my sincere gratitude to Mark Winkelman for his exceptional mentorship and guidance throughout this journey. Not only has he taught me a great deal about dredging, but he has also emphasized the significance of effective communication. Moreover, I extend my appreciation to the Research Development and Innovation department at Damen for their continuous support. Furthermore, I would like to express my gratitude to Marco Gatto for his guidance and support throughout my graduation project. His mentorship and trust in my abilities have played a big role in encouraging me to excel. I am truly grateful for his expertise, dedication, and belief in my potential.
Lastly, I would like to extend my heartfelt thanks to my parents, Gharsa and Mohammed, for their unwavering support through these years and their belief in my abilities. I am also grateful to my brother Amin and sister Arij; their love has been a constant source of strength.

6th June 2023, Middelburg

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Nomenclature

A	Adhesive force on the blade	kN
a	Adhesion	kPa
C	Cohesive force on the shear plane	kN
c	Cohesion	kPa
E	Energy level	J/kmol
E_a	Activation energy level	J/kmol
E_l	Limiting (maximum) energy level	kPa
E_{sp}	Specific cutting energy	kN/m^2
F_h	Horizontal cutting force	kN
F_v	Vertical cutting force	kN
h_b	Blade height	m
h_i	Layer thickness	m
N	Avogadro constant (6.02·1026 1/kmol)	-
p	Probability	-
R	Universal gas constant (8314 J/kmol/K)	J/kmol/K
T	Absolute temperature	K
v_c	Cutting velocity	m/s
w	Blade width	m
r	Ratio adhesive force to cohesive force	-
α	Blade angle	rad
β	Angle of the shear plane with the direction of cutting velocity	rad
$\dot{\varepsilon_0}$	Strain rate	1/s
λ	Distance between equilibrium positions	m
λ_a	Strain rate factor adhesive force	-
λ_c	Strain rate factor cohesive force	-
λ_{HF}	Horizontal cutting force coefficient for the Flow Type	-
λ_s	Strain rate factor average adhesion and cohesion, Strengthening factor	-
τ_0	Dynamical shearing resistance factor (material property)- Miedema	kPa
τ_y	Shear strength (yield stress, material property)- Miedema	kPa
σ	Normal stress	kPa
σ_e	Effective stress	kPa

1. Introduction

1.1 Host Organization

Damen Dredging Equipment, originally known as De Groot Nijkerk, started as a dredging contractor in the late 1930s for the development of the IJsselmeer polders. The company then shifted its attention to dredger maintenance, both for its dredgers and those of partner contractors. The company expanded its business, leading to the creation of Damen Dredging Equipment. It is located in Nijkerk, Netherlands, and is a subsidiary of the Damen Shipyards Group. The company specializes in the design, manufacturing, and delivery of dredging equipment for various applications. Since its inception, Damen Dredging Equipment has constructed several dredgers and provided maintenance and customization services for its machines. As with all Damen yards, DDE builds vessels on stock, and prepares them for outfitting. Moreover, the company provides customized dredgers with fast lead times at reasonable costs.

Figure 1:
DAMEN Dredging Equipment, Nijkerk

1.2 Background

Dredging has been a fundamental activity that has significantly contributed to the development of civilization. At its core, dredging involves the excavation of material from water bodies such as rivers, lakes, and seas, and the relocation of the extracted material to a new deposition area. This process is instrumental in increasing the navigable depths of ports, harbors, and shipping channels, thus facilitating international trade and commerce. Dredging can also be deployed to improve drainage, reclaim land, strengthen marine and river defenses, or for environmental purposes.

The importance of technological advancement within dredging can be traced back to ancient times when sand and clay were excavated by hand. The first-ever recorded dredging project was initiated by the Egyptian Pharaoh Senausert III, who envisioned connecting the Red Sea and the Mediterranean (Georg Halim Kirlus, 1964). This project was a significant feat of engineering at the time and laid the foundation for future dredging projects.

A project that stands out in innovation and technology, is the construction of the Panama Canal, which utilized cutting-edge technologies to make a modern marvel of engineering. The Panama Canal required extensive dredging to create a navigable waterway that could accommodate large ships. The project involved the use of powerful dredging equipment, such as suction dredgers and cutter suction dredgers, which could extract large amounts of material quickly and efficiently. Thus, while the first dredging project was carried out using simple technologies and manual labor, the construction of the Panama Canal demonstrates the enormous strides that have been made in dredging technology over the centuries.

Figure 2:

Satellite view of the Pacific Ocean entrance to the Panama Canal before (left, November 20, 2002) and after (right, June 11, 2016) the Expansion Project.

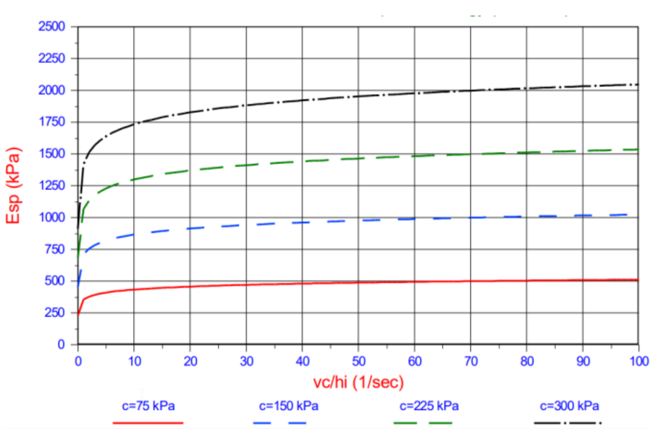
Note. "From HySpeed Computing LLC, 2016"

According to demographic and economic projections, dredging will continue to be necessary for the foreseeable future; as a fact, statistics imply that human engagement with water-related concerns will continue to grow over time. Presently, about 70% of the world's population lives within 80 kilometers of a shoreline or river system. As coastal populations grow, so will the demand for residential, employment, and recreational amenities, as well as beach protection and other health and safety standards (Peter Hamburger, 2003). Moreover, the necessity of waterborne transportation of goods and commodities will become apparent, making clear the necessity of having accessible ports and harbors. According to Peter Hamburger, Secretary General of the International Association of Dredging Companies (IADC), dredging must be an integral part of any infrastructure plan to ensure that ports and harbors, as well as residential and recreational areas, can fulfill the increasing needs.

Other than sand and rock, clay is one of the three most frequent soil types found in waterbodies beds. Due to the cohesive nature of clayey soil, the dredging process could be challenging. During the cutting of clay, the mechanical stress imparted by the cutting tools aims to break the attractive forces between the clay particles. The cutting process can, however, cause the clay particles to become more compacted, which can increase their cohesion and make them more difficult to dredge. The cutting process can also influence the adhesion; when clay is getting cut it can be exposed to new surfaces which might have different adhesive properties than the previous surface. This affects how clay interacts with other materials, such as the cutter head or the deposition surface (T. A. A Combe, 2015). When clay is broken by the dredger, clumps of material can indeed attach to the cutter head and cause the tool to clog, causing not only the impossibility to cut additional material but also issues when traveling through the discharge pipeline.

Research and innovation play a vital role in the dredging industry, particularly in the context of clay dredging. As discussed earlier, dredging clay is a complex process due to the cohesive nature of the material. This complexity requires an in-depth understanding of the physics and in the processes involved in the cutting mechanism. The challenges that are encountered when dredging clay enhance the necessity of analytical models that describe the resulting cutting mechanism. However, because of the nature of clay, presently, there are no models capable of describing the soil behavior accurately. By understanding the behavior of clay, it is indeed possible to optimize dredging activities and raise overall productivity. Miedema, in “The Delft Sand, Clay & Rock Cutting Model” (2016), has formulated a model that describes the cutting mechanisms for the different types of soils, the model is widely used within the dredging sector, for example to design new equipment. The second tool often employed is the graph represented below which allows to estimate production when dredging clay, **Figure 3**.

Figure 3:
Strain Rate Effect on the Specific Energy



Note. (Miedema A. Sape , 2016)

This research is focused on the evaluation of the clay-cutting model introduced by Miedema in 2016. As this model is widely utilized, it is necessary to conduct a thorough analysis to identify any limitations and discrepancies. To accomplish this, a comprehensive investigation has been undertaken. Furthermore, for future purposes, a cutting rig has been specifically designed to allow the validation of the theory and enable a deeper exploration of the failure mechanisms associated with clay cutting. The cutting rig is indeed a crucial tool, as it allows the collection of data from various types of clay subjected to different cutting parameters. Ultimately, the evaluation of Miedema's clay-cutting model aims to enhance the understanding of the fundamental principles underlying clay cutting and advance the knowledge in this field.

The outcomes of this research have the potential to improve the accuracy and reliability of future clay-cutting predictions. To conclude, it can be said that research and innovation are critical components in the dredging industry, particularly in the context of clay dredging. Continued investment in research and innovation is necessary to improve the efficiency and sustainability of dredging activities and to address the social challenges above mentioned. As such, this research proposal represents a step in advancing understanding of the clay-cutting process with the final aim of optimizing advancements within dredging.

1.3 Problem Statement

Dredging operations face significant challenges when dealing with clay due to its cohesive nature. The material properties of clay are highly influenced by its water content, making it inherently complex to accurately describe and model the cutting process.
In literature several models describe the behavior of clay during the cutting mechanism, the focus of this research is to analyze "The Delft Sand, Rock & Clay Cutting Model" (Miedema A. Sape , 2016). The model relies solely on the empirical findings of Hatamura and Chijiiwa that analyze the shearing behavior of Kanto loam through a cutting rig.
Through an extensive analysis of the theoretical model of Miedema as well as Hatamura and Chijiiwa reports, several shortcomings have been identified within Miedema's clay cutting model. These shortcomings form the scope of study for this research. Considering its potential implications for dredging operations, it is crucial to assess the reliability and predictive accuracy of the model. By conducting a thorough analysis, the aim of this research is to evaluate Miedema's model by understanding its limitations and the points in which the model falls short.

The first issue to be addressed within Miedema's cutting-clay model is the deviation between Miedema's nomenclature and Hatamura and Chijiiwa's nomenclature.
There is indeed a disparity between the dynamical shear resistance factor[1] defined by Miedema (4 kPa) and the actual value reported by Hatamura and Chijiiwa (28 kPa), this raises indeed questions about the origin and accuracy of Miedema's chosen value. Additionally, Miedema considers the shear strength to be equal to 28 kPa, further contributing to the inconsistency and lack of clarity in the model's definitions. These discrepancies undermine the accuracy, reliability, and applicability of the model. Resolving these nomenclature and parameter discrepancies is crucial for precise and unambiguous definitions of the cutting theory.

The second problem in Miedema's cutting-clay model relates to the strain rate definition incorporated in the theory. It deviates indeed from the calculated strain rate of Hatamura and Chijiiwa. While Miedema cites a strain rate of 0.03 1/s, Hatamura and Chijiiwa's actual calculations indicate a strain rate of 3 1/s. This discrepancy raises significant doubts about the accuracy and validity of Miedema's chosen strain rate values.
Miedema extensively utilizes the strain rate (0.03 1/s), shear strength (28 kPa), and the dynamical shear resistance factor (4 kPa) within his theory. The mismatch between values suggests that Miedema may be relying on incorrect quantities. This highlights the need for more precise parameter selection in the model and emphasizes the importance of accurately determining the strain rate associated with the cutting process. By addressing these issues, the model's reliability and accuracy can be improved.

Another problem in Miedema's cutting-clay model arises from the adjustments made to the formulation of Wismer and Luth's strength rate. Miedema introduces a "constant" of 0.03 to their formulation, fitting it to Hatamura and Chijiiwa's constant. However, considering the

[1] In the context of Miedema's theory, the term "shear dynamical resistance factor" is utilized, despite the inclusion of the unit kPa. It is worth noting that factors, by definition, are typically dimensionless quantities.

earlier discussion, this raises concerns about the appropriateness of this approach and the accuracy of the associated parameter values within the context of clay-cutting models.

Moreover, to assess the validity of Miedema's claim regarding the minimal influence of shear angle on the strengthening factor and horizontal forces in clay cutting, an examination of the relationship between the shear angle and the strengthening factor is necessary. Miedema's shearing factor formulation acknowledges that the strengthening factor varies with different shear angles. However, Miedema not only he considers certain parameters, such as τ_0, τ_y, and $\dot{\varepsilon}_0$, as constants for all types of clays, but he also asserts that the strengthening factor for clays can be universally regarded as 2 for velocities used in dredging.
An investigation into the actual variations of the strengthening factor for different shear angles is crucial to verify the accuracy of Miedema's assumption. By analyzing these variations, a deeper understanding of the influence of shear angles on the strengthening factor in clay cutting can be gained.

By addressing these problems, the research aims to critically evaluate Miedema's clay-cutting model, identify its limitations and discrepancies, and contribute to the development of more accurate and reliable clay-cutting models for practical dredging applications.
Furthermore, it is essential to acknowledge that the main limitation of Miedema is that his formulations are based on findings from a single research study. While Miedema's work provides valuable insights into the cutting behavior of clay, it is imperative to recognize the need for a broader re-evaluation of his proposed model. Therefore, this research aims to expand upon Miedema's work by incorporating information from the literature and by conducting a comprehensive analysis.

1.4 Research Question

Based on the problem statement, the main research question is as follows:

“What are the discrepancies within Miedema's clay-cutting model that have an impact on its reliability and on the accuracy of its predictions regarding clay-cutting mechanical quantities?

The following research sub-questions can be branched from the main research question:

1. What are the discrepancies in nomenclature between Miedema's clay cutting model and Hatamura and Chijiiwa's findings, and how do they impact the clarity and consistency of the model?
2. What are the results of calculating the strain and strain rate using Hatamura and Chijiiwa's data, and how do these results demonstrate that Miedema's chosen strain rate value is incorrect?
3. To what extent do the adjustments made by Miedema to the formulation of Wismer and Luth's strength rate contribute to inaccuracies in his cutting-clay model?
4. What is the relationship between shear angle and the strengthening factor in clay cutting, and how does it challenge Miedema's claim of the minimal influence of shear angle on the strengthening factor and horizontal forces?
5. What design should a cutting rig have to investigate the soil mechanics properties related to clay-cutting?

1.5 Research Objectives

The primary aim of this study is to undertake a thorough evaluation of Miedema's clay-cutting model, with a specific emphasis on identifying and addressing its limitations and discrepancies. By focusing on the shortcomings and inconsistencies of the model, the research aims to provide a detailed and critical evaluation of the model. Furthermore, the research aims to ultimately contribute to the development of more robust and precise clay-cutting models. Before defining the objective of this research, it is necessary to state that Miedema's formulations are based exclusively on the empirical studies of Hatamura and Chijiiwa.

Miedema's nomenclature introduces discrepancies in comparison to Hatamura and Chijiiwa, resulting in a lack of clarity within the clay cutting model. Specifically, the dynamical shearing resistance factor and shear strength are mistakenly defined. The main objective of this research is to shed light on these discrepancies and emphasize the distinct nature of these two quantities. By doing so, the research aims to highlight the importance of accurate parameter definitions and clarify the differences between the dynamical shearing resistance factor and the shear strength in the context of clay cutting.

Miedema's theory incorporates a strain rate that differs from the one calculated based on Hatamura and Chijiiwa's findings. In this research, the objective is to recalculate the strain rate using Hatamura's photographs of the Kanto loam during cutting. By analyzing these images and conducting the necessary calculations, it is possible to accurately determine the strain rate associated with the cutting process. This analysis provides evidence to support the claim that Miedema's theory relies on incorrect values for the strain rate. By establishing this discrepancy, the aim is to contribute to the understanding of the accurate strain rate in clay cutting and highlight the need for precise parameter selection in the theoretical model.

A further objective of this research is to analyze and evaluate the modifications made by Miedema to the formulation of Wismer and Luth's strength rate, specifically the introduction of the "constant[2]" of 0.03 1/s. The aim is to investigate the appropriateness of Miedema's approach. To achieve this objective, the calculated fitted strength rate and strengthening factor values are compared. The calculations are performed based on Hatamura and Chijiiwa's soil characteristics. By quantifying the deviation between the calculated and expected values, it can be determined the extent to which Miedema's modifications introduce inaccuracies. Through this analysis, the goal is to reinforce the assertion that Miedema associates wrong values and attributes incorrect constants to the parameters in the clay-cutting model. By highlighting the discrepancies between the calculated values and the expected values based on soil characteristics, evidence is provided of the need for a more appropriate and accurate formulation of the strengthening factor in clay cutting models.

Lastly, one more aspect to be addressed in this research is the statement made by Miedema regarding the low influence of the shear angle on the strengthening factor and horizontal forces

[2] Miedema defines the value 0.03 as a constant, despite the fact that constants typically do not have units associated with them. This discrepancy serves as one of the mistakes I am attempting to highlight in my thesis.

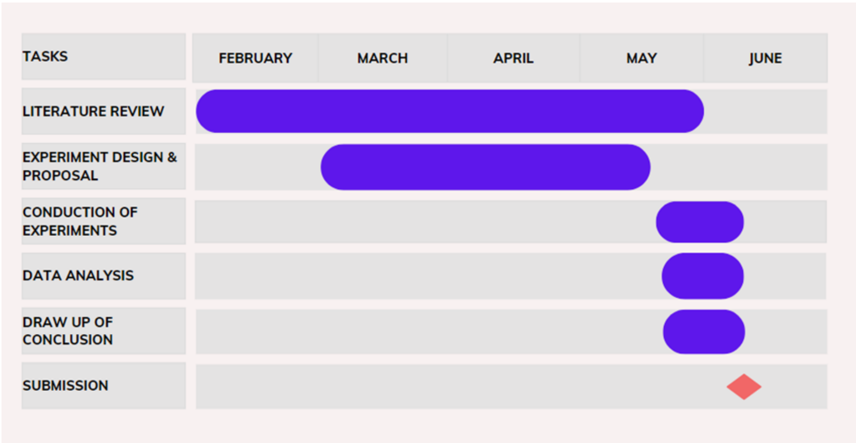
in clay cutting. Miedema's claim suggests that the shearing factor remains constant at 2 for all clays. However, it is important to investigate the validity of this statement by examining how the strengthening factor varies with different shear angles. By analyzing data, the aim is to highlight the variations in the strengthening factor as the shear angle is adjusted.

1.6 Research Plan

The research project commenced on February 6th, 2023, as an internship at Damen Dredging Equipment in the Research and Innovation department. The project is connected to a PhD study conducted at Delft University of Technology that focuses on the topic of clay cutting within the field of dredging.

The figure depicts a summary of the various stages of the research project. It serves as a visual guide to track the progress made and the sequence of activities conducted throughout the study. The timeline spans from the project's initiation to its expected completion, offering a clear overview of the research's duration and key events.

Figure 4:
Schedule of activities



1.7 Research Outline

The following chapter presents the theoretical framework of this research, providing essential background knowledge to facilitate the reader's comprehension of the study. The first section provides an introduction to clay and its properties. This is followed by an overview of clay cutting models, with a specific focus on the Delft clay cutting model.

The subsequent portion of the chapter explores the soil mechanics quantities that are pertinent to this study, further enhancing the reader's understanding of clay's cutting behavior.

The final sections of the chapter focus on Hatamura and Chijiiwa's research, which forms the empirical basis for this study. Detailed descriptions are given regarding the cutting rig employed in their experiments, along with the corresponding results obtained.

By adopting a structured approach that starts with a broad overview of clay and progressively delves into the research topic, the chapter aims to guide the reader toward a comprehensive grasp of the subject matter.

2. Theoretical Framework

2.1 Clay Properties

Clay is defined as "a naturally occurring material composed primarily of fine-grained minerals, which is generally plastic at appropriate water contents and will harden when dried or fired" (Guggenheim and Martin, 1995).

Minerals that impart plasticity to clay are referred to as "clay minerals" these, according to the Association Internationale pour l'Etude des Argiles (AIPEA) may be phyllosilicates or non-phyllosilicates. The minerals that do not cause plasticity in clay are named "accessory minerals". Clay minerals are crystalline sheet-like structures that consist of hydrous alumino-silicates and metallic ions.

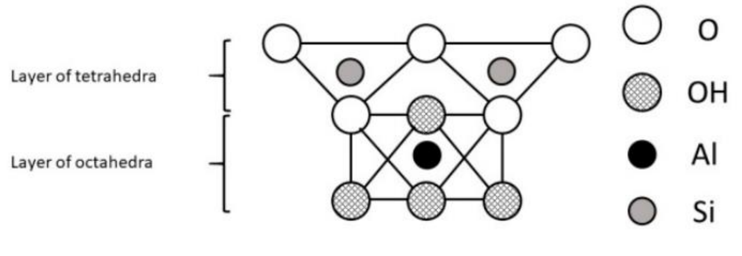
Two fundamental crystal units of clay minerals can be identified i.e., tetrahedral, and octahedral units. A tetrahedral unit encloses silicon and presents four oxygen anions in the vertices, whereas an octahedral unit is comprised of closely packed oxygens and hydroxyls surrounding aluminum, magnesium, iron, or other ions. Based on the arrangements of bonds, the presence of metallic ions, and isomorphous substitution, different clay minerals can be constituted. Kaolinite, montmorillonite, illite, nontronite, and muscovite are the most common clay minerals (Peng, Horn, Peth, Smucker, 2006).

The different physical and chemical properties of clay are due to multiple factors: the structure of the minerals, the type of bonds between atoms and molecules, the distribution of negative and positive charges on the surface, and the type of ions and their exchangeability. Together with the distance between the layers, these factors contribute to the behavior of clayey soils.

There are two types of phyllosilicates, the 1:1 layer type (T-O; **Figure 5**) consists of one sheet of SiO_4 tetrahedra linked to one sheet of Al- or Mg-octahedra, while the 2:1 layer type (T-O-T; **Figure 6**) consists of one sheet of Al- or Mg-octahedra encased between two sheets of Si-tetrahedra (Małgorzata Nadziakiewicza, 2019).

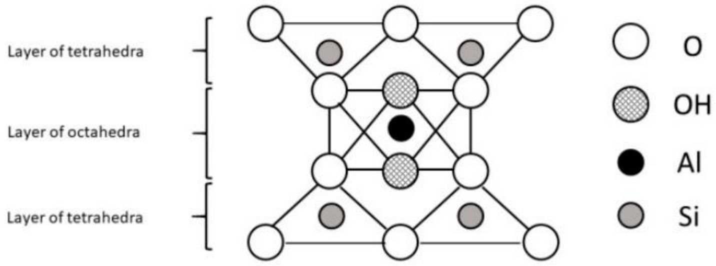
An additional group of phyllosilicates can be identified, the 2:1:1 layer type, which has a 2:1 structure with an interlayer brucite (with cations Mg^{2+} or Fe^{2+}) or gibbsite (with cation Al^{3+}) sheet. This group is represented by chlorites. It is important to note that there is water adsorption within the interlayer space, these are an example of non-expansive minerals (**Figure 7).**

Figure 5:
1:1 layer phyllosilicate structure



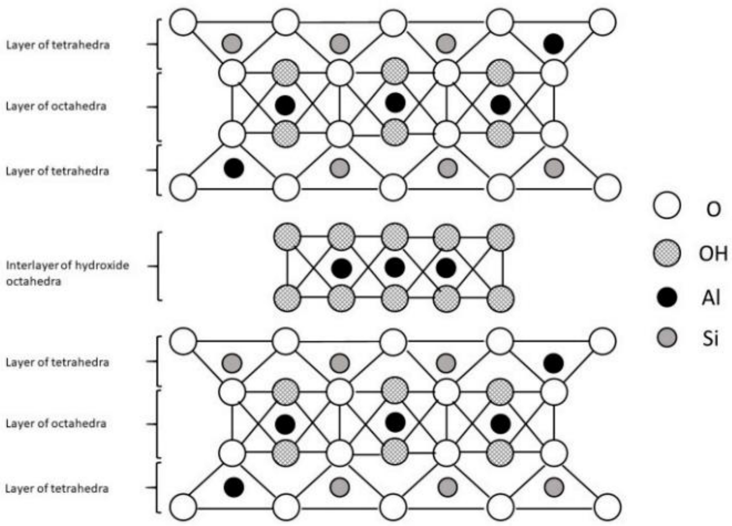
Note. (Małgorzata Nadziakiewicza, 2019)

Figure 6:
2:1 layer phyllosilicate structure



Note. (Małgorzata Nadziakiewicza, 2019)

Figure 7:
2:1:1 layer phyllosilicate structure

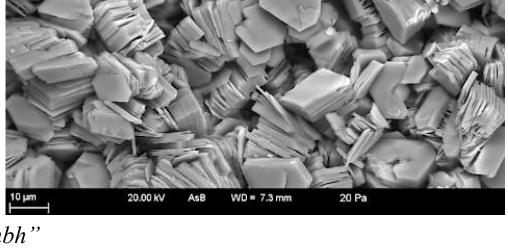


Note. (Małgorzata Nadziakiewicza, 2019)

The shape of clay crystals is determined by the lattice. Each sheet of aluminum silicate structure contains thousands of atoms. A clay crystal is formed from thousands of stacked sheets. Usually, the layers are slightly displaced rather than fitting over one another in exact repetition, this pattern is clear in the figure below. Nonetheless, the entire crystal is flattish and appears to be about hexagonal (

Figure 8).

Figure 8:
Dickite, SEM image of the structure of clay minerals aggregate.



Note. From "Krakow Rohstoffe, Gmbh"

Clay minerals are frequently generated over extended periods by the progressive chemical weathering of silicate-bearing rocks by low concentrations of carbonic acid and other diluted solvents. After leaching through upper worn layers, these acidic liquids travel through the weathering rock. Hydrothermal activity, in addition to weathering, produces several clay minerals. Clay deposits can form in place as residual deposits, although thick deposits are normally created as a result of a secondary sedimentary deposition process after they have been eroded and transported from their original point of formation.

2.1.1 Strengthening of clay

Within the context of clay cutting, under certain conditions, such as high strain rates, clay exhibits a notable property known as "strengthening". This phenomenon, known as strain rate strengthening, refers to the increase in the internal and external shear strength of clay with an increasing rate of deformation or strain. It is moreover possible to state that the reverse of strengthening is creep: under a constant load, the material continues to deform with a certain strain rate (Miedema A. Sape , 2016).

The strengthening of clay can be explained by its adhesion and cohesion properties. Adhesion refers to the tendency of clay particles to stick to other surfaces, such as the cutter head of a dredger. Cohesion, on the other hand, refers to the tendency of clay particles to stick together, forming aggregates.

When clay is subjected to deformation, in other words, when it is compressed or sheared, the adhesion and cohesion properties are subjected to variations. As the clay particles move relative to each other, the adhesive forces between them increase, which leads to an increase in the shear strength of the material. Similarly, the cohesive forces between the particles also increase, which contributes to the overall strength of the material. This is mainly due to the repositioning of the clay particles and the engagement of clay units with water units.

In fact, the strength of clay can also be affected by the pore water pressure, which is the pressure exerted by the water that fills the spaces between the clay particles. When the strain rate is high, the pore water pressure in clay decreases, which causes an increase in the effective stress and therefore an increase in the shear strength (Hiroyuki Tanaka, 2006).

Additionally, the strength of clay can also be influenced by factors such as mineral composition, pore size distribution, and temperature. For instance, the presence of certain minerals such as mica and quartz can enhance the shear strength of clay due to their rigid and durable structure. On the other hand, the presence of organic matter or soluble salts can weaken the clay structure by reducing the cohesive forces between particles.

The pore size distribution of clay can also impact its strength, as smaller pores can increase the adhesion and cohesion forces between particles, leading to higher shear strength.

In summary, the ability of clay to strengthen under high strain rates is due to the increase in adhesion and cohesion forces between particles, as well as the reduction in pore water pressure.

To conclude, dredging can alter the pore water pressure in clay, which can affect its strength. During dredging, the removal of sediments can create voids or spaces in the clay, which can

cause the pore water pressure to decrease. This reduction in pore water pressure can increase the effective stress in the clay and result in an increase in its shear strength.
However, if the dredging process continues for an extended period, the pore water pressure can eventually increase due to the influx of water into the voids. This can cause a decrease in the effective stress in the clay and lead to a reduction in its shear strength. Finally, dredging can also induce strain rate effects in clay, as the process involves the deformation and displacement of the sediment.

2.2 Introduction to cutting theory and its applications in dredging

Cutting theory is an essential component when understanding the mechanics of dredging operations (Miedema, 2001). The cutting theories in mechanics deal with the analysis of cutting processes and it involves the study of the forces, stresses, and deformations that occur when a cutting tool interacts with a material. The aim of cutting theories is to develop mathematical models that can accurately predict the forces and resulting phenomena in a cutting process, such as cutting forces, specific energy, and chip formation. Several cutting theories have been developed so far to explain the deformation that occurs in clay during the cutting mechanism. The scope of work of this research is limited to the Rate Process Theory, however other approaches are described in literature such as the Composite Dilatancy Model or the Multi Mechanisms Deformation Model.

2.2.1 Rate process theory

The rate process theory describes the phenomena occurring in the process of clay cutting. The theory has been developed for the modeling of absolute reaction rates, and in 1976 Mitchell made it applicable to soil mechanics. It is known that the cohesion and adhesion of clay increase with an increasing strain rate, however the rate process theory, does not allow strain rate independent stresses such as real cohesion and adhesion. The theory states that the probability of atoms, molecules, and flow units having a certain thermal vibration energy is in accordance with the Boltzmann distribution:

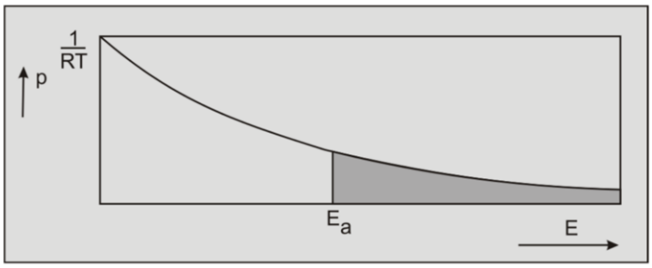
$$p\ (E) = \frac{1}{RT} \exp\left(-\frac{E}{RT}\right) \qquad (1)$$

The movement of units in a time-dependent flow is limited by energy barriers that separate nearby equilibrium locations. To overcome such an energy barrier, a flow unit's energy level must be greater than a particular activation energy $\mathbf{E_a}$. The activation energy highly depends on the type of material that it is being considered.

2.2.2 The rate process theory proposed by Miedema

The rate process theory does not allow shear strength if the deformation is null. Creep will always occur as any material is exposed to its weight. According to the Boltzmann distribution in the "Rate process theory," there is always a probability that a flow unit exceeds an energy level, between an energy level of zero and infinity (**Figure *9***).

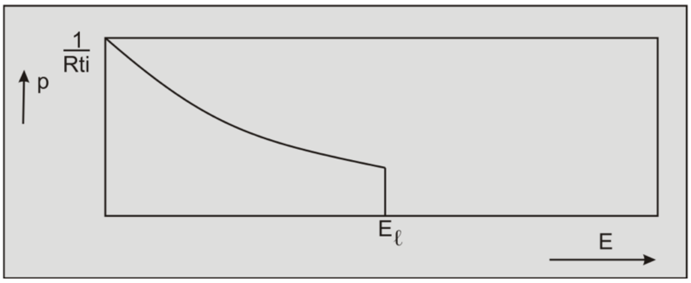
Figure 9:
Probability of exceeding an energy level Ea.



Note. (Miedema A. Sape , 2016)

Stating that the probability of a flow unit having an infinite energy level is infinitely small, allows saying that the time span between the occurrences of flow units having an infinite energy level is also infinite. The likelihood that the energy level of a limited number of flow units does not surpass a specific limiting energy level in a certain time span is close to one. This verifies the premise that the energy level of a flow unit cannot surpass a particular limiting energy level **El** for a certain number of flow units in a finite time frame.
In the figure below the resulting adapted Boltzmann distribution is illustrated, **Figure 10**.

Figure 10:
Adapted Boltzmann probability distribution.



Note. (Miedema A. Sape , 2016)

The following equation has been derived by Mitchell for the shear stress as a function of the strain rate (Mitchell, J., 1976).

$$\tau = a \cdot \left\{(E_a - E_l) \cdot \frac{2}{\lambda \cdot N} + R \cdot T \cdot \frac{2}{\lambda \cdot N} \cdot \ln\left(1 + \frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right)\right\} + b \cdot \left\{(E_a - E_l) \cdot \frac{2}{\lambda \cdot N} + R \cdot T \cdot \frac{2}{\lambda \cdot N} \cdot \ln\left(1 + \frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right)\right\} \cdot \sigma_e \qquad (2)$$

The above theory differs from others as it allows yield strength (cohesion or adhesion). At a certain consolidation pressure level, the above formula can be simplified to:

$$\tau = \tau_y + \tau_0 \cdot \ln\left(1 + \frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right) \qquad (3)$$

Miedema states that the previous formulations "have been fitted to data obtained by Hatamura and Chijiiwa". He then introduces the following quantities, declaring taking these values from Hatamura and Chijiiwa reports:

- Shear strength: $\tau_y = 28\ kPa$;
- Dynamical shear resistance factor: $\tau_0 = 4\ kPa$;
- Strain rate: $\dot{\varepsilon}_0 = 0{,}03/s$;

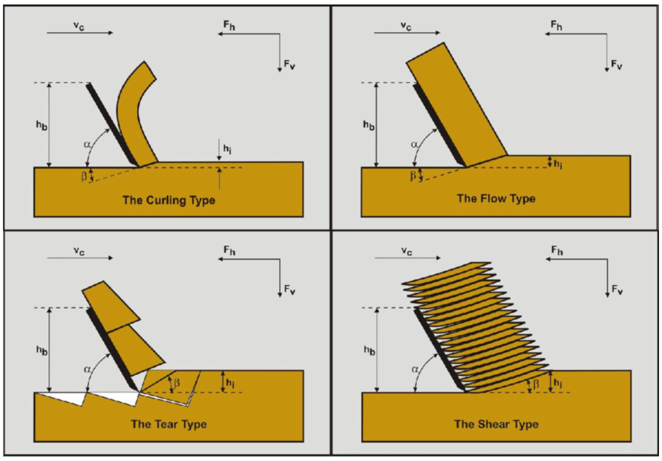
2.3 Miedema resulting equations of the cutting process

The cutting theory of Miedema is based on four different failure types of soil. Three of the failure types have been observed by Hatamura and Chijiiwa (Hatamura, Chijiiwa, 1975), they distinguished indeed: the shear type, flow type and tear type. Miedema defines a fourth cutting mechanism, the curling type, see the figure below.

To determine cutting forces, the equilibrium of forces on a layer or chip of soil cut is considered. To derive cutting forces the assumption that has been made is that the stresses on the shear plane and the blade are constant and equal to the stresses acting on these surfaces.

In cutting operations, soil failure can happen quickly, leading to significant deformation rates, moreover, the specific pattern of failure that occurs in front of the blade is influenced by various factors, including the soil's cohesion, tensile strength, and adhesion, as well as operational conditions like cutting velocity, cutting depth, blade angle, and water depth (Kong, 2018).

Figure 11:
The four types of failure mechanisms



Note. (Miedema A. Sape , 2016)

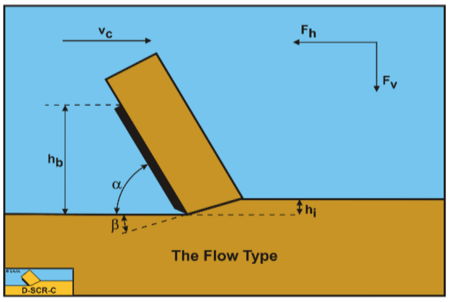
2.3.1 The flow type failure mechanism

The most common failure mechanism in clay is the flow type. The curling type and the tear type may occur under special circumstances and have been derived from the equations of the flow type (Miedema A. Sape , 2016).

Specifically, the curling type occurs when: the adhesive force is big with respect to the normal force on the shear plane, when the blade height is big with respect to the layer thickness when the adhesion is high compared with the cohesion, or when the blade angle is relatively big. On the other side, the tear type can occur in stiff clays when the blade height is small with respect to the layer thickness, the adhesion is small compared to the cohesion and the blade angle is relatively small.

The flow type occurs generally in materials without an internal friction angle, and it's characterized by a continuous chip sheared from the material without a clear shear line, moreover, failure occurs in a shear plane.

Figure 12:
The flow type cutting mechanism



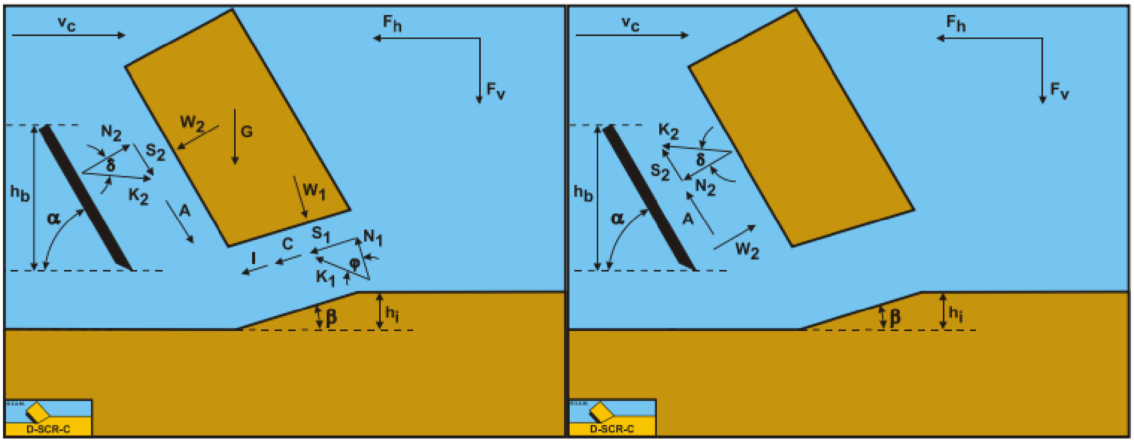
Note. (Miedema A. Sape , 2016)

On the blade a force F_h with a horizontal direction and a F_v with a vertical direction can be defined. Since λ_c and λ_a are almost identical, an average value λ_s is used in the following equations (Miedema A. Sape , 2016).

$$F_h = \frac{\dfrac{\lambda s \cdot c \cdot h_i \cdot w}{sin(\beta)} \cdot sin(\alpha) + \dfrac{\lambda s \cdot a \cdot h_b \cdot w}{sin(\alpha)} \cdot sin(\beta)}{sin(\alpha + \beta)} = \lambda s \cdot c \cdot hi \cdot w \cdot \frac{\dfrac{\sin(\alpha)}{\sin(\beta)} + r\,\dfrac{\sin(\beta)}{\sin(\alpha)}}{\sin(\alpha + \beta)} \tag{4}$$

$$F_v = \frac{\dfrac{\lambda s \cdot c \cdot h_i \cdot w}{sin(\beta)} \cdot cos(\alpha) + \dfrac{\lambda s \cdot a \cdot h_b \cdot w}{sin(\alpha)} \cdot cos(\beta)}{sin(\alpha + \beta)} = \lambda s \cdot c \cdot hi \cdot w \cdot \frac{\dfrac{\cos(\alpha)}{\sin(\beta)} - r\,\dfrac{\cos(\beta)}{\sin(\alpha)}}{\sin(\alpha + \beta)} \tag{5}$$

Figure 13:
Forces acting on the soil chip and on the blade



Note. (Miedema A. Sape , 2016)

In **Figure 13** the forces acting on the soil chip and on the blade are represented. The cohesive force C, the adhesive force A and the ac ratio can be defined by the following equations:

$$C = \frac{\lambda s \cdot c \cdot h_i \cdot w}{sin(\beta)} \quad (6)$$

$$A = \frac{\lambda s \cdot a \cdot h_b \cdot w}{\sin(\alpha)} \quad (7)$$

$$r = \frac{a \cdot h_b}{c \cdot h_i} \quad (8)$$

Cohesion, c, is usually determined in the laboratory from the direct shear test, by plotting the shear stress versus shear displacement curve, the cohesion and friction angle of the soil can be determined. The cohesive strength measured in the test represents the soil's ability to resist shearing forces in the absence of any normal stress. Adhesion can be measured using a tensiometer. By measuring the capillary rise of water or liquid in the tube, the adhesion between the soil particles and the liquid can be determined.

2.3.2 Strain rate and strain rate factors for cohesive and adhesive forces

The strain rate is the rate with which the strain changes with respect to time. In The Delft Sand, Clay & Rock Cutting Model (2016) Miedema defines the strain rate considering that the deformation velocity is different for the cohesion in the shear plane and the adhesion on the blade, two equations are found for the strain rate in function of the cutting velocity. From the formula above Miedema states that adhesion and cohesion can be now modeled through $\dot{\varepsilon_c}$ and $\dot{\varepsilon_a}$, relatively the strain rate on the shear plane and the strain rate on the blade.

$$\dot{\varepsilon_c} = 1{,}4 \cdot \frac{v_c}{h_i} \cdot \frac{\sin(\alpha)}{\sin(\alpha + \beta)} \quad (9)$$

$$\dot{\varepsilon_a} = 1{,}4 \cdot \frac{v_c}{h_i} \cdot \frac{\sin(\beta)}{\sin(\alpha + \beta)} \quad (10)$$

Moreover, Miedema derives the strain rate factor for cohesive and adhesive force. He then introduces a strengthening factor after stating that λ_c and λ_a are almost equivalent.

$$\lambda_c = 1 + \frac{\tau_0}{\tau_y} \cdot ln\left(1 + \frac{1{,}4 \cdot \frac{v_c}{h_i} \cdot \frac{\sin(\alpha)}{\sin(\alpha + \beta)}}{\dot{\varepsilon_0}}\right) \quad (11)$$

$$\lambda_a = 1 + \frac{\tau_0}{\tau_y} \cdot ln\left(1 + \frac{1{,}4 \cdot \frac{v_c}{h_i} \cdot \frac{\sin(\beta)}{\sin(\alpha + \beta)}}{\dot{\varepsilon_0}}\right) \quad (12)$$

$$\lambda_s = 1 + \frac{\tau_0}{\tau_y} \cdot \ln\left(1 + \frac{1{,}4 \cdot \frac{v_c}{h_i} \cdot \frac{\sin\alpha}{\sin(\alpha+\beta)}}{\dot{\varepsilon_0}}\right) \quad (13)$$

Miedema considers the ratio $\frac{\tau_0}{\tau_y} = \frac{28}{4} = 0{,}1428$ and $\dot{\varepsilon_0} = 0{,}03s^{-1}$ for all type of clays, as a derivation from literature, specifically from Hatamura and from Chijiiwa's research. When defining the average strengthening factor Miedema takes into consideration the Hatamura and Chijiiwa values. Furthermore, he states that the strengthening factor is equal to 2 for all type of clays.
The aim of this research becomes evident. As the two Japanese researchers conducted experiments on a single type of clay, these numbers can't be generalized for all type of soils.

2.3.3 Specific cutting energy

In the dredging industry these formulas and values play a relevant role, as they influence the specific cutting energy which can be defined as the amount of energy, which has to be added to a volume unit of soil to excavate the soil. This quantity is utilized to estimate production **Figure 3**.

$$E_{sp} = \frac{F_h}{h_i w} = \lambda_s \cdot c \cdot h_i \cdot w \cdot \lambda_{HF} \quad (14)$$

To conclude this chapter, it is important to note that Miedema didn't provide additional explanation on the derivation of the resulting equations of the cutting process. This document aims to investigate further the validity of the four equations reported above.

2.3.4 Strength rate- Wismer and Luth

Wismer and Luth, within agriculture and earth moving study, defined a formulation for the strength rate naming it as a strength rate. The quantity has been defined observing how the cone index varied with the penetration in soil. The investigation consisted in a horizontal penetrometer attached to a bladed dynamometer. The penetrometer measured the cone index at a given speed.

$$\lambda_s = \frac{CI}{\gamma z}\left(\frac{\frac{v}{l}}{\frac{r_s}{d_s}}\right)^{0.1} = \frac{CI}{\gamma z}\left(0.667\ \frac{v}{L}\right)^{0{,}1} \quad (15)$$

Where L is the characteristic length of the soil-blade system, r_s/d_s is the penetration rate/cone diameter ratio of standard penetrometer, CI is the cone index at penetration rate r_s=1.2 in/sec and d_s=7.798 in, z is the blade depth [in] and γ [lb/ft^3] is the unit weight of soil[3].

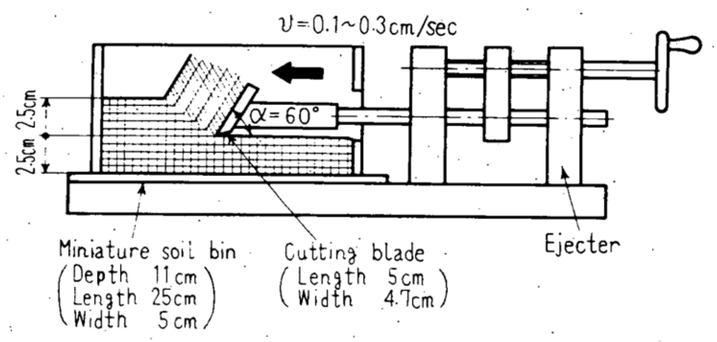
[3] The dimensions provided in this paragraph are expressed in the American system. Please note that these units differ from the International System of Units (SI) commonly used in scientific research.

2.4 Hatamura and Chijiiwa: Analysis of the Mechanism of Soil Cutting

Hatamura and Chijiiwa conducted research to define the mechanism of soil cutting. The results have been presented in five publications under the title of "Analysis of the Mechanism of Soil Cutting."
The first publication focuses on defining the cutting patterns and the correspondence of cutting patterns to the characteristics of soils (Hatamura, Chijiiwa, 1975).

In the following paragraph, the experiment of Hatamura and Chijiiwa is explained, the investigations aim to clarify the deformations of several types of soil: quartz sand, river sand, "Masado" soil, alluvial silt, "Kanto" loam, "Kibushi" clay and bentonite. The soils that have been selected represented a problem in civil engineering in Japan or present already interesting characteristics.
The scope of work of this document and research is limited to the study of clay, a major focus is indeed put on what Hatamura and Chijiiwa define as "loam". The apparatus of the experiment is a miniature soil bin shown in the figure below.

Figure 14:
Apparatus for investigating the deformation of soil by cutting.



Note. (Hatamura, Chijiiwa, 1975)

Moreover, in the following table, the characteristics of the Kanto loam are reported.

Figure 15:
Kanto loam soil properties

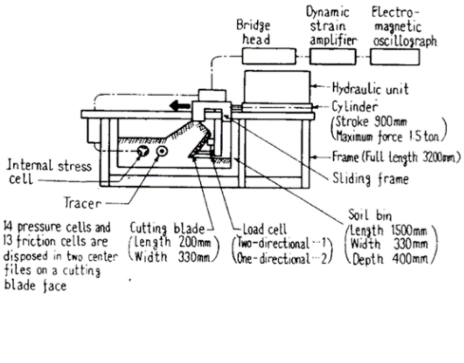
Parameters	Value
ρ, Density/g cm^{-3}	1.83
E, Young's modulus/MPa	3.04
μ, Poisson's ratio	0.3
ϕ, Internal friction angle/°	6.3
c, Cohesion/kPa	16
β, The slope of the Drucker-Prager yield surface/°	10.7
d, The t_d −axis intercept in the p-t_d plane/kPa	27.5
K, Stress ratio	0.778
ψ, Dilation angle/°	10.7

Note. (L.B. Zhang, 2017)

The apparatus shown in **Figure 14** consists of a cutting blade that cuts soil priorly placed within a soil bin. The cutting blade is moved with an ejector, during the test the speed is constant.

In order to be able to see the soil deformations, a frontal glass plate is placed. The soil is put on a frictionless bed. Moreover, a lubricant (seaweed paste and grease) is used to reduce the friction between the clay and the side plates.
The results of the experiment of deformation by cutting allows the classification of three cutting patterns: shear type, flow type, and tear type.
The main cause of the different cutting patterns is the differences in their shear and tensile failure conditions. Hatamura and Chijiiwa observe how in the case of shear type and flow type, soil breaks in shear failure. The difference between the failures is induced by the intermittent or continuous appearance of the shear lines. In case of tear type, soil breaks in tensile failure.
The researchers state moreover how the difference between the cutting pattern induced by shear failure and the one induced by tensile failure depends upon the ratio of tensile strength to shearing strength of soils.
In the second bulletin, an investigation on dry quartz sand and loam was conducted in a larger soil bin to obtain more detailed results (Hatamura, Chijiiwa, 1976). This has allowed Hatamura and Chijiiwa to explain the distribution of internal principal stresses in soil. In the experiment, dry quartz sand is utilized as a representative of the shear type and the plastic loam as the flow type.
The cutting conditions are: $\alpha = 60°$, the depth of cut $d = 10\ cm$ and the cutting speed $v = 5\ cm/s$. The distributions of major stresses are quite similar in both cases of dry quartz sand and plastic loam. Both the highest and minimum principal stresses are compressive in the zone before and above the cutting blade, and the directions of maximum principal stresses are horizontal or slightly inclined nearly parallel. Only the maximum principal stress trajectories originating from the cutting-edge deviate abruptly. In the zone under the cutting edge both in the front and the back of it, the maximum principal stresses are compressive, whereas the minimum principal stresses are zero or tensile.
A different but comparable equipment to the first apparatus is used in Hatamura and Chijiiwa's second experiment **Figure 16**. A cutting blade chops soil in a soil bin and the blade is coupled to a sliding frame by load cells. The sliding frame is propelled horizontally along guided rails by a hydraulic cylinder. 14 pressure cells and 13 friction cells are arranged in two center files on the cutting blade phase to measure pressures and frictional loads acting on the blade. Moreover, tracers and internal stress cells are buried in the soil to detect the distributions of internal stress. A glass plate installed on the side of the soil bin allows to view the deformation and to photograph the position of the tracers.

Figure 16*:*
Outline of the experiment of soil cutting



Note. (Hatamura, Chijiiwa, 1976)

The quantities that have been measured during the investigation are the following:

- Deformation of soil; direction of shear plane.
- Distribution of internal stresses; magnitudes and directions of principal stresses.
- Distribution of stresses on the cutting blade face; pressure and frictional stress.
- Cutting force; magnitude and direction of cutting force and distance from the cutting edge to its application point.

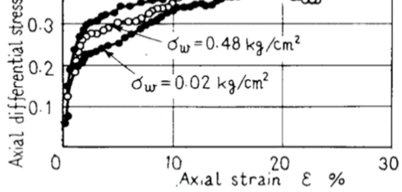
Hatamura and Chijiiwa state that the cutting phenomena are affected by three kinds of cutting conditions: cutting angle, depth, and cutting speed, besides kinds of soils. For this reason, three conditions are selected as variable parameters: cutting angle (30°, 45°, 60°, 75°, 90°), depth of cut (5, 10, 15 cm), cutting speed (5, 10, 14 cm/s).
In Hatamura and Chijiiwa investigation only the two-dimensional scenario has been taken into account, the sides of the cutting blade touch the inner side of the soil bin, and the frictional stress between the soil and the inner side of the soil bin is negligibly small. The plane strain condition has been achieved thanks to lubricant.
The results of the experiment report, in the case of loam, state that flow type appears irrespective of the depth of cut when the cutting angle is larger than 60°, but the mixed type of flow and tear appears at 45° and tear type appears at 30°. Moreover, the clear shape of the shear plane does not show as it does in the sand, for this reason, the "shear plane" is obtained by connecting the points where the deformations are the most remarkable. Lastly, the direction of the shear line decreases as the cutting angle increases and it increases as the depth of cut increases.

The fourth publication of Hatamura and Chijiiwa (Hatamura, Chijiiwa, 1977A) refers to the first apparatus of investigations and as stated above the following soil are assessed:

- Dry quartz sand- mean grain size 0,22 mm, water content 0,2%, shar failure condition $\tau = 0{,}78\ \sigma$;
- Plastic loam- water content 32,9-34,7%, shear failure condition $\tau = 0{,}16 + 0{,}11\ \sigma$;

The following graph represents the stress-strain relations of loam, the stress increases proportionally to an increase in strain and the stress becomes saturated when the strain reaches a certain magnitude (5-20%). When hydraulic pressure is changed the stress-strain curve does not record relative changes.

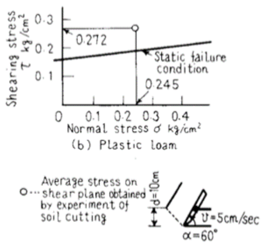
Figure 17:
Relation between stress and strain in plastic loam



Note. (Hatamura, Chijiiwa, 1977A)

Hatamura and Chijiiwa in their 4th paper consider the following cutting conditions: $\alpha = 60°$, depth of cut $d = 10\ cm$ and cutting speed $v = 5\ cm/s$, in the case of loam the average normal stress σ acting on the shear plane is equal to $\sigma = 0{,}25\ kg/cm^2$. Actual stresses on the shear plane when loam fails are calculated from results of the experiment of the two researchers on soil cutting. The graph in **Figure 18** shows how dynamic stress and failure conditions are supposed to depend on the speed of deformation.

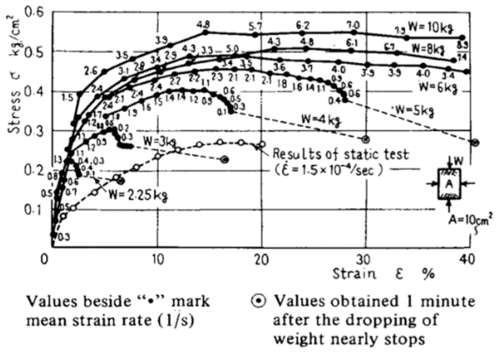
Figure 18:
Comparison of the stresses on shear plane with static failure conditions



Note. (Hatamura, Chijiiwa, 1977A)

In this section, the relation between stress, strain, and strain rate is investigated. When the strain rate is maintained constant the stress-strain curve is a saturation one and the saturation value changes according to the strain rate. The measure values of the stress-strain rate in the dynamic compression test of plastic loam are shown in the following graph:

***Figure 19**:*
Measured values of stress-strain-strain rate in dynamic compression test of plastic loam.



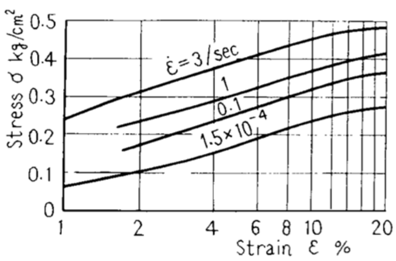
Note. (Hatamura, Chijiiwa, 1977A)

In the figure above, the values given beside every dotted point are strain rates. $\dot{\varepsilon} = 1{,}4 \cdot 10^{-4}/s$ is the result of a static mono-axial compression test. When the strain rate is maintained constant the stress-strain curve is a saturation one and the saturation value changes according to the strain rate. Generally, stress depends on both strain and strain rate, and its magnitude increases in proportion to an increase in strain or strain rate. The following formula has been derived from the graphs:

$$\sigma = 0{,}192 \log\left(\frac{\varepsilon}{0{,}15}\right) + 0{,}42(\dot{\varepsilon})^{0{,}089} \qquad (16)$$

The strain and the strain rate belong to the following range: $\varepsilon = 0{,}01 \sim 0{,}2$ and $\dot{\varepsilon} = 10^{-1} \sim 10/s$.

Figure 20:
Change of stress-strain curves of plastic loam induced by strain rate change.

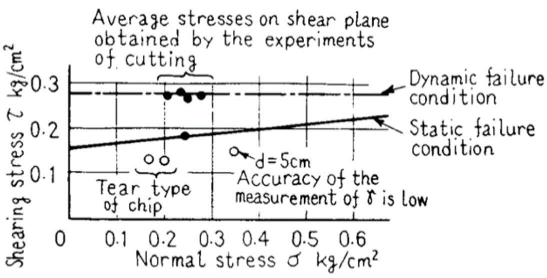


Note. (Hatamura, Chijiiwa, 1977A)

2.4.1 Actual stresses on shear plane

The stress on the shear plane during the investigation shows the average normal and tangential stresses acting on the shear plane when the loam is cut. In the figure below the black points correspond to the flow type, it can be noticed how all the points are greater than the static shear failure stresses and coincide with the dynamic shear failure stresses $\tau = 0{,}279\ kg/cm^2$. This translates in the fact that loam failure must be observed from a dynamic failure point of view.

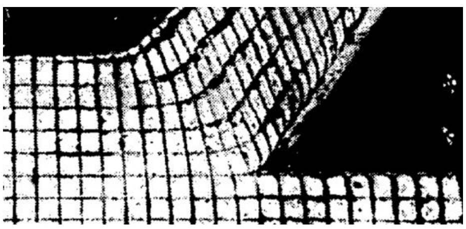
Figure 21:
Relation between average stresses on the shear plane in cutting and failure conditions.



Note. (Hatamura, Chijiiwa, 1977A)

Lastly the following figure represents the deformation of plastic loam induced by the cutting mechanism. The calculation of strain and strain rate have been calculated by Hatamura and Chijiiwa from this picture. The dimensions of the cells have been measured and calculations have been conducted in order to define the soil mechanics quantities.

Figure 22:
Deformation of plastic loam induced by cutting



Note. (Hatamura, Chijiiwa, 1975)

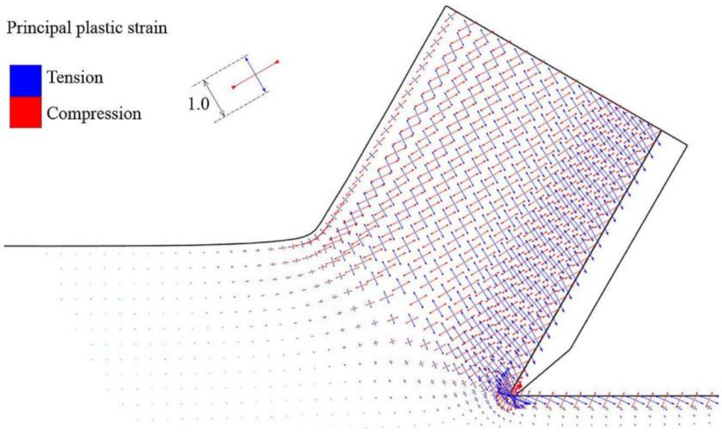
Recent studies conducted at Tianjin university utilized an arbitrary Lagrangian-Eulerian finite element (ALE-FE) formulation for simulating the soil-blade interaction. This method allowed plotting the principal plastic strain components, this can be seen in the figure below (L.B. Zhang, 2017).

The tensile and compressive principal plastic strain vectors represent the magnitudes and the directions of the tensile and compressive deformations of soil. The non-parallelism of the vectors occurs close to the soil-blade interface, this is due to the frictional behavior at the interface. Note how further away from the shear deformation zone, the magnitude of the plastic strain components gradually reduces.

The study has reached good modeling results in regards of describing the behavior of clay. However, to prove the accuracy level, the predictions have been compared with Hatamura and Chijiiwa findings, confirming again the need of conducting more experiments with a cutting rig in order to have a reliable and more rich set of data.

Figure 23

Principal plastic strain distribution



Note. (L.B. Zhang, 2017)

2.4.2 Deformation by cutting and strain rate

To define the strain and the strain rate that occurs when cutting, grid lines have been drawn on the clay block. Distribution of strains and strain rates are calculated from photographs taken before and after the deformation.

The magnitude of the maximum shearing strain rate $\dot{\gamma}$ is high in the region of the shear plane (region of largest deformation), and it is small in other regions. For velocities equal to $v = 5\ cm/s$ the recorded maximum shearing strain rate on the shear plane is $3/s$. On the other hand, longitudinal strain along flow line ε increases rapidly in the region of the shear plane and becomes about $0{,}3\ (30\%)$. It is concluded that the maximum magnitude of the shearing strain rate coincides with the magnitude of the maximum compressive strain rate (maximal principal strain rate) (L.B. Zhang, 2017).

2.4.3 Comparison of soil mechanic quantities

To conclude this chapter, a comparison is made between the findings of Miedema and the findings of Hatamura and Chijiiwa. Note that the comparison regards both the values and the nomenclature.

Miedema		**Hatamura and Chijiiwa**	
Dynamical shearing resistance factor	$\tau_0 = 4\ kPa;$	Dynamical shear failure stress	$\tau_0 = 0.279\ kg/cm^2$
Shear strength	$\tau_y = 28\ kPa;$	Shear strength	-
Strain rate	$\dot{\varepsilon_0} = 0{,}03/s;$	Strain rate	$\dot{\varepsilon_0} = 3/s;$
Strain	-	Strain	$\varepsilon = 3;$
Strengthening factor	$\lambda_s = 2$	Strengthening factor	-

3. Methodology

This chapter provides a comprehensive overview of the research methods employed to evaluate Miedema's model for clay cutting. The chapter begins with a description of the research methodology, followed by a detailed explanation of the research design and approach, outlining the steps taken to achieve the research objectives. The chapter delves into an elaborate explanation of the data analysis procedures, highlighting their significance in obtaining consistent conclusions and answering the main and sub-questions posed initially. Lastly, an essential section of the chapter involves a thorough examination of the experimental setup design proposed to validate the model of Miedema. Furthermore, in the Appendix additional details on the design choices made during the setup design are discussed, providing insights into the considerations and factors influencing the design of the cutting rig.

3.1 Research Design and Approach

The research design employed in this study utilizes a mixed-methods approach, combining an extensive literature review with the analysis of data extracted from Hatamura and Chijiiwa. This approach enables a comprehensive analysis of the research problem by incorporating theoretical insights.

The literature review critically evaluates the existing theoretical model and empirical studies related to soil cutting, aiming to identify any gaps in current knowledge. To conduct the literature review, a thorough search strategy has been devised, including searches in relevant databases, scholarly papers, and research studies. The search strategy involves a combination of keywords and subject headings related to cutting forces, soil mechanics, clay behavior, Miedema's model, and the Hatamura and Chijiiwa study. The literature review process consists of three phases: screening, data extraction, and synthesis.

During the screening phase, the titles and abstracts of identified studies are carefully evaluated to determine their relevance and alignment with the inclusion criteria. Subsequently, in the data extraction phase, pertinent information and details are extracted from the selected studies. Finally, in the synthesis phase, the extracted data is synthesized to provide a comprehensive analysis of the existing literature, informing the subsequent stages of the research.

To effectively address the main and sub-questions derived from the problem statement, a detailed examination has been undertaken in order to explore the underlying assumptions and simplifications inherent in Miedema's cutting model.

By adopting this comprehensive methodology, which includes critical analysis, data analysis, and comparative studies, the research ensures a robust and systematic approach to answer the main and sub-questions. This methodology not only enables a thorough evaluation of Miedema's model but also contributes to the broader understanding of cutting forces in clay cutting processes.

3.2 Research Activities

Research Question 1: What are the discrepancies in nomenclature between Miedema's clay cutting model and Hatamura and Chijiiwa's findings, and how do they impact the clarity and consistency of the model?
Activity: Critical analysis of Miedema's clay-cutting model, focusing on the nomenclature and definitions used in the model. This analysis involves comparing Miedema's terminology with the findings of Hatamura and Chijiiwa to identify any discrepancies and assess their impact on the clarity and consistency of the model's definitions.

Research Question 2: What are the results of calculating the strain and strain rate using Hatamura and Chijiiwa's data, and how do these results demonstrate that Miedema's chosen strain rate value is incorrect?
Activity: Calculation of strain and strain rate using Hatamura and Chijiiwa's data. This activity involves utilizing the experimental data provided by Hatamura and Chijiiwa to calculate the strain and strain rate values. The calculated values need then to be compared with Miedema's chosen strain rate value to evaluate the accuracy and correctness of Miedema's choice.

Research Question 3: To what extent do the adjustments made by Miedema to the formulation of Wismer and Luth's shear strength contribute to inaccuracies in his cutting-clay model?
Activity: Evaluation of the adjustments made by Miedema to the strength rate formulation of Wismer and Luth. This activity involves analyzing Miedema's modifications to the shear strength equation and assessing their impact on the accuracy of the cutting-clay model. By examining the adjustments made, the study aims to determine the extent to which these changes contribute to inaccuracies in the model.

Research Question 4: What is the relationship between shear angle and the strengthening factor in clay cutting, and how does it challenge Miedema's claim of minimal influence of shear angle on the strengthening factor and horizontal forces?
Activity: Investigation of the relationship between shear angle and the strengthening factor in clay cutting. This activity involves analyzing existing data to explore the correlation between shear angle and the strengthening factor. By examining this relationship, the study aims to challenge Miedema's claim of minimal influence and assess the impact of shear angle on both the strengthening factor and horizontal forces.

Research Question 5: What design should a cutting rig have to investigate the soil mechanics properties related to clay cutting?
Activity: Conducting a literature review to study Hatamura and Chijiiwa's cutting rig designs and methodologies for investigating soil mechanics properties related to clay cutting. Subsequently the feasibility of replicating their cutting rig using modern instruments and equipment was studied. The main activity to answer this research question was sketching the cutting rig design, considering its components and materials. Lastly the selection of the most suitable components for the cutting rig occurred.

3.3 Methods of Analysis

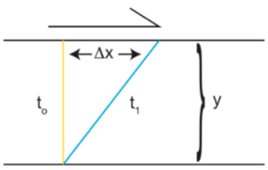
In this chapter, a concise and systematic method of analysis has been presented, specifically tailored to address the research questions that necessitate calculations and further analytical study. The purpose of this methodological framework is to guide the researcher in understanding the investigation, ensuring that the research questions are adequately explored and answered.

3.3.1 Shear strain and Strain rate

This section is instrumental to answer the second research question of this research, it describes indeed the formulas for calculating the strain and the strain rate. The data has been extrapolated from Hatamura and Chijiiwa photographs of the clay being sheared by the cutting rig. Specifically, five cells have been selected. The cells that have been chosen are the one close to the shear plane **Figure 25Figure 25:** Kanto loam deformation and division in cells for the calculation of strain and strain rate, subsequently through a measuring tool all the dimensions have been recorded. The results of the calculation of the strain and the strain rate are defined in chapter Results.

Strain can be defined as the change in shape or size of an object relative to its original shape or size. It can be calculated with the following formula, where Δx is the length slided by the shear force, and the y is the thickness considered. As stated, before the lengths of the cells have been measured through a graphic-measuring tool, **Figure 25**.

Figure 24:
Shear variables



$$\varepsilon = \frac{\Delta x}{y} \tag{17}$$

Strain rate is the change in strain (deformation) of a material with respect to time. The velocity is known as Hatamura and Chiijiwa make it present, while the length of the cell is again measured.

$$\dot{\varepsilon}_0 = \frac{\mathrm{d}\varepsilon}{\mathrm{d}t} = \frac{d(L(t)-L)}{dt(L_0)} = \frac{v_0}{L} \tag{18}$$

The strain and the shear strain have been calculated by Hatamura and Chijiiwa, they recorded that the values for these two quantaties are respectively 0,3 and 3 1/s.

Figure 25:
Kanto loam deformation and division in cells for the calculation of strain and strain rate

3.3.2 Strengthening factor- Miedema, Wismer and Luth

In order to answer the research question number 3 investigations have been conducted by defining both the strength rate of Wismer and Luth and the fitted shearing factor.
The analysis aims in assessing the accuracy of Midema's choices. The calculations have been performed by taking into consideration the properties of Kanto loam. The original definition of the Wismer and Luth strength rate, denoted as λ_s , is given by:

$$\lambda_s = \frac{CI}{\gamma z}\left(\frac{v/L}{r_s/d_s}\right)^{0.1} = \frac{CI}{\gamma z}\left(0.667\ \frac{v}{L}\right)^{0,1} \quad (19)$$

In contrast, Miedema presents, the following expression for the strengthening factor:

$$\lambda_s = \left(\frac{v_c}{h_i}/0.03\right)^{0.1} \quad (20)$$

Calculations have been performed on the data of Kanto loam. As the table shows, when substituting the clay information, the value within parenthesis is not 0,03 but rather a very small number.

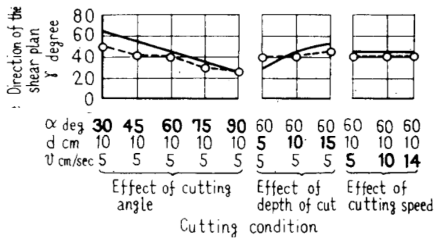
Table 1:
Comparison of multiplication factors in Wismer and Luth strengthening factor for Kanto loam

Multiplication Factor within parenthesis	**r_s/d_s**	**Kanto clay γ**	**CI**	**Wismer and Luth**	**Miedema**
	0,667	17,95	42	9,12E-33	0,03

3.3.3 Shearing factor dependency on shear angle

Further examinations have been performed to answer the research question number 4. To define how the shear angle influences the shearing factor an analysis has been conducted on data extrapolated from Hatamura and Chijiiwa findings. The following figure shows the data utilized.

Figure 26:
Cutting conditions



As it can be observed the shear angle varies with the cutting angle, the table below summarizes the cutting conditions observed withing this experiment, moreover in chapter 4 an analysis has been conducted underlying the dependency of the strengthening factor to the shear angle.

Figure 27:
Shearing factor

h_i [m]	v_c [m/s]	τ_0 [kPa]	τ_y [kPa]	α	β	$\dot{\varepsilon_0}$ [1/s]	λ_s	N
0,1	0,05	4	28	30	55	3	1,12	**1**
0,1	0,05	4	28	45	50	3	1,04	**2**
0,1	0,05	4	28	60	45	3	1,01	**3**
0,1	0,05	4	28	75	40	3	0,99	**4**
0,1	0,05	4	28	90	35	3	0,94	**5**

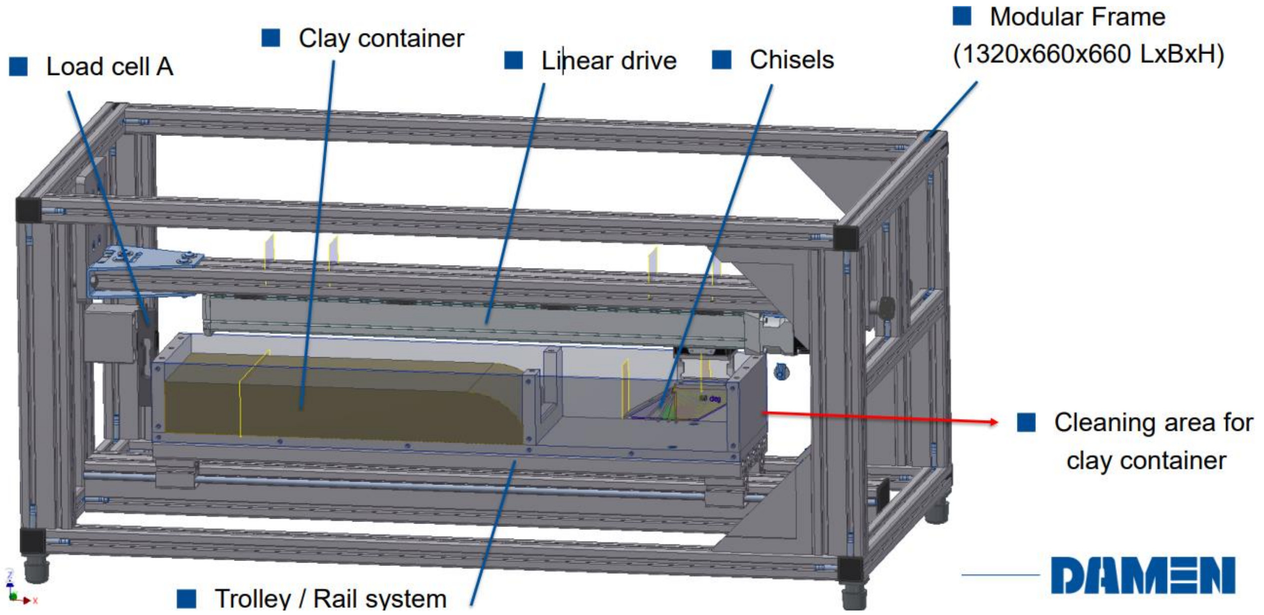
3.3.4 Design of the cutting rig

The replication of the Hatamura and Chijiiwa soil bin experiment setup is a highly specialized tool designed to measure the dynamic shear strength of soil, the setup is indeed critical for understanding the behavior of soil under various cutting conditions. This section aims to define the methodology for answering the research question 5.

When designing the cutting rig, the aim was to reproduce the dimensions of Hatamura and Chijiiwa's cutting rig. A primary collection of data has been conducted; subsequently brainstorming sessions took place to define the mechanics of the rig. A detailed explanation of the components of the cutting rig is provided in the Appendix A: Cutting rig components.

The experiment involves placing a soil sample inside the soil bin, where a steel cutting blade is positioned to cut through the soil at a specific angle and velocity. The driver applies a force to the blade, which moves through the soil sample, causing it to shear along a plane. Throughout the experiment, load cells accurately measure the forces exerted on the soil sample, enabling the calculation of the dynamic shear strength of the soil.

Figure 28:
Test rig for clay cutting



4. Results

The results chapter presents the key findings drawn from the comprehensive analysis and examination of Miedema's cutting theory for clay. This chapter aims to provide a detailed overview of the outcomes obtained through the research methodology, investigations, and critical analysis of existing literature. The primary objective of this study is to evaluate Miedema's model for clay cutting and assess its accuracy.
By addressing the research questions related to strain rate, shear strength, and dynamic shear resistance, as well as studying Miedema's nomenclature and the choice of parameters, this chapter sheds light on the limitations, and discrepancies within Miedema's theory. Furthermore, the influence of the shear angle on the strengthening factor and horizontal forces is examined. The following sections delve into the specific results obtained, providing a comprehensive understanding of the implications and potential areas for improvement in Miedema clay cutting model.

4.1 Nomenclature and Parameter definitions

The first topic that demands comment is the significant issue of the lack of clarity in Miedema's nomenclature when defining the cutting theory. Specifically, Miedema introduces the dynamical shear resistance factor as $\tau_0 = 4kPa$, attributing this value to the investigations conducted by Hatamura and Chijiiwa. Miedema defines the value of 4 kPa as a factor in his theory and assigns it a unit of kPa. While it is customary for factors to be dimensionless quantities. Moreover, upon closer examination of Hatamura and Chijiiwa's work, it becomes apparent that they define the dynamical shear stress of Kanto loam as equal to 28kPa. This discrepancy raises questions regarding the origin of the value of 4kPa employed by Miedema, especially when considering that Miedema sets equal to 28 kPa the shear strength. One possibility is that Miedema derived the 4 kPa from graphs presented by Hatamura and Chijiiwa without explicitly referencing it, and that he mixed up the nomenclature.

4.2 Strain rate Analysis

During the evaluation of Miedema's theory within this research, several issues concerning the strain rate utilized by Miedema to calculate the strengthening factor have been identified. Miedema claims to derive this value from Hatamura and Chijiiwa, specifically citing a strain rate of $0.03\frac{1}{s}$. However, upon closer examination of Hatamura and Chijiiwa's work, it becomes evident that they calculate a strain of 0.3 and a strain rate of $3\frac{1}{s}$. This inconsistency raises concerns regarding the validity of the chosen strain rate in Miedema's theory.

To address this discrepancy, an investigation was conducted to calculate the strain rate and compare it with the values obtained by Hatamura and Chijiiwa. The results of these calculations are explained in the Methodology chapter in section 3.3.1, page 32. The calculations confirmed that considering a strain rate of $0.03\frac{1}{s}$ cannot be deemed accurate. Instead, the calculated values closely align with those reported by the two Japanese researchers, indicating that the strain rate utilized in Miedema's theory may require reassessment. **Table 2:**

Calculation of Strain and Strain rate from Hatamura and Chijiiwa photographs aims to show the procedure with which the strain and strain rate values of Hatamura and Chijiiwa have been confirmed, the methodology is described in chapter Methodology.

Table 2:
Calculation of Strain and Strain rate from Hatamura and Chijiiwa photographs

		L_f	Δx	y	ε	AVG	$\dot{\varepsilon_0}$	AVG
	1	0,02	0,40	1,50	0,27		3,13	
	2	0,01	0,20	2,40	0,08		5,00	
A	**3**	0,01	1,20	2,20	0,55	0,27	4,55	4,03
	4	0,01	0,60	2,00	0,30		4,17	
	5	0,02	0,30	2,10	0,14		3,33	
Hatamura and Chijiwa						0,30		3,00

4.3 Strengthening factor- Miedema, Wismer and Luth

Further insights regarding the value of the strain rate of $0.03\frac{1}{s}$ can be obtained by considering the Wismer and Luth strength rate (R.D. Wismer, 1972). In "The Delft Sand, Clay & Rock Cutting Model," Miedema introduces a modified version of the Wismer and Luth strength rate, which deviates from the original definition.
Despite Miedema's assertion that the factors in the formula of strength rate of Wismer and Luth can be converted to SI units, the calculated numbers do not result in a value of 0.03 for Hatamura and Chijiiwa's soil characteristics. Instead, it yields to a very small number defined in the Methodology chapter in section3.3.2, page 33. This discrepancy indicates the necessity for a comprehensive reevaluation of the calculation of the strengthening factor and its relationship to the strain rate in clay cutting models.
The contrasting definitions of the strengthening factor between Wismer and Luth's original formulation and Miedema's modified expression raises questions about the appropriateness of Miedema's approach. It’s important to repeat the fact that the strain rate of a material can’t be used as a constant value, however this statement has been repeatedly used by Miedema when defining his model.
The significant deviation in the calculated values suggests that a thorough investigation is required to determine the correct formulation of the strengthening factor and its connection to the strain rate in the context of clay cutting models.

Table 3:
Comparison of Miedema's strengthening factor for Kanto loam

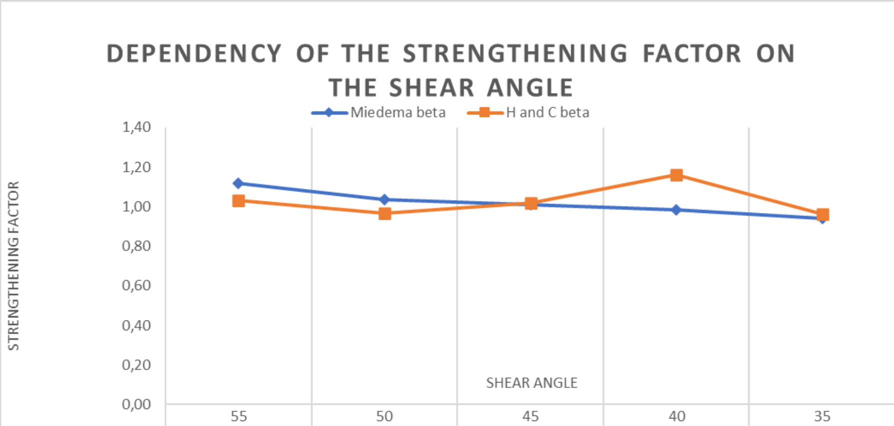
Strengthening factor	**Miedema**	**Midema fitted Wismer and Luth**
	1,01	1,32

4.4 Dependency of the strengthening factor on the shear angle

Furthermore, an investigation was carried out to explore the influence of the shear angle on the strengthening factor. Miedema asserts that the strengthening factor exhibits limited dependence on the shear angle. It is important to state that the shear angle is present in the shearing factor formulation. However, Miedema states that the shearing factor can be considered to be equal to 2 for every type of clay, neglecting the influence of the shear angle. The analysis conducted in this study reveals variations when the shear angle is altered. This observation is visually represented in the graph below, where it is evident that modifying the shearing angle results in corresponding changes in the strengthening factor.

The shear angle plays a crucial role in determining the value of the strengthening factor, which subsequently has a direct impact on the magnitude of horizontal forces exerted during clay cutting. This finding highlights the significance of considering the shear angle as a contributing factor when evaluating the strengthening factor and its associated implications.
Collectively, these findings emphasize the significance of the shear angle in determining the strengthening factor and subsequently affecting the horizontal forces exerted during clay cutting. The relationship between the shear angle, the strengthening factor, and the resulting horizontal forces necessitates careful consideration when developing and refining clay cutting models.

Figure 29:
Dependency of the strengthening factor on the shear angle

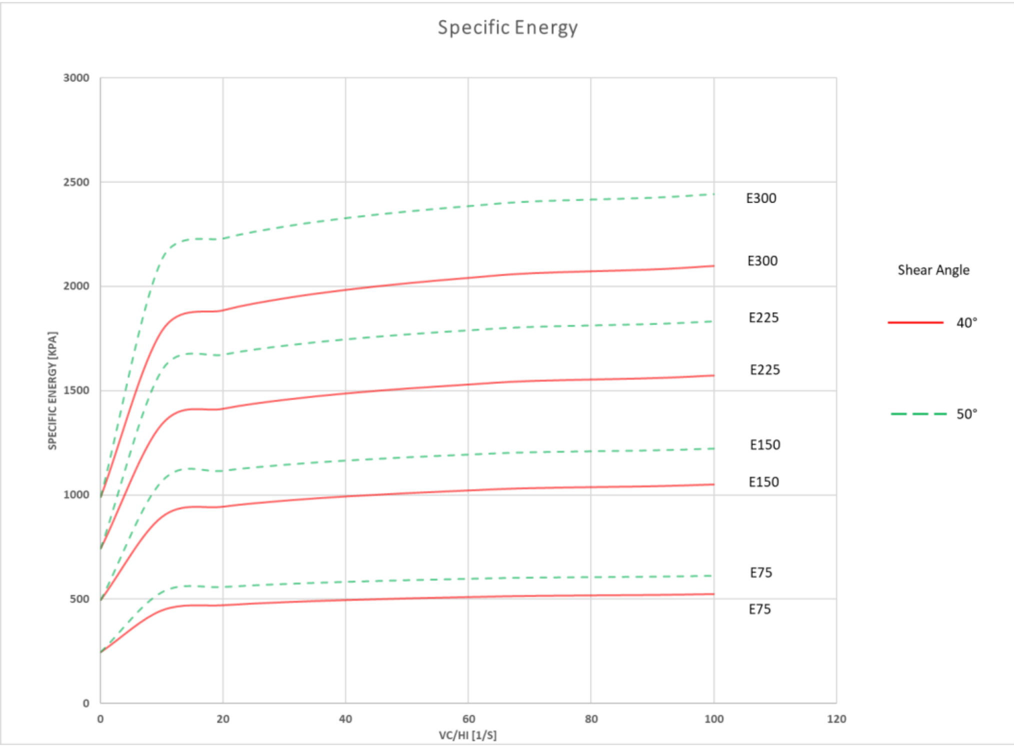


	55	50	45	40	35
Miedema beta	1,12	1,04	1,01	0,99	0,94
H and C beta	1,03	0,97	1,02	1,16	0,96

A further observation is the significant impact of changing the shear angle on the specific energy graph. The graph has been presented earlier on at page 4.
The graph below displays two distinct series of data. The first series corresponds to the values presented by Miedema model, which were obtained using Hatamura and Chijiiwa's data and a shear angle of 40 degrees. The second series of data is obtained by considering a shear angle of 50 degrees.
This comparison clearly demonstrates that each clay type possesses its own unique soil characteristics and behavior, highlighting the impossibility to generalize clay properties. The differences in the specific energy values obtained by varying the shear angle indicate the importance of considering the specific characteristics and behavior of individual clay types when developing clay cutting models. This further emphasizes the need for a more refined and accurate approach that accounts for the variations in clay behavior associated with

different shear angles. Lastly, it is important to note that the specific energy graph presented by Miedema holds true only for Kanto loam. Miedema's depiction of multiple curves, each corresponding to a different cohesion value, may give the impression that the graph can be universally applied. However, this assumption is false.
The variations in the specific energy curves based on different cohesion values indicate that each clay type has its own unique behavior and characteristics. Therefore, it is not appropriate to generalize the specific energy graph across all clay types. Instead, a more accurate and reliable approach would involve considering the specific soil characteristics and behavior of each individual clay type when developing cutting models. This observation emphasizes the need for caution and precision in the application of clay cutting models, recognizing that the behavior of clay is highly dependent on its specific properties and cannot be generalized based on a single graph.

Figure 30:
Specific energy for different values of shear angle



In summary, the conclusions drawn from this study highlight several critical issues and discrepancies within Miedema's cutting theory for clay. The assumptions of constant values for strain rate, shear strength, and dynamic shear resistance across all types of clay are found to be inaccurate. The nomenclature used by Miedema lacks clarity and deviates from the definitions provided by Hatamura and Chijiiwa. The choice of strain rate and the calculation of the strengthening factor present inconsistencies when compared to the original research by Hatamura and Chijiiwa and the work of Wismer and Luth. Additionally, the influence of shear angle on the strengthening factor and horizontal forces challenges Miedema's assertion of its independence. These findings underscore the need for further research and refinement of

Miedema's cutting theory. By addressing these discrepancies and considering the specific characteristics and behaviors of different types of clay, it is possible to develop more accurate and reliable models for clay cutting. The insights gained from this study contribute and will serve as a foundation for future research in the field.

To conclude, this chapter has provided a comprehensive overview of the conclusions derived from the analysis and examination of Miedema's cutting theory. The limitations and implications of these findings have been discussed, highlighting the areas that require further exploration and research.

5. Discussion

This chapter presents a comprehensive discussion of the findings and implications derived from the evaluation of Miedema's cutting theory for clay. The discussion aims to provide a deeper understanding of the limitations and discrepancies identified. By critically analyzing the results obtained from the research, this chapter offers insights into the weaknesses of Miedema's theory and highlights potential areas for improvement in clay-cutting models.

Currently, several clay models primarily rely on the findings of Hatamura and Chijiiwa as a means to validate their results. This can be observed in a specific research study titled "A novel approach for simulation of soil-tool interaction based on an arbitrary Lagrangian-Eulerian description" (L.B. Zhang, 2017). However, this thesis specifically focuses on Miedema's model due to its widespread use in the dredging industry.

The evaluation of Miedema's cutting theory has revealed several significant limitations and discrepancies. One key limitation pertains to the lack of clarity in Miedema's nomenclature when defining the cutting theory. Moreover, the discrepancy between the dynamical shear resistance values attributed to Hatamura and Chijiiwa's investigations raises questions regarding the accuracy and derivation of the specific value employed by Miedema.

Another area of concern is the strain rate utilized by Miedema to calculate the strengthening factor. The inconsistency between the stated strain rate and the values obtained from Hatamura and Chijiiwa's work raises doubts about the validity of the chosen strain rate in Miedema's theory.

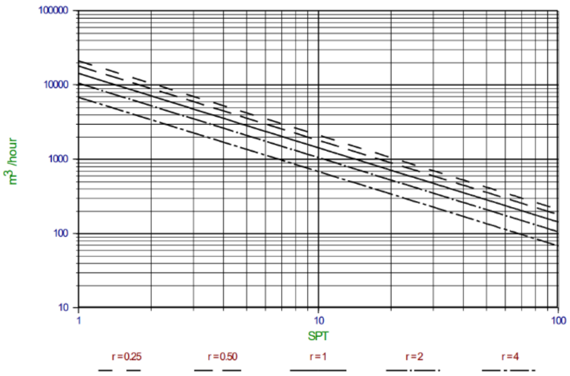
The modified version of the Wismer and Luth strength rate introduced by Miedema deviates from the original definition, leading to discrepancies in the calculated values. This inconsistency emphasizes the need for a thorough reevaluation of the calculation of the strengthening factor and its relationship to the strain rate in clay cutting models. A study conducted in 2022, reports values of strain rate for different clayey materials being sheared (Konstantinov, July 2022). That proves that introducing a constant strain value of 0,03 within Wismer and Luth can't be considered correct.

The influence of the shear angle on the strengthening factor and horizontal forces also challenges Miedema's assertion of its independence. The analysis conducted in this study reveals variations in the strengthening factor when the shear angle is altered, suggesting that the shear angle plays a crucial role in determining the value of the strengthening factor and subsequently affects the magnitude of horizontal forces exerted during clay cutting. The study however is limited to the data available to carry on the calculations. A study conducted in 1983, states that shear strength is dependent on the strain rate, these two quantities influence each other (Graham, 1983). For a complete analysis of the dependency of the shearing factor on the shear angle, the dependency of the shear strength on the strain rate must be considered.

Miedema's formulations reveal notable limitations, particularly in the definition of the graph describing specific energy, **Figure 3**. Another main issue arises from the application of a uniform strengthening factor of 2 across all types of clay. This oversimplification doesn't account for the variations within different clay compositions. Similarly, the accuracy of

estimating production for dredging projects using this approach is questionable (see figure below).
These limitations highlight the necessity of reassessing and refining Miedema's formulations to improve the accuracy and reliability of predictions related to specific energy and dredging project productivity.

Figure 31:
Production for 100 kW



Note. (Miedema A. Sape , 2016)

The design of the cutting rig however provides valuable insights and opportunities for future research in several ways. By using the cutting rig to conduct experiments and collect data, researchers can validate and refine the existing theoretical models related to clay cutting. The data obtained from the cutting rig can be compared with the predictions of existing models, helping to identify any discrepancies and improve the accuracy of future predictions.
The cutting rig enables moreover, researchers to study and analyze the failure mechanisms associated with clay cutting in a controlled environment. By manipulating various cutting parameters and using different types of clay, researchers can investigate how different factors influence the failure mechanisms, such as tool clogging, adhesion, and material compaction. This understanding can lead to the development of improved techniques and strategies for efficient clay dredging.
Lastly, the cutting rig allows for the collection of data on various cutting parameters, such as cutting speed, tool geometry, and applied forces. By analyzing the data obtained from the cutting rig experiments, researchers can identify optimal cutting parameters for different types of clay. This optimization can lead to increased efficiency, productivity, and cost-effectiveness in future dredging operations.

The recognition of limitations and discrepancies in Miedema's cutting theory underscores the critical importance of refining the existing clay cutting model. The refinement of Miedema's theory holds the potential to enable more accurate estimations and predictions for dredging projects, facilitating improved planning and decision-making processes.
The results chapter of this study sheds light on the need to redefine the concept of the strengthening factor, a key parameter in Miedema's theory. This can be accomplished through an extensive enrichment of the database documenting the behavior of clay under cutting

conditions. To establish a more comprehensive and robust strengthening factor, it is essential to utilize Hatamura and Chijiwa's cutting rig and gather a diverse range of data encompassing various types of clay analyzed under different types of cutting conditions.

Lastly, by defining an accurate strengthening factor the development of more efficient equipment is allowed, as well as better estimations for dredging projects, driving progress in the field and enabling advancements in the field of clay cutting technology.

6. Conclusions and Recommendations

This chapter provides answers to the main and sub questions obtained through the comprehensive analysis and examination of Miedema's cutting theory for clay. This chapter aims to present a thorough overview of the outcomes derived from the research methodology, investigations, and critical analysis of existing literature. The primary objective of this study is to evaluate Miedema's model for clay cutting and assess its accuracy, with a specific focus on addressing the research questions related to nomenclature and parameter definitions, strain rate, shear strength, dynamic shear resistance, and the influence of shear angle on the strengthening factor and horizontal forces. The following section delves into each sub-question providing an answer.

Research Sub-question 1: What are the discrepancies in nomenclature between Miedema's clay cutting model and Hatamura and Chijiiwa's findings, and how do they impact the clarity and consistency of the model?

The first topic of analysis is about the discrepancies and lack of clarity in Miedema's nomenclature and parameter definitions within the clay-cutting model. The research findings reveal that Miedema mistakenly introduces the dynamical shear resistance equal to $\tau_0 = 4\,kPa$, attributing this value to Hatamura and Chijiiwa's findings. However, a detailed examination of Hatamura and Chijiiwa's research demonstrates that the actual value reported for the dynamical shear resistance is 28 kPa. This significant disparity raises questions about the origin and accuracy of Miedema's chosen. By highlighting these discrepancies, the research findings emphasize the importance of accurate and unambiguous parameter definitions in the context of clay cutting.

Research Sub-question 2: What are the results of calculating the strain and strain rate using Hatamura and Chijiiwa's data, and how do these results demonstrate that Miedema's chosen strain rate value is incorrect?

The next aspect of analysis focuses on the strain rate incorporated in Miedema's clay-cutting model. The research findings demonstrate a notable discrepancy between Miedema's stated strain rate of 0.03 1/s and the actual strain rate calculated based on Hatamura and Chijiiwa's data in this research, which is 4 1/s as found in section 3.3.1, page 32 . This value is in the same order of magnitude of the declared strain rate of Hatamura and Chijiiwa (3 1/s). This discrepancy raises significant doubts about the accuracy and validity of Miedema's chosen strain rate values. By recalculating the strain rate using Hatamura's photographs of the Kanto loam during cutting, the research findings provide evidence to support the claim that Miedema's theory relies on incorrect values for the strain rate.

Research Sub-question 3: To what extent do the adjustments made by Miedema to the formulation of Wismer and Luth's strength rate contribute to inaccuracies in his cutting-clay model?

The adjustments made by Miedema to Wismer and Luth's strength rate formulation significantly impact the accuracy of his cutting-clay model. Despite Miedema's claim that the multiplication factor of Wismer and Luth can be converted to SI units and aligned with

Hatamura and Chijiiwa Kanto clay, the calculation of this research reveal a substantial misalignment. The obtained value deviate significantly from the specified strain rate of 0.03 1/s, resulting in extremely small value that do not correspond to the intended characteristics, this can be observed in section 3.3.2, page 33. This discrepancy underscores the need for a comprehensive reassessment of the formulation to ensure accurate representation of strength rates in clay cutting models.

Research Sub-question 4: What is the relationship between shear angle and the strengthening factor in clay cutting, and how does it challenge Miedema's claim of minimal influence of shear angle on the strengthening factor and horizontal forces?
The research findings challenge Miedema's claim of minimal influence of shear angle on the strengthening factor by examining the relationship between shear angle and the strengthening factor. Through data analysis, the research findings highlight the variations in the strengthening factor as the shear angle is adjusted, section 3.3.3, page 34. This analysis provides insights into the complex dynamics involved in clay cutting and contributes to a more accurate representation of clay behavior in cutting models.

Research Sub-question 5: What design should a cutting rig have to investigate the soil mechanics properties related to clay cutting?
The design of a cutting rig is crucial for investigating the soil mechanics properties related to clay cutting. Replicating Hatamura and Chijiiwa's soil bin experiment setup provides a specialized tool for measuring the dynamic shear strength of soil. By reproducing the dimensions of their cutting rig, comparability and consistency with their experiments are ensured. Through primary data collection from Hatamura and Chijiiwa reports and brainstorming sessions, the mechanics of the cutting rig has been defined, and the components are detailed in Appendix A: Cutting rig components, at page 52. The cutting rig allows for placing a soil sample in the soil bin and cutting it with a specific angle and velocity using a steel blade. Load cells accurately measure the forces exerted on the soil sample, enabling the calculation of dynamic shear strength. By considering these design considerations, valuable insights into the mechanical properties of clay cutting can be obtained.

By expanding on the results chapter, the research findings provide a comprehensive evaluation of Miedema's clay-cutting model, emphasizing the discrepancies and limitations within the study. The analysis underscores the importance of accurate parameter definitions, precise parameter selection, and appropriate formulation of key factors in clay-cutting models. Furthermore, the findings highlight the need for further research and development to enhance the accuracy and reliability of clay-cutting models for practical dredging applications.

Recommendations

This section presents recommendations based on the conclusions drawn from the research conducted on Miedema's cutting theory for clay. The following recommendations are made:

- *Refinement of Nomenclature and Parameter Definitions:* It is recommended to refine the nomenclature and parameter definitions in Miedema's cutting theory to enhance clarity and eliminate ambiguity. Establishing clear and consistent definitions will facilitate a better understanding and application of the theory in practical scenarios. Additionally, providing a detailed procedure for deriving the formulations will strengthen the validity and transparency of the model.
- *Conduct Additional Experiments:* To further advance the understanding of clay cutting behavior and develop more accurate cutting models, it is crucial to perform additional experiments. Utilizing the specially designed cutting rig from this research, further testing and data collection on the mechanical behavior of clay should be conducted. This empirical data will enable the development of more accurate and reliable cutting models.
- *Strain rate for cohesion and adhesion:* Further research is needed to clarify and justify the specific value of 1.4 used for the strain rate in Miedema's equations, typically, the strain rate is determined by dividing velocity by a specific length. However, Miedema does not clarify the meaning or origin of value 1.4 in this context.

Implementing these recommendations will contribute to the advancement of knowledge in the field of clay cutting, enabling more accurate predictions and enhancing the efficiency and effectiveness of cutting operations in clay-rich environments.

Bibliography

Day, R. W. (2001). Soil Testing Manual: Procedures, Classification Data, and Sampling Practices. McGraw-Hill.

Georg Halim Kirlus. (1964, Cairo). Suez Canal and universal maritime Canal. *Dar Al-Fakr Alarabi*, p. 64.

Graham, C. (1983). *Time effects on the stress-strain behaviour of natural soft clavs.* University of Manitoba.

Guggenheim and Martin. (1995). *Definition of clay and clay mineral: Joint report of the AIPEA nomenclature and CMS nomenclature committees.* Chicago.

Hatamura, Chijiiwa. (1975). Analysis Of the Mechanism of Soil: 1st Report. Cutting Patterns of Soils. *JSME*, pp. 619-626.

Hatamura, Chijiiwa. (1976). Analysis of the Mechanism of Soil Cutting : 2nd Report. Deformation and Internal Stress of Soil in Cutting. *JSME*, pp. 555-563.

Hatamura, Chijiiwa. (1977A). Analysis of the Mechanism of Soil Cutting : 4th Report, Properties of Soils Related to Cutting. *JSME*, pp. 130-137.

Hatamura, Chijiiwa. (1977B). Analyses of the mechanism of soil cutting: 5th report, Cutting theories of soils. *JSME*, pp. 388-395.

Hiroyuki Tanaka, K. U. (2006). *Strain Rate Dependency of Cohesive Soils in Consolidation Settlement.* Oyo Corporation, Japan: Okkaido University, Port and Airport Research Institute.

Ivan B. Gratchev, K. S. (2015). *Shear Strength of Clay at Different Shear Rates.* Journal of Geotechnical and Geoenvironmental Engineering.

Kong, L. &. (2018). *Experimental study on the mechanical properties of soft clay during cutting process.* Soils and Foundations.

Konstantinov, A. (July 2022). *Experimental Study and Identification of a Dynamic Deformation* . Shahid Chamran : Journal of Applied andComputational Mechanics.

L.B. Zhang, Z. C. (2017). *A novel approach for simulation of soil-tool interaction based on an arbitrary Lagrangian–Eulerian description.* Tianjin University: Elsevier.

Małgorzata Nadziakiewicza, S. K. (2019). *Physico-Chemical Properties of Clay Minerals and.* Kraków: MDPI.

Miedema A. Sape . (2016). *The Delft Sand, Clay & Rock Cutting Model.* Netherlands: IOS Press BV, Delft University Press.

Miedema, S. (2001). *The cutting process in dredging. PhD thesis.* Delft University of Technology.

Mitchell, J. (1976). *Fundamentals of soil behavior.* John Wiley & Sons.

Newton, J. (1960). *Clay: its composition, properties and use.* Moscow, Idaho.

Peng, Horn, Peth, Smucker. (2006). *Quantification of soil shrinkage in 2D by digital image processing of soil surface.* Soil and Tillage Research.

Peter Hamburger. (2003). In Defence of Dredging: Increasing Public Awareness. *Terra et Aqua*, pp. 18-25.

R.D. Wismer, H. L. (1972). *Rate effects in soil cutting.* Great Britain: Journal of Terramechanics, Pergamon Press .

T. A. A Combe, S. A. (2015). The influence of adhesion on cutting processes in dredging. *Dredging Summit and Expo*.

Tetteh, G. M. (2016). *Foundation Soil Characterisation for a Building with Multiple Cracks at Tarkwa.* Ghana: University of Mines and Technology.

X. Chen, J.W. van den Broecke , G.Liu, G.Hong and S.A. Miedema. (2019). *A study on the clay adhesion factor.* Delft University of Technology and CCCC National Engineering Research Center of Dredging Technology and Equipment Co.

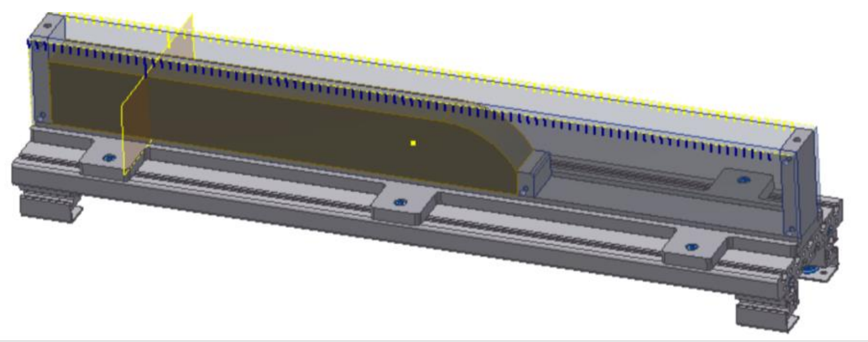
Appendix

Appendix A: Cutting rig components

The replication cutting rig represented in the figure above, consists of several key components, including:

- Soil bin- The soil bin is a rectangular container featuring plexiglass sides and a steel bottom. It serves as a confined space to securely hold the soil sample during the experiment, ensuring accurate and controlled testing conditions. Additionally, the soil container has been thoughtfully constructed to allow easy extraction from the rig, facilitating the placement and removal of clay within the container.
  The soil container has an effective cutting length of 440 mm. Furthermore, the design of the soil bin enables the replication of underwater conditions, enabling to explore and study soil behavior in submerged scenarios. In fact, the height of the container permits the addition of up to 30 mm of water on top of the clay sample.
  The soil container with its sturdy construction and adaptability to underwater conditions, provides a reliable and versatile platform for conducting experiments, ensuring precise control and accurate observations in the study of soil behavior.

Figure 32:
Soil bin



- Steel cutting blade- The cutting blades are carefully engineered to exert force on the soil sample at specific directions and angles. In order to ensure optimal performance and avoid excessive stress, the blades are constructed using robust steel material.
  The steel cutting blades are securely mounted on a rigid frame and can be vertically adjusted using slotted holes, as illustrated in ***Figure 34:***
  Slotted holesThis adjustability feature enables precise positioning of the blades at desired depths. Moreover, the blades' positions can be modified to accommodate various angles of attack and depths of cut.
  The blades used for cutting through the clay samples are manufactured from S235 steel, chosen for its durability and strength. These blades possess a roughness of 6μ, approximately equivalent to an R_a of 1.6 μm, ensuring efficient cutting performance. Additionally, it's worth noting that a second set of chisels with a roughness of 3.2 has been manufactured. However, this set will be reserved for further studies beyond the

scope of this current research, as the aim is to replicate the specific blade conditions of Hatamura and Chijiiwa cutting rig. By utilizing steel cutting blades with carefully chosen roughness levels, the experimental setup can accurately replicate cutting conditions, allowing for precise and controlled investigations into the behavior of the soil sample.

Table 4:
Blade angles

Blade angles	45 °, 60 °, 75 °, 90°

Figure 33:
Chisels

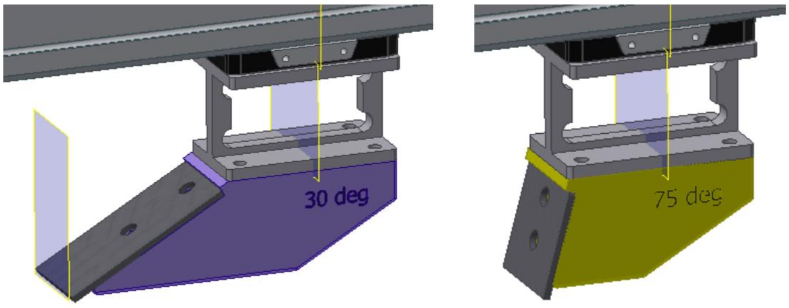
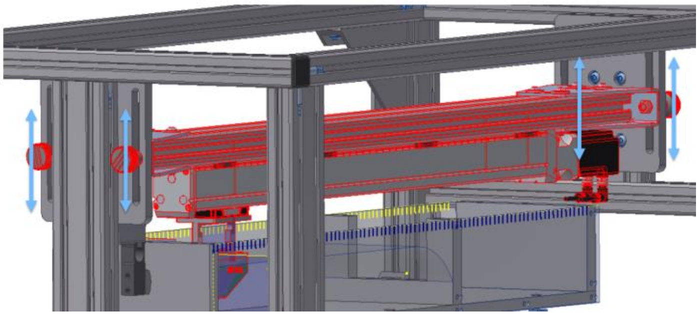


Figure 34:
Slotted holes

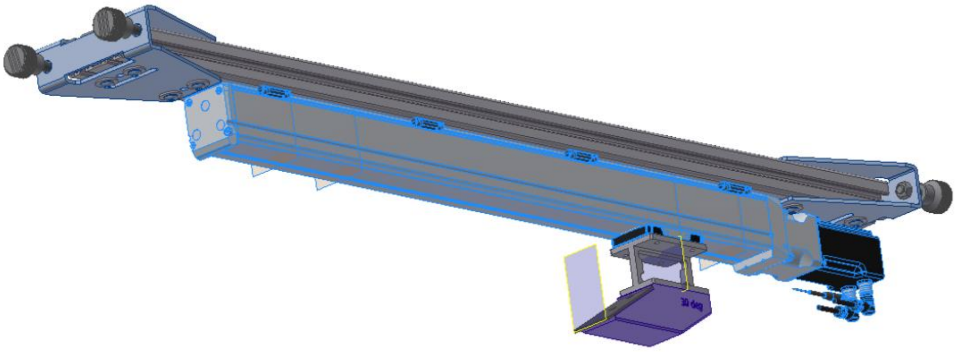


- Linear drive system- The linear drive system within the experimental setup serves to provide a controlled force to propel the steel cutting blade through the soil sample. Specifically, a programmable system equipped with a closed-loop stepper motor has been selected as the driver. This choice ensures precise control over the velocities required for the experiment, as specified in the range defined in the table below.
  The chosen driver's reliability and performance are key factors in achieving consistent results. Its precision and accuracy contribute to obtaining reliable data from the experiment. Additionally, the driver boasts a generous stroke length of 700mm, allowing for effective movement and penetration of the cutting blade through the soil sample.
  By incorporating the programmable system with a closed-loop stepper motor as the driver, the experimental setup benefits from its capability to deliver controlled forces and velocities.

Table 5:
Penetration speed

Penetration speed	v [m/s]
Minimum velocity	1
Maximum velocity	14

Figure 35:
Linear drive system

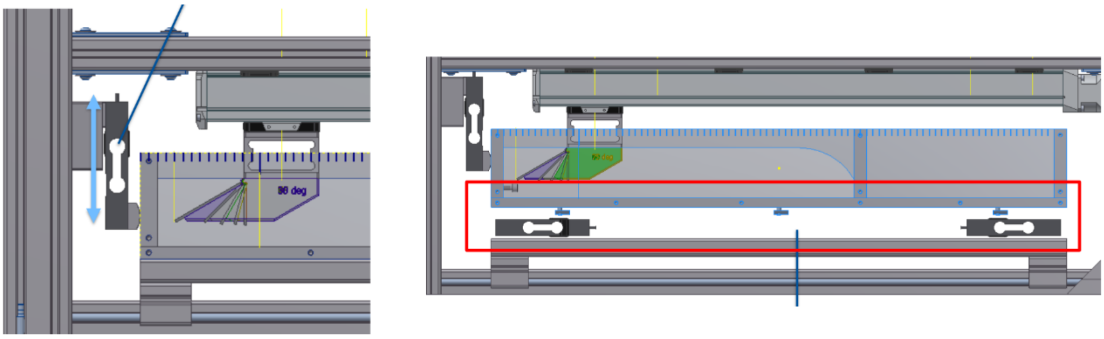


- Load cells- In the experimental setup, two load cells have been incorporated to accurately measure the forces applied to the soil sample. One load cell is specifically designed to measure the horizontal force, while the other load cell is dedicated to measuring the vertical forces acting on the soil sample. These load cells have been carefully calibrated to ensure precise measurements throughout the experiment.
  To account for any potential out-of-range signals, special considerations have been made during the incorporation of the load cells. Measures have been taken to prevent or handle situations where the load applied exceeds the load cell's specified range, thus ensuring the integrity of the measurements.
  The load cells are connected to an amplifier and data visualizer, allowing the recorded data to be displayed and analyzed. This setup enables the calculation of the dynamic shear strength of the soil based on the measured forces. By accurately capturing and processing the data from the load cells, valuable insights can be gained regarding the behavior and characteristics of the soil sample under different conditions.
  See the following section for mechanic related choices when measuring the horizontal and the vertical forces: **Comparative analysis of measuring systems for soil mechanics quantities: load cell, dynamometer, scale**.
  Below, the maximum forces that the load cell can measure.

Table 6:
Cutting force

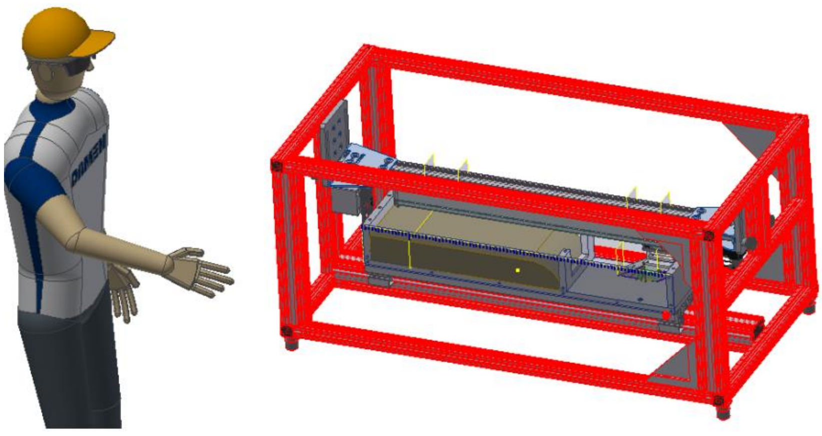
Cutting force	F [N]
Vertical force	150 N
Horizontal force	300 N

Figure 36:
Position of the vertical and horizontal load cells



- Frame- The cutting rig, designed for the experiment, consists of essential components that work to achieve accurate and controlled cutting. The total weight of the experimental setup amounts to 115 kg, ensuring stability and robustness throughout the testing process.
  The key elements of the cutting rig include a soil bin acting as a container, a stepper motor responsible for driving the cutting blades, and a sturdy steel frame that provides structural support to these components. The frame comprises two horizontal rails, each serving a specific purpose. The bottom rail facilitates the insertion and removal of the soil bin from the frame, allowing for convenient handling and cleaning of the container. On the other hand, the top rail enables the stepper motor to smoothly drive the cutting blades at a predetermined velocity, as illustrated in the figure below.
  By incorporating this well-constructed cutting rig the cutting process can be controlled, ensuring reliable and accurate results.

Figure 37:
Frame



Appendix B: Multi-Criteria Analysis and Design Choices

Multiple design choices have been made to design the experimental setup described in the chapter Methodology. This section describes various elements and systems that have been taken into consideration when designing the cutting rig. All the following components have undergone a thorough comparative analysis that is extensively described in the following section. This has allowed to choose the most suitable component for the cutting rig.

Forces Measuring System

In order to measure the forces acting on the soil, three measuring systems have been thought, it's needless to say that only one will be the ideal choice. Before comparing the three systems it's necessary to understand in what they consist of.

1) Load cell

The experimental setup is provided with a load cell that serves as a transducer; it converts forces into an electrical signal that can be measured. As the force applied to the load cell increases, the electrical signal changes proportionally. The type of load cell utilized is a strain gauge type. The load cell has an aluminum body, as force is exerted on the load cell, its spring element undergoes slight deformation, which causes a corresponding alteration in the strain gauges' resistance. The resulting alteration to the resistance in the strain gauges can be measured as a voltage. The change in voltage is proportional to the amount of force applied to the cell, thus the amount of force can be calculated from the load cell's output. Notably, the load cell's spring element always returns to its original shape, except when overloaded, ensuring the accuracy and reliability of the measurements obtained. Moreover, an amplifier has been chosen to amplify the small electrical signals produced by the load cell, making them stronger and more readable by a data acquisition system. The data are collected and displayed on a computer monitor using software for data acquisition and analysis.

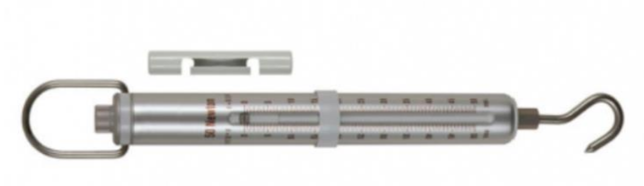
Figure 38:
Load Cell Al 3-30kg

Note. From "Scaime"

2) Dynamometer

A dynamometer is a device that can measure forces. To incorporate a dynamometer in a cutting soil bin to measure the forces, the dynamometer can be attached to the cutting tool or the cutting soil bin itself. The dynamometer can then measure the force required to cut through the soil.

Figure 39:
Dynamometer



Note. From "Weegschaal-online.com"

3) Scale

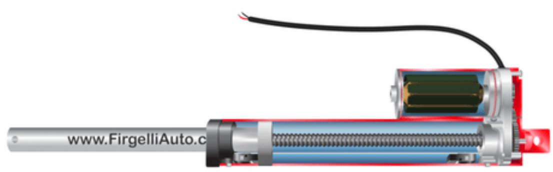
The scale can be utilized to calculate the forces that act on the system by placing it on a fix surface at the end of the soil bin. The pressure of the soil that is created due to the cutting tool can be visualized directly on the scale itself. A laboratory scale is not built to work in a vertical position, however a normal kitchen scale is perfect for this application.

Driving system

1) Linear drive

A linear drive is a type of actuator that produces linear motion instead of rotational motion, which is typical of conventional rotary motors. Linear drives convert electrical energy into linear motion by generating a linear force. The linear actuator works in a way that the main leadscrew is turned by the gears which are turned from the electric motor. The rotatory motion is converted by the leadscrew into linear motion of the main shaft. This can be seen in the following image.
The considered linear drives in this research are: AC motor with end switches, Servo system and Stepper motor. In the following section the three liner actuators are described.

Figure 40:
Linear drive



Note. From "Firgelli Auto"

1.1) AC motor with end switches

An AC motor is a type of electric motor that operates on alternating current. The end switches, also known as limit switches, are used to detect when the actuator reaches its maximum extension or retraction. These switches are typically wired to the motor control circuit and are designed to stop the motor when the actuator reaches the desired position. The main advantage of this type of actuator is its simplicity and relatively low cost. However, it can be difficult to control the speed of the actuator and measure its position accurately, which may limit its performance in certain applications.

1.2) Servo system

A servo system is a closed-loop control system that uses feedback signals to control the position and speed of the actuator. It typically consists of a servo motor, a position sensor, and a controller. The position sensor provides feedback on the current position of the actuator, which is then compared to the desired position by the controller. The controller adjusts the voltage supplied to the servo motor to achieve the desired position and speed. The advantages of a servo system include high accuracy, fast response times, and the ability to control both position and speed. However, they are generally more expensive than other types of linear actuators.

1.3) Stepper motor

A stepper motor is an open-loop type of electric motor that moves in small, precise steps. It is typically used in applications that require high precision and accuracy. The motor rotates in small increments, or steps, in response to electrical pulses from the controller. The number of steps required to achieve a certain position is determined by the motor's step angle and the pitch of the lead screw. The main advantage of a stepper motor is its precise control over position, which makes it ideal for applications that require high accuracy. However, they can be less efficient than other types of motors, and their performance can degrade at high speeds.

2) Rack and pinion system

A rack and pinion system is a type of mechanical device used to convert rotational motion into linear motion. It consists of a gear called a pinion, which is attached to a rotating shaft, and a long, flat bar with teeth called a rack. The rack is positioned perpendicular to the pinion and meshes with the teeth on the pinion.

As the pinion rotates, its teeth push against the teeth on the rack, causing the rack to move linearly. This linear motion can be used to move the cutting blade.

Figure 41:
Rack and pinion driving system

Note. From "Motioncontroltips.com"

3) Spindle and nut system

The spindle and nut system is a mechanical system used to convert rotational motion into linear motion. It typically consists of a spindle, which is a rotating shaft, a thread, and a nut, which is a component that engages with the thread and moves along the spindle when it rotates.

The system can be used as a driver to push the blade that cuts the soil. The spindle is typically powered by an electric motor or other source of rotational power. As it rotates, the thread on the spindle engages with the nut, causing it to move along the spindle in a linear direction. The extremity of the thread has been adjusted by decreasing the diameter such that it would fit a hand drill attachment.

By attaching the nut to the blade, the linear motion of the nut can be used to push the blade forward, allowing it to cut through the soil in the bin. A more complete representation can be seen in ***Figure 44***.

Figure 42:
Thread, part of the Spindle and nut System

MCA:

The following section involves carrying out multiple comparative analyses. Firstly, the aim is to determine the ideal force-measuring system to be incorporated into the experimental setup. Secondly, the focus is on selecting the most suitable material for constructing the soil bin sides through another comparative analysis. Lastly, the typologies of the driving systems are investigated in the final MCA.

During the design phase of the experimental setup, the importance of each attribute/criterion varies. Therefore, a numerical value is assigned to each attribute to determine its level of significance in the design process. The analysis will be performed using a 5-point rating scale for each attribute, with 5 being the best and 1 being the worst.

Table 7:
Rating scale for MCA attributes

5: This is the most important attribute to consider when designing the experimental setup. A rating of 5 means that this attribute is critical to the success of the experiment and cannot be compromised. For example, if accuracy is rated as a 5, it means that precise and reliable measurements are essential for the experiment to yield meaningful results.
4: This attribute is highly important and should be given close attention during the design process. A rating of 4 means that the attribute can have a significant impact on the success of the experiment and should not be overlooked.
3: This attribute is moderately important and should be considered in the design process. A rating of 3 means that the attribute can influence the experiment's success, but not to a critical extent.
2: This attribute is of relatively low importance and can be given less attention in the design process. A rating of 2 means that the attribute is not critical to the success of the experiment but should still be considered.
1: This is the least important attribute to consider when designing the experimental setup. A rating of 1 means that the attribute is of little importance and can be given low priority in the design process.

1) Comparative analysis of measuring systems for soil mechanics quantities: load cell, dynamometer, scale

Measuring system for the horizontal forces

When designing an experimental setup to measure soil mechanics quantities, the choice of measurement equipment is critical. Three options have been considered: a load cell, a dynamometer, and a scale. Here, these options are compared based on six attributes: accuracy, cost, delivery time, durability, and sensitivity.

- **Accuracy 5/5**: How precise and reliable are the measurements obtained from each system?
- **Cost 3/5**: What is the cost of each piece of equipment, including any necessary accessories or software required for data analysis?
- **Delivery Time 2/5**: How long does it take to obtain the equipment, and is it readily available from existing inventory or will it require special ordering?

- **Durability 2/5**: How well the measuring system can withstand overloading?
- **Sensitivity 1/5**: How well the measuring system can detect small changes in the quantity being measured?

These rankings reflect the priority of each attribute in the context of the experimental setup. Since the accuracy of the measurements is crucial to the success of the experiment, it is assigned the highest importance score of 5. Cost is also an important factor to consider, but it's slightly less important than accuracy, with scores of 3. Delivery time and durability are also relevant considerations, but not as critical as the previous attributes, with scores of 2 and 4, respectively. The sensitivity of the equipment scores 1 as it doesn't differ relevantly from one piece of equipment to the other.

Table 8:
MCA Measuring System

Measuring System	Accuracy	5/5	Cost	3/5	Delivery Time	2/5	Durability	2/5	Sensitivity	1/5	TOT
Load Cell	5	100%	2	24%	3	24%	2	16%	5	20%	32,8%
Dynamometer	3	60%	3	36%	3	24%	3	24%	3	12%	31,2%
Scale	2	40%	1	12%	5	40%	5	40%	2	8%	26.4%

- **Accuracy**: Load cells (5) have the highest accuracy due to their ability to measure the smallest changes in force. Dynamometers (3) and scales (2) provide rough measurements, especially in case of the scale, for which the human eye must be able to detect the values.
- **Cost**: Load cells are the most expensive option among the three systems, with prices ranging from several hundred to several thousand dollars depending on the capacity and accuracy required. Dynamometers are also relatively expensive, but they are usually less expensive than load cells. Scales are generally the least expensive option, for a price that ranges within few dozen euros. Therefore, load cells receive a score of 2 for cost, while dynamometers and scales receive a score of 3 and 5, respectively.
- **Delivery Time**: Load cells and dynamometers may take longer to order and receive because they are not as commonly used as scales. For this reason, the scale receives a score of 5, a load cell of 3, and the dynamometer.
- **Durability**: Load cells are relatively fragile and can be damaged if overloaded, resulting in significant repair costs. Dynamometers are generally more robust than load cells but are also susceptible to damage if used improperly. Scales are generally the most durable of the three systems. Therefore, load cells receive a score of 2 for durability, while dynamometers and scales receive a score of 3 and 5, respectively.

- **Sensitivity**: Load cells are highly sensitive and can measure small changes in force with high precision. Dynamometers are less sensitive than load cells, but they are still capable of measuring forces with a high degree of accuracy. Scales are generally the least sensitive option. Therefore, load cells receive a score of 5 for sensitivity, while dynamometers and scales receive a score of 3 and 2, respectively.

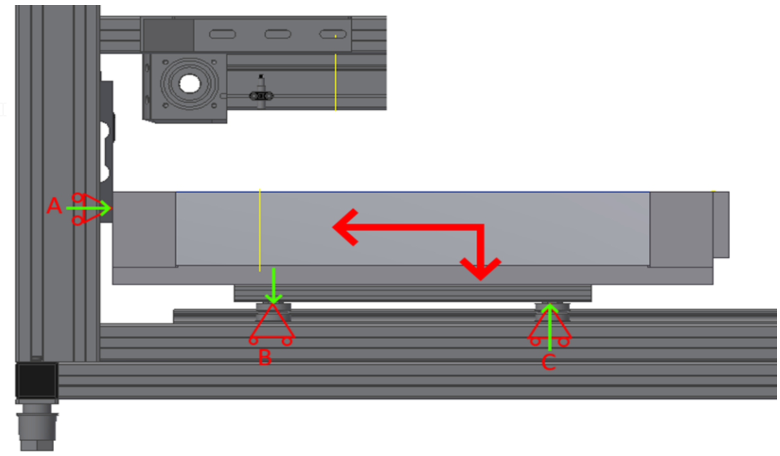
Overall, load cells are the most accurate and sensitive but also the most expensive. Dynamometers and scales are generally more affordable, but may not be as accurate or sensitive as load cells.
For the purpose of this experiment, the load cell resulted to be the ideal measuring system for the load cell that measures the horizontal force.

Measuring system for the vertical forces
In regards to the load cell that measures the vertical forces, different considerations must be done. In order to simplify the scope of work, an MCA Analysis won't be performed to decide what type of measuring system is required in this scenario. In the following section mechanical consideration are however presented.
The container filled with the soil sample is driven in the longitudinal direction and is restricted transversely by 4 wheels. The forces in the soil bin can range from 0 to the following values:

- F.x max=300N
- F.z max=150N

On the left side of the cutting rig, the load cell has been placed vertically to measure the horizontal force. Placing a measuring system such as a load cell beneath the soil bin, in order to measure the vertical forces, would cause the two load cell to influence each other. The left load cell generates a moment on the wheels, which creates vertical reaction forces that could affect the other load cell.

Figure 43:
Mechanical scheme



To counteract this problem two solutions have been thought, the first consist in purchasing a multi-axis load cell that would measure both the vertical and horizontal forces, this solution is however not feasible from an economic point of view. For this reason a second concept have been thought, the horizontal and vertical forces are going to be measured in different moments, this is allowed by replacing the load cells with two dummy aluminum blocks.

2) **Comparative Analysis for Material for Soil Bin Sides: plexiglass, acrylic, glass**

In order to select the most suitable material to utilize as a clear side for the soil bin a multi-criteria analysis has been run for the following materials: plexiglass, glass, and acrylic.
The chosen criteria necessary to make the selection are listed below.

- **Durability 4/5** – How much the material can resist damage or cracking?
- **Visibility 5/5** – How much the material can maintain clear visibility without getting hazy?
- **Cost 3/5** - What is the cost of each material?

These rankings reflect the priority of each attribute in the context of the experimental setup. The visibility is important because the soil bin sides will be subject to wear and tear over time, and the ideal material is the one that will last as long as possible.
A score of 4 reflects the high importance of this attribute. Cost is also an important factor to consider, but it's slightly less important than accuracy, with scores of 3.
Durability is also relevant, as we would like to avoid the material to break or to crack, this is why it scores 4.

The following step is to compare the three materials:

Table 9:
MCA Material of Soil bin sides

Material	Durability	4/5	Visibility	5/5	Cost	3/5	TOT
Plexiglass	4	64%	5	100%	3	36%	66.6%
Acrylic	5	80%	2	40%	4	48%	56%
Glass	2	32%	4	80%	2	24%	45,3%

- **Durability**: Acrylic (5) has the highest score as it's a very sturdy material, and plexiglass (4) properties are relatively good compared to glass (2) as it's a fragile material that is subjected to cracks it breaks.
- **Visibility**: A high score is given to Plexiglass (5) as scratches are able to fill up themselves with water, this causes the material not to be subjected to the foggy look typical of Acrylic (2). Lastly, glass has a good response to scratches (4).
- **Cost**: Acrylic (4) it's the cheapest material with €8.5 - €42.5 per sheet, depending on size and thickness. On the other hand, glass is the most expensive (2), it costs indeed €42.5 - €170 per sheet. Plexiglass is in between scoring (3), with the following prices €17 - €85 per sheet.

Based on these scores, plexiglass seems to be the best choice overall, with the highest score for visibility, which represents the priority in the experimental setup.

3) **Comparative Analysis for the Driving system: spindle and nut, rack and pinion, linear drive**

A multi-criteria analysis was conducted to determine the most suitable material for driving the blade in the experimental setup. The two options considered were the rack and pinion system and the spindle and nut system. By evaluating each system against these criteria, the optimal solution can be identified. The chosen criteria for the selection are:

- **Safety 5/5** - To what extent does the system ensure safe operation?
- **Stability 5/5** - How stable is the system and how constant is the speed generated?
- **Cost 2/5** - What is the cost of each piece of equipment, including any necessary accessories?

It is crucial to develop an experimental setup that is safe, this is reason for which Safety scores 5. Moreover if the setup in not stable the cutting conditions won't reflect what must be performed, this is why it's a crucial attribute and it scores 5. Lastly the cost reflects the possibility to build the rig using materials that are already present in the DAMEN laboratory, it's not however a limiting attribute.The following step is to compare the two systems:

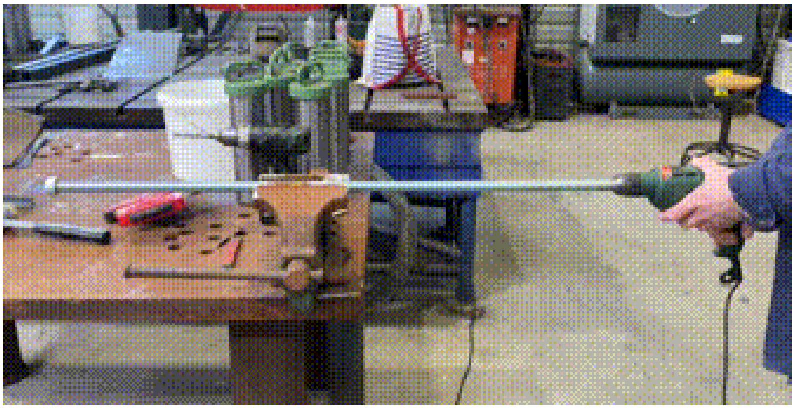
Table 10:
MCA for the Driving System

Driving system	Safety	5/5	Stability	5/5	Cost	2/5	TOT
Spindle and nut	3	60%	1	20%	5	40%	60%
Rack and pinion	5	100%	4	80%	3	24%	68%
Linear drive	5	100%	5	100%	3	24%	74,6%

- **Safety:** The safety of the spindle and nut spindle is relatively low, hazards can be identified when drilling and getting to the end of the thread (3), the rack and pinion system is overall safe (5). The linear drive has a strong safety record, scoring 5 out of 5.
- **Stability:** The spindle and nut system scores 1 as the overall stability and efficiency are low, this can be observed in ***Figure 44***. The metal thread and nut are not designed for a high-precision. The rack and pinion system scores 4, it provides a consistent and precise motion, resulting in accurate and repeatable cuts. The rack and pinion system has a high stiffness, which means it can handle higher loads and maintain its accuracy even under heavy cutting conditions.. The linear drive has a highly stable performance (5), it has the abilitcannstant and precise speed during operation. The linear drive system can offer a high level of stability and precision due to its design, which uses a linear motor to move the cutting tool along a straight path. The linear motor is able to produce precise movements with high accuracy and repeatability, which makes it suitable for applications that require precise control and stability

- **Cost:** The materials required to realize the spindle and nut system are all found in the DAMEN laboratory (5), contrary to the rack and pinion systems and the linear drive that need to be purchased (3).

Figure 44:
Performance of the rod in the nut and spindle system



4) Comparative Analysis of the linear drive: AC motor with end switches, servo system, stepper motor

The MCA shows that the linear drive is he most suitable choice for the experimental setup. The following step is to determine which linear drive should be utilized in the driving system. As explained before the choice relies between: The considered linear drives in this research are: AC motor with end switches, servo system and stepper motor. In the following section the three liner actuators are described.

- **Speed control 5/5** - How well can the speed of the motor be controlled?
- **Precision 4/5** - How accurately can the motor move to a specific position?
- **Cost 4/5** - What is the overall cost?

It is important to develop an experimental setup with precise and controlled linear movement, which is why Precision and Speed Control score 5. Inaccurate positioning and speed can lead to inaccurate results and experimental failure. Cost is also an important factor as linear drives can get expensive it is important to evaluate well the cost.

Table 5:
MCA for the Linear drive

Linear drive	Speed control	5/5	Precision	4/5	Cost	4/5	TOT
AC motor with end switches	3	60%	2	32%	4	64%	52%
Servo system	5	100%	5	80%	1	16%	65,3%
Stepper motor	4	80%	4	64%	4	64%	69,3%

- **Speed control:** The speed of an AC motor is determined by the frequency of the AC power supply and the number of poles in the motor. While it is possible to vary the speed of an AC motor by adjusting the frequency of the power supply, this method of speed control is not as precise as other methods such as using a servo system or a stepper motor (3). From the other side servo systems are known for their precision and speed, making them a great choice for applications where accuracy is key (3). Lastly, stepper motors operate by rotating a fixed amount in response to each pulse of electricity they receive, which makes them highly precise. However, this precision comes at the cost of speed. Stepper motors are not as fast as some other types of motors because they have to pause and receive a new pulse of electricity for each incremental rotation. This process can slow down the overall speed of the motor, which can be a disadvantage in some applications where speed is a critical factor (4).

- **Precision:** Precision refers to the ability of a motor to accurately control its movement or position. When it comes to precision, servo systems and stepper motors are often preferred over AC motors. Servo systems are designed for precise control of position, velocity, and acceleration, and can maintain accurate positioning even under varying loads (5). Stepper motors are known for their high precision because they move in small, incremental steps. Each step corresponds to a fixed angle of rotation, making them well-suited for applications that require precise control of movement or position (4). In contrast, the precision of an AC motor is not as high as that of servo systems and stepper motors. AC motors rely on the frequency of the AC power supply and the number of poles in the motor to determine their speed and position, which can result in some degree of imprecision (2).
- **Cost:** In this case, the cost of the motor has been evaluated based on the available quotations. The servo system has been quoted at approximately 2900 euros (1), which is relatively high compared to the stepper motor which has been quoted at 1800 euros (5). The cost of an AC motor is 1700 euros.

As a result of the multi-criteria analysis, the linear drive chosen is the stepper motor as it results to be the most suitable.