

Design and Development of a Mechanised Cutting Tool for Foundation Piles

A Novel Mechanism to Reduce Operator Musculoskeletal Load

MSc Thesis

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Design and Development of a Mechanised Cutting Tool for Foundation Piles

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by

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Preface

This thesis marks the completion of my Master of Science degree in Mechanical Engineering at Delft University of Technology. The work presented in this report focuses on the design and development of a mechanised cutting tool for foundation piles. The goal is to reduce the musculoskeletal load experienced by operators during manual pile grinding.

What started as a relatively straightforward design challenge quickly evolved into a complex engineering project involving ergonomics, concept development, mechanical design, prototyping, iterating, testing and structural analysis. Throughout the project, I learned that designing a functional solution is only one part of the challenge. Understanding the practical realities of a construction site and the needs of the people who ultimately use the product proved equally important.

I would like to thank my supervisor, Dr. Ir. Arno Stienen, for his guidance, critical feedback and support throughout my MSc thesis. His ability to challenge the assumptions I made and encouragement to actually build something has been invaluable during the development of this thesis.

Also, I would like to express my gratitude to Ryan Eggers, the employees of De Waalpaal B.V. and the employees of Van 't Hek for their willingness to share their experience, knowledge and practical insights. Their openness during interviews, on-site visits and the final test session provided the foundation for this project and ensured that the developed solution remained relevant to real-world practice.

Furthermore, I would like to thank my girlfriend, family and friends for their support and encouragement during my study and thesis. Their patience and confidence in me helped me remain motivated during the more challenging phases of my study and of this project. I am proud of the result and hope that this work can serve as a meaningful first step towards reducing the musculoskeletal load placed on operators in practice.

J.C.H.M. Tuijp
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Abstract

Manual pile grinding of foundation piles (screw injection piles) with an angle grinder is the most physically demanding task at foundation pile contractor De Waalpaal B.V, which is part of the Van 't Hek group. A Rapid Entire Body Assessment (REBA) identified it as the task with the highest ergonomic risk level with a REBA score of 11. This score corresponds to a "Very High" ergonomic risk level. Indicating that the operators using an angle grinder endure a high musculoskeletal load during this process. However, currently no dedicated tool exist to mechanise this process in order to reduce this musculoskeletal load.

This thesis presents the design and development of a mechanised cutting tool aimed at reducing operator musculoskeletal load during pile grinding. Requirements were derived from on-site interviews and observations using a Quality Function Development (QFD) method. These requirements were the basis of the three developed clamping concepts. Using these requirements, a final clamping concept was chosen and refined through an iterative design process. Furthermore, three cutting subsystem concepts were made and the best was selected.

The final design clamps around the pile using a ratchet tie down and rotates around its circumference on a set of contact wheels. The finalised mechanised cutting tool was evaluated in two test sessions. The first test session was performed by the author, while the second test session was performed by an intended end-user.

The tool met most of its defined requirements. Most importantly, it reduced the REBA score from 11 to a maximum of 6, moving the task from a "Very High" to a "Medium" ergonomic risk level. However, some limitations remained. Future work should focus on solving these limitations.

In conclusion, these results show that the developed tool is a functional proof of concept that substantially reduces the ergonomic risk level. However, it still requires further development before it is suitable for reliable use on construction sites.

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1

Introduction

Musculoskeletal disorders (MSDs) are defined as injuries in the musculoskeletal system [1]. They consist of diverse conditions affecting bones, joints, muscles, and connective tissues [2]. Common causes of MSDs are physically demanding work, repeating heavy tasks in unfavourable ergonomic positions, neglect and excessive muscle strain. For example, repeated strain and fatigue on the lower extremity muscles and joints are non-trivial and can lead to poor balance, fall, additional weight on the lumbar spine and musculoskeletal disorders of the lower extremities [3].

Such injuries sustained at work are called Work-related musculoskeletal disorders (WMSDs). They are a leading cause of absence from occupational work and disability [4]. According to Luttmann et al. it is generally accepted that working conditions and workload are important factors for the development and continuance of these disorders [4]. In the United States, for example, these disorders are among the most disabling and costly conditions [2]. WMSDs account for approximately one third of all health-related absences in industrialised countries, of which approximately 60% are back injuries [4]. In Europe alone, it affects about 40 million workers [5].

In addition to the health consequences for employees, being absent due to WMSDs developed by having physically demanding work also imposes substantial financial burdens on society and on employers. The average cost of an absent employee is estimated to be between €250 and €400 per employee per day [6]. When viewed in industrial environments, it costs up to 240 billion euro annually to companies and governments [5].

For employees suffering from WMSDs, this means a significant reduction in quality of life due to temporary or permanent work incapacity and loss of income. Besides the direct costs associated with WMSDs, it also results in indirect costs for employers. These indirect costs include reduced productivity, the need to replace or reassign employees, overtime costs, increased administrative costs and prolonged rehabilitation trajectories [4].

In order to reduce the chance of developing WMSDs, various ergonomic assistive technologies have been developed. These include lifting aids, arm supports, telemanipulators, mechanical support systems and exoskeletons. However, these ergonomic assistive technologies all have one thing in common: the effectiveness of these technologies is highly dependent on the task and working environment in which they are applied.

Exoskeletons, for example, have shown potential to reduce local muscular demand during specific tasks [7]. An exoskeleton designed to support the lower back may provide beneficial support while the operator is standing upright, but the same assistance can interfere with natural movement when the operator bends or changes posture. Mechanical support systems could potentially help, but require a lot more space than is available on construction sites. Arm supports can relieve the load on the arms of operators, but they are fixed in place and offer only a limited range of motion.

While various ergonomic aids exist to reduce musculoskeletal load, each has drawbacks that limit its use in specific situations. Therefore, an effective solution for reducing physical workload and WMSDs, needs to be tailored to the specific requirements of the task.

Foundation pile contractor De Waalpaal B.V. is directly confronted with this problem. De Waalpaal B.V. is part of the Van 't Hek Group, which specializes in foundation engineering and piling works. As part of foundation construction done by De Waalpaal B.V., steel foundation piles are driven into the

ground. These piles provide structural support for buildings. After the foundation piles are driven into the ground, the top of each pile must be cut to the correct height before further construction can continue. This process, known as manual pile grinding, is currently performed entirely by hand. A single operator uses an angle grinder to cut through the steel pipe wall, working around the full circumference of the pile. These working conditions are physically demanding. Radial clearance around the piles can be as little as $20\ cm$. The operator must reposition on average seven times per cut, with each cut taking approximately five minutes. These physically demanding tasks force the operator into unfavourable ergonomic postures. An example of such an unfavourable ergonomic posture is visible in Figure 1.1 below.



Figure 1.1: Example of an unfavourable ergonomic posture of a De Waalpaal B.V. employee who is manually grinding down a foundation pile using an angle grinder.

Employees reported manual pile grinding as the most physically demanding task they have. They mentioned experiencing significant lower back fatigue following prolonged cutting sessions. Moreover, management of De Waalpaal B.V. mentioned that most of their absentees are related to injuries sustained when doing these physically demanding tasks, especially manual pile grinding.

For manual pile grinding, the combination of frequent repositioning, confined workspace, varying working postures and continuous handling of an angle grinder makes the use of existing ergonomic assistive technologies difficult. Despite the physical demands of this task, no dedicated tool currently exists to assist or mechanise the vertical pile grinding process.

Therefore, this MSc thesis aims to address that gap. This MSc thesis presents the design and development of a mechanised cutting tool for foundation piles. This is a novel tool with the objective of reducing the operator musculoskeletal load.

In order to optimally design and develop the mechanised cutting tool, a detailed background to the problem is presented in Chapter 2. This includes an overview of the physically demanding tasks at De Waalpaal B.V., relevant pile types and their dimensions. Chapter 3 presents the method used to determine the requirements. Based on these requirements, concepts are developed in Chapter 4 where boundary conditions determine which technologies are applicable for concept development. An iterative design process then results in the final design, presented in Chapter 5. This final design is evaluated in Chapter 6, after which the results are discussed in Chapter 7 and conclusions are drawn in Chapter 8.

2

Background

This chapter provides the necessary background for the design and development of a mechanised cutting tool for foundation piles. It begins with an analysis of the foundation work of the company De Waalpaal B.V., including the results of an ergonomic assessment of operator postures. These operations are explained in Section 2.1 and visible in Appendix B.

Postures during foundation work are evaluated using REBA scores. The REBA score demonstrates that pile grinding is the most physically demanding task, as reported by employees and management.

In addition, Section 2.2 presents an overview of the relevant pile types and their dimensions. Finally, a problem statement and research question is given in Section 2.3.

2.1. Foundation work of De Waalpaal B.V.

During on-site visits conducted at construction sites where De Waalpaal B.V. worked, the most physically demanding tasks of employees were identified. This was done via interviews with employees present on-site and with management of De Waalpaal B.V. These physically demanding tasks are described in this section and they can be divided into three tasks: Lifting the foundation piles, grinding of foundation piles and handling the foundation pile debris.

2.1.1. Lifting the foundation piles

The first identified physically demanding task is the process of lifting the foundation piles into the foundation machines. The piles are transported horizontally and must be lifted into a vertical position before they are entered into the foundation machine. These lifting tasks can be seen in Appendix B.2. This task is physically demanding due to the weight of the piles combined with the awkward postures required to reposition them. The operator must support and guide the pile during the transition from horizontal to vertical without mechanical assistance, all while lifting the heavy pile segment above the ground. Moreover, this task is highly repetitive as this process needs to be repeated several times before one foundation pile is completed. The risk of developing WMSDs increases due to the workers being frequently involved in risk factors such as lifting the weights of the piles, lifting durations and lifting postures during repetitive lifting tasks [8].

2.1.2. Grinding of the foundation piles

The second identified physically demanding task is the process of grinding the foundation piles. After the piles have been driven or screwed into the ground, the top of each pile must be cut to the correct height before construction can continue. This is necessary because the top of the pile often ends up at the wrong height relative to the intended foundation level. To allow the construction to rest correctly on the pile, the excess material is removed by use of an angle grinder.

The grinding process is entirely manual, carried out by a single operator using an angle grinder. The desired cut height is first determined, either by laser or by manual measurement and a reference line is sometimes drawn around the pipe as a guide. In order to actually grind down the foundation pile, the operator must continuously lift the angle grinder and provide the necessary force to grind into the pile surface. This process must happen around the full circumference of the pipe to sever the top section.

The operator therefore relies on the visual, tactile and force feedback received from the angle grinder to continuously adjust its position and the applied force during the cutting process.

The working conditions during grinding are often unfavorable. Radial clearance around the pile can be as little as $20\ cm$. In some cases, piles are located inside pump pits. These are excavation pits of approximately $2 \times 2\ m$ or $3 \times 2\ m$ and have a depth of around $1.0\ m$ to $1.5\ m$. In these pump pits, working space is extremely restricted. As mentioned before, the closest a pile can get to a wall is $20\ cm$. These confined conditions force the operator into sustained awkward postures and require frequent repositioning around the pile. Workers reported significant lower back fatigue following prolonged cutting sessions. The postures observed during grinding are shown in Appendix B.3. The process of cutting down one pile takes 5 minutes. The grinding disc is replaced after 3 piles, depending on the pile diameter.

2.1.3. Handling of the foundation pile debris

The third identified physically demanding task is the handling of the foundation pile debris. After grinding, the severed section of pile must be removed from the pile and work area. Cut sections can be significant in mass. Namely, a cut section of $75\ cm$ in length already weighs approximately 30 kg, while longer sections or sections filled with grout can easily reach $100\ kg$ to $150\ kg$. The operator must therefore not only cut the pile but also handle and remove these heavy sections afterwards, placing significant load on the trunk and upper extremities. The postures observed during this task are shown in Appendix B.4. In practice, cut sections are sometimes broken off rather than fully ground through, as this is faster. However, this approach is physically hazardous. the section can fall uncontrollably and poses a direct safety risk to the operator.

2.1.4. Results first ergonomic risk assessment

Appendix B provides information on the used REBA assessment method and this method was chosen. Table 2.1 presents the results of the ergonomic risk assessment. For each analysed posture, the table lists the REBA score, the corresponding risk level and the recommended action. The risk levels and suggested actions follow the guidelines of Hignett and McAtamney [9]. Additional details, including the REBA scoring sheet and posture photographs, are provided in Appendix B.

Table 2.1: Result table for the ergonomic risk assessment. Suggested actions are derived from Hignett and McAtamney [9].

Figure	Posture	REBA score	Risk Level	Suggested action
Figure B.2	Posture A1	3	Low	Action may be necessary.
Figure B.3	Posture A2	6	Medium	Action is necessary, requires more investigation.
Figure B.4	Posture A3	5	Medium	Action is necessary, requires more investigation.
Figure B.5	Posture B1	11	Very High	Action is necessary NOW!
Figure B.6	Posture B2	11	Very High	Action is necessary NOW!
Figure B.7	Posture B3	11	Very High	Action is necessary NOW!
Figure B.8	Posture B4	11	Very High	Action is necessary NOW!
Figure B.9	Posture B5	10	High	Action is necessary soon.
Figure B.10	Posture B6	10	High	Action is necessary soon.
Figure B.11	Posture B7	7	Medium	Action is necessary, requires more investigation.
Figure B.12	Posture C1	7	Medium	Action is necessary, requires more investigation.

As shown in Table 2.1, pile grinding (Postures B1, B2, B3 and B4) is the most physically demanding task performed at De Waalpaal B.V., which is consistent with the experiences reported by employees and management.

2.2. Foundation pile specifications

In an interview with the operational manager the foundation pile specifications were discussed. According to the operational manager, the most commonly used pile is the ”schroefinjectiepaal”, translated to

screw injection pile. This is a steel pile filled with grout. Grout in construction is the process of filling gaps, voids and joints with a fluid mixture that hardens to create a solid, stable load bearing mass [10]. De Waalpaal B.V. also use ”stalen buispalen” and ”casing draaipalen” or translated to steel tubular piles and cased rotary piles. These piles are larger, heavier and are less commonly when compared to screw injection piles.

2.2.1. Screw injection piles

According to the operational manager, three types of different screw injection piles can be used depending on which scenario the construction has. These scenario’s are visible in Figure 2.1 and are denoted as #1, #2 or #3.

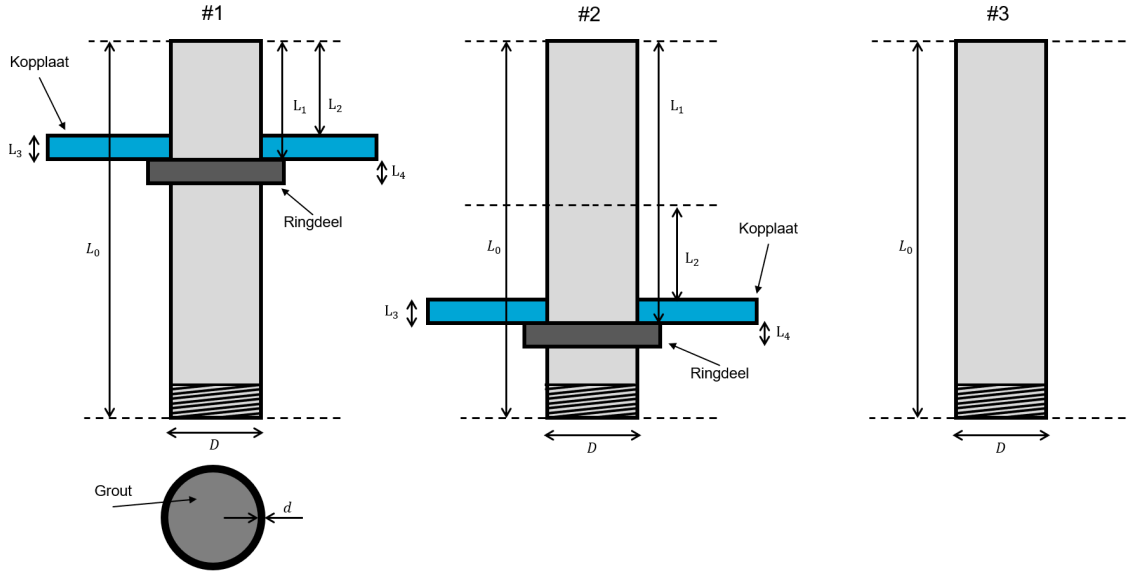


Figure 2.1: The three configurations of the screw injection pile as used by De Waalpaal B.V. In #1 and #2, a bearing plate rests on a spacer ring at different heights along the pile. In #3, both parts are absent and are welded on after the pile has been cut to the required foundation level. The cross-section at the lower left shows the grout-filled steel tube.

The screw injection pile will always be equipped with a ”ringdeel” and a ”kopplaat”, translated to spacer ring and bearing plate. These two parts can be seen in scenario #1 and #2 in Figure 2.1. In scenario #3, these two parts will be welded on later after the correct foundation level has been established and the screw injection pile has been cut. In order to create more foundational support, the ”kopplaat” will be welded on top of the spacer ring. The bearing plate is a steel bearing plate on which the foundation will rest. The spacer ring acts to ensure the bearing plate sits at exactly the correct height.

In every scenario, the following lengths are visible for the screw injection pile: a standard pile length L_o, protrusion length L_1 from the top of the pile to the top of the spacer ring, protrusion length L_2, bearing plate thickness L_3, spacer ring thickness L_4, outer diameter D and pile thickness d. For the screw injection pile, the standard pile length is always equal to $L_o = 1\ m$, the pile thickness $d = 0,01\ m = 10\ mm$, the bearing plate thickness $L_3 = 0,05\ m = 5\ cm$ and the spacer ring thickness $L_4 = 0,035\ m = 3,5\ cm$. The screw injection pile can have one of the following outer diameters:

- $D = 0,0889\ m = 88,9\ mm$
- $D = 0,1143\ m = 114,3\ mm$
- $D = 0,1397\ m = 139,7\ mm$
- $D = 0,1683\ m = 168,3\ mm$
- $D = 0,2191\ m = 219,1\ mm$

In scenario #1, protrusion length is equal to $L_1 = 0,25\ m$, whereas in scenario #2 protrusion length is equal $L_1 = 0,75\ m$. Protrusion length L_2 can be found in the following manner: $L_2 = L_1 - L_3$. In practice, the choice between a protrusion length of $L_1 = 0,25\ m$ or $L_1 = 0,75\ m$ provides the contractor

with an important degree of flexibility. For example, if a pile reaches its final depth at $22\ m$, selecting either the $0,25\ m$ or $0,75\ m$ ring height allows the final level of the bearing plate to be adjusted by approximately $0,5\ m$ without the employees having to weld the spacer ring themselves. As mentioned before in scenario #3, there is no spacer ring and bearing plate yet. Normally, the pile must still protrude approximately $l_2 = 0,20\,m$ above the "kopplaat". In practice this varies between 5 and 20 cm depending on the situation.

2.2.2. Steel tubular piles and cased rotary piles

According to the operational manager, these piles are used less common compared to screw injection piles. These piles are larger, heavier and not filled with grout. Instead, they are hollow and filled with concrete after foundational work has finished. These piles have thickness which ranges from $d = 5\,mm$ to $d = 8\ mm$. Their outer diameters range from $D = 168\ mm$ to $D = 457\ mm$.
In most cases, these foundation piles are cut using a cutting torch rather than an angle grinder. This method is effective for these hollow piles, as it allows for rapid material removal and reduces cutting time. However, cutting torches are less suitable for screw injection piles, where the grout filling complicates the cutting process. An angle grinder is more effective in such cases, as it only needs to cut through the outer steel wall, making the influence of the internal grout negligible.

2.3. Problem statement and research question

The background analysis presented in this chapter demonstrates that manual pile grinding is the most physically demanding task performed by employees of De Waalpaal B.V.. This conclusion is supported by both the REBA assessment and by interviews with operators and the operational manager. During the ergonomic assessment, pile grinding consistently received the highest REBA scores, with multiple observed postures reaching scores of 11, indicating a "Very High" ergonomic risk level that requires immediate intervention. In addition, operators consistently identified pile grinding as the task that causes the greatest physical fatigue, particularly in the lower back after prolonged periods of work.

Despite the high physical workload and ergonomic risks associated with pile grinding, no dedicated mechanised tool currently exists that performs this operation for the operator as mentioned in the introduction (Chapter 1). Instead, the process remains almost entirely manual and relies on the operator to guide an angle grinder around the complete circumference of the pile. Consequently, operators remain exposed to repetitive awkward postures, high physical loading and an increased risk of developing work-related musculoskeletal disorders.

As mentioned in Section 2.2, De Waalpaal B.V. works with several types of foundation piles. These are screw injection piles, steel tubular piles and cased rotary piles. Of these, screw injection piles are by far the most frequently installed pile type within the company's operations. Therefore, this thesis focuses exclusively on screw injection piles. The problem addressed in this thesis can be formulated as follows:

No dedicated tool currently exists to reduce the musculoskeletal load of operators during manual pile grinding.

This exposes them to a high risk of work-related musculoskeletal disorders. Based on this problem statement, the following design goal is formulated:

Design and develop a mechanised cutting tool for screw injection piles that reduces the musculoskeletal load of operators during pile grinding.

The tool must remain suitable for the confined and demanding conditions encountered on construction sites. To complete this goal, the requirements for the tool are first established in Chapter 3. Based on these requirements, concepts are developed in Chapter 4 where boundary conditions determine which technologies are applicable for concept development. An iterative design process then results in the final design, presented in Chapter 5. This final design is evaluated in Chapter 6, after which the results are discussed in Chapter 7 and conclusions are drawn in Chapter 8.

3

Requirements

In order to design and develop a mechanised cutting tool for the foundation piles used by De Waalpaal B.V., a structured approach is required. To ensure the requirements are based on actual pile grinding operator needs, rather than made assumptions by the author, the Quality Function Development (QFD) method was used [11]. The method consists of the following steps.

First of all, customer needs and statements are gathered through observations and on-site interviews. These are documented in a Voice of Customer Table (VOCT), which is visible in Table 3.1. Secondly, the collected statements are categorized into demanded qualities, specifications, failure modes and functions. The demanded qualities will be clustered into separate categories using an affinity diagram. Finally, these categories will be rated according to the importance rating of De Waalpaal B.V. employees in Table 3.3. The result is a structured set of customer-driven quality requirements that forms the foundation for the concept development and product design. Moreover, the identified specifications and functions are translated into technical requirements.

The acquired quality and technical requirements form the basis for the concept development in Chapter 4. The customer importance ratings of the quality requirements are used as the basis for evaluation during concept selection. Each concept will be made in accordance with the Technical requirements. The failure modes are translated into boundary conditions in Chapter 4.

3.1. Voice of the Customer

Table 3.1 presents the Voice of Customer Table (VOCT). This table contains the statements of De Waalpaal B.V. employees collected during interviews and on-site visits. These statements are visible under ”Voice of Customer”.

In addition to the Voice of Customer statements, the table includes contextual information about Who uses the product, What it is used for, Where and When it is used and How it is used [11]. By capturing both the Voice of Customer and the context of use of the tool, helps ensure that the identified requirements accurately reflect the customer needs. Moreover, it helps to ensure that customer requirements are interpreted correctly and provide a reliable foundation for any conceptual analysis later on.

The Integrated data combines the customer statements together with the concepts of application to generate the customer needs. This integration ensures that the meaning behind each statement is correctly interpreted before translating it into a requirement.

Table 3.1: Voice of Customer Table (VOCT).

Person	Info about person	Voice of customer	I = infered E = explicit	Context of application										Integrated Data	ID
			Who	What		Where		When		Why		How			
Angle grinder operator 1	has years of experience	"My lower back kills me after cutting pile a whole day. "	E Angle grinder operator	E Foundation pile grinding	E	Construction sites	E	During work hours	E	Less sustained akward postures	E	Positioning of the employee to use the tool		Tool must reduce operator musculoskeletal load	ID-01
Angle grinder operator 1	has years of experience	"I have to reposition myself about seven times."	E Angle grinder operator	E Grinding around pile circumference	E	Around the foundation pile	E	During the pile grinding process	E	Easy rotation of the cutting mechanism of the tool	E	Manual repositioning		Tool must rotate around the foundation pile without the operator having to reposition himself.	ID-02
Angle grinder operator 2	has years of experience	"Cutting one pile takes about 5 minutes. The product must not require more time to cut one pile."	E Angle grinder operator	E Foundation pile grinding	E	Construction sites	E	During the pile grinding process	E	The tool needs the same or less time during pile grinding operations.	E	By making sure the time per cut does not exceed 5 minutes		Cutting time must not exceed 5 minutes per pile.	ID-03
Employee 1	Construction site manager *(Dutch: uitvoerder)*	"The pile grinder operator cut about 20 to 25 piles per day."	E Angle grinder operator	E Foundation pile grinding	E	Construction sites	E	During work hours	E	High daily workload	E	N/A		The tool must allow for repeated use during work hours.	ID-04
Employee 2	Construction site manager *(Dutch: uitvoerder)*	"The angle grinder disc needs replacement after cutting about 3 piles.	E Angle grinder operator	E Grinding disc replacement	E	Construction sites	E	During work hours	E	Grinding disc wear	E	Good accessibility		The tool must allow for easy and quick grinding disc replacement.	ID-05
Management	Operational manager	"The tool must ensure the safety of the employee during operation."	E Angle grinder operator	E Employee safety		Construction sites		During the pile grinding process		An employee may not get injured when working		By genereting enough clamp force and designing the tool in such that dangerous elements are closed off		The tool must ensure the safety of the employee by generating sufficient clamp force and enclosing dangerous elements.	ID-06
Management	Operational manager	"It must clamp securly to the pile, without having to rely on the spacer ring."	E Angle grinder operator	E Tool mounting	E	On a foundation pile	E	During the pile grinding process	E	The tool may not fall of the pile during the grinding process.	E	The tools own weight and cutting forces must be resisted using a clamping mechanism on the pile		The tool must generate sufficient clamping forces to resist its own weight and cutting forces.	ID-07
Management	Operational manager	"The tool must be lightweight enough to be carried by one person."	E Angle grinder operator	E Tool transport	E	To different foundation piles	E	Before and after the grinding process	E	No mechanical assistance available	E	Carried manually by hand		The tool weight may not exceed 23 kg. *	ID-08
Management	Operational manager	"Setup time must be fast.	E Angle grinder operator	E Tool setup	E	Construction sites	E	During setup of the tool	E	Before the pile grinding process	E	Manual setup		Setup time must not exceed 2 minutes. **	ID-09
Management	Operational manager	"The pile grinding process is purely manual work."	E Angle grinder operator	E Foundation pile grinding	E	Construction sites	E	During the pile grinding process	E	No mechanised tool exists for the grinding of these foundation piles	E	Manual pile grinding		Tool must mechanise the pile grinding process.	ID-10
Management	Operational manager	"The tool must be work for mutliple pile diamers."	E Angle grinder operator	E Tool placement	E	Construction sites	E	During setup of the tool	E	De Waalpaal B.V. uses multiple pile diameters	E	Manual repositioning		The tool must be usable for all relevant pile diameters.	ID-11
Management	Operational manager	"Sometimes the minimum work space around the pile to the wall is 20 centimeters"	E Angle grinder operator	E Foundation pile grinding	E	Construction sites	E	When working in confined spaces or pump pits	E	Restricted space around the foundation pile	E	Manual repositioning		Tool must operate within 20 cm radial clearance on one side.	ID-12
Management	Operational manager	"A perfect cut is not necessary, but the deviation of the cut must not exceed 1 centimeter."	E Angle grinder operator	E Cut quality	E	Construction sites	E	During the pile grinding process	E	Not necessary to cut perfectly	E	Manual pile grinding		Cut deviation must not exceed 1 centimeter.	ID-13
Management	Operational manager	"Water is not always accesible on every construction site."	E Angle grinder operator	E Tool operation	E	Construction sites	E	Duriing the pile grinding process	E	Limited contruction site facilities	E	N/A		Tool must not require water for operation or cooling.	ID-14
Management	Operational manager	"The protrusion height above where the cut needs to be made, can be as little as 5 centimeters."	E Angle grinder operator	E Tool mounting	E	Construction sites	E	Before and after the grinding process	E	Minimal protrusion above ground	E	N/A		Tool must function with minimum 5 cm pile protrusion above cut height.	ID-15
N/A	N/A	N/A	I N/A	I Wet ground conditions	I	Construction sites	I	During cutting	I	Weather and ground water	I	N/A		Tool must not be placed on the ground for stability.	ID-16

** According to the Dutch Ministry of Social Affairs and Employment, the maximum recommended lifting weight under ideal conditions is 23 kg [12].*
*** If the setup time exceeds 2 minutes, employees will not use the mechanised tool. Therefore, it is important that the setup time is minimized.*

Based on the Integrated data in Table 3.1, the customer statements are categorized into demanded qualities, specifications, functions and constraints in Section 3.2. This categorization follows the QFD method mentioned by Terninko [11]. Moreover, it ensures that the integrated data obtained is treated separately before translating it into the requirements in Section 3.5.

3.2. Categorization of Integrated Data

According to Terninko [11], the demanded qualities are the customer's subjective descriptions of the desired performance of a product and its functions. Specifications define measurable performance requirements and are expressed as numerical values. Functions describe what the product must do to

satisfy customer needs. Failure modes represent defects or situations in which the product does not perform as intended.

Terninko mentions more categorization terms, however, these four are the ones that are applicable to this design process. Therefore, the obtained integrated data visible in Table 3.1, is categorized into these four categories. Which is visible in Table 3.2.

Table 3.2: Categorisation of integrated customer statements.

Category	VOCT ID	Integrated Data
Demanded Qualities	ID-01	Tool must reduce operator musculoskeletal load
	ID-02	Tool must rotate around the foundation pile without the operator having to reposition himself
	ID-04	Tool must allow for repeated use during work hours
	ID-05	Tool must allow for easy and quick grinding disc replacement
	ID-07	Tool must generate sufficient clamping forces to resist its own weight and cutting forces
	ID-10	Tool must mechanise the pile grinding process
	ID-11	Tool must be usable for all relevant pile diameters
Specifications	ID-03	Cutting time must not exceed the normal duration of 5 minutes per pile
	ID-08	Tool weight may not exceed $23\ kg$
	ID-09	Setup time must not exceed 2 minutes
	ID-12	Tool must operate within $20\ cm$ radial clearance on one side
	ID-13	Cut deviation must not exceed $1\ cm$
	ID-15	Tool must function with minimum $5\ cm$ pile protrusion above cut height
Failure Modes	ID-06	Tool must ensure the safety of the employee by generating enough clamp force.
	ID-14	Tool must not require water for operation or cooling
	ID-16	Tool must not be placed on the ground for stability
Functions	ID-07	Clamp around foundation pile
	ID-02	Rotate around foundation pile circumference
	ID-03	Cut through steel pile wall
	ID-06	Enclose dangerous elements during pile grinding

The demanded qualities identified in the table above will be further discussed in Section 3.3. Specifications, failure modes and functions are already sufficiently concrete and are therefore translated directly into requirements in Section 3.5, without requiring further grouping.

3.3. Affinity Diagram

Following the QFD method described by Terninko [11], the demanded qualities identified in Table 3.2 are grouped into clusters using an affinity diagram in Figure 3.1. This grouping ensures that the demanded qualities are expressed at the same level of abstraction before being prioritized in Section 3.4.

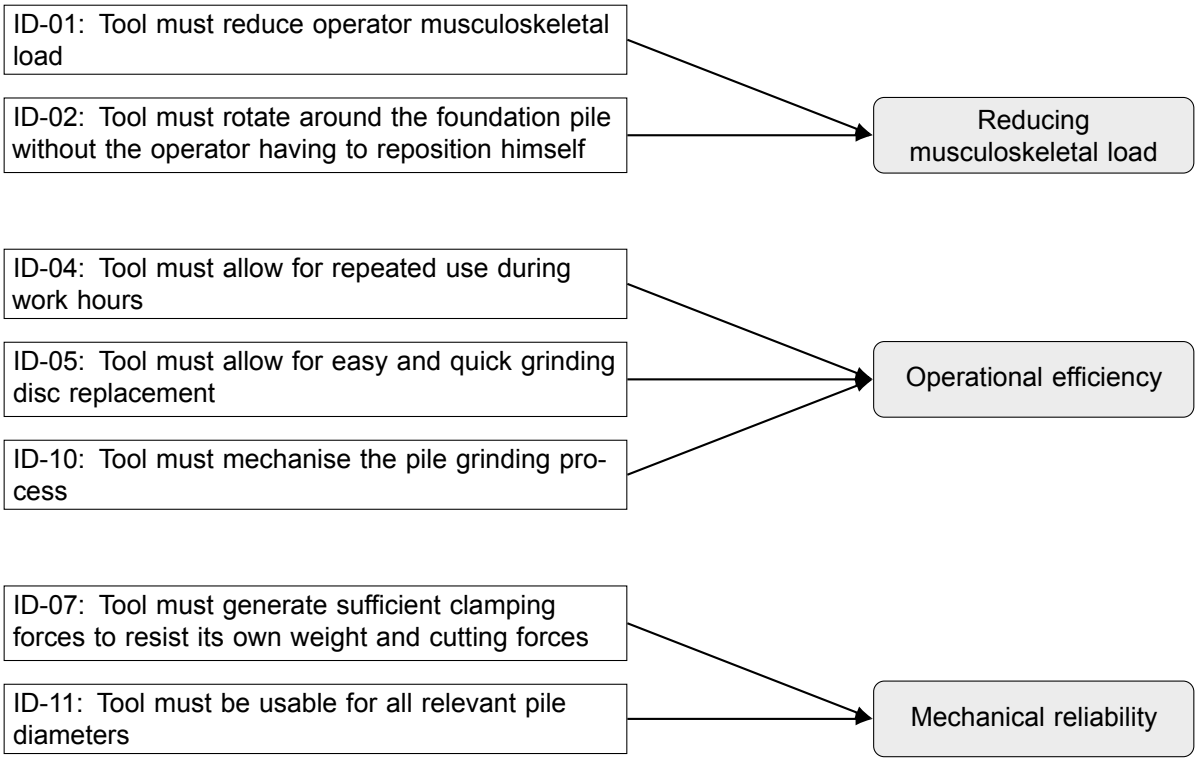


Figure 3.1: Affinity diagram of demanded qualities.

As can be seen in Figure 3.1, the several demanded qualities can be categorized under three terms. Clustering of these Integrated Data reduces the number of items that need to be individually evaluated and ensures that all customer quality demands are considered [11]. These three terms will be rated on importance in Section 3.4.

3.4. Customer Importance Rating

As visible in Figure 3.1, the demanded qualities can be clustered under the following terms: Reduces physical operator load, Operates efficiently during work hours and Mechanically reliable on any screw injection pile. However, due to the fact that setup time was found to be a key concern among employees, it will be included in the Customer Importance Rating. The Customer Importance Rating will be made in accordance with the ratings of De Waalpaal B.V. employees.

Table 3.3: Customer Importance Rating table. Employees ratings where 0 is the lowest and 5 is the highest.

	Reducing musculoskeletal load	**Operational efficiency**	**Mechanical reliability**	**Setup time**	**Total**
Management	5	3	5	3	
Operator 1	4	4	5	5	
Operator 2	$4,5$	4	5	5	
Employee 1	5	$3,5$	5	4	
Employee 2	5	3	5	3	
Total score	$23,5$	$17,5$	25	20	86
Score [%]	$\frac{23,5}{86} \approx 27,3\,\%$	$\frac{17,5}{86} \approx 20,3\,\%$	$\frac{25}{86} \approx 29,1\,\%$	$\frac{20}{86} \approx 23,3\,\%$	100 %

Table 3.3 presents the importance ratings of the demanded qualities. As can be seen, Mechanical reliability received the highest score, indicating that safe and dependable operation of the tool is considered

the most important requirement by the employees. Reducing musculoskeletal load was ranked second, highlighting the importance of improving operator ergonomics and reducing physical load during pile grinding operations. Setup time received the third highest rating, suggesting that minimizing preparation time is valued, although not at the cost of reliability or operator safety. Operational efficiency obtained the lowest score of the four categories. However, the differences between the ratings are relatively small, indicating that all four demanded qualities are considered important.

3.5. Identified Tool Requirements

The requirements presented in this section are derived directly from the QFD analysis in Section 3.1 through Section 3.4. They are divided into two categories: Quality requirements and Technical requirements. The quality requirements, listed in Table 3.4, are derived from the demanded qualities identified in Table 3.2 and grouped according to the affinity diagram in Figure 3.1. Their relative importance with respect to each other, is reflected by the customer importance ratings in Table 3.3. This rating will be important for the concept selection in Chapter 4.

Table 3.4: Quality requirements

ID	Requirement	Description	VOCT
QR-01	Reduce musculoskeletal load	The tool must reduce the physical load on the operator during pile grinding.	ID-01, ID-02, ID-10
QR-02	Operational efficiency	The tool must allow for repeated, efficient and safe use during work hours, including easy grinding disc replacement.	ID-04, ID-05
QR-03	Mechanical reliability	The tool must generate sufficient clamping force to operate reliably on all relevant pile diameters.	ID-07, ID-11
QR-04	Setup time	The setup time of the tool should be minimized and may not exceed 2 minutes.	ID-09

The technical requirements, listed in Table 3.5, are derived from the specifications and functions listed in Table 3.2. These define the functional and performance boundaries within which the tool must operate. The failure modes identified in Table 3.2 are not translated into requirements here, as these are addressed and added as boundary conditions in Chapter 4, Table 4.3.

Table 3.5: Technical requirements

ID	Requirement	Description	VOCT
TR-01	Cutting time	The cutting time must not exceed $t \leq 5$ min per pile.	ID-03
TR-02	Tool weight	The tool weight must not exceed $m \leq 23$ kg.	ID-08
TR-03	Confined space operation	The tool must be operable within $20\ cm$ radial clearance on one side. This requirement will also be shown as a boundary condition, as it limits the use of large technologies.	ID-12
TR-04	Cut deviation	The cut deviation must not exceed 1 cm.	ID-13
TR-05	Pile protrusion	The tool must function with an available space of 5 cm pile protrusion.	ID-15
TR-06	Pile fixation	The tool must fixate itself securely to the pile during operation.	ID-06
TR-07	Circumferential movement	The tool must traverse the full circumference of the pile.	ID-02
TR-08	Pile cutting	The tool must cut through the steel wall of the pile.	ID-03
TR-09	Operator exposure	The tool must enclose or redirect dangerous elements like as sparks or removed material, such that the operator is protected or not exposed during operation.	ID-06

4

Concepts

Based on the pile grinding process described in Chapter 2 and the requirements established in Chapter 3, the concept development of the mechanised cutting tool is presented in this chapter. First, the existing clamping and cutting technologies are discussed in Section 4.1. The boundary conditions present at construction sites are identified in Section 4.2. These narrow down the suitable technologies before concept generation begins. However, before starting with the concept generation, the level of automation is determined in Section 4.3. Based on the remaining technologies visible in Section 4.2, concepts are developed for the clamping subsystems in Section 4.4 and cutting subsystems in Section 4.5.

4.1. Existing clamping and cutting technologies

This section provides an overview of existing cutting and clamping technologies that could potentially be used for cutting down foundation piles. The technologies were selected based on their applicability to cutting and clamping cylindrical steel piles. Table 4.1 summarises the cutting technologies. It includes a summarised description. More detailed information on each technology is provided in Appendix C.

Table 4.1: Summary of existing pile cutting technologies. More detailed information can be seen in Appendix C.

Technology	Summarised description Source
Abrasive cutting	Removes material through a rotating abrasive disc. The compact tool makes it suitable for construction site applications [13].
Thermal cutting	Uses heat to melt or separate material. Offers fast cutting of metals, but is less suitable for grout-filled piles and requires relatively large equipment [14].
Saw cutting	Uses a moving toothed blade to cut the workpiece. Can produce straight cuts, but requires secure clamping, guidance, sufficient space for blade movement and must be cooled during operation [15].
Water jet cutting	Uses a high-pressure water jet, optionally mixed with abrasives. Provides accurate cuts without a heat-affected zone, but requires complex and large equipment [16].
Diamond wire cutting	Uses a continuously moving diamond-coated wire. Provides a narrow cutting kerf with relatively low vibration, but requires space for wire routing and tensioning [17].

Table 4.2 summarises possible clamping technologies. More detailed descriptions of these technologies are provided in Appendix C.

Table 4.2: Summary of existing pile clamping technologies. More detailed information can be seen in Appendix C.

Technology	Description
Claw clamp	Uses rigid, mechanically actuated jaws to grip the pile. Different jaw configurations can clamp different geometries, but the mechanical mechanism introduces additional design complexity. It is also called a mechanical gripper [18].
Chain clamp	Uses a tensioned chain wrapped around the pile. Can be used for different diameters and contours, but uneven tensioning can reduce positioning accuracy. [19].
Magnetic clamp	Uses magnets to hold ferromagnetic materials. It allows for quick clamping, but its holding force depends on the material and surface conditions [20].
Hydraulic clamp	Uses pressurised fluid and cylinders to generate high clamping forces. It requires a pump, hoses and valves, which increases the systems complexity and limits its compactness [21].
Pneumatic clamp	Uses compressed air to actuate the clamping mechanism. Provides rapid clamping and releasing, but requires an external air supply. Thus, limiting its compactness [22].
Orbital clamp	Uses circumferential contact points to secure the tool while allowing it to rotate around the pile. Suitable for circumferential cutting, as demonstrated by the rotary pipe cutters developed by a company called REED Manufacturing.
Hose clamp	Uses a tightened metal band to apply circumferential pressure. Offers a compact and adjustable design [23].

The technologies shown in Tables 4.1 and 4.2 represent a range of potentially suitable technologies for the cutting and clamping of foundation piles. However, not all of these technologies are suitable for use on construction sites due to the specific working conditions. Therefore, several boundary conditions are used to narrow down the applicable technologies. Section 4.2 describes these boundary conditions and identifies the technologies that remain suitable for further concept generation.

4.2. Boundary conditions

As mentioned before, the suitable cutting and clamping technologies summarised in Section 4.1 and further elaborated upon in Appendix C, are not all suitable for use on construction sites. Several boundary conditions narrow down the applicable technologies.

Based on information obtained via background information, interviews and on-site visits, see Chapter 2 and Chapter 3, several existing boundary conditions became clear. These boundary conditions are listed in Table 4.3.

Table 4.3: Construction site boundary conditions

ID	Boundary Condition	Limits the usage of:
BC-01	The tool must be able to operate in a space of 20 cm (see Subsection 2.1.2).	Large cutting and clamping methods such as: Diamond wire cutting, Water jet cutting, Pneumatic clamps and Hydraulic clamps.
BC-02	Access to water is not always guaranteed on every construction site.	Cutting methods which require water or water to cool it: Saw cutting, Diamond wire cutting, Water jet cutting
BC-03	Screw injection piles have a internal grout filling	Thermal cutting
BC-04	System must be robust against dust, debris and moisture.	Magnetic clamps
BC-05	Having the system support itself on ground is not advisable, due to wet ground conditions.	Large cutting and clamping methods such as: Diamond wire cutting, Water jet cutting, Pneumatic clamps and Hydraulic clamps.
BC-06	Pile grinding work is performed by a single Employee.	Large cutting and clamping methods such as: Diamond wire cutting, Water jet cutting, Pneumatic clamps and Hydraulic clamps.

As can be seen above, the boundary conditions visible in Table 4.3 limit the usage of several technolo-

gies. The remaining technologies which can be suitable for the design and development of the mechanised cutting tool are: Abrasive cutting, Claw clamp, Chain clamp, Orbital clamp and Hose clamp. However, a hose clamp is not considered suitable as the sole clamping mechanism, as it provides limited possibilities for attaching and supporting the external mechanisms.

Therefore, claw clamping, chain clamping and orbital clamping are used as the basis for the clamping concept generation. While abrasive cutting is used for the cutting concept generation.

4.3. Level of automation

Before starting the concept generation, a choice needed to be made regarding the tool's level of automation. Should the tool be fully automated? Or should the operator retain direct physical interaction with the tool?

As described in Section 2.1.2, the operator currently relies on visual, tactile and force feedback to control the grinding process. Together, the tactile and force feedback are referred to as haptic feedback, which allows the operator to perceive changes in cutting resistance. It also provides the operator with feedback from the environment that would otherwise be unavailable and can improve aspects of task performance such as force regulation [24].

Considering the variable working conditions and the need for the operator to continuously adapt the cutting tool to the pile, a fully autonomous solution was not considered suitable. Retaining the direct interaction was therefore considered important. An operator-guided approach was selected, allowing the operator to remain in direct control of the cutting motion while the mechanism provides the required mechanical support.

4.4. Subsystem: Clamping

As discussed in Section 4.2, the boundary conditions present at construction sites make three clamping technologies suitable for use: Claw clamp, Orbital clamp and chain clamp. Therefore, three clamping concepts were developed. Each concept was based on one of these clamping technologies, while complying with the requirements listed in Table 3.4 and Table 3.5. These concepts are visible below and a detailed description of the working principles of each concept is provided in Appendix D.

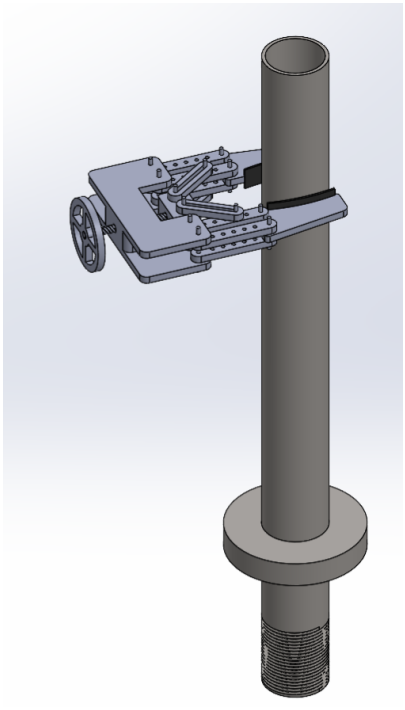


Figure 4.1: Concept 1: Claw clamp

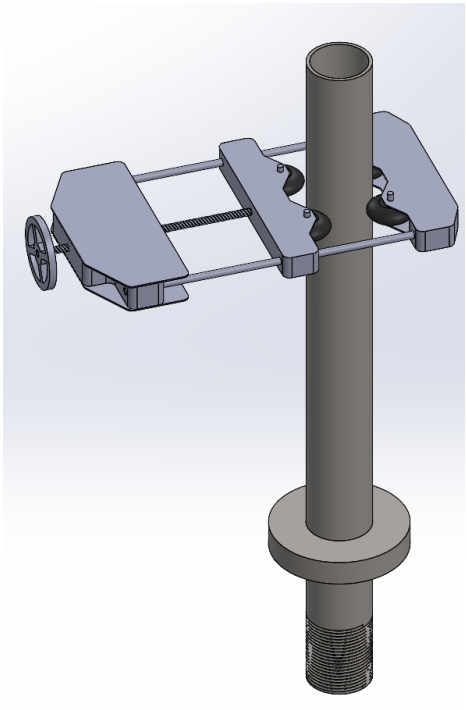


Figure 4.2: Concept 2: Orbital clamp

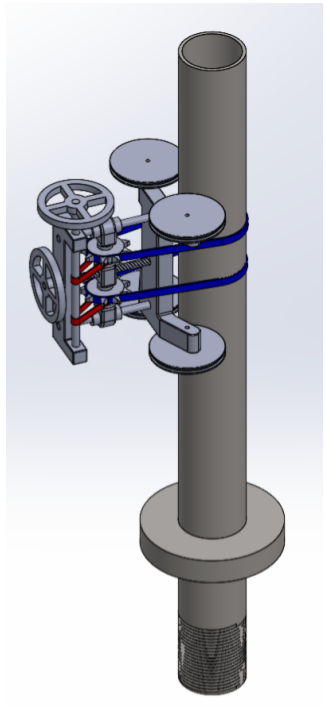


Figure 4.3: Concept 3: Chain clamp

4.4.1. Clamping concept expectations

The three concepts were 3D printed and used for preliminary evaluation. Based on physical interaction with the printed models, each concept was assessed against the quality requirements established in Table 3.4. It should be noted that these expectations reflect expected performance based on working principles and physical interaction, rather than measured values. The concept expectations are visible in Table 4.4.

Table 4.4: Concept expectations per quality requirement

Quality Requirement	Concept 1	Concept 2	Concept 3
Reduce musculoskeletal load	Expected to reduce operator load, but requires manual repositioning	Eliminates manual repositioning through orbital motion	Eliminates manual repositioning through chain-driven motion
Operational efficiency	Simple and intuitive operation, with minimal process complexity	Simple and intuitive operation, with minimal process complexity	Complex process, requires routing and tensioning of the chain before operation
Mechanical reliability	Low clamping force expected due to parallelogram mechanism	High clamping force expected due to orbital clamp mechanism.	Highest clamping force expected due to chain clamp mechanism.
Setup time	Low, straightforward clamping operation	Medium, device must be placed around pile	High, chain must be routed and tensioned

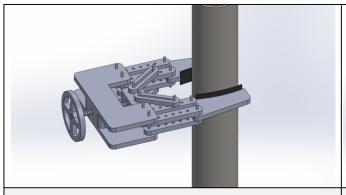
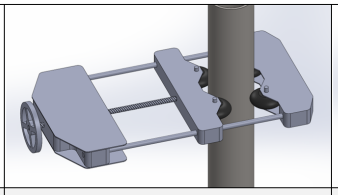
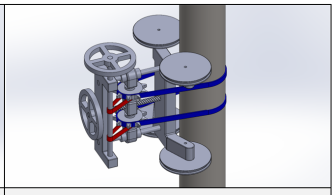
4.4.2. Clamping concept selection

The concept selection is performed using a weighted criteria table. This table combines the customer importance rating (Table 3.3) with the concept expectations (Table 4.4). As mentioned before, each concept was 3D printed and evaluated against the quality requirements. As can be seen in Table 4.5, each concept was assigned a score based on its expected performance on a scale of 0 to 5. The total score for a concept is then calculated as follows:

$$S_{total} = \sum_{i=1}^{n} w_i \cdot s_i \tag{4.1}$$

where n is the number of quality requirements, w_i is the importance weight of requirement i, such that $\sum_{i=1}^{n} w_i = 100\%$. Finally, $s_i \in [0, 5]$ is the score assigned to the concept for requirement i. With weights normalized in this way, the maximum achievable score is $S_{total,max} = 5$.

Table 4.5: Weighted Criteria Table

							
		Concept 1: Claw clamp		**Concept 2: Orbital clamp**		**Concept 3: Chain clamp**	
Expectation on:	**Weight [%]**	**Prediction**	**Score**	**Prediction**	**Score**	**Prediction**	**Score**
Mechanical Reliability	29,1%	Low clamping force expected due to parallelogram mechanism.	1	High clamping force expected due to multiple contact points of the orbital clamp mechanism.	4	Highest clamping force expected due to chain clamp mechanism.	5
Reducing musculoskeletal load	27,3%	Expected to reduce operator load, but requires manual repositioning.	1	Eliminates manual repositioning through orbital motion.	5	Eliminates manual repositioning through chain-driven motion.	5
Setup time	23,3%	Lowest setup time as paralellogram claw closes relatively quickly.	3	Low setup time as it is only dependaple the lead of the leadscrew.	2	High setup time as you first need to place the chain around the chain and afterwards tensioning it.	1
Operational efficiency	20,3%	Simple and intuitive operation, with minimal process complexity.	5	Simple and intuitive operation, with minimal process complexity.	4	Complex process, requires routing and tensioning of the chain before operation.	1
Total	**100,0%**		**2,278**		**3,807**		**3,256**

As can be seen in Table 4.5, Concept 2: Orbital clamp, has received the highest total score of $S_{total} = 3.807$. Concept 3: Chain clamp has received the second highest score of $S_{total} = 3.256$. Finally, Concept 1: Claw clamp has received the lowest total score of $S_{total} = 2.278$. Based on this result, Concept 2: Orbital clamp is selected for further development and will be taken forward to the failure analysis in Section 4.4.3, where it will be iterated upon to address identified weaknesses.

4.4.3. Clamping Concept failure analysis and improvements

This Subsection will cover the failure analysis and concept improvements of the clamping concept chosen in Subsection 4.4.2. The conceptual improvements were based on physical interaction with the 3D printed models. This leads to the first prototype of the clamping mechanism.

Reducing setup time

From the weighted criteria table (Table 4.5) in Subsection 4.4.2, one weakness of Concept 2 becomes clear. The setup time is expected to be low, as it is given a score of 2. This indicates that the current design does not meet the setup time requirement mentioned in QR-04 of Table 3.4.

This weakness can be explained as follows: the setup time of the current design depends on the lead of the leadscrew. If the operator rotates the handle n times, the leadscrew translates by:

$$x = n \cdot L \tag{4.2}$$

where L is the lead of the leadscrew. Now, as mentioned in Appendix D, the concept uses a TR-10x2 self-locking leadscrew. Then, one handle rotation would mean it translates with $2\ mm$. Therefore, in order to achieve the required clamping displacement, a high number of rotations is needed. Which directly increases setup time.

However, a strength of the leadscrew is its ability to generate a high clamping force from a small input torque. The generated clamping force can be found by the following formula:

$$F = \frac{2\pi \cdot T \cdot \eta}{L} \tag{4.3}$$

Where T is the input torque applied by the operator at the handle and η is the efficiency of the thread, which takes friction losses into account.

Therefore, a tensioning method is required that maintains the high clamping force capability of the leadscrew while reducing the setup time needed to achieve the required clamping displacement. To address this, the leadscrew mechanism will be replaced by a ratchet tie down mechanism.

Like a leadscrew, a ratchet tie down uses mechanical advantage to convert a relatively small operator input force into a high clamping force. The ratchet mechanism gradually tensions the strap through repeated lever strokes while preventing loss of tension through its locking mechanism. According to

the ratchet tie down user manual, it can generate a maximum manual force of $500\ N$. Thus, tightening the ratchet strap will cause the mechanism to close around the pile due to the design of the concept. As a result, the needed displacements can be achieved faster compared to a leadscrew. All while still generating the high clamping force required for the application.

Reducing destabilising moment

From the evaluation of the 3D printed model of concept 2: Orbital clamp, one thing became clear. A destabilizing moment around the y-axis in point O occurs when clamping around the pile. This axis is visible in Figure 4.4. When looking at the 3D schematic representation of the concept in Figure 4.4, this observation can be explained as follows:

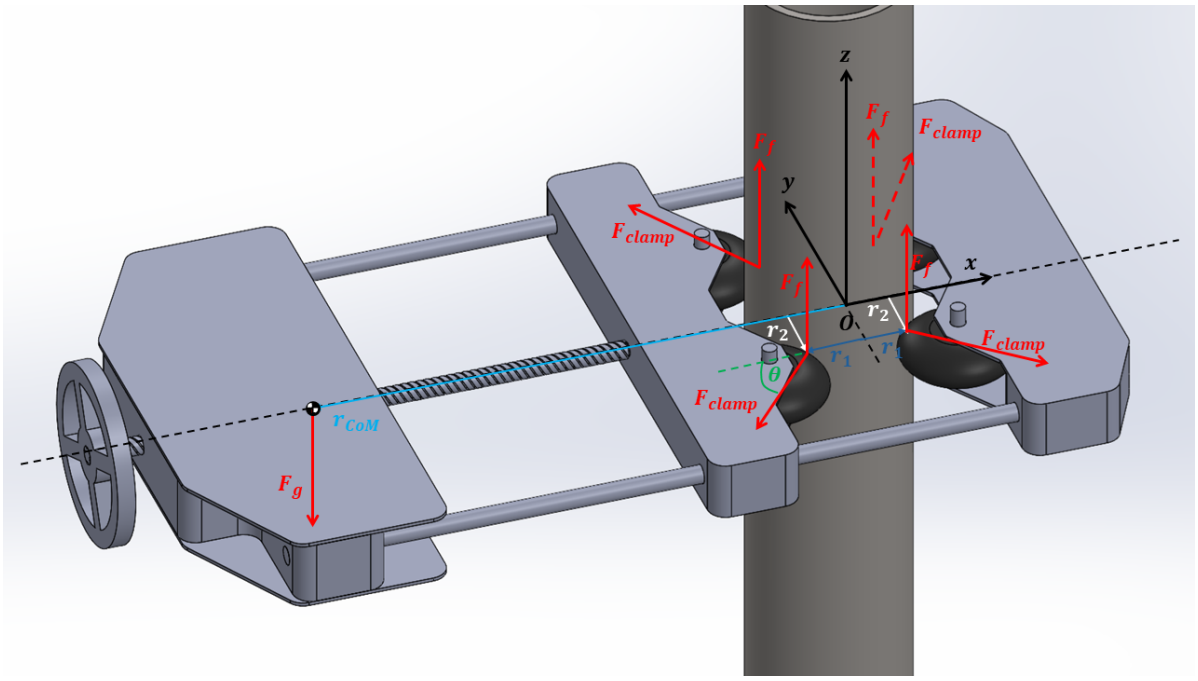


Figure 4.4: Free Body Diagram of the of concept 2: Orbital clamp. Due to the symmetric design of the concept, only one side of the distance parameters (r_1 and r_2) are depicted.

If the tool stays clamped onto the pile, static balance can be assumed. Moreover, due to the symmetric design of concept 2, it can be assumed that the clamping force F_{clamp} and friction force F_f are distributed equally across all contact wheels. Besides this, the distances between each contact point are equal in their respective directions. Then, the following is true:

$$\Sigma F_x = 0 \rightarrow 2\cos(\theta)F_{clamp} - 2\cos(\theta)F_{clamp} = 0 \tag{4.4}$$

$$\Sigma F_y = 0 \rightarrow 2\sin(\theta)F_{clamp} - 2\sin(\theta)F_{clamp} = 0 \tag{4.5}$$

$$\Sigma F_z = 0 \rightarrow 4F_f - F_g = 0 \rightarrow F_g = 4F_f \tag{4.6}$$

The friction force F_f is equal to the coefficient of friction multiplied by its normal force:

$$F_f = \mu F_{normal} = \mu F_{clamp} \tag{4.7}$$

If the acting gravitational force is less than its counter force, then it stays clamped on the pile and the following must be true:

$$F_g \leq 4\mu F_{clamp} \tag{4.8}$$

However, as mentioned before, a rotation occurs around the y-axis in point O of the conceptual clamping tool. This means:

$$\Sigma M_O \neq 0 \tag{4.9}$$

This moment results from the acting forces and the geometry of the clamping concept. It can be calculated using the cross product of the position vector (r_{CoM}, r_1 and r_2) and the force vectors. This can be seen in the following equation:

$$\begin{aligned}\Sigma M_O = &\begin{bmatrix}-r_{CoM}\\0\\0\end{bmatrix} \times \begin{bmatrix}0\\0\\-F_g\end{bmatrix} + \begin{bmatrix}-r_1\\-r_2\\0\end{bmatrix} \times \begin{bmatrix}-\cos(\theta)F_{clamp}\\-\sin(\theta)F_{clamp}\\F_f\end{bmatrix} + \begin{bmatrix}-r_1\\r_2\\0\end{bmatrix} \times \begin{bmatrix}-\cos(\theta)F_{clamp}\\\sin(\theta)F_{clamp}\\F_f\end{bmatrix} \\ &+ \begin{bmatrix}r_1\\r_2\\0\end{bmatrix} \times \begin{bmatrix}\cos(\theta)F_{clamp}\\\sin(\theta)F_{clamp}\\F_f\end{bmatrix} + \begin{bmatrix}r_1\\-r_2\\0\end{bmatrix} \times \begin{bmatrix}\cos(\theta)F_{clamp}\\-\sin(\theta)F_{clamp}\\F_f\end{bmatrix} \\ = &\begin{bmatrix}0\\-r_{CoM}F_g\\0\end{bmatrix} \neq 0\end{aligned} \tag{4.10}$$

As can be seen in Eq. 4.10, the rotation moment occurs due to the fact that the gravity acting on the tool is not prevented by geometry design of the tool. This result is exactly as observed.

In order to solve this, the geometry of the design must force Eq. 4.10 to equal zero. Therefore, the following changes to the design are made, see Figure 4.5.

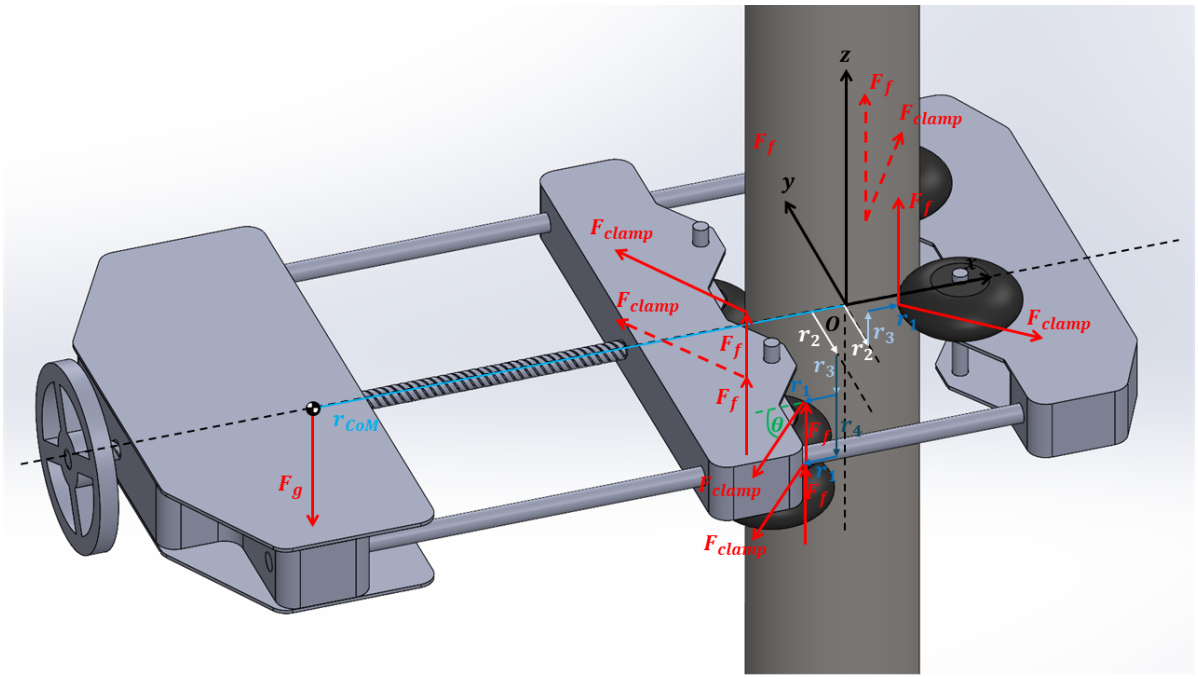


Figure 4.5: Free Body Diagram of the improved concept 2: Orbital clamp. The design improvements are: two extra contact points on the left, the left-most contact points are moved downward and the right-most contact points are moved upwards.

The first implemented change is the addition of two extra contact points on the left. Moreover, the left-most contact points are moved downward and the right-most contact points are moved upwards. This is done such that Eq. 4.6, Eq. 4.8 and Eq. 4.10 turn into the following equations:

$$F_g \leq 6\mu F_{clamp} \tag{4.11}$$

$$\begin{aligned}
\Sigma M_O = &\begin{bmatrix} -r_{CoM} \\ 0 \\ 0 \end{bmatrix} \times \begin{bmatrix} 0 \\ 0 \\ -F_g \end{bmatrix} + \begin{bmatrix} -r_1 \\ -r_2 \\ -r_3 \end{bmatrix} \times \begin{bmatrix} -\cos(\theta)F_{clamp} \\ -\sin(\theta)F_{clamp} \\ F_f \end{bmatrix} + \begin{bmatrix} -r_1 \\ -r_2 \\ -r_4 \end{bmatrix} \times \begin{bmatrix} -\cos(\theta)F_{clamp} \\ -\sin(\theta)F_{clamp} \\ F_f \end{bmatrix} \\
&+ \begin{bmatrix} -r_1 \\ r_2 \\ -r_3 \end{bmatrix} \times \begin{bmatrix} -\cos(\theta)F_{clamp} \\ \sin(\theta)F_{clamp} \\ F_f \end{bmatrix} + \begin{bmatrix} -r_1 \\ r_2 \\ -r_4 \end{bmatrix} \times \begin{bmatrix} -\cos(\theta)F_{clamp} \\ \sin(\theta)F_{clamp} \\ F_f \end{bmatrix} \\
&+ \begin{bmatrix} r_1 \\ r_2 \\ r_3 \end{bmatrix} \times \begin{bmatrix} \cos(\theta)F_{clamp} \\ \sin(\theta)F_{clamp} \\ F_f \end{bmatrix} + \begin{bmatrix} r_1 \\ -r_2 \\ r_3 \end{bmatrix} \times \begin{bmatrix} \cos(\theta)F_{clamp} \\ -\sin(\theta)F_{clamp} \\ F_f \end{bmatrix} \\
= &\begin{bmatrix} 0 \\ -r_{CoM}F_g + 2(2r_3 + r_4)\cos(\theta)F_{clamp} + 2r_1F_f \\ 0 \end{bmatrix}
\end{aligned} \tag{4.12}$$

When combining Eq. 4.7, Eq. 4.11 and Eq. 4.12, ΣM_O equals:

$$\Sigma M_O = \begin{bmatrix} 0 \\ 2F_{clamp}(\mu\,(r_1 - 3r_{CoM}) + (2r_3 + r_4)\cos(\theta)) \\ 0 \end{bmatrix} \tag{4.13}$$

F_{clamp} cannot be equal to zero, as it is required to keep the mechanism secured to the pile. Therefore, $\Sigma M_O = 0$ can only be achieved by ensuring the sum of the remaining geometric terms are equal to zero.

$$\begin{aligned}
\Sigma M_O &= 2F_{clamp} \underbrace{(\mu\,(r_1 - 3r_{CoM}) + (2r_3 + r_4)\cos(\theta))}_{=0} \\
&= F_{clamp} \cdot 0 = 0
\end{aligned} \tag{4.14}$$

The distance parameters were primarily determined by the boundary condition TR-03 that the mechanism must fit within $20\ cm$ radial clearance of the pile. For the current geometry, the moment equilibrium $\Sigma M_O = 0$ is satisfied when $\mu\,(r_1 - 3r_{CoM}) + (2r_3 + r_4)\cos(\theta) = 0$. Here, μ is determined by the contact interface between the wheels and the pile. The value of μ can be seen in Table 5.1.

As the effect of all design changes on this geometric term is not yet known, Chapter 5 will verify whether this condition still holds after all the initial design improvements.

Structural Reinforcement

As mentioned before, for the preliminary evaluation of the design a 3D-printed model was used to evaluate the concept. For the current iteration of the prototype, the structure has been rebuilt using 3030 aluminum extrusion profiles. This material was selected for the following four reasons:

- Aluminum extrusion profiles provide structural strength for the loads expected during operation. For more details on the strength of the structure, see Section 5.4 or Appendix G.
- Aluminum extrusion profiles are widely available and can be modified without custom manufacturing.
- The slot-and-bracket system of an aluminum extrusion profile allows wheel, rod and clamp positions to be reconfigured with relative ease.
- Aluminum extrusion profiles are relatively low-cost when compared to alternative structural solutions such as custom-machined or welded steel frames.

4.5. Subsystem: Cutting

The cutting mechanism is developed after the final design of the clamping mechanism was finished. This is due to the fact that the design of the cutting mechanism is highly dependent on the geometry of the clamping mechanism. Chapter 5 provides more information regarding the final design of the clamping mechanism.

As mentioned in Section 4.2, the boundary condition present at the construction sites reduce the applicable cutting technologies to a single option: Abrasive cutting. So, in contrast to the clamping subsystem in Section 4.4, the cutting technology that can be used is fixed. However, the method to implement the abrasive cutting technology into the final design of the clamping mechanism, is not. Therefore, this section focuses on how the cutting mechanism can be integrated into the geometry of the final design of the clamping mechanism.

4.5.1. Constraints imposed by the geometry of the clamping concept

In order to properly mount the angle grinder on the clamping mechanism, the geometry of the final design of the clamping mechanism needs to be taken into account. The geometry of the clamping system provides a dedicated space for mounting the cutting mechanism. Moreover, the cutting concepts are constrained in the following four ways:

- The cutting mechanism must be mounted in such a way that the clamping mechanism can still traverse the full circumference of the pile. Then it complies with TR-07 mentioned in Table 3.5
- While traversing around the pile, the tool must remain within the 20 cm radial clearance. Then it complies with TR-03 mentioned in Table 3.5.
- The abbrasive cutting mechanism must not interfere with the clamping ability of the clamping mechanism.
- The cutting mechanism must be able to withstand the forces and moments generated during grinding.

Given the constraints mentioned in Subsection 4.5.1, two options were considered for the cutting subsystem. The first option is a commercially available angle grinder, while the second option is a custom-built cutting disc coupled to a motor via a separate transmission. The first option is selected for the following reasons:

First, a commercially available angle grinder and its grinding discs are widely available and can be replaced quickly when damaged, which supports QR-02 in Table 3.4. Second, a commercially available angle grinder is already designed to comply with the applicable machinery safety requirements, whereas a custom-built solution would require its own conformity assessment before it could be used on construction sites [25].

4.5.2. Cutting concept selection

Now that the geometry imposed constraints and the selected cutting implementation method are known, this section will show three possible methods of mounting the angle grinder on the clamping mechanism. For more details about their working principles, see Appendix D.2.

The three concepts were developed based on the feasible ways of mounting the angle grinder to the existing clamping mechanism. The geometry and available mounting locations of the clamping mechanism limited the number of feasible mounting configurations to these three concepts.

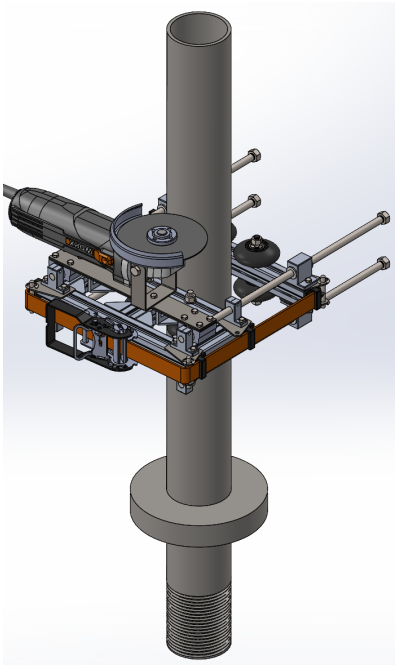


Figure 4.6: Method 1: Sliding mechanism

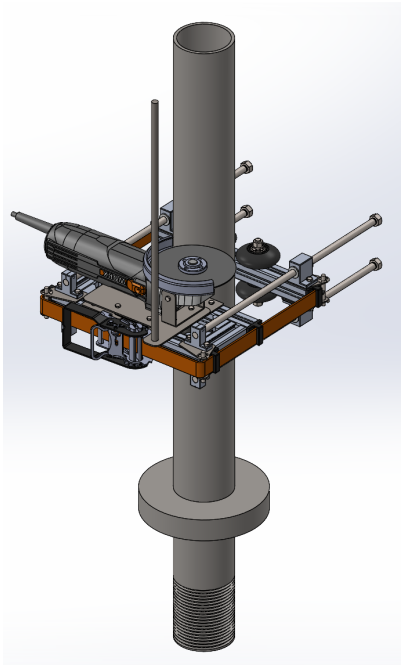


Figure 4.7: Method 2: Swivel bearing mechanism

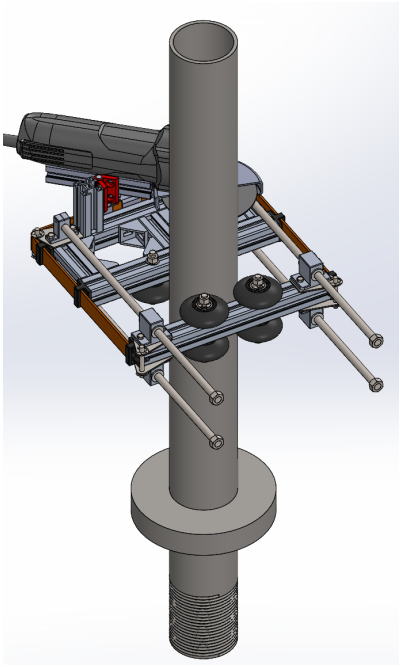
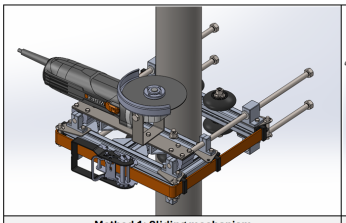
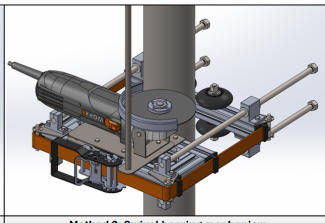
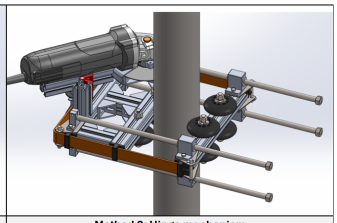


Figure 4.8: Method 3: Hinge mechanism

The three mounting methods visible above are screened against the constraints listed in Section 4.5.1. This screening process is a hard Pass/Fail process. If one method fails to meet even one of the criteria in subsection 4.5.1, then it will not be further developed into a final design of the cutting mechanism. This pass-fail process is visible in Table 4.6

Table 4.6: the Pass/Fail screening process of choosing the appropriate cutting mechanism.

						
	Method 1: Sliding mechanism		**Method 2: Swivel bearing mechanism**		**Method 3: Hinge mechanism**	
Expectation on:	**Prediction**	**Pass / Fail**	**Prediction**	**Pass / Fail**	**Prediction**	**Pass / Fail**
Full circumferential traverse	The mechanism is expected to be able to for full circumferential traversal.	Pass	The mechanism is expected to be able to for full circumferential traversal.	Pass	The mechanism is expected to be able to for full circumferential traversal.	Pass
20 cm radial clearance	The mechanism is expected to be able to for full circumferential traversal.	Pass	The mechanism is expected to be able to for full circumferential traversal.	Pass	The mechanism is expected to be able to for full circumferential traversal.	Pass
Does not interfere with clamping ability	The grinding forces are transferred through the guide rods. These loads are expected to bend the rods, which can affect the clamping function.	Fail	It is expected that the grinding forces are transfered into the aluminum extrusion profiles. So, the clamping ability is expected to not be affected.	Pass	The cutting mechanism is not expected to interfere with the clamping function.	Pass
Ability to withstand grinding forces and moments.	The reaction forces and moment generated during grinding are expected to introduce bending loads into the guide rods, causing the clamping function to be lost.	Fail	The swivel bearing is expected to uniformly distribute grinding forces. So, the clamping ability is expected to not be affected.	Pass	The reaction forces and moment generated during grinding are expected to be concentrated at the single hinge. The hinge is expected to be insufficient to resist these loads.	Fail
Total		**Fail**		**Pass**		**Fail**

As can be seen in Table 4.6, method 2: Swivel bearing mechanism will be further developed into the final cutting mechanism. However, first it will be taken forward to the failure analysis for further improvements in Section 4.5.3.

4.5.3. Cutting concept failure analysis and improvements

This Subsection will cover the failure analysis and concept improvements of the mounting method chosen in Subsection 4.5.2. This leads to the first prototype of the cutting mechanism. The chosen conceptual cutting method is a swivel bearing mechanism. More information regarding this method is visible in Appendix D.2

Operator exposure during cutting

The swivel bearing mechanism shown above has the angle grinder mounted on top in an orientation where the grinder disk is directed upward. This orientation is not only unsafe, it will also direct sparks, material and potential disc fragments towards the operator. This is conflicting with TR-09 in Table 3.5, which requires that sparks and removed material must be directed away from the operator's working position during cutting. To address this, the angle grinder must be mounted in an orientation where the grinding disc is directed downward. This redirects the guard such that sparks and dislodged material are directed away from the operator's position. Thus, complying with TR-09.

Interference with the clamping structure

The constraints mentioned in Subsection 4.5.1 specifies that the cutting mechanism must not interfere with the clamping ability of the clamping mechanism. However, the swivel bearing mechanism shown above does not yet satisfy this constraint. As it is now, is the swivel bearing is mounted directly on the clamping mechanism. This will cause the angle grinder to make contact with the guiding rods. Therefore, in order to avoid this and comply with the constraints, the swivel bearing will be mounted on a raised platform.

Angle grinder mounting frame

As can be seen in Figure 4.7 (or Appendix D.2), the angle grinder is only secured through its existing mounting holes. This creates a single point of fixation where translation is fixed, however rotation is not. Besides the obvious safety concerns this can cause, it also causes the angle grinder to not remain properly aligned with the clamping mechanism. To improve this, an additional mounting frame is mounted around the grinder. This frame positions the grinder and constrains its movement, ensuring that it remains properly aligned with the clamping mechanism during operation. Additionally, a hose clamp is added at the rear of the angle grinder to provide an additional point of support. Together with the mounting frame, this further constrains the grinder and prevents rotational movement during operation.

5

Final Design

Based on the concepts developed in Chapter 4, the final design of the mechanised cutting tool is presented in this chapter. First, the preliminary clamping prototype is shown. Observations and design improvements are discussed. Finally, the final design of the clamping mechanism are presented in Section 5.1.

Secondly, the preliminary cutting prototype is presented. Observations and design improvements are discussed. Finally, the final design of the cutting mechanism are presented in Section 5.2. These two subsystems are then combined into the final design of the mechanised cutting tool in Section 5.3. Finally, a Finite Element Analysis of the combined final design is conducted in Section 5.4 to evaluate its structural integrity.

5.1. Clamping mechanism prototype

The design improvements of the clamping mechanism were made based on information mentioned in Chapter 4, Subsection 4.4.3. As mentioned there, the leadscrew is replaced with a ratchet-tie down. Besides this, two more contact points are added, the location of the contact points are changed and instead of 3D printing the prototype, the internal structure is now made from 3030 aluminum extrusion profiles. Figure 5.1 shows an isometric view of the preliminary design of the clamping mechanism.

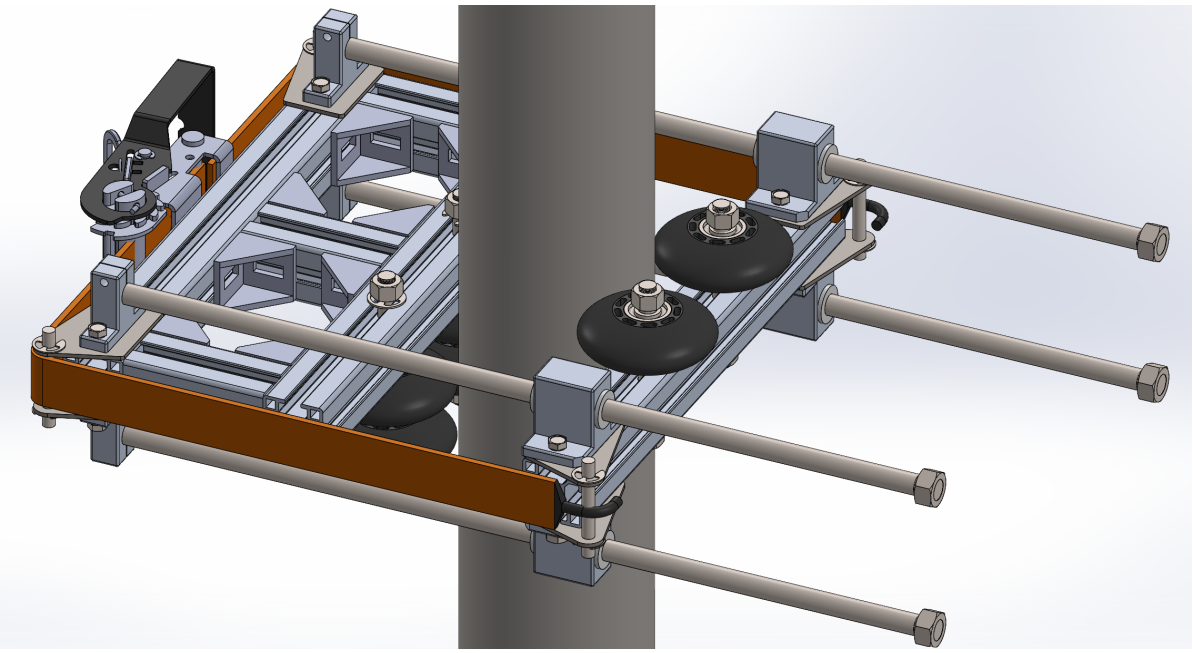


Figure 5.1: Isometric view of the preliminary design of the clamping prototype.

This preliminary clamping prototype will be manufactured and tested. If key observations made during testing highlights any problems, iterative design improvements will follow.

5.1.1. Clamping prototype observations and iterations

In Figure 5.2, the test setup is visible. This figure shows the clamping prototype clamped onto a foundation pile with a diameter $D = 114.3\ mm$. The following key observations were made during testing.



Figure 5.2: Testing the first design of the clamping prototype.

Setup time

The first key observation was that the setup time is significantly reduced, due to the introduction of the ratchet tie down. The results of the reduced setup time are shown in Chapter 6.

Clamping ability

It is observed that the prototype is securely clamped to the pile while also being able to rotate around the pile. The ratchet tie down generates a clamping force of $500\ N$ as mentioned in Subsubsection 4.4.3. This force is high enough to securely clamp the prototype to the pile, while also still enabling the prototype to rotate around the pile. The rotational ability of the clamping mechanism worked perfectly as intended.

Rotational moment around pile center

A noticeable observation was the fact that the use of the ratchet tie down, still generates a positive rotational moment around the y-axis point O. Which means that $\Sigma M_O > 0$. This rotation causes the internal structure, the 3030 aluminum extrusion profiles, to get damaged due to contact with the foundation pile. This damage is visible in Appendix E in Figure E.1 and E.2.

This rotational moment can be explained by the assumption made in Subsubsection 4.4.3. There, it was assumed that the following term is equal to zero:

$$\begin{aligned} \Sigma M_O &= 2F_{clamp} \underbrace{\left(\mu \left(r_1 - 3r_{CoM}\right) + \left(2r_3 + r_4\right)\cos(\theta)\right)}_{=0} \\ &= F_{clamp} \cdot 0 = 0 \end{aligned} \tag{5.1}$$

Due to the occurring positive rotation, it can be concluded that this assumption is wrong. As mentioned before, F_{clamp} cannot be reduced. Therefore, the only remaining option to solve this moment is to change the distance parameters. This change is visible in Figure 5.3 below.

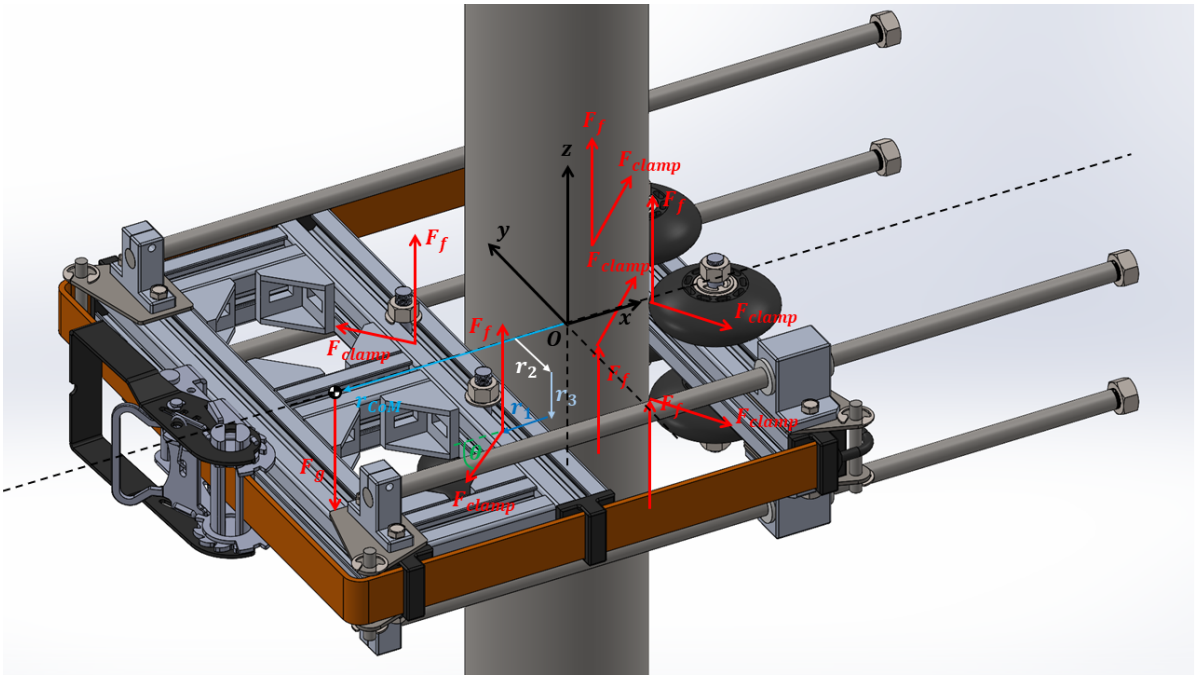


Figure 5.3: Free Body Diagram of the clamping prototype with changed distance parameters.

In Figure 5.3 the following changes can be seen. The first implemented change is the removal of the lowest pair of contact points on the left, thus removing r_4. This pair of contact points will be added to the right. The way these distance parameters are changed, still leaves room for the cutting mechanism to be mounted on top of the dedicated spot. Moreover, this way Eq. 4.11 will not change. However, Eq. 4.12 will change in the following manner:

$$\begin{aligned}\Sigma M_O = &\begin{bmatrix}-r_{CoM}\\0\\0\end{bmatrix}\times\begin{bmatrix}0\\0\\-F_g\end{bmatrix}+\begin{bmatrix}-r_1\\-r_2\\-r_3\end{bmatrix}\times\begin{bmatrix}-\cos\theta F_{clamp}\\-\sin\theta F_{clamp}\\F_f\end{bmatrix}+\begin{bmatrix}-r_1\\r_2\\-r_3\end{bmatrix}\times\begin{bmatrix}-\cos\theta F_{clamp}\\\sin\theta F_{clamp}\\F_f\end{bmatrix}\\ &+\begin{bmatrix}r_1\\r_2\\-r_3\end{bmatrix}\times\begin{bmatrix}\cos\theta F_{clamp}\\\sin\theta F_{clamp}\\F_f\end{bmatrix}+\begin{bmatrix}r_1\\r_2\\r_3\end{bmatrix}\times\begin{bmatrix}\cos\theta F_{clamp}\\\sin\theta F_{clamp}\\F_f\end{bmatrix}+\begin{bmatrix}r_1\\-r_2\\r_3\end{bmatrix}\times\begin{bmatrix}\cos\theta F_{clamp}\\-\sin\theta F_{clamp}\\F_f\end{bmatrix}\\ &+\begin{bmatrix}r_1\\-r_2\\-r_3\end{bmatrix}\times\begin{bmatrix}\cos\theta F_{clamp}\\-\sin\theta F_{clamp}\\F_f\end{bmatrix}\\ =&\begin{bmatrix}0\\-r_{CoM}F_g+2r_3\cos(\theta)F_{clamp}-2r_1F_f\\0\end{bmatrix}\end{aligned}\tag{5.2}$$

When combining Eq. 4.7, Eq. 4.11 and Eq. 5.2, ΣM_O will be equal to:

$$\Sigma M_O = \begin{bmatrix}0\\F_{clamp}(2r_3\cos(\theta)-2\mu(3r_{CoM}+r_1))\\0\end{bmatrix}\tag{5.3}$$

The equation above shows that the moment equilibrium $\Sigma M_O = 0$ of the final design, is only satisfied when $2r_3\cos(\theta)-2\mu(3r_{CoM}+r_1)=0$. When comparing Eq. 5.3 to Eq. 4.13, it is visible that the term

r_4 has been removed and the sign of the r_1 contribution has changed from $+$ to $-$. μ is the coefficient of friction that the contact points need to provide. Whether the final design satisfies this condition is determined in Subsection 5.3

5.1.2. Final design of the clamping mechanism

The design improvements mentioned in Subsection 5.1.1 are implemented in the final design of the clamping mechanism. This final design is visible in Figure 5.4 below.

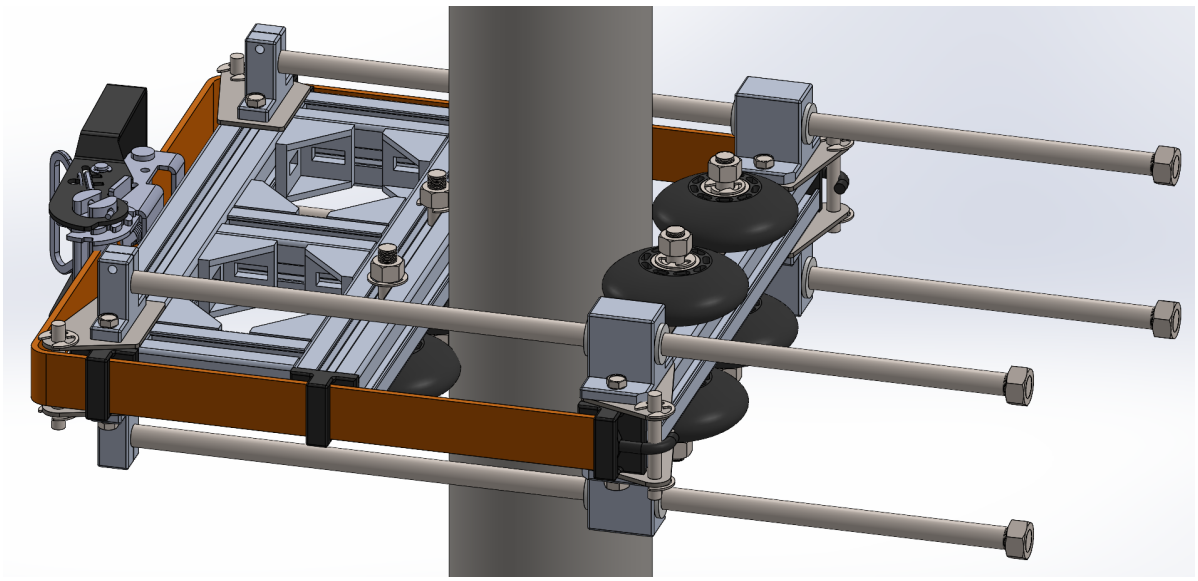


Figure 5.4: Final design of the clamping mechanism.

During testing of the final design, no further damage to the internal structure occurred while clamping and rotating around the pile. This indicates that the rotational moment is reduced sufficiently compared to the first design.

5.2. Cutting mechanism prototype

Based on the failure analysis of the cutting concept mentioned in Chapter 4, Subsection 4.5.3, several design improvements were implemented in the cutting mechanism prototype. To improve operator safety, the angle grinder must be reorientated downwards. To avoid contact with the clamping mechanism, the cutting mechanism will be mounted on a raised platform. Finally, a mounting frame and hose clamp are added to securely support the angle grinder and prevent unwanted rotational movements. These improvements can be seen in Figure 5.5 below.

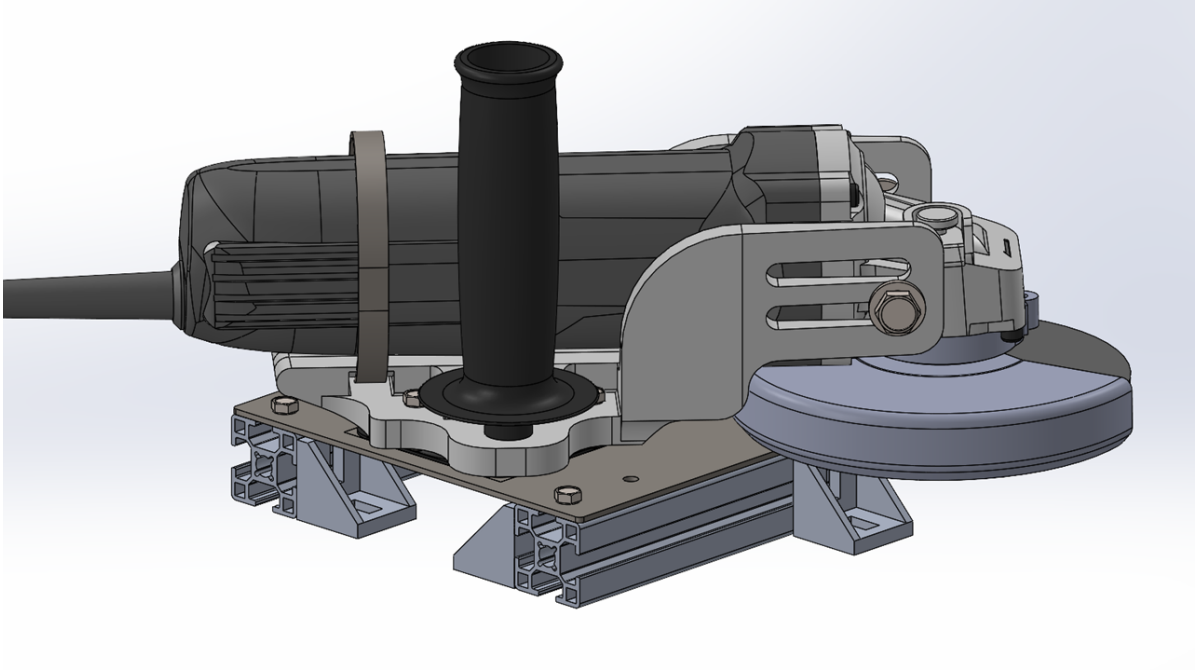


Figure 5.5: Preliminary design of the cutting prototype.

This preliminary cutting prototype will be manufactured and tested. Like the clamping mechanism, if any observations made during testing highlight any problems, iterative design improvements will follow.

5.2.1. Cutting prototype observations and iterations

Figure E.3 shows the test setup of the preliminary design of the cutting prototype. The following observations were made during concept testing. To see the actual first cutting prototype, see Appendix E.

Angle grinder disc clearance

The testing of the first prototype revealed that the angle grinder cutting disc makes contact with the raised mounting platform, as highlighted by the red circle in Figure E.3 of Appendix E. Causing it to be unable to rotate and perform a cutting action on the pile. It also results in making a grinder disc replacement to become difficult. Moreover, due to the insufficient clearance, the safety guard of the angle grinder does not fit and cannot be mounted on it. These observations not only raise safety concerns, but are also in direct conflict with TR-09 of Table 3.5 and QR-02 of Table 3.4.

To resolve this, the frame in which the angle grinder is mounted, will be raised. Thus, removing the contact, enabling the rotational movement, restoring clearance for the safety guard and allowing the cutting disc to be changed without difficulty.

Handle mounting simplification

The first prototype included a separate handle mounting hole next to the frame. For the final prototype, this hole will be removed in favor of the already present mounting hole on top of the angle grinder. Using this existing mounting hole, avoids the need for a separate mounting hole. Besides this, it was also found to feel more rigid during handling.

5.2.2. Final design of the cutting mechanism

The design improvements mentioned above in Subsection 5.2.1 are implemented in the final design of the cutting mechanism. The assembled version of the final design is visible in Figure 5.6 below.

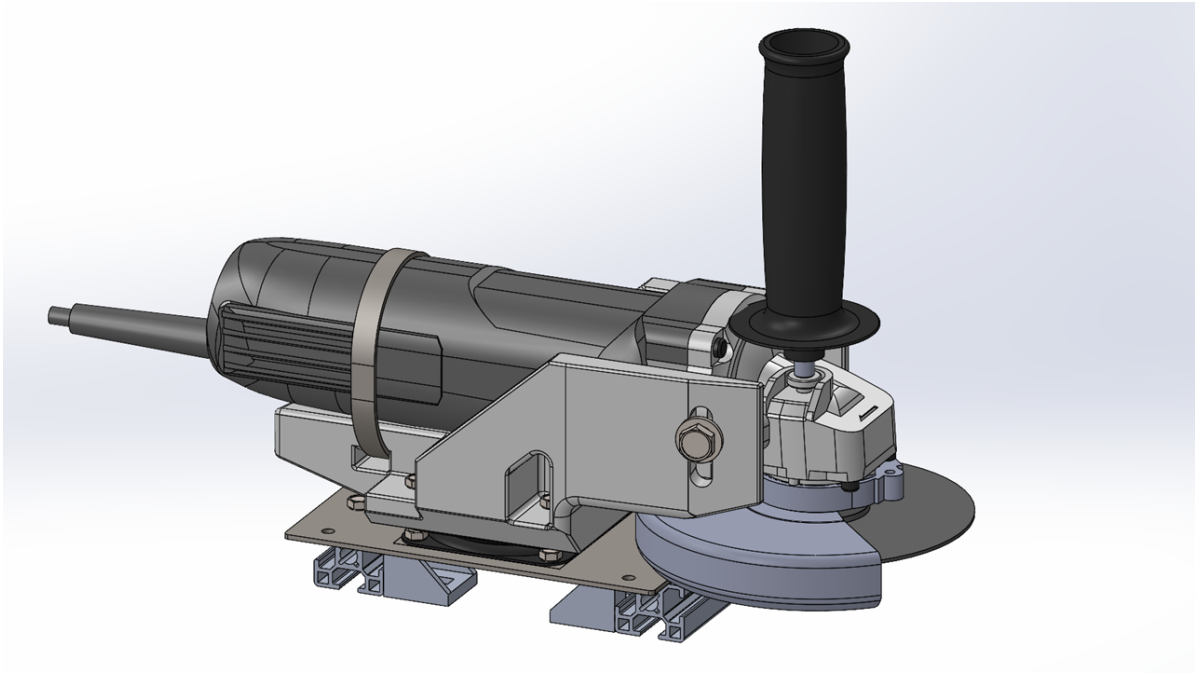


Figure 5.6: Final design of the cutting mechanism.

Testing of the final design confirmed that the cutting disc no longer contacts the raised platform or the clamping mechanism. Moreover, the safety guard can be mounted and the cutting disc can be changed without difficulty. Thus, resolving the issues identified in Section 5.2.

5.3. Combined final design

Now that both the final design of the clamping and cutting mechanisms are completed, the combined final design can be assembled. The assembled final tool can be seen in Figure 5.7.



Figure 5.7: Combined final design of the mechanised cutting tool. Here the tool is clamped to a foundation pile.

Detailed information about the combined final design is given in Appendix F. This includes an overview of the individual components, their functions within the mechanised cutting tool, the material used and, if necessary, additional information about the individual components. Table 5.1 below provides information about the necessary parameters in a conservative setting. As can be seen in Table 5.1, $m_{external}$ is visible. This mass accounts for any possible externally applied force, exerted by an angle grinder operator. The value of this mass depicts the maximum allowable mass an operator can exert on the tool before the swivel bearing breaks.

Table 5.1: Information about parameters in final design of the mechanised cutting tool

Parameter	Value	Extra information
m_{total}	$6,35\ kg$	$m_{clamp} = 3,6\ kg$ and $m_{cut} = 2,75\ kg$
$m_{external}$	$30\ kg$	Maximum allowable mass an operator can exert on the tool.
μ_{static}	$0,86$	See the information in Table F.1 in Appendix F.
$\mu_{dynamic}$	$0,2$	See the information in Table F.1 in Appendix F. According to the company Gallagher [26] the coefficient of friction ranges between $0,2$ and $2,5$ depending on the hardness. Due to the fact that the contact wheels have hardness 82A, we can assume $\mu_{dynamic} = 0,2$.
F_{clamp}	$500\ N$	Maximum manual force generated manually in the ratchet tie down.
r_{CoM}	$\approx \frac{D}{2} + 0,0125$	This is an approximate distance, as it is determined from the CAD model without foundation piles.
r_1	$\approx \frac{D}{2}\ m$	Due to the variable pile diameters, it can be assumed this distance is approximated via this formula.
r_2	$0,027\ m$	This distance is measured
r_3	$0,027\ m$	This distance is measured
θ	45 or $\frac{\pi}{4}$	This value will also be used in Section 5.4.

Now, if the tool stays clamped on the foundation pile during static fixation but also during rotation, Eq. 4.11 needs to be true for both the static and dynamic coefficients of frictions. So the values in Table 5.1 can be substituted in Eq. 4.11. The following can be concluded for the slip condition check:

$$F_g \leq 6\mu_{static}F_{clamp} \rightarrow (6,35 + 30) \cdot 9.81 \leq 6 \cdot 0,86 \cdot 500 \rightarrow 359,54 \leq 2580$$

$$F_g \leq 6\mu_{dynamic}F_{clamp} \rightarrow (6,35 + 30) \cdot 9.81 \leq 6 \cdot 0,2 \cdot 500 \rightarrow 359,54 \leq 600$$

As can be seen above, Eq. 4.11 holds. This means that the mechanised cutting tool will stay securely clamped to the pile after tensioning it using the ratchet tie down. This will be further discussed in Chapter 6. In order to determine whether a rotation around point O, will occur. The values visible in Table 5.1 need to be substituted in Eq. 5.3.

$$\Sigma M_O = F_{clamp}(2r_3\cos(\theta) - 2\mu(3r_{CoM} + r_1)) \rightarrow 500(2 \cdot 0,027\cos(\frac{\pi}{4}) - 2\mu(3 \cdot (\frac{D}{2} + 0,0125) + \frac{D}{2}))$$

When filling in the values of D mentioned in Subsection 2.2.1 and μ, the following maximum values for ΣM_O are obtained:

Table 5.2: Maximum values for ΣM_O in the critical state, in which the friction force is fully mobilised. So $F_f = \mu F_{clamp}$ and $F_g = 6\mu F_{clamp}$.

Parameter	$D = 0,0889\ m$	$D = 0,1143\ m$	$D = 0,1397\ m$	$D = 0,1683\ m$	$D = 0,2191\ m$
$\mu_{static} = 0,86$	$-166,1\ Nm$	$-209,8\ Nm$	$-253,4\ Nm$	$-302,6\ Nm$	$-390,0\ Nm$
$\mu_{dynamic} = 0,2$	$-24,0\ Nm$	$-34,1\ Nm$	$-44,3\ Nm$	$-55,7\ Nm$	$-76,1\ Nm$

These values describe the boundary case, in which the tool is at the verge of slipping. These values do not represent the loading in normal use where $F_f = \frac{F_g}{6}$. At this friction limit, $\Sigma M_O \neq 0$ for all diameters, so a rotation around point O cannot be excluded. What the implications of these results are or whether this is even true in practice, will be discussed in Chapter 6.

5.4. Finite Element Analysis

Now that the combined prototype of the mechanised cutting tool for foundation piles has been completed, a Finite Element Analysis (FEA) will be conducted. The goal of the Finite Element Analysis is to predict the structural response of the combined tool when subjected to external loads. In particular, the analysis will be used to evaluate the resulting von Mises stress, deformations and strain. The goal is to determine whether the structural integrity of the tool is maintained under the expected force conditions.

Before conducting the analysis, it is necessary to determine the effective clamping force $F_{effective}$ acting on the tool. Figure 5.8 provides a schematic representation of the force components used to determine the effective clamping force $F_{effective}$.

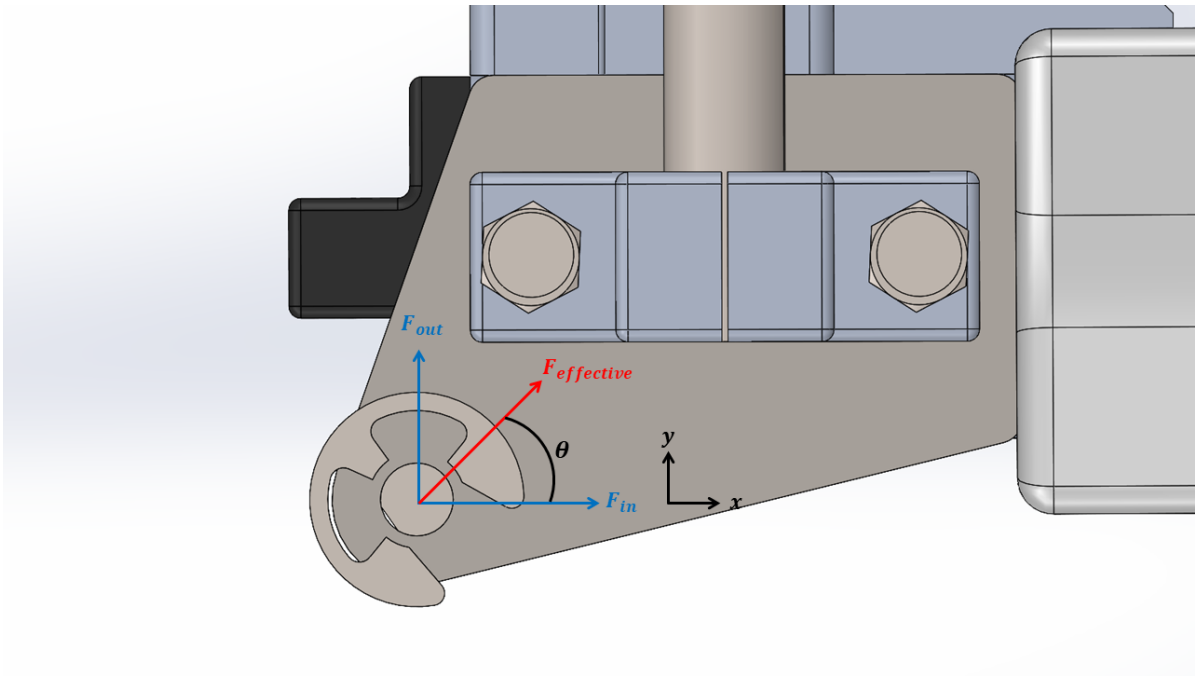


Figure 5.8: Schematic representation of the force components used to determine the effective clamping force $F_{effective}$.

F_{in} represents the force generated by the ratchet tie down, while F_{out} represents the force after the tie down has been redirected around the structure. As shown in Figure 5.8, the effective clamping force $F_{effective}$ is determined by the resultant of F_{in} and F_{out}.

For the Finite Element Analysis, a worst-case scenario assumption is used. It is assumed that the ratchet tie down is subjected to its maximum allowable manual tension and that both force components reach this maximum value simultaneously. Furthermore, based on the schematic configuration, F_{in} and F_{out} are assumed to act perpendicular to each other. Therefore, the maximum force components can be defined as

$$F_{in} = F_{out} = F_{max} \tag{5.4}$$

where F_{max} is the maximum manual force that can be applied using the ratchet tie down. According to the instruction manual of the ratchet tie down used in this design, this maximum force is equal to $500\ N$. Since F_{in} and F_{out} are perpendicular, the effective clamping force can be calculated using the Pythagoras formula:

$$F_{effective} = \sqrt{F_{in}^2 + F_{out}^2} = \sqrt{2F_{max}^2} = F_{max}\sqrt{2} \tag{5.5}$$

This corresponds to the same angle $\theta = 45$ used in Section 5.3. To account for uncertainties in the loading conditions, material properties, modeling assumptions and possible variations in the actual use of the tool, a safety factor SF is applied to the calculated effective clamping force.

Due to the fact that the internal structure of the mechanised cutting tool is made out of 3030 aluminum extrusion profiles, NEN-EN 1999-1-1 [27] is used as the reference standard for the design of aluminum structures. According to Table 4.1(NDP) of this standard, partial safety factors are defined on the resistance side. The ones applicable here are $\gamma_{M1} = 1,1$ for the resistance of cross-sections and members to instability (based on f_o) and $\gamma_{M2} = 1,25$ for the resistance of cross-sections to fracture (based on f_u).

However, these partial safety factors are applied to the structural resistance and are therefore not directly applicable as a load factor in the Finite Element Analysis. Therefore, a conservative safety factor of $SF = 2$ is applied directly to the effective clamping force. Now, it accounts for uncertainties in the loading conditions, material properties, modeling assumptions and possible variations in the actual use of the tool. This choice is more conservative than the partial factors prescribed by NEN-EN 1999-1-1 [27] and ensures that the Finite Element Analysis is performed under a worst-case loading scenario.

$$\begin{aligned} F_{effective} &= SF \cdot F_{max}\sqrt{2} \\ &= 2 \cdot 500\sqrt{2} \approx 1414\ N \end{aligned} \tag{5.6}$$

Therefore, a force of approximately $1414\ N$ is used as the effective clamping force in the Finite Element Analysis. As mentioned above, this force is calculated using a conservative assumption of the worst-case scenario. Therefore, any reduction in the effective clamping force relative to the maximum manual force of the ratchet tie down would result in lower stresses and deformations in the structure.

Figure 5.9 below, shows a simplified isometric version of the mechanised cutting tool during operation. The parts highlighted in green are assumed to be fixations, as the contact wheels transfer their contact forces to these parts. The guiding rods are left out for the Finite Element Analysis, as these have no forces acting on them.

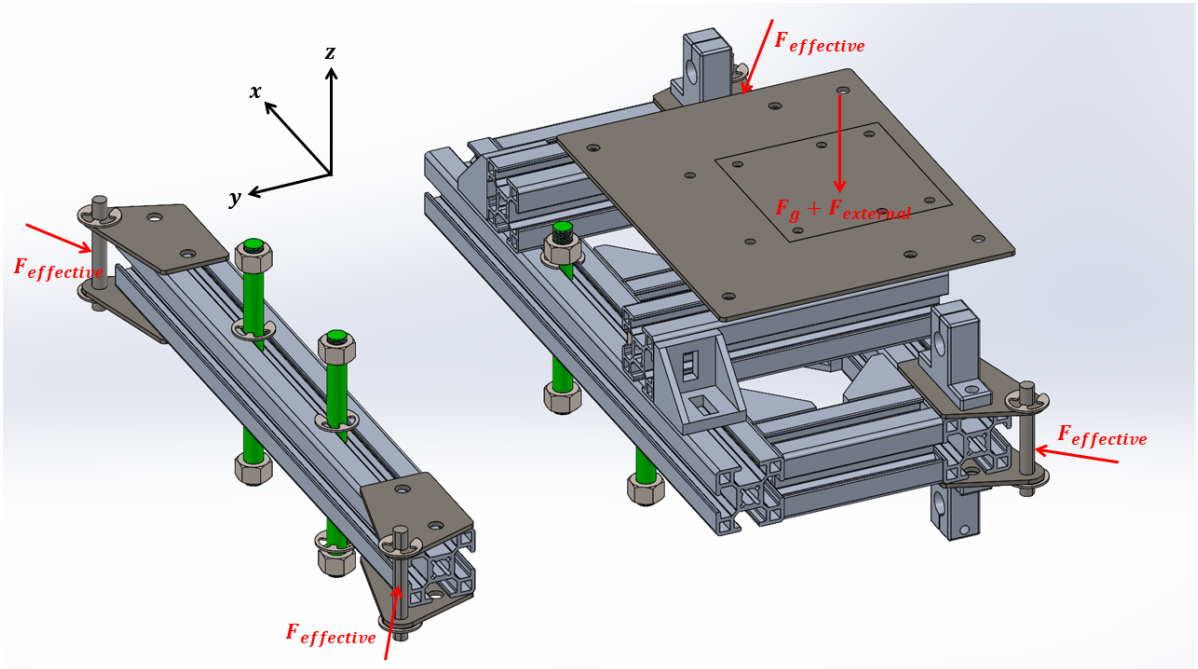


Figure 5.9: Simplified isometric view of the loading condition during operation of the tool.

As can be seen, $F_{effective}$ is visible 4 times. Therefore, the magnitude of each $F_{effective}$ is equal to:

$$F_{effective} = \frac{1414}{4} = 353,5\ N.$$

The force $F_g + F_{external}$ is also visible. The force F_g accounts for the gravitational force of the entire mechanised tool including angle grinder, whereas $F_{external}$ accounts for any possible externally applied force exerted by the angle grinder operator. As mentioned before in Section 5.3, the mass of the entire mechanised tool is $6,35\ kg$ and, as mentioned before, the swivel bearing has a maximum load of $30\ kg$. So, there is no need to multiply this maximum load of $30\ kg$ with a safety factor here. Now, the load acting on the raised surface is equal to:

$$F_{combined} = (F_g + F_{external}) = (6,35 + 30) \cdot 9,81 \approx 357\ N \tag{5.7}$$

The Finite Element Analysis will be conducted in two parts. Part one will be the left-most fixation, while part two will be the right-most fixation. The von Mises stress results of the Finite Element Analysis are shown below, as these are the most important to determine whether the tool would yield under the conservatively applied loads. More details about the FEA results are shown in Appendix G.

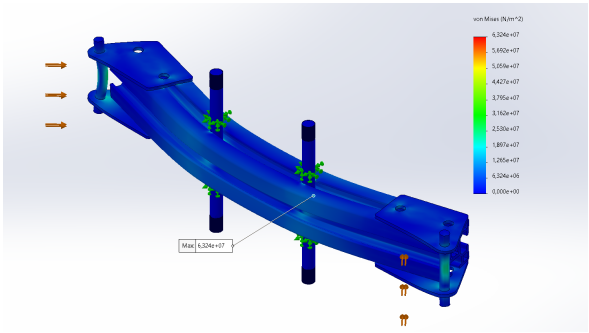


Figure 5.10: Finite Element Analysis stress result on the left-most fixation.

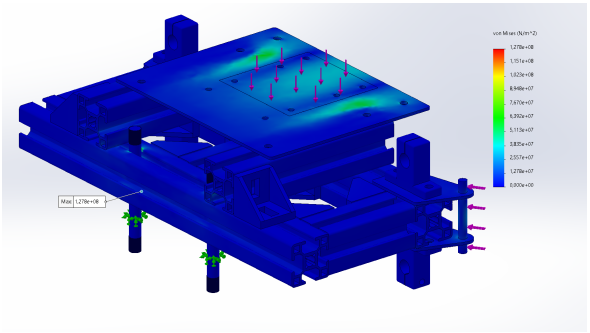


Figure 5.11: Finite Element Analysis stress result on the right-most fixation.

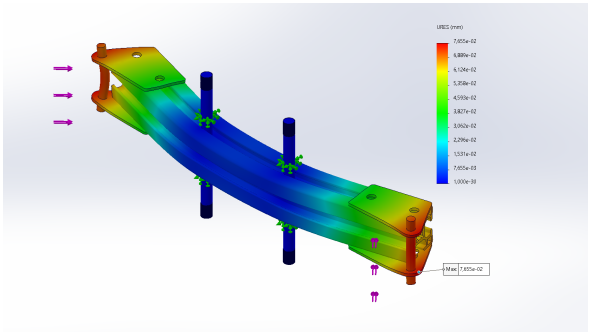


Figure 5.12: Finite Element Analysis displacement result on the left-most fixation.

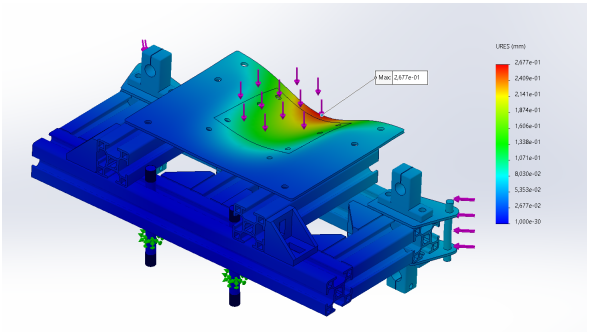


Figure 5.13: Finite Element Analysis displacement result on the right-most fixation.

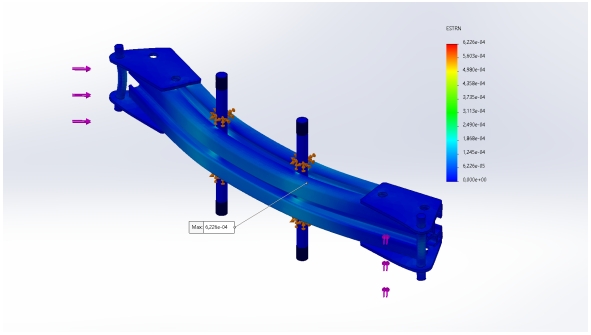


Figure 5.14: Finite Element Analysis strain results on the left-most fixation.

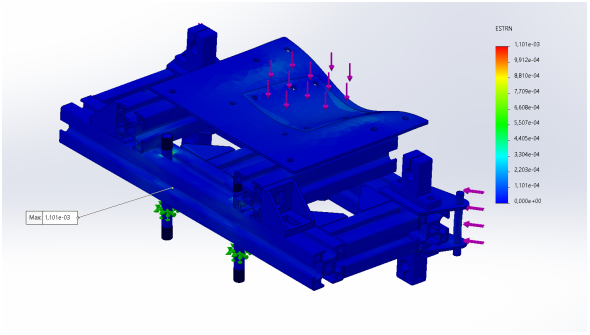


Figure 5.15: Finite Element Analysis strain results on the right-most fixation.

To know whether yielding will occur, the results of the stress analysis are needed. Figure 5.10 and Figure 5.11 show the results of the stress analysis. The FEA results of the left-most fixation show that the maximum stress equals $\sigma = 6,324e7N/m^2 = 63,24\ MPa$, see figure 5.10. And the FEA results of the right-most fixation show that the maximum stress equals $\sigma = 1,278e8N/m^2 = 127,8\ MPa$, see figure 5.11. As can be seen in Appendix G, the stress concentration of both the left-most and right-most fixations are located in the aluminum extrusion profiles. The yield strength of this material is $\sigma_y = 145\ N/mm^2 = 145\ MPa$. So $\sigma < \sigma_y \rightarrow 63,24\ MPa < 145\ MPa$ for the left-most fixation, while $\sigma < \sigma_y \rightarrow 127,8\ MPa < 145\ MPa$ for the right-most fixation. Therefore, we can conclude that the yield strength criterion is satisfied and yielding will not occur.

6 Evaluation

This Chapter evaluates the combined final design of the mechanised cutting tool visible in Chapter 5. First, the test setup and the test method used to evaluate the combined final prototype are described in Section 6.1 and Section 6.2. Based on these, the test results are presented in Section 6.3, covering the setup time, clamping behaviour, cutting performance, structural response and the final ergonomic risk assessment. Finally, these results are used to assess whether the quality and technical requirements defined in Chapter 3 are satisfied in Section 6.4.

6.1. Test setup

The combined final prototype was tested in two sessions, which differed in operator, pile surface condition, pile fixation and test location. The first session was conducted by the author on a dry, rusted pile segment lying on the ground. The second session was conducted by an intended end-user on a pile segment coated with grout and mud and secured vertically in a bench vise. More information is given in Appendix H.

6.2. Test method

Both test sessions followed the same method. This method is described in Table 6.1 below. As mentioned in Appendix H, the first test session was repeated four times, whereas the second test session was performed once. Appendix H shows the two test sessions.

Table 6.1: Test procedure

Step	Description	Observing
1	The tool was positioned around the pile and clamped using the ratchet tie down.	The time between initial positioning of the tool against the pile and the point at which it was securely clamped.
2	Once clamped, the tool was rotated manually around the full pile circumference.	The clamping behaviour, structural response and whether any slip occurred between the contact wheels and the pile surface.
3*	With the tool at the intended cut height, the angle grinder was used to grind into the pile.	The resulting partial cut was inspected for deviation from the intended cut line.
4	Throughout steps 1–3, the operator posture was observed during lifting/positioning the tool, clamping and grinding.	Operator posture in order to make the final ergonomic assessment.

* The goal is not to grind through the entire pile at this stage, but to document any deviation from the intended cut line.The reason is discussed in Subsection 6.3.2

6.3. Test results

This section reports the outcomes tests discussed in Section 6.1 and 6.2. The test results of the final prototype consist of evaluating the setup time, clamping behaviour under varying surface conditions, cutting performance, structural response and the final ergonomic assessment. Other observations made will also be discussed here.

6.3.1. Setup time

Table 6.2 below shows an overview of the setup time per performed test trial for both the first and second test session.

Table 6.2: Setup time per trial

Session	Test t_i	Performed by	Setup time t_i*
1	Test 1.1	Author	$t_1 = 15\ s$
1	Test 1.2	Author	$t_2 = 12\ s$
1	Test 1.3	Author	$t_3 = 13\ s$
1	Test 1.4	Author	$t_4 = 11\ s$
2	Test 2.1	Intended end-user	$t_5 = 20\ s$

* The setup times are rounded to the nearest second.

As can be seen in the table above, the tests were performed a total of $N = 5$ times. The resulting average setup time is calculated as follows:

$$t_{avg} = \frac{\sum_{i=1}^{N} t_i}{5} = \frac{(15 + 12 + 13 + 11 + 20)}{5} = \frac{71}{5} \approx 14\ s \tag{6.1}$$

So, we can conclude that the average setup time $t_{avg} = 14\ s$ per test trail. Thus, complying with QR-04 of Table 3.4.

6.3.2. Clamping behaviour

During both test sessions mentioned in Section 6.1 and shown in Appendix H, the tool remained clamped to the pile and no detachment was observed. The rotational ability of the mechanised cutting tool also functioned as intended. This is consistent with the results from the slip condition check in Section 5.3, which showed that $F_g \leq 6\mu F_{clamp}$ holds for both μ_{static} and $\mu_{dynamic}$. However, as discussed in that section, at the boundary case where the tool is at the verge of slipping, a slight rotation about point O was could not be excluded due to the fact that $\Sigma M_O \neq 0$ (see Table 5.2).

During the first test session, the tool remained in its intended position both statically and while rotating around the pile. In the second test session, however, the tool gradually slid downwards during rotation. The difference between the two tests can likely be attributed to the different surface conditions of the pile. The first test was performed on a dry, rusted pile surface, whereas the second test was performed on a pile coated with a mixture of grout and mud.

The contact wheels are made of polyurethane with a hardness of $82A$. As shown in Table 5.1, there is a difference between the static and dynamic coefficients of friction. The value $\mu_{dynamic} = 0,2$ used to assess whether Eq. 4.11 remains valid under both static and dynamic conditions is based on a manufacturer specification for polyurethane with a hardness of $82A$ [26]. However, this value does not account for the actual contact conditions during the second test session. The grout and mud coating likely reduced the coefficient of friction below the assumed value of $\mu_{dynamic} = 0,2$, causing Eq. 4.11 to no longer hold during rotation.

Once the tool slides, the boundary case of Table 5.2 applies. The resulting moment, where $\Sigma M_O \neq 0$, may redistribute the normal forces over the contact wheels, so that some wheels carry less load or lose contact with the pile. This would reduce the total friction capacity below $6\mu F_{clamp}$ and could contribute to the downward sliding. This provides a likely explanation for the downward sliding observed during the second test session.

6.3.3. Cutting performance

As mentioned in Section 6.2, the goal of step 3 was not to fully sever the pile but to document the cut deviation. Therefore, no cutting time data was obtained here. The resulting partial cut was inspected using a tape measure.

Across the four tests trials of the first test session, the measured cut deviation ranged from $0,5\ cm$ to $0,9\ cm$. The largest observed cut deviation during the first test session, is shown in Figure H.6. During the second test session, the cut deviation was measured to exceed $1\ cm$. Sadly, no photographic documentation of this result was made. The larger cut deviation during the second test session is caused by the downward sliding motion mentioned in Subsection 6.3.2.

The cutting time was not recorded during either test session, due to the fact that a pile segment was not fully severed. Although the test sessions showed that it could cut through the steel wall, a full circumferential cut was not made. As mentioned in Section 6.2, the goal was to inspect the cut deviation here. Moreover, according to management, the angle grinder cutting discs used during the test sessions were thicker than the discs typically used by De Waalpaal B.V. in practice. A thinner disc removes less material per rotation, this is expected to result in a shorter cutting time than observed during testing. For this reason, cutting time is not reported as a test result.

6.3.4. Structural response

Via visual inspection during operation of the mechanised cutting tool, no visible deformation or damage to the internal structure of the mechanised cutting tool has been observed. The final combined tool behaved as expected. Thus, it can be concluded that the conclusion drawn in Section 5.4 is valid. The conclusion drawn from the Finite Element Analysis was that no yielding will occur, as $\sigma < \sigma_y$.

6.3.5. Other observations

- Replacing the angle grinder cutting disc was very straightforward and easy.
- The ratchet tie down allowed for quick clamping and releasing of the tool.
- Sparks generated during cutting could potentially burn and damage the ratchet tie down strap. This would result in a loss of clamping force, creating a dangerous situation.
- A ratchet tie down inherently applies tension from one side only, which caused a small rotation of the left-most fixation.
  - Under none of the tested conditions did this affect the clamping force or the rotational capability of the tool.
  - The clamping section ended up at a very small angle relative to the right-most fixation. This could easily be reduced by lubricating the shaft over which the strap passes (see Appendix F for the shaft). It is considered a minor design improvement.
- The distance between the lowest contact point and the cutting disc was measured at $9.2\ cm$, whereas TR-05 requires this distance to be $5\ cm$.
  - As stated in Chapter 2, Subsection 2.2.1, the protrusion height of screw injection piles varies between $5\ cm$ and $20\ cm$.
  - The tool would therefore not function on piles with less than $9.2\ cm$ of available space, which limits its practical applicability.

6.3.6. Final ergonomic risk assessment

During the manual grinding process described in Chapter 2 Subsection 2.1.2, the operator must continuously lift the weight of the angle grinder and reposition himself, all while applying pressure to cut through the pile wall. With the use of the mechanised cutting tool, the operator no longer needs to support the weight of the grinder once it is clamped. Now, only the pressure required for cutting and the force needed to rotate the tool around the pile remain. As the REBA method includes a Force/Load Score component, this reduction in load is reflected in the Force/Load Score assigned in the final ergonomic assessment below. This score is visible in the captions of the figures of Appendix H.

In order to assess the postures during testing of the mechanised cutting tool, the same approach was taken as in in Subsection 2.1.4. The posture during each test session is visible in Appendix H. Table 6.3 represents the results of the final ergonomic risk assessment. In order to properly compare

the results, the previous REBA score of manual pile grinding is also visible in this table. In Chapter 2 Subsection 2.1.4, manual pile grinding was found to be the most physical demanding task and had a REBA score of 11.

Table 6.3: Result table for the final ergonomic risk assessment. Suggested actions are derived from Hignett and McAtamney [9].

Figure	Posture	Previous REBA score	Final REBA score	Risk Level	Suggested action
Figure H.1	Test 1.1	11	6	Medium	Action is necessary, requires more investigation.
Figure H.2	Test 1.2	11	6	Medium	Action is necessary, requires more investigation.
Figure H.3	Test 1.3	11	6	Medium	Action is necessary, requires more investigation.
Figure H.4	Test 1.4	11	5	Medium	Action is necessary, requires more investigation.
Figure H.5	Test 2.1	11	3	Low	Action may be necessary.

As can be seen in Table 6.3, the final REBA scores obtained during the two test sessions range from 3 to 6. The difference in final REBA score can be explained by the different fixation method of the pile. The bench vise used in the second test session secured the pile segment at a higher vertical position. This allowed the operator to have a better posture, which explains the lower REBA score.

The highest final REBA score is 6, which corresponds to a medium ergonomic risk level. According to Hignett and McAtamney [9], action and further investigation is still necessary. However, it is not as pressing as before. Compared to the previous REBA score of 11, this is a notable decrease. The actions required in order to further improve the REBA score will be discussed in Chapter 7.

6.4. Requirement evaluation

All quality and technical requirements are defined in Chapter 3 were systematically assessed based on the test results mentioned in Section 6.3. Table 6.4 and Table 6.5 below, provide a clear overview of their satisfaction status and the reason for this status is also given.

Table 6.4: Status Quality Requirements

Quality Requirement	Satisfied?	Reason
QR-01	Yes	As can be seen in Subsection 6.3.6, the REBA score is reduced from 11 to 6. Although action is still necessary according to Hignett and McAtamney [9], the ergonomic risk level has reduced from very high risk to medium risk.
QR-02	Yes	The use of the mechanised cutting tool was considered safe and efficient. Replacing the angle grinder cutting disc was found to be straightforward. The ratchet tie down allowed for quick clamping and releasing.
QR-03	Partially	The design of the tool allows for use on all pile diameters. Moreover, testing showed that enough clamping force was generated when the mechanised cutting tool was stationary. However, it gradually slid down when it was rotated.
QR-04	Yes	As can be seen in Subsection 6.3.1, the average setup time was approximately $t_{avg} \approx 14\ s$. This is well below the maximum allowable setup time of $t = 2\ min$.

Table 6.4 shows that QR-01, QR-02 and QR-04 have been fully satisfied, while QR-03 has been partially satisfied.

These results indicate that the mechanised cutting tool achieves the intended improvements in ergonomics, operational efficiency and setup time. QR-03 has been partially satisfied, due to the fact that the tool generated enough clamping force while being stationary but was unable to maintain its position during rotational movement in the second test session. This is further discussed in Chapter 7.

Table 6.5: Status Technical Requirements

Technical Requirement	Satisfied?	Reason
TR-01	N/A	See Subsection 6.3.3 for more information.
TR-02	Yes	As mentioned in Subsection 5.3, the total weight of the mechanised cutting tool is $m_{total} = 6,35\ kg$. Where to total weight of the clamping mechanism equals $m_{clamping} = 3,6\ kg$ and the total weight of the cutting mechanism, including angle grinder, equals $m_{cutting} = 2,75\ kg$. So, the total weight of the mechanised cutting tool is way below the maximum allowable weight of $23\ kg$ [12].
TR-03	Yes	The design of the tool ensures the $20\ cm$ space restriction has been met.
TR-04	Partially	Deviation in the first test session ranged from $0,5\ cm$ to $0,9\ cm$. This is within the $1\ cm$ limit. The second test session exceeded $1\ cm$, as mentioned in Subsection 6.3.3.
TR-05	No	The tool must function with an available space of $5\ cm$. The measured distance between the lowest contact point and the cutting disc was measured to be $9,2\ cm$. This exceeds the space guaranteed to be available on-site, as screw injection pile protrusion ranges from $5\ cm$ to $20\ cm$. Therefore, the current mechanised cutting tool would not function on piles where the available space is less than $9,2\ cm$.
TR-06	Partially	The tool remained properly fixated while stationary in both test sessions, but it slid along the pile axis during rotation during the second test session. For more information, see Subsection 6.3.2.
TR-07	Yes	The mechanised cutting tool performed a full circumferential movement in all test trials. It worked without problems.
TR-08	Yes	The tool could cut through the steel wall of the screw injection pile.
TR-09	Yes	The design ensures that dangerous elements are enclosed as much as possible. Moreover, sparks and removed material are directed away from the operator during operation.

Table 6.5 shows that TR-02, TR-03, TR-07, TR-08 and TR-09 have been satisfied. Whereas TR-04 and TR-06 have been partially satisfied, while TR-05 has not been satisfied. Although it was determined that the tool could cut through the steel wall of the foundation pile, an entire segment was not cut off. Therefore, TR-01 could not be determined as mentioned in Subsection 6.3.3.

These results show that the mechanised cutting tool meets most of the defined requirements, while several limitations remain. Potential improvements to address these limitations are discussed in Chapter 7. Any additional observations mentioned in Section 6.3 that are not captured by these requirements, are discussed there.

7

Discussion

This chapter reflects on the results presented in Chapter 6. Section 7.1 gives an interpretation of these results. Section 7.2 reflects on the strengths and weaknesses of the final design. Section 7.3 discusses the design justification and whether operators would use the tool in their daily activities. Section 7.4 provides the current status of the mechanised cutting tool. There, the overall readiness of the tool for field use is discussed based. Section 7.5 provides recommendations about future work that will improve the mechanised cutting tool.

7.1. Interpretation of the test results

The test sessions described in Chapter 6 show that the mechanised cutting tool is capable of performing its intended function. The tool could be clamped around the pile, rotated around its full circumference and was able to grind into the pile. Most of the defined requirements were achieved, as can be seen in Section 6.4.

The main improvement was observed in the ergonomic performance. The REBA score decreased from 11 during manual grinding to a maximum of 6 during the use of the mechanised cutting tool. This indicates a reduction in ergonomic risk, although an unfavourable trunk posture still occurs when working at a low pile height. To solve this, see Section 7.5.

The two test sessions showed that the tool remained securely clamped when it was stationary. However, during the second test session, it moved downward when rotated around the pile circumference. The pile surface conditions were different during the first and second test session, as mentioned in Chapter 6. This indicates that the dynamic stability of the tool is influenced by the pile surface condition. Consequently, the pile surface conditions affect the cutting accuracy. The deviations were between $0,5\ cm$ and $0,9\ cm$ in the first test session and exceeded $1\ cm$ in the second session. Therefore, TR-04 and TR-06 were only partially achieved.

The setup time was well within the required limit, with an average of $t_{avg} = 14\ s$. See Subsection 6.3.1 for more information. Furthermore, no visible deformation or damage occurred to the final prototype during testing. However, other limitations were found during the test sessions. These will be discussed in Subsection 7.2.2 below.

7.2. Reflection on the final design of the mechanised cutting tool

7.2.1. Strengths

A major strength of the final design is that most of the defined requirements were achieved. As summarised in Section 6.4, QR-01, QR-02 and QR-04 were achieved, while the tool also met most of the technical requirements. The final design of the mechanised cutting tool therefore demonstrates that the research question mentioned in Section 2.3 has been largely achieved within a relatively compact and lightweight system.

As mentioned before, the ergonomic improvement is one of the most important results of the final design. The reduction in the REBA score from 11 during manual grinding to a maximum of 6 during the use of the developed tool demonstrates that the musculoskeletal load on the operator is substantially

reduced. The operator no longer needs to continuously support the weight of the angle grinder during cutting. Instead, the tool carries the grinder while the operator mainly controls the rotation of the tool and applies the required cutting pressure.

The clamping system is another strength of the design. The ratchet tie down allows the tool to be secured quickly and securely around the pile, as it quickly generates a high clamping force. Moreover, the average setup time $t_{avg} = 14\ s$. This is way below the maximum of $2\ min$. The system also allows the tool to be released, repositioned and maintained easily, making use of the tool very efficient. Thus meeting QR-02. These factors greatly contributed to requirements defined in Chapter 3.

The design is also sufficiently lightweight to be handled by one person. The total mass of the tool is $6,35\ kg$, which is well below the maximum mass of $23\ kg$. The entire mechanism can therefore be transported and positioned by one operator without requiring additional lifting equipment. Besides this, the final design allows for the operator to replace angle grinder cutting disc without difficulty. These characteristics are relevant for practical use during operation.

Another advantage is the ability to rotate the cutting mechanism around the complete circumference of the pile. During all tests, the tool could be moved around the pile without the operator having to reposition the tool. This demonstrates that the basic guiding principle works as intended and provides a practical alternative to manually moving an angle grinder around a pile.

7.2.2. Limitations and weaknesses

Despite the positive results, several limitations remain. The most important limitation concerns the dynamic stability of the tool. Although the tool remained securely clamped during both test sessions, it moved downward during rotation on the pile with a grout and mud-covered surface. This demonstrates that the current wheel-pile interface is sensitive to surface conditions. The tool therefore cannot yet be considered stable on wet pile surfaces. It can only be considered stable on dry or rusty pile surfaces.

The use of a ratchet tie down also introduces a potential safety concern. During cutting, sparks are generated close to the clamping system. These sparks could damage or burn the ratchet strap. If the strap were to become damaged during operation, the applied clamping force could be reduced. This creates a potential failure mode that should be addressed before industrial use.

Another minor limitation was observed in the left-most fixation point. Because the ratchet applies the tension from one side, the fixation can rotate slightly when the strap is tensioned. This did not have a functional effect during the performed tests, but it indicates that the clamping mechanism could be improved. For example, reducing friction between the ratchet tie down strap and shaft could further reduce this already small rotational movement.

The cutting accuracy also remains a limitation. Although the first test session produced deviations between $0,5\ cm$ and $0,9\ cm$, the second test resulted in a deviation greater than $1\ cm$. This means that the required cutting accuracy was not consistently achieved under all tested conditions. More controlled testing is required to determine whether this deviation is caused by the cutting mechanism, the pile surface, the operator interaction or a combination of these factors.

A further limitation is the available space between the pile and the cutting mechanism. The distance between the lowest contact point of the tool and the angle grinder disc is $9,2\ cm$, whereas TR-05 specifies an available space of $5\ cm$. As a result, the current configuration cannot be used in situations where less than $9,2\ cm$ of pile protrudes above the surrounding surface. This limits the applicability of the tool in situations where the pile has to be cut very close to the ground.

Finally, the ergonomic improvement should not be interpreted as the complete elimination of ergonomic risk. Although the REBA score was substantially reduced, the maximum score of 6 still corresponds to a ”Medium” ergonomic risk level. The operator can still adopt an unfavourable trunk posture when working at a low cutting height. This indicates that further ergonomic optimisation of the interaction between the operator and the cutting mechanism is possible.

7.3. Design justification and willingness to adopt

Operators already carry out manual pile grinding work. So why should this task be mechanised at all? To answer this, this Section discusses the opinion of the operational manager and another employee of De Waalpaal B.V., who were asked for their opinion on the final design of the mechanised cutting tool following the second test session and their willingness to adopt the tool into their daily operations.

After the second test session, both employees of De Waalpaal B.V. indicated a clear willingness to

adopt the tool. However, this willingness was not unconditional. The operational manager stated that although the physical load on the body is greatly reduced, the current design still requires the operator to position himself in an unfavorable posture. This should be addressed in order to increase the user comfort and ergonomics. The second employee mentioned his willingness to adopt the tool, as soon as the tool is ready to operate in the field. The employee mentioned that the operators in the field are physically wrecked after manual pile grinding. The use of this tool must fix that.

This suggests that for both employees the adoption is not primarily focused on matching the manual grinding speed or precision, but on reducing the physical strain on the body. In manual pile grinding, the operator controls the process by continuously adjusting the position and force of the angle grinder based on the feedback received from it. For more information about this process, see Subsection 2.1.2. The problem is therefore not the control of the process, but the physical cost at which this control is achieved. The operator must support the weight of the grinder in an unfavourable posture, resulting in a REBA score of 11 as can be seen in Table 2.1.

The mechanised cutting tool separates these two aspects. It carries the weight of the grinder, whereas the operator retains control of the cutting pressure and the rotation. The reduction of the REBA score to a maximum of 6 shows the effect of this on the posture of the operator.

7.4. Tool status

Based on the results obtained in Chapter 6, the developed prototype can be considered a functional proof of concept rather than a finished and ready-to-use product. The two test sessions demonstrated that the main functions of the tool worked as intended.

At the same time, the partially achieved and not achieved requirements show that further development is necessary. In particular, the dynamic clamping behaviour and available working space require improvement. In addition, the potential damage to the ratchet strap caused by sparks should be addressed before the tool is used in regular industrial operation. Moreover, a method to further improve the REBA score should also be investigated, see Section 7.5.

The current design of the mechanised cutting tool should therefore be regarded as a successful proof of concept, while additional development and testing are required to make the tool suitable for reliable industrial use.

7.5. Future work

Future development should focus on resolving the limitations mentioned in Subsection 7.2.2. Below, the main improvements that could be investigated are discussed.

First of all, the clamping mechanism should be further developed to maintain its position during rotation under different pile surface conditions. The observed downward sliding motion on the pile covered with grout and mud indicates that the wheel-pile interaction requires further investigation. Different wheel materials, wheel geometries or contact pressures could be investigated to determine a better solution. Solving this will result in a better cut accuracy, thus complying with TR-04.

Secondly, the geometry of the cutting mechanism should be redesigned to reduce the distance between the lowest contact point and the angle grinder cutting disc. The current distance of $9,2\ cm$ should be reduced to the required $5\ cm$. Then, the tool can operate on all screw injection piles.

Moreover, the ratchet tie down strap is identified as a weakness. Although the ratchet tie down brings many advantages, the generation of sparks during cutting operations can potentially damage the strap. This damage can potentially cause the tool to lose its clamping force. Future work should include an investigation into different tensioning methods where this risk does not apply to, but where the main advantages of the ratchet strap still remain.

The REBA results in Chapter 6 demonstrate that the current design already reduces the ergonomic risk from a score of 11 during manual grinding to a maximum score of 6 with the developed tool. However, the results also show that the operator can still adopt an unfavourable trunk posture when the pile is positioned relatively low. A possible design improvement is, for example, attaching a vertically oriented handle or rod to the angle grinder and extends upwards from the cutting mechanism. The on/off control could be positioned at the upper end of this handle. Thus, allowing the operator to control the mechanised cutting tool from a more upright position. This upright position should force the operator to maintain a better posture while operating the tool, which will reduce the REBA score. If successful, this modification will reduce the ergonomic risk even further and increase the chance of operators adopting

the tool into their daily work.

Overall, future work should focus on the points mentioned above. Addressing these points would bring the mechanised cutting tool closer to an industrial available tool instead of a promising proof of concept.

8

Conclusion

Work-related Musculoskeletal Disorders (WMSDs) are a leading cause of absence from occupational work and disability [4]. These WMSDs account for approximately one third of all health-related absences in industrialised countries. Of these absences, 60% are back injuries [4]. In Europe alone it affects about 40 million workers [5]. Besides health consequences for employees, being absent due to physically demanding work imposes substantial financial burdens on society and employers. The average cost of an absent employee is estimated to be between 250 and 400 per employee per day [6]. When viewed from industrialised environments, it costs up to 240 billion euro annually to companies and governments [5].

De Waalpaal B.V., which is part of the Van 't Hek group, is directly affected by this problem. Manual grinding of vertical foundation piles with an angle grinder, was identified as the company´s most physically demanding task. This is confirmed by a REBA score of 11. According to Hignett and McAtamney [9] this corresponds to a "Very High" ergonomic risk level, which requires immediate action. This is in line with the statements De Waalpaal B.V. employees.

Existing ergonomic assistive devices are not suitable for manual foundation pile grinding, as their effectiveness depends on the specific task and working environment. This highlights the need for an ergonomic solution that addresses solely the particular demands of the grinding process. However, no dedicated tool currently exists to reduce the musculoskeletal load of operators performing this task.

This thesis addresses that gap by designing and developing a mechanised cutting tool. The main function of the tool is to reduce the musculoskeletal load experienced by operators during manual pile grinding. The requirements of the tool were identified through a Quality Function Development method (QFD). The tool itself is designed in an iterative process and evaluated through two independent test sessions. The first test session is performed by the author, while the second test session is performed by the operational manager of De Waalpaal B.V. who represented an end-user of the tool.

The tool met most of its defined requirements, as can be seen in Section 6.4. Its most significant result is the fact that the REBA score dropped from 11 to a maximum score of 6 across the test sessions. This moves the task from a "Very High" ergonomic risk level to a "Medium" ergonomic risk level, which highlights the fact that the musculoskeletal load of the operator has reduced. Thus satisfying QR-01.

Operation of the tool was found to be very efficient during repeated use of the tool, which satisfies QR-02. Furthermore, the setup time was $t_{avg} = 14\ s$ when it may not have exceeded $t = 2\ min$ as can be seen in QR-04.

The tool weight was $6,35\ kg$ which is well below the $23\ kg$ weight limit defined in TR-02. Moreover, it is operable within the defined $20\ cm$ radial clearance mentioned in TR-03. As mentioned before, the tool remained securely fixed to the pile when stationary but slid downwards when rotating. Thus partially satisfying TR-06. TR-07 is also satisfied, as no problems were recorded during the circumferential movement of the tool around the pile. Although the tool did not grind down an entire pile segment, it was confirmed to be able to cut through the steel outer wall. Satisfying TR-08. Finally, the tool is designed in such a way that the operator is minimally exposed to dangerous elements stated in TR-09.

Not all requirements were satisfied. Mechanical reliability, defined in QR-03, was only partially achieved as the tool held securely while stationary but slid downwards the pile during rotation during the second test session. Cut deviation stayed within the limit in the first test session, however it exceeded

the $1\ cm$ limit in the second session due to the sliding downward motion. Furthermore, the tool requires a minimum of $9,2\ cm$ of pile protrusion to be able to operate, against a stated requirement of $5\ cm$ mentioned in TR-05. Which means that it is currently not usable on all foundation piles, due to the fact that the cut-height ranges between $5\ cm$ to $20\ cm$ in real-world scenarios.

Besides the stated requirements, a safety concern was also identified. Although the use of the ratchet tie down brings a lot of benefits, the following concern needs to be addressed. The ratchet tie down strap can get damaged from generated sparks during grinding operations. If damaged, the tool would lose its clamping force mid-operation. This could create a potentially dangerous situation.

Future work should focus on addressing the limitations mentioned above. The wheel-pile interface should be improved in order to prevent sliding on foundation piles during rotation. This will also improve the cut accuracy. Furthermore, the distance between the lowest contact point and the angle grinder cutting disc should be reduced towards the required $5\ cm$. Besides this, the ratchet tie down strap must be protected from sparks during pile grinding. Or, alternatively, it can be replaced with another material or tensioning method. To further improve the REBA score of the operators, an extended handle with elevated angle grinder control buttons can be added. This will further improve operator posture at low pile heights.

In conclusion, the use of the developed mechanised cutting tool demonstrates that it can substantially reduce operator musculoskeletal load. Both interviewed end-users indicated willingness to adopt it. However, the unresolved identified requirements mean the current prototype is a functional proof of concept rather than a tool ready for deployment on De Waalpaal B.V.'s construction sites. All in all, there is a lot of potential for this mechanised cutting tool to reduce musculoskeletal disorders for employees using an angle grinder to grind down vertical foundation piles.

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A

Statements

A.1. Integrity statement

This MSc Thesis is made entirely by myself and I declare the following:

"I declare that I have not used unauthorized help from people or other sources for completing my MSc Thesis. I created this MSc thesis and the final design of the mechanised cutting tool myself. I did not receive the help of any other student or unauthorized person."

A.2. AI statement

I acknowledge the use of Anthropic's Claude AI (Sonnet 5) to support the development of this assessment by improving readability and flow of sentences. However, the content, logic and structure of the report was developed entirely by myself without the use of any unauthorized tools. Moreover, all outputs from this AI tool were critically evaluated, reviewed and adapted by myself.

B

Ergonomic risk assessment

This appendix provides a detailed ergonomic assessment of the tasks performed during foundation pile operations. Each task is described in Subsections 2.1.1, 2.1.2 and 2.1.3. First of all, the three most widely used ergonomic risk assessment methods are compared and the best applicable method is used. The tasks are evaluated using the REBA method. Posture descriptions are visible in Sections B.2, B.3 and B.4.The results of the REBA assessment method are visible in Table 2.1 in Subsection 2.1.4

B.1. Selection of the ergonomic risk assessment method

In order to asses the ergonomic risk associated with postures, an observational method is used. Several observational methods have been developed to assess ergonomic risk factors related to musculoskeletal disorders. Of these methods OWAS, RULA and REBA are among the most widely used in industrial environments [28]. These methods differ in their level of detail, body coverage and ability to account for task-specific characteristics.

Ovako Working Posture Analysis System (OWAS) is a simple and efficient method for classifying working postures based on predefined posture combinations. A key strength of OWAS is its simplicity and rapid application, making it suitable for large-scale observational studies. It requires no special equipment. Moreover, it can be used by work-study engineers in their daily routine and it gives reliable results after a short training period [29]. According to Kee [28], Its seven lower limb posture codes provide greater sensitivity to leg loading than either RULA or REBA, making it well-suited for tasks involving squatting, kneeling or asymmetric stance [28]. However, OWAS does not take into account the neck, elbow, or wrist and does not account for repetitive or static posture effects [28]. Moreover, OWAS does not account for external force or load exerted by the worker. These limitations are relevant to physically demanding tasks. Thus, making OWAS not practical to asses the postures of the employees seen in Appendices B.2, B.3 and B.4.

Rapid Upper Limb Assessment (RULA) provides a more detailed assessment of upper body postures. and includes factors such as force, repetition and static muscle activity [30]. According to McAtamney and Corlett [30], an advantage of the RULA assessment method is that this tool does not require special equipment in providing a quick assessment of the postures of the neck, trunk and upper limbs. Moreover, this assessment also take into account the static muscle function and the external loads experienced by the body [30]. It also takes repetitive motion into account. According to Kee [28], RULA assessed postural loads at higher risk levels compared to OWAS and REBA, meaning it uses a more conservative approach to risk estimation and is therefore less likely to underestimate musculoskeletal load. A disadvantage of RULA is its simplified classification of leg posture. This is restricted to only two categories: legs and feet well supported with evenly distributed weight and legs not supported or weight unevenly distributed [30]. As a result, the method does not account for knee flexion and extension. Therefore, postures such as squatting or kneeling are not distinguished from a standing posture with uneven weight distribution. Therefore, RULA cannot be used to assess the postures seen in Appendices B.2, B.3 and B.4.

Rapid Entire Body Assessment (REBA) assesses the trunk, neck, legs, upper arms, lower arms and

wrists. It produces a combined score to which load/force, coupling and activity scores are added, giving a final REBA score of 1 through 15. This corresponds to five action levels [9]. Since all three physically demanding tasks mentioned above involve full-body loading, forceful tool handling and continuously changing postures, REBA is considered the most appropriate method for assessing the ergonomic risks in this study. However, according to Kee [28], REBA has notable weaknesses for assessing postures. Kee [28] found that REBA assessed more postures as low risk compared to the RULA method. Thus, the REBA method is using a less conservative approach when compared to RULA. However, this method assesses the entire posture of the body and includes force/load and a coupling factor. This makes it highly suitable to be used when assessing all postures. Detailed REBA scoring procedures and results are provided in Appendix B.1.1 below.

B.1.1. REBA score details

The postures of the employees of De Waalpaal B.V. are assessed using the REBA method. The scoring procedure is divided into two groups of body segments, as shown in Figure B.1. Group A covers the trunk, neck and legs, while Group B covers the upper arms, lower arms and wrists. Each body segment is assigned a posture score based on the observed joint angle [9].

For Group A, the posture scores for the trunk, neck and legs are combined using Table A to produce a single score, to which a load or force score is added depending on the weight handled. This gives Score A. For Group B, the posture scores for the upper arm, lower arm and wrist are combined using Table B, to which a coupling score is added to reflect the quality of the grip. This gives Score B [9].

Score A and Score B are then combined using Table C to produce Score C. Finally, an activity score is added to account for the nature of the movement: body parts are held statically, actions are repeated or the posture involves an unstable base. The sum of Score C and the activity score gives the final REBA score, ranging from 1 to 15, corresponding to one of five action levels. These levels indicate the urgency of corrective intervention [9].

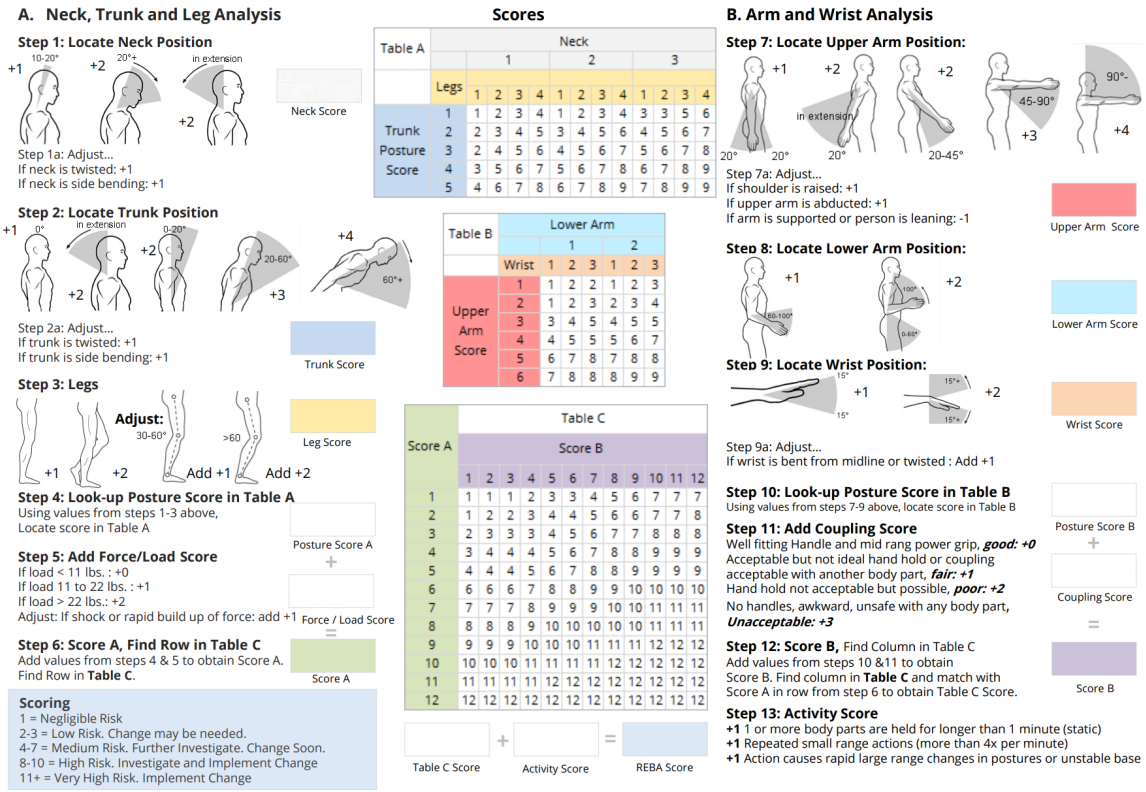


Figure B.1: Original Worksheet Developed by Dr. Alan Hedge [31]. Based on Technical note: Rapid Entire Body Assessment (REBA), Hignett, McAtamney, Applied Ergonomics 31 (2000) 201-205 [9].

B.2. Task A: Lifting the foundation piles



Figure B.2: Posture A1 → Neck = 1, Trunk = 1, Legs = 1, Upper Arm = 1, Lower Arm = 1, Wrist = 1, Force/Load Score = 2, Coupling Score = 0, Activity Score = 1, REBA score = 3.



Figure B.3: Posture A2 → Neck = 1, Trunk = 1+1, Legs = 1+1, Upper Arm = 1+1, Lower Arm = 1, Wrist = 2, Force/Load Score = 2, Coupling Score = 2, Activity Score = 1, REBA score = 6



Figure B.4: Posture A3 → Neck = 1, Trunk = 1+1, Legs = 1+1, Upper Arm = 1, Lower Arm = 1, Wrist = 1, Force/Load Score = 2, Coupling Score = 1, Activity Score = 1, REBA score = 5

B.3. Task B: Grinding of the foundation piles



Figure B.5: Posture B1 → Neck = 2, Trunk = 4, Legs = (1+2), Upper Arm = 2, Lower Arm = 1, Wrist = (1+1), Force/Load Score = 2, Coupling Score = 1, Activity Score = 2, REBA score = 11



Figure B.6: Posture B2 → Neck = 2, Trunk = 4, Legs = (1+2), Upper Arm = 2, Lower Arm = 1, Wrist = (1+1), Force/Load Score = 2, Coupling Score = 1, Activity Score = 2, REBA score = 11



Figure B.7: Posture B3 → Neck = 2, Trunk = 4, Legs = (1+2), Upper Arm = 2, Lower Arm = 1, Wrist = (1+1), Force/Load Score = 2, Coupling Score = 1, Activity Score = 2, REBA score = 11



Figure B.8: Posture B4 → Neck = 2, Trunk = 4, Legs = (1+2), Upper Arm = 2, Lower Arm = 1, Wrist = (1+1), Force/Load Score = 2, Coupling Score = 1, Activity Score = 2, REBA score = 11



Figure B.9: Posture B5 → Neck = 2, Trunk = 3, Legs = 1+2, Upper Arm = 1, Lower Arm = 1, Wrist = 1+1, Force/Load Score = 2, Coupling Score = 1, Activity Score = 2, REBA score = 10



Figure B.10: Posture B6 → Neck = 2, Trunk = 3, Legs = 1+2, Upper Arm = 1, Lower Arm = 1, Wrist = 1+1, Force/Load Score = 2, Coupling Score = 1, Activity Score = 2, REBA score = 10



Figure B.11: Posture B7 → Neck = 1, Trunk = 2, Legs = 1+2, Upper Arm = 1, Lower Arm = 1, Wrist = 1+1, Force/Load Score = 2, Coupling Score = 1, Activity Score = 2, REBA score = 7

B.4. Task C: Handling of foundation pile debris



Figure B.12: Posture C1 → Neck = 1, Trunk = 3, Legs = 1, Upper Arm = 2, Lower Arm = 1, Wrist = 1+1, Force/Load Score = 2+1, Coupling Score = 0, Activity Score = 1, REBA score = 7

C

Existing solutions

Appendix C discusses existing pile clamping and cutting technologies and the underlying mechanisms they use. These principles form the basis for the concept design and development of the mechanised cutting tool. They will be discussed separately below. A summary of these technologies is given in Chapter 4, Section 4.1.

C.1. Cutting mechanisms

Several pipe and pile cutting mechanisms are currently used in industry. These mechanisms differ in operating principle, cutting speed, accuracy, equipment requirements and suitability for different applications. The most relevant cutting mechanisms for this project are discussed below.

Abrasive cutting

Abrasive cutting is a mechanical material removal process in which abrasive particles remove material from a workpiece. The abrasive action can be generated by a rotating abrasive disc or wheel, where material is progressively removed along the cutting path [13].

Abrasive cutting is widely applicable to hard materials and can be performed using relatively compact equipment. The combination of a rotating cutting disc and a portable power tool makes this principle particularly suitable for construction-site applications. For these reasons, abrasive cutting is currently used by De Waalpaal B.V. for manually grinding the tops of foundation piles. This technology can be seen below and in Appendix B.3.



Figure C.1: Abrasive cutting using an angle grinder.

Thermal cutting

Thermal cutting removes material by using heat to melt or otherwise thermally separate the workpiece. Common thermal cutting processes include oxy-fuel, plasma and laser cutting. These processes can provide relatively fast cutting of metallic materials, but introduce heat into the workpiece [14].

To cut down the foundation piles, thermal cutting is less attractive because the pile contains grout. Once hardened, it is hard to melt. In addition, the equipment required for thermal cutting can be less compact than a conventional abrasive cutting tool.

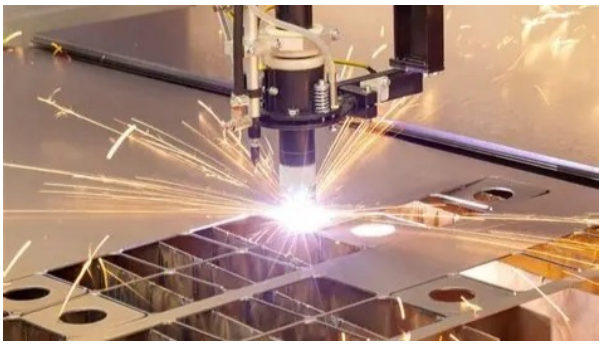


Figure C.2: Example of thermal cutting.

Saw cutting

Saw cutting is a mechanical cutting process in which a hardened cutting edge removes material along a defined cutting path. Depending on the saw design, the cutting edge can move reciprocally, rotate continuously and form a continuous band [15]. Circular saws provide continuous cutting action and can produce relatively straight cuts, while band saws provide continuous cutting with relatively low vibration. The choice of blade and tooth geometry depends on the material being cut.

An important requirement for saw cutting is that the workpiece is securely supported during cutting. Proper fixation prevents movement of the workpiece and helps maintain predictable cutting forces [15]. For pile cutting, this means that the saw and pile would require a suitable guiding and clamping arrangement. The required blade movement and space for the saw mechanism may therefore influence the suitability of this principle for confined construction-site applications.

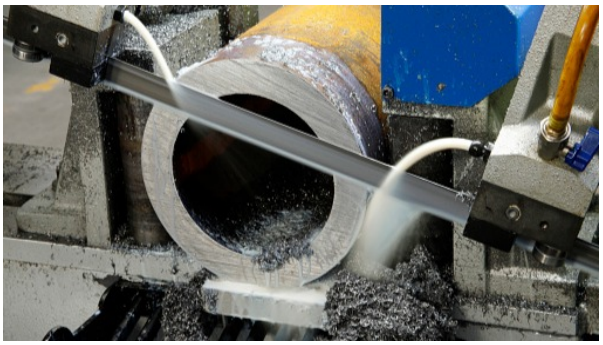


Figure C.3: Example of saw cutting.

Water jet cutting

Water jet cutting is a cold mechanical cutting process in which a high-pressure stream of water is directed through a small nozzle. For cutting hard materials such as metals, an abrasive material can be added to the water stream [16]. The abrasive particles increase the cutting capability of the water jet and allow materials such as metals, ceramics and stone to be processed.

An important advantage of water jet cutting is that it does not create a heat-affected zone because the process is non-thermal. The method can also provide high cutting accuracy and good edge quality [16]. However, the process requires a high-pressure pump, high-pressure tubing and a cutting head. For abrasive water jet cutting, an additional abrasive supply is required. These components make the system considerably more complex than a conventional portable cutting tool.



Figure C.4: Example of water jet cutting.

Diamond wire cutting

Diamond wire cutting uses a flexible wire containing diamond abrasive particles to remove material through controlled abrasion [17]. The wire moves continuously through the workpiece while the diamond particles gradually remove material. The cutting process is controlled through parameters such as wire tension and feed speed. Coolant can be used to reduce heat and remove cutting debris [17].

An important advantage of diamond wire cutting is the relatively small kerf, which reduces material loss. Diamond wires can also cut a wide range of hard materials and generally generate relatively low vibration and noise compared with conventional cutting methods [17]. However, the system requires a suitable wire-routing and tensioning arrangement around the workpiece. This can make the principle less suitable for applications where only limited space is available around the pile.



Figure C.5: Example of diamond wire cutting.

C.2. Clamping mechanisms

Besides the cutting mechanism itself, a clamping mechanism is required to position and stabilize the tool around the pile during operation. Several clamping principles can be considered below.

Claw clamp

A claw clamp uses rigid arms or jaws that mechanically grip the outer surface of the pile. The clamping force is generated through mechanical linkages, bolts or actuators. In addition, they can be designed to accommodate multiple pile diameters through adjustable jaws. However, the mechanism may become mechanically complex when a large diameter range must be supported [18].



Figure C.6: Example of a claw clamp mechanism around a pipe.

Chain clamp

A chain clamp uses a flexible chain that wraps around the workpiece and is subsequently tensioned to generate a clamping force. The chain conforms to the outer contour of the workpiece and can therefore be used for cylindrical, irregular or large-diameter components [19].

The chain is tightened using a mechanical locking mechanism, such as a screw, lever or cam. Tightening the chain distributes the clamping load around the circumference of the workpiece, providing a relatively stable grip [19]. An important advantage for the present application is the ability to accommodate different pile diameters without requiring a large rigid clamping structure. However, the flexibility of the chain can make precise positioning more difficult if the chain is not tensioned uniformly.



Figure C.7: Example of a mechanism using a chain clamp around a pipe.

Magnetic clamp

Magnetic clamps use magnetic fields to generate a holding force between the clamp and a ferromagnetic workpiece [20]. Two common types are permanent magnetic clamps and electromagnetic clamps. Permanent magnets provide a continuous magnetic holding force without requiring an external power supply, while electromagnets can be switched on and off and their magnetic force can be controlled through the supplied current [20].

The main advantage of magnetic clamps is their quick and simple operation. However, they can

only be used with materials that are sufficiently attracted to magnets. Their performance can also be affected by the surface condition and temperature of the workpiece [20]. Since the pile considered in this project is made from steel, magnetic clamping is technically possible, although the required holding force during cutting would need to be verified.



Figure C.8: Example of a magnetic clamp on a pipe.

Hydraulic clamp

Hydraulic clamps generate clamping forces by using pressurised hydraulic fluid. A typical system consists of a hydraulic pump or power pack, hydraulic cylinders, valves, hoses and clamping elements [21]. Hydraulic pressure acts on a piston within the cylinder and is converted into mechanical clamping force.

A major advantage of hydraulic clamping is the ability to generate high and repeatable clamping forces with relatively little manual effort. Hydraulic systems are particularly suitable for heavy workpieces, repetitive operations and applications where stable workholding is required [21]. However, the required pump, hoses, valves and hydraulic fluid increase the complexity of the system. For a compact pile-cutting tool, these additional components may therefore be undesirable.



Figure C.9: Example of a mechanism using hydraulic cylinders to clamp a pipe.

Pneumatic clamp

Pneumatic clamps use compressed air to generate a clamping force. A typical pneumatic clamp consists of a cylinder and piston, together with valves for controlling the air supply. When compressed air enters the cylinder, the piston moves and actuates the clamping mechanism [22].

An important advantage of pneumatic clamping is the rapid engagement and release of the clamp, which makes the principle suitable for repetitive operations. Pneumatic clamps can also provide a consistent clamping force when the air pressure is controlled properly [22]. However, the system depends on a continuous compressed-air supply. Leaks, insufficient pressure or component failure can therefore affect the clamping performance. The requirement for an external air supply also increases the equipment required for the pile-cutting application.

Orbital clamp

An orbital clamp uses multiple contact points distributed around the circumference of the pile to create a stable connection while allowing the clamped device to move around the pile. The contact points can consist of rollers, wheels or friction pads. The clamping force is generated by moving one or more contact points towards the pile, creating sufficient friction to hold the mechanism in place. An orbital clamp mechanism can be inspired by the rotary pipe cutters developed by REED Manufacturing.

An important advantage of this principle is that the tool can remain clamped while rotating around the pile. This makes the principle particularly suitable for applications where a cutting or processing tool needs to follow the circumference of a cylindrical workpiece. The main disadvantage is that the mechanism requires sufficient control of the contact forces to prevent slipping during operation.



Figure C.10: Example of an orbital pipe clamp. This specific example is developed by REED manufacturing.

Hose clamp

A hose clamp is primarily designed to attach and seal a hose to a fitting by applying pressure around its circumference [23]. Several designs exist, including worm-drive and spring-type clamps. Worm-drive clamps use a screw mechanism to tighten a metal band around the workpiece, allowing the clamping diameter to be adjusted [23]. Hose clamps are compact and provide circumferential pressure, making the principle potentially interesting for applications where limited space is available. Their relatively simple construction also allows quick installation and adjustment. However, conventional hose clamps are primarily designed for sealing hoses rather than resisting the cutting loads generated during pile grinding work. Their suitability as a structural clamp for the pile cutting tool would therefore require verification of the available clamping force and mechanical strength.



Figure C.11: Example of a hose clamp.

D

Concept details

This appendix provides more details about the design and working principles of each of the concepts mentioned in Chapter 4. Information about the concepts that was too detailed for the main text has been moved here to keep Chapter 4 more concise.

D.1. Clamping concepts

Concept 1: Claw clamp

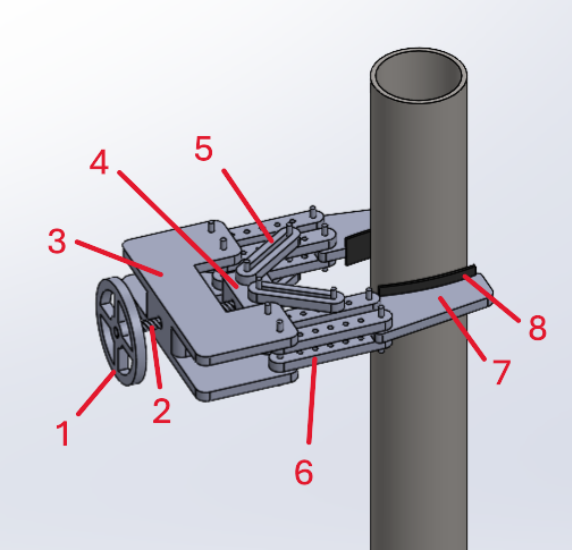


Figure D.1: Isometric view

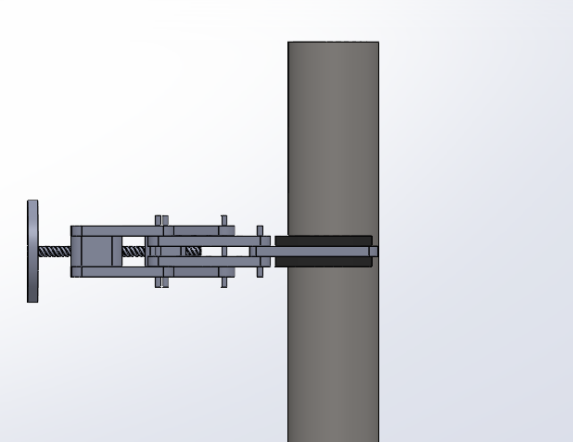


Figure D.2: Side view

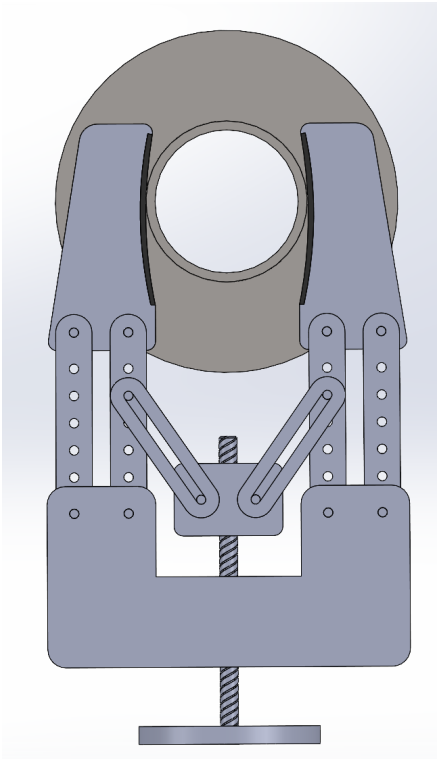


Figure D.3: Top view

Figure D.1, D.2 and D.3 show the design of concept 1: Claw clamp. This concepts has the following working principle:

The operator turns the handle (1), which rotates the TR10x2 self-locking leadscrew (2) running through the base (3). This rotation is converted into linear translation via a connector piece (4), forming a linear guide system. Linkages (5), mounted on the connector piece, transfer this linear motion as rotation into a parallelogram mechanism (6), driving the claw's open and close motion. The claws (7), attached to the parallelogram mechanism, grip the pile upon closing. Two friction strips (8) are fixed to the claws to increase clamping force against the pile surface. This claw design is multi-diameter compatible. The numbered components (1–8) are indicated in figure D.1.

Concept 2: Orbital clamp

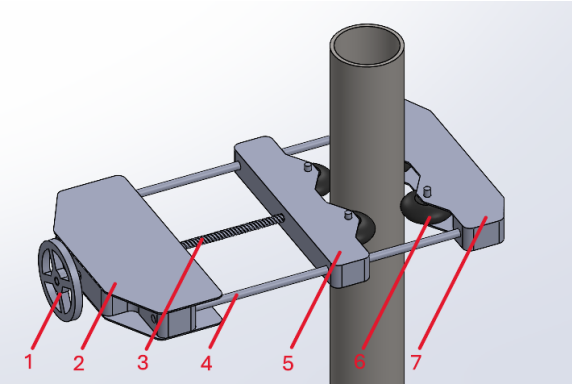


Figure D.4: Isometric view

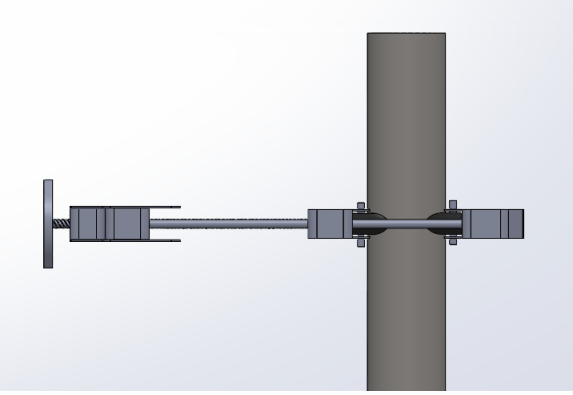


Figure D.5: Side view

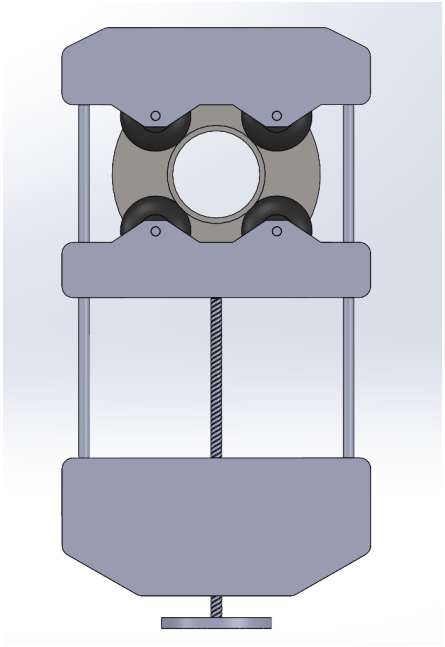


Figure D.6: Top view

Figure D.4, D.5 and D.6 show the design of concept 2: Orbital clamp. This concepts has the following working principle:

The operator places the device around the pile and turns the handle (1), which rotates the TR10x2 self-locking leadscrew (3) running through the fixed base (2). Two linear guide rods (4), mounted between the fixed base, the sliding base (5) and end base (7), constrain the sliding base to a purely linear translation as the leadscrew rotates. Mounted on both the slinding base (5) and the end base (7) are high-friction wheels (6). As the sliding base translates, the wheels clamp against the pile surface. Because the wheels allow rotation, the operator can spin the entire device around the pile once clamped. This design is compatible with multiple pile diameters. The numbered components (1–7) are indicated in Figure D.4.

Concept 3: Chain clamp

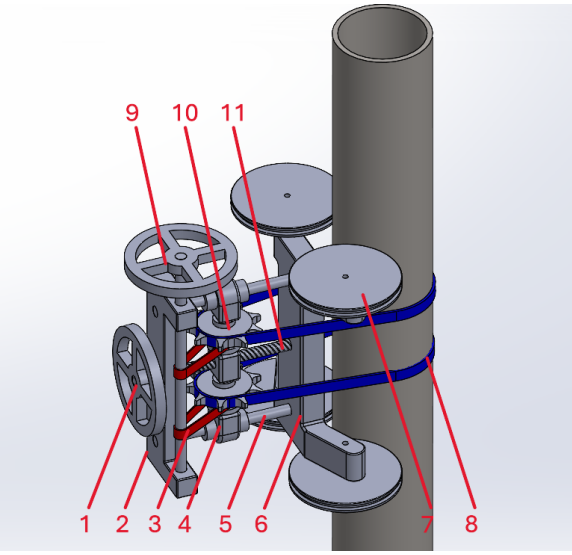


Figure D.7: Isometric view

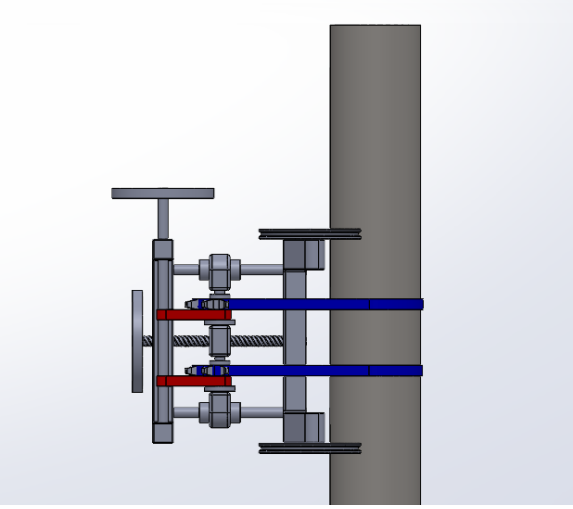


Figure D.8: Side view

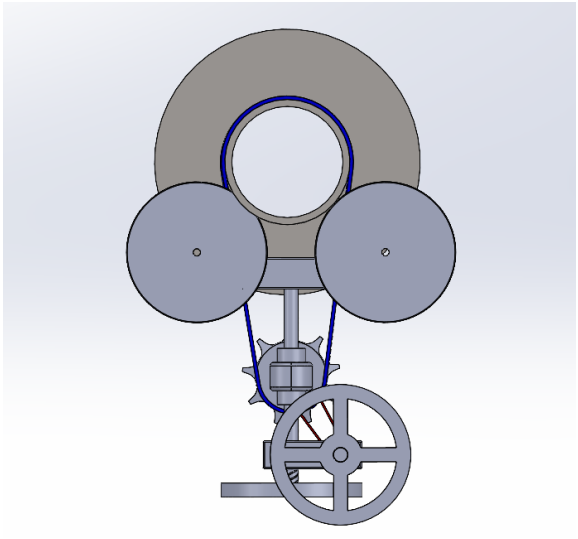


Figure D.9: Top view

Figure D.7, D.8 and D.9 show the design of concept 3: Chain clamp. This concepts has the following working principle:

The operator places the device around the pile, ensuring the chains (8), highlighted in blue, are set to the correct length and the wheels (7) are in contact with the pile surface. The operator then turns the leftmost handle (1), rotating the TR10x2 self-locking leadscrew (11) and thus translating the movable platform (4) linearly along the guide rods (5). This translation tensions the chain (8), pulling the wheels (7) firmly against the pile and creating a clamped connection. The device is mounted on a base (6), which carries the two guide rods (5), the leadscrew (11), and the upper fixed platform (2).

Once securely clamped, the operator turns the upper handle (9). This rotates a rod, which drives two timing belts (3), highlighted in red. The timing belts transfer this rotation to the chain sprockets (10), which in turn drive the entire device around the pile. This eliminates the need to manually reposition it. Due to the fact that the chain length is adjustable, this design is compatible with multiple pile diameters. The numbered components (1–11) are indicated in Figure D.7.

D.2. Cutting concepts

Conceptual cutting method 1: Sliding mechanism

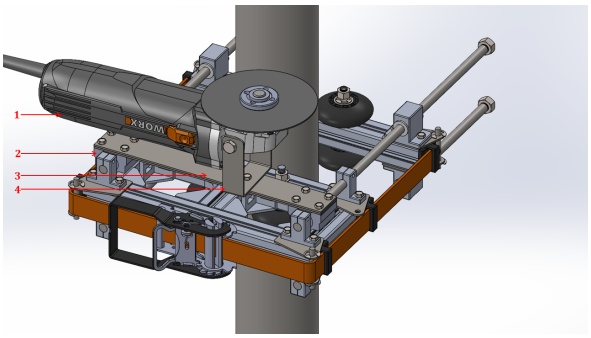


Figure D.10: Isometric view of the concept.

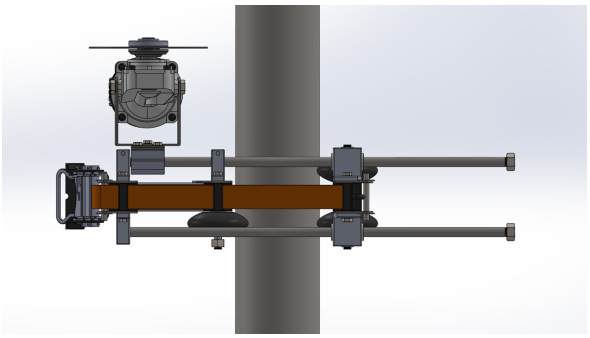


Figure D.11: Side view of the concept.

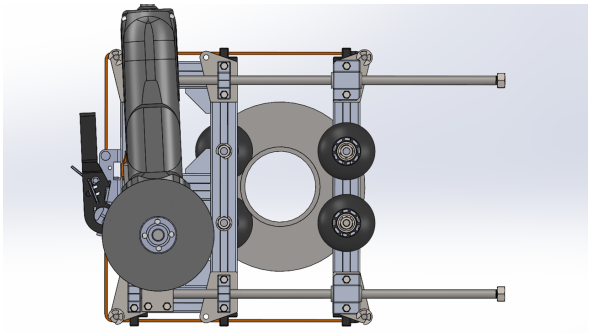


Figure D.12: Top view of the concept.

Figure D.10, D.11 and D.12 show the design of cutting method 1: Sliding mechanism. This conceptual method has the following working principle:

The existing guiding rods of the clamping mechanism are used to support the cutting mechanism. SCS10UU linear ball bearings (2) allow a raised platform (3) to translate along the guiding rods. The angle grinder (1) is mounted to this platform using a connector frame (4). By translating the platform along the guiding rods, the angle grinder can be moved towards the pile to perform the cut. In addition, the rotational ability of the clamping mechanism allows the complete cutting mechanism to be rotated around the pile. This enables the angle grinder to follow the required cutting path while making use of the existing features of the clamping mechanism. The numbered components are indicated in Figure D.10.

Conceptual cutting method 2: Swivel bearing mechanism

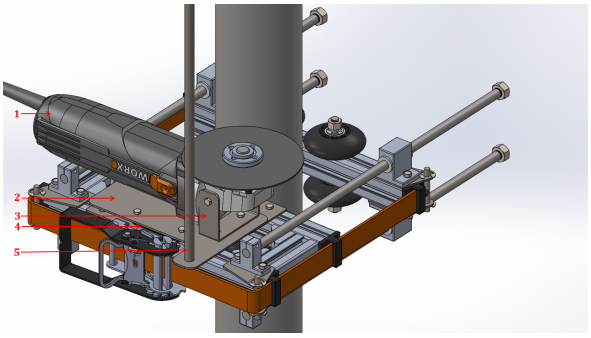


Figure D.13: Isometric view of the concept.

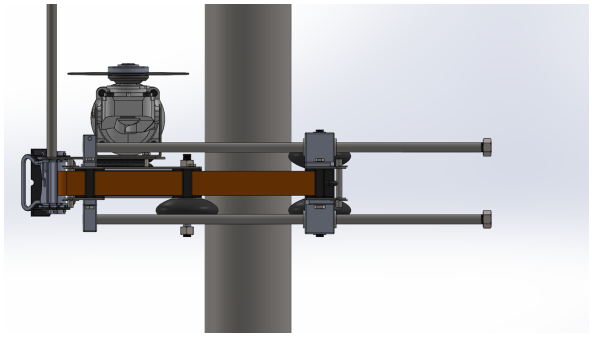


Figure D.14: Side view of the concept.

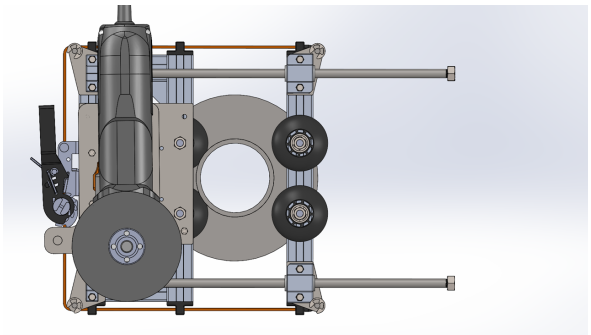


Figure D.15: Top view of the concept.

Figure D.13, D.14 and D.15 show the design of conceptual cutting method 2: Swivel bearing mechanism. This conceptual method has the following working principle:

A swivel bearing (4) is mounted in the dedicated space of the clamping mechanism. The swivel bearing supports a raised platform (2), on which the angle grinder (1) is mounted using a connector frame (3). The swivel bearing allows the platform and angle grinder to rotate around the pile. This rotational movement is controlled manually using the upward-reaching handle (5). By rotating the platform, the angle grinder can be positioned along the required cutting path around the pile. The numbered components are indicated in Figure D.13.

Conceptual cutting method 3: Hinge mechanism

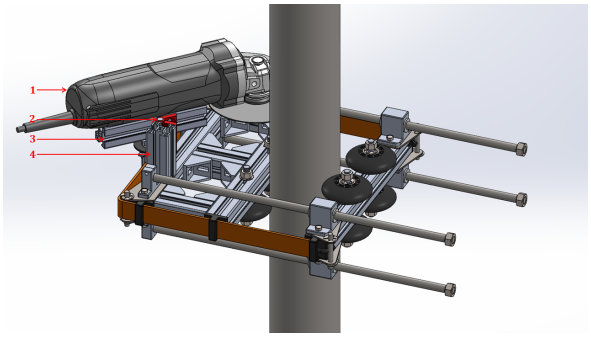


Figure D.16: Isometric view of the concept.

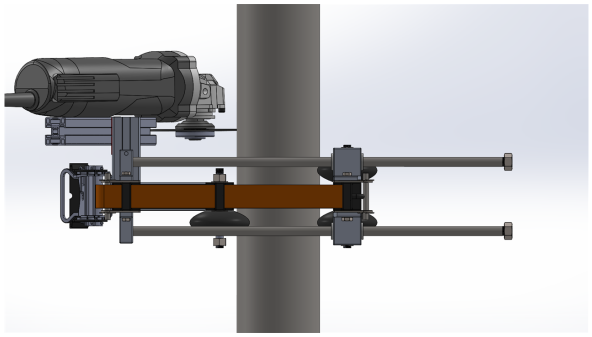


Figure D.17: Side view of the concept.

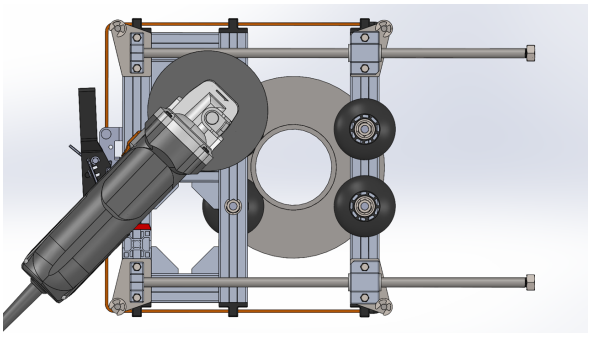


Figure D.18: Top view of the concept.

Figure D.16, D.17 and D.18 show the design of conceptual cutting method 3: Hinge mechanism. This conceptual method has the following working principle:

A vertical aluminium 3030 extrusion profile (3) is secured in the dedicated mounting space of the clamping mechanism. A horizontal extrusion profile is connected to the vertical profile through a hinge (2), allowing it to rotate around the vertical axis. The angle grinder (1) is mounted to the horizontal profile and can also be rotated relative to the profile. This combination of rotational movements allows the angle grinder to be positioned around the pile and oriented towards the required cutting location. The hinge mechanism therefore provides the necessary freedom of movement to guide the angle grinder along the cutting path. The numbered components are indicated in Figure D.16.

E

Photographic documentation of prototype testing

This appendix provides photographic documentation of the first prototype testing mentioned in Chapter 5. Section E.1 shows the documentation on the prototype testing on the clamping mechanism, while Section E.2 provides the documentation of the first prototype testing of the cutting mechanism.

E.1. Damage to the first prototype of the clamping mechanism

For more information regarding the photographic documentation below, see Subsection 5.1.1.



Figure E.1: Damage on internal structure due to pile contact.

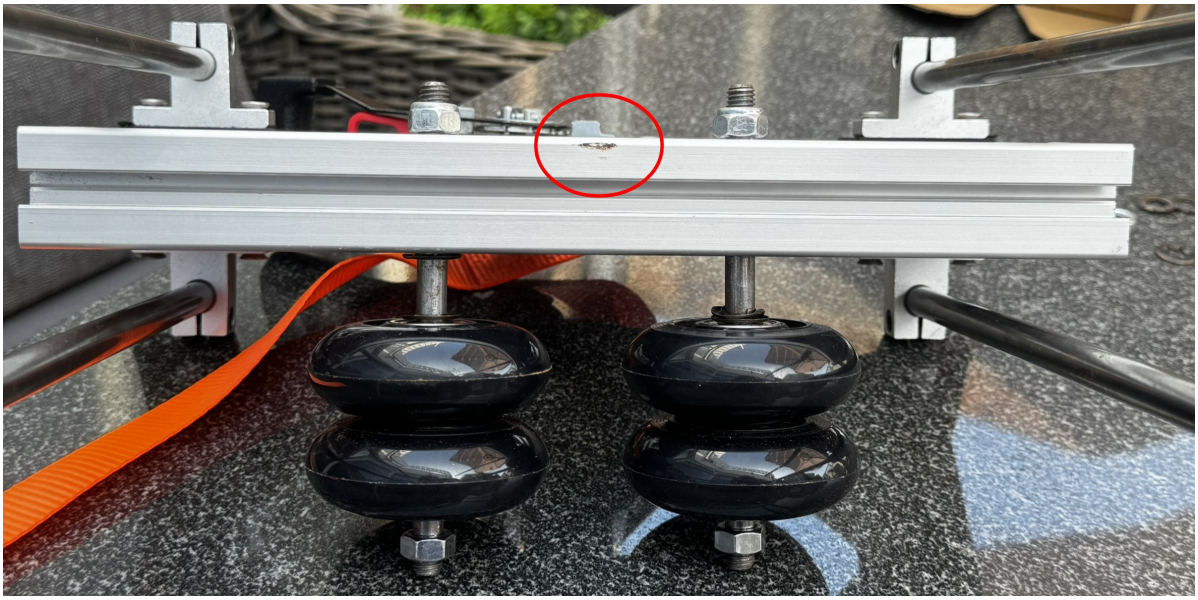


Figure E.2: Damage on internal structure due to pile contact.

As can be seen above, there is damage to the internal structure of the tool due to pile contact. The damage is highlighted by the red circles.

E.2. Observation of the first prototype of the cutting mechanism

For more information regarding the photographic documentation below, see Subsection 5.2.1.

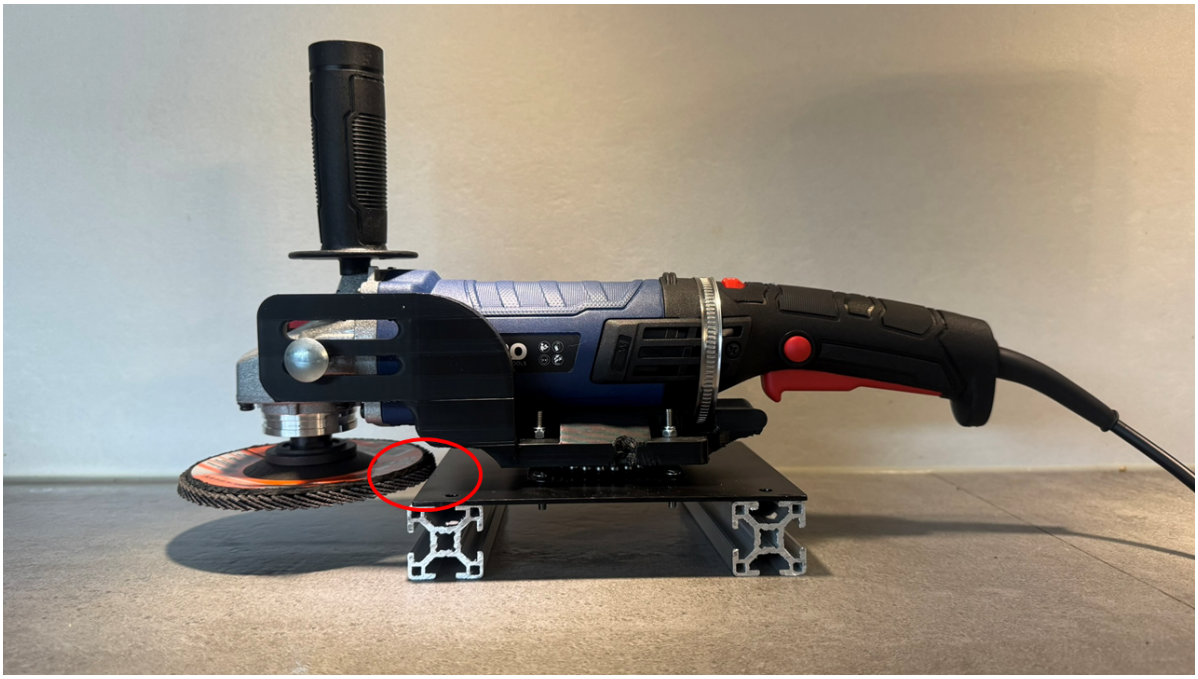


Figure E.3: Testing the first design of the cutting prototype.

As can be seen above, the angle grinder is unable to rotate due to the fact that the cutting disc makes contact with the raised mounting platform. This is highlighted by the red circle.

F

Mechanised cutting tool information

This appendix serves to provide more details about the final design of the mechanised cutting tool. Figure F.1 below, shows an isometric view of the final deisng of the mechanised cutting tool. In this figure, numbers are visible. These numbers highlight the parts in the tool.

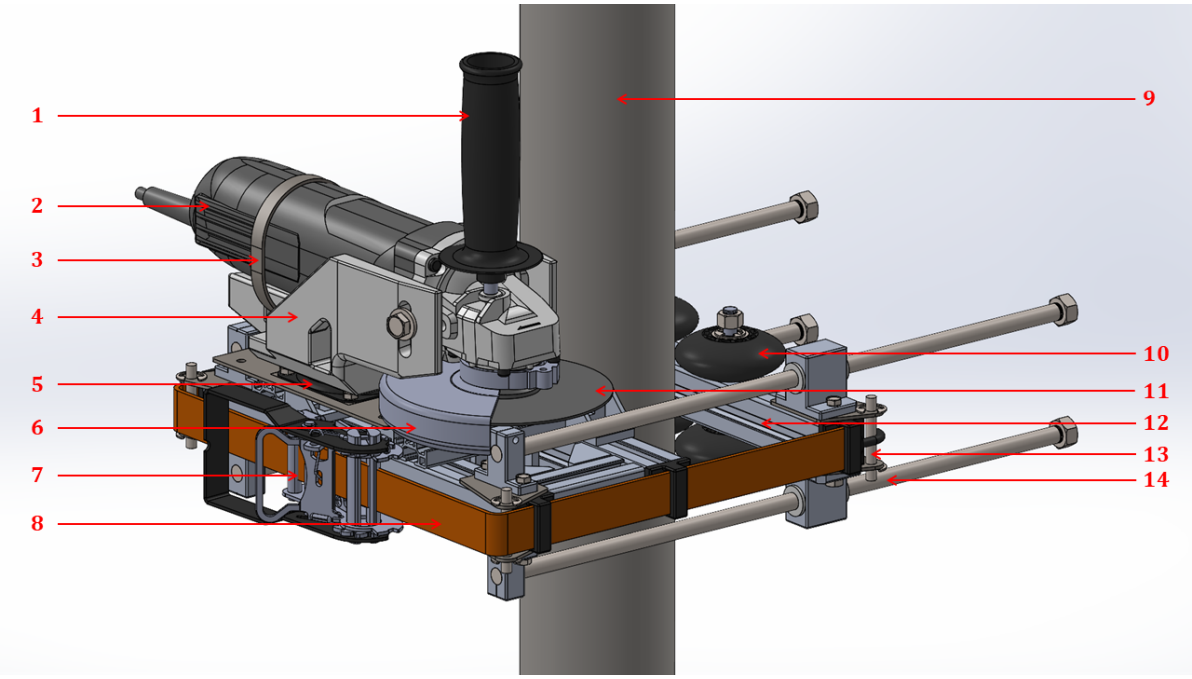


Figure F.1: Parts overview of the final design.

Table F.1 below gives an overview of the parts names, their material if necessary and other remarks.

Table F.1: Final design parts

Number	Description	Material	Remark
01	Angle grinder handle	N/A	Included when buying the angle grinder (number 2).
02	Angle grinder	N/A	The angle grinder used in real-life has been bought via the following site: `https://www.action.com/nl-nl/p/3223709/varo-haakse-slijper/`
03	pipe clamp	Stainless steel	This is a commercially available pipe clamp.
04	Angle grinder holder frame	PLA	The yield strength of this material cannot be determined, due to the properties of 3D printing.
05	Swivel bearing	Alloy steel	The maximum load bearing capacity is $30\ kg$ according to the site it was ordered from: `https://www.amazon.nl/dp/B0B3X7R961?ref=ppx_yo2ov_dt_b_fed_asin_title`
06	Angle grinder guard	N/A	Included when buying the angle grinder (number 2).
07	Ratchet tie down	N/A	The ratchet tie down used in the tool has been bought via the following site: `https://www.action.com/nl-nl/p/3016310/c-c-spanband-met-ratelsluiting/`
08	Ratchet tie down strap	N/A	This material is not fire proof.
09	Screw injection pile	S355JR	This material has a yield strength of $\sigma_y = 355\ MPa$
10	Contact wheel	Polyurethane (PUR)	The friction coefficient of polyurethane is according to the company Gallagher [26] similar to that of rubber. The static coefficient of friction of rubber on steel is equal to $\mu_{static} = 0,86$ [32]. According to Gallagher [26], the dynamic coefficient of friction of polyurethane ranges from $0,2$ to $2,5$ depending on the hardness. The contact wheels were bought via the following site: `https://www.amazon.nl/dp/B08MZRPY89?ref_=ppx_hzod_title_dt_b_fed_asin_title_0_0#`.
11	Angle grinder cutting disc	N/A	The largest diameter available for this tool is $= 125\ mm$
12	3030 aluminum extrusion frame	Aluminum 6063 T5	This material has a yield strength of $\sigma_y = 145\ MPa$.
13	strap support shaft	S235JR	This material has a yield strength of $\sigma_y = 235\ MPa$.
14	Guiding rod	S235JR	This material has a yield strength of $\sigma_y = 235\ MPa$.

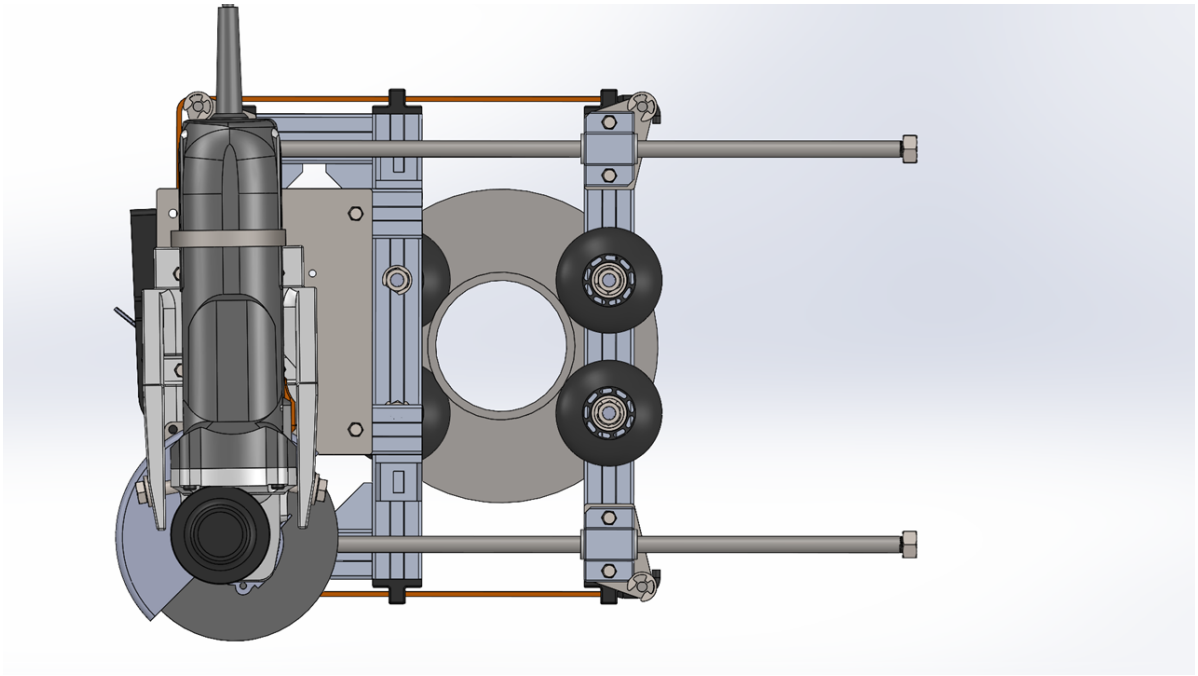


Figure F.2: Top view of the final design of the mechanised cutting tool.

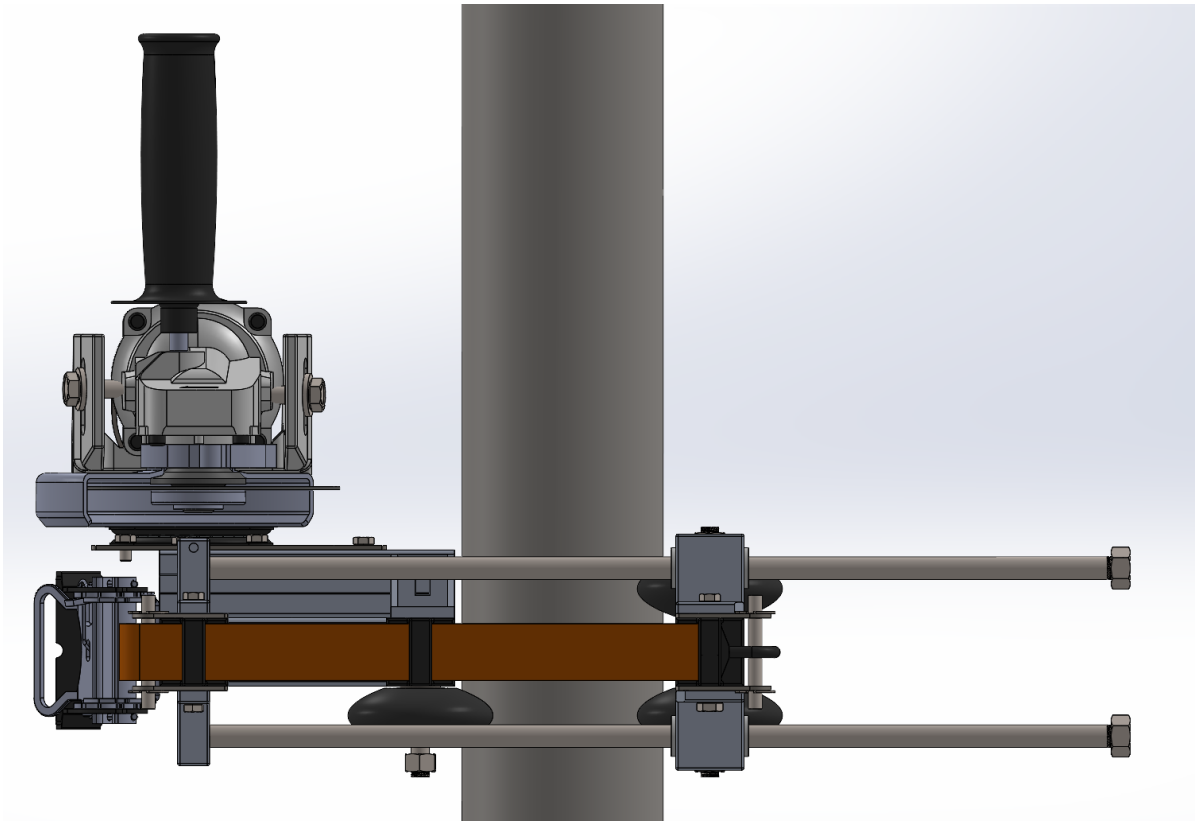


Figure F.3: Side view of the final design of the mechanised cutting tool.

G

Finite Element Analysis details

This appendix shows the zoomed-in results of the Finite Element Analysis. The purpose of this appendix is to provide insight into the exact location of the maximum stress, displacement and strain. The locations are in line with what would be expected under real-life operating conditions.

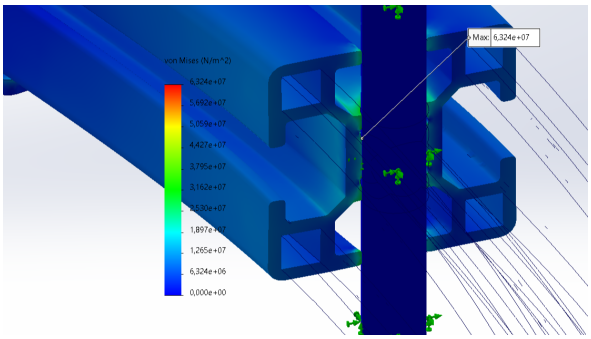


Figure G.1: Zoomed-in FEA stress result on the left-most fixation.

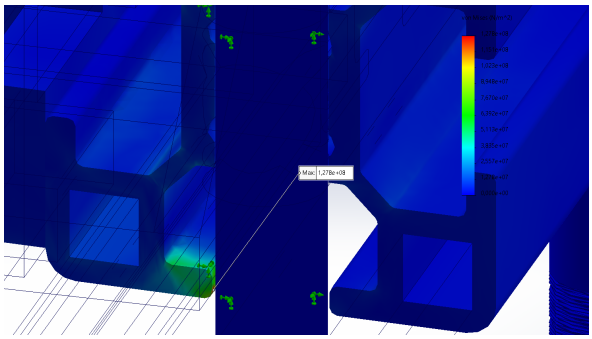


Figure G.2: Zoomed-in FEA stress result on the right-most fixation.

As can be seen in the figures above, the locations of the maximum stress for both the left-most and right-most fixations, are in the interface between the aluminum extrusion profiles and the steel rod.

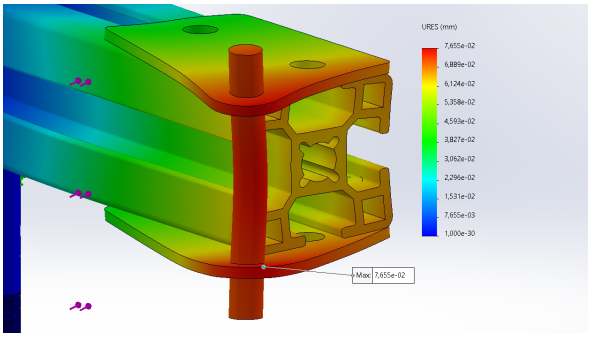


Figure G.3: Zoomed-in FEA displacement result on the left-most fixation.

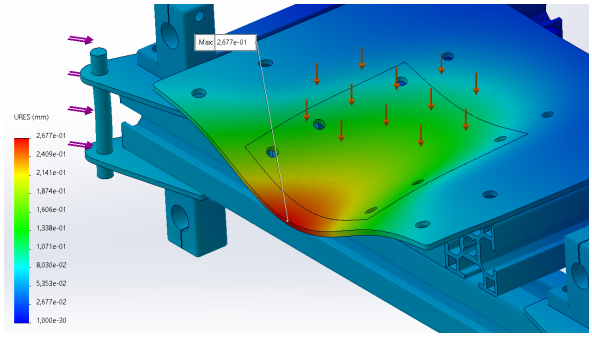


Figure G.4: Zoomed-in FEA displacement result on the right-most fixation.

The maximum displacement on the left-most fixation is located at the point of force application. Similarly, the maximum displacement on the right-most fixation occurs at the point of force application on the raised platform.

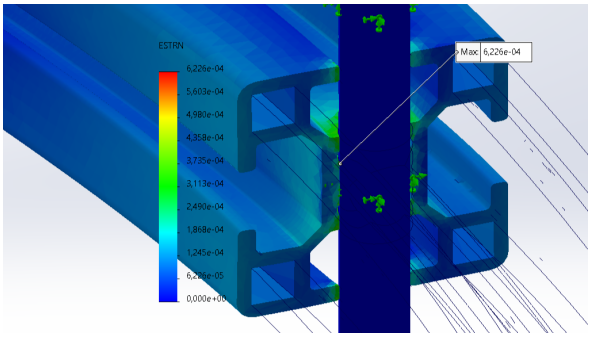


Figure G.5: Zoomed-in FEA strain results on the left-most fixation.

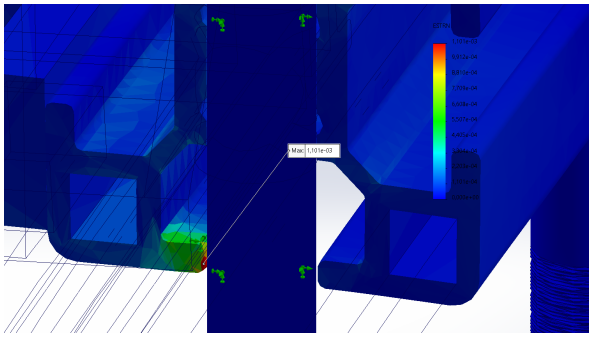


Figure G.6: Zoomed-in FEA strain results on the right-most fixation.

As can be seen in the figures above, the locations of the maximum strain for both the left-most and right-most fixations, are in the interface between the aluminum extrusion profiles and the steel rod.

H

Testing

In this appendix, the two test sessions are visible. In both cases, a pile segment with diameter $D = 114,3\ mm$ is used. To assess the results, the first test session was repeated four times, while the second test session was performed once, giving a total of five test trials.

H.1. First test session

As mentioned in Chapter 6, the first test setup was performed by the author. This allowed for direct results and observations. In order to see how the first test session was conducted, see the figures below.



Figure H.1: Test 1.1 → Neck = 2, Trunk = 4, Legs = 1, Upper Arm = 3-1, Lower Arm = 1, Wrist = 1+1, Force/Load Score = 0, Coupling Score = 0, Activity Score = 2, REBA score = 6



Figure H.2: Test 1.2 → Neck = 2, Trunk = 4, Legs = 1, Upper Arm = 3-1, Lower Arm = 1, Wrist = 1+1, Force/Load Score = 0, Coupling Score = 0, Activity Score = 2, REBA score = 6



Figure H.3: Test 1.3 → Neck = 2, Trunk = 4, Legs = 1, Upper Arm = 3-1, Lower Arm = 1, Wrist = 1+1, Force/Load Score = 0 , Coupling Score = 0, Activity Score = 2, REBA score = 6



Figure H.4: Test 1.4 → Neck = 2, Trunk = 2, Legs = 1, Upper Arm = 2-1, Lower Arm = 1, Wrist = 1+1, Force/Load Score = 1, Coupling Score = 1, Activity Score = 2, REBA score = 5

H.2. Second test session

As mentioned in Chapter 6, the second test setup was performed by management. Management represented an intended end-user of the mechanised cutting tool during this test. This test was conducted at the premises of De Waalpaal B.V. at Visserijweg 1 in Purmerend. See Figure H.5 below, to see how the second test was conducted:



Figure H.5: Test 2.1 → Neck = 1, Trunk = 1, Legs = 1, Upper Arm =3-1 , Lower Arm = 2, Wrist = 1+1, Force/Load Score = 0, Coupling Score = 1, Activity Score = 2, REBA score = 3

As can be seen here, the foundation pile segment is coated with a mixture of grout and mud. furthermore, the fixation of the pile segment is different during the second test. the pile segment was placed securely on the ground, whereas during the second test it is secured vertically in a bench vise.

H.3. Cut deviation

Accros the four tests in the first test session, the cut deviation ranged from $0,5\ cm$ to $0,9\ cm$. The largest deviation observed in the first test session is shown below.



Figure H.6: Cut deviation of the first test session.

As can be seen in Figure H.6 above, the cut deviation is less than $1\ cm$. In the second test session, the cut deviation exceeded $1\ cm$. Sadly, no photographic documentation of this result was made.