Mobility of Subsea Tracked Equipment
A comprehensive study of the interaction between trencher mobility and seabed trafficability.

H.S. Daanen

Offshore and Dredging Engineering
Mobility of Subsea Tracked Equipment

A comprehensive study of the interaction between trencher mobility and seabed trafficability.

H.S. Daanen

to obtain the degree of Master of Science at the Delft University of Technology.

Student number: 4301374
Project duration: July, 2016 – June, 2017
Thesis committee: Prof. dr. ir. C. van Rhee, TU Delft
Dr. ir. S. A. Miedema, TU Delft
Ir. J. den Haan, TU Delft

An electronic version of this thesis is available at http://repository.tudelft.nl/.
This report is a presentation of the final work carried out for the completion of my Master of Science study at the Offshore and Dredging department of the Delft University of Technology. This work was completed with the support of several people at the TU and at Tideway Offshore Solutions.

First of all, I would like to thank my supervisors at the TU, Cees van Rhee and Sape Miedema. Their feedback and guidance during our meetings has been instrumental to the success of this project. I would like to thank Prof. van Rhee for his guidance when pointing me in the right direction when I was looking for a thesis subject. Great appreciation goes out to Sape for being my daily supervisor. Our discussion regarding core subjects (and other less related subjects), where very helpful to me. I would like to thank all committee members for their time and effort during reading, listening and providing feedback.

Furthermore I would like to thank Connie Visser, for her involvement with my thesis and giving me the opportunity to do this project within the engineering department of Tideway Offshore Solutions. I would also like to express great appreciation to Cristina Lupea and Joost de Haan whose support, guidance and time investment have shown to be crucial to the completion of this thesis. I would like to thank Cristina for her time and efforts spend supplying me with the extra knowledge needed regarding geotechnical engineering. I would like to thank Joost for his interest and ideas regarding my subject. Our brainstorm sessions turned out to be very effective. I would also like to thank both for their input while I was writing this report. I would also like to express my appreciation to Paul Vercruysse, his experience and advice regarding the subsea behavior of tracked vehicles was also an important factor.

I wish to thank my partner Tamara for her unconditional support and believe in me. For helping me creating an environment where it was possible to take on this challenge. Last word goes out to our daughter Fay whose presence provided me with an endless amount of motivation.

H.S. Daanen
June 2017
Abstract

The Offshore wind industry harvests energy in offshore locations, using large turbines to convert this energy to electrical power. The electricity is gathered and transported to shore via cables. These cables need to be protected from external hazards that could result in damages and thus economic losses. Generally the cables are buried in the seabed or covered with solid objects like rocks or concrete mattresses. For cable burial a trench needs to be created in the seabed, this process is called trenching. Tideway acquired a trenching vehicle to enable provision of a wider range of cable protection solutions besides rock placement. Instead of more familiar trenching ploughs, this machine is equipped with a track drive and is self-propelling. To create trenches the vehicle has two options, mechanical cutting and jetting.

Expected progress rates of the vehicle are to be determined to make a more realistic assessment of the expected project durations in the pre-execution stages. This can only be done if specific knowledge regarding the interaction between seabed soils and track drive is available. Furthermore it is interesting to look at the most optimal setup of the vehicle for each project, make the machine work more efficiently and decrease the trenching duration. The current thesis proposes a model that can assess the trench production rates for a tracked trenching vehicle. Inputs for the model are CPT results, operational conditions and general vehicle specifications. Furthermore, the model considers the fact that the vehicle has a limited amount of power onboard. The sensitivity of the model parameters and impact on production is analyzed via a tool created specifically for Tideway’s subsea trencher.

The project is based on a review of literature regarding soil mechanics, soil cutting and terramechanics. Using this knowledge the model is developed considering a rest state and a steady driving state of the vehicle. The final model incorporates several sub-models, accounting for the resistant-, thrust forces, slopes and more. Phenomena as shear displacement and slip are incorporated and build towards the output for the model, a forward speed of the vehicle while cutting. The model can include
seabed slopes and layered homogeneous soils. The presence of boulders, currents and effects of acceleration/braking are outside the scope of this thesis. Based on the developed model a software algorithm is developed in the open-source programming language Python. This algorithm generates a working area which indicates the zone within which all operational and machine boundaries are fulfilled. Additionally an optimal working-point is also suggested. This point corresponds to the given combination of operational and vehicle specifications, where the machine operates at a desired efficiency.

Several conclusions are drawn, accompanied with recommendations regarding optimization of the model and industry procedures. The goal of thesis has been achieved, by developing the model and the tool. A validation process based on measured field data shows that the several (sub)models are within range of the measured data.
# Contents

List of Figures ................................................................. ix  
List of Tables ................................................................. xi 

1 Introduction 
   1.1 Project ............................................................... 1  
   1.2 Track driven vehicles ............................................. 3  
   1.3 Summary ............................................................. 6  

2 Soil mechanics 
   2.1 Basics ............................................................... 7  
   2.2 Skirted foundations ............................................... 13  
   2.3 Summary ............................................................. 14  

3 Rigid track belt theory 
   3.1 Rest state ........................................................... 17  
   3.2 Driving state ....................................................... 20  
   3.3 Summary ............................................................. 26  

4 Modeling ................................................................. 29  

5 Validation ............................................................... 31  

6 Conclusions and recommendations ................................ 33  

Appendices 
   A CBT11100 Trencher ................................................... 37  
   B Software Algorithm .................................................. 41  
   C Westermost Rough .................................................... 43  

Bibliography ................................................................. 45
<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1</td>
<td>Examples of tracked vehicles in different applications. (Source: wikipedia.org)</td>
<td>4</td>
</tr>
<tr>
<td>1.2</td>
<td>The main components of a general track drive (source: tpub.com).</td>
<td>4</td>
</tr>
<tr>
<td>1.3</td>
<td>Flexible tracks on the left, rigid tracks on the right.</td>
<td>5</td>
</tr>
<tr>
<td>1.4</td>
<td>A flat track belt (top) and one equipped with grousers (bottom)</td>
<td>5</td>
</tr>
<tr>
<td>1.5</td>
<td>The simplified working principle of a track</td>
<td>6</td>
</tr>
<tr>
<td>2.1</td>
<td>Mohr circle in cohesive soils</td>
<td>10</td>
</tr>
<tr>
<td>2.2</td>
<td>Example of a stress - strain relationship</td>
<td>11</td>
</tr>
<tr>
<td>2.3</td>
<td>Self-weight sinkage of a skirted foundation</td>
<td>14</td>
</tr>
<tr>
<td>3.1</td>
<td>Ground pressure distributions due to a centric loading</td>
<td>18</td>
</tr>
<tr>
<td>3.2</td>
<td>Ground pressure distributions due to an eccentric loading</td>
<td>19</td>
</tr>
<tr>
<td>3.3</td>
<td>Ground pressure distributions due to a slope</td>
<td>20</td>
</tr>
<tr>
<td>3.4</td>
<td>Slip and shear displacement distribution</td>
<td>21</td>
</tr>
<tr>
<td>3.5</td>
<td>Ground pressure distribution on slopes</td>
<td>26</td>
</tr>
</tbody>
</table>
List of Tables

2.1 Soil classifications and their particle size distributions .............................. 7
2.2 The classification of clays ........................................................................ 8
2.3 Soil shear curves ..................................................................................... 12
# Nomenclature

## Greek Symbols

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>γ</td>
<td>Unit or volumetric weight</td>
<td>$N/m^3$</td>
</tr>
<tr>
<td>μ</td>
<td>Shape factor</td>
<td>–</td>
</tr>
<tr>
<td>ν</td>
<td>Poisson ratio</td>
<td>–</td>
</tr>
<tr>
<td>ζ</td>
<td>Settlement</td>
<td>$m$</td>
</tr>
<tr>
<td>δ</td>
<td>External friction angle</td>
<td>$deg$</td>
</tr>
<tr>
<td>κ</td>
<td>Permeability</td>
<td>$m/s$</td>
</tr>
<tr>
<td>φ</td>
<td>Internal friction angle of soil</td>
<td>$deg$</td>
</tr>
<tr>
<td>τ</td>
<td>Shear stress</td>
<td>$kPa$</td>
</tr>
</tbody>
</table>

## Roman Symbols

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>T</td>
<td>Thrust force</td>
<td>$kN$</td>
</tr>
<tr>
<td>a</td>
<td>Adhesion</td>
<td>$kPa$</td>
</tr>
<tr>
<td>A</td>
<td>Area</td>
<td>$m^2$</td>
</tr>
<tr>
<td>B</td>
<td>Width</td>
<td>$m$</td>
</tr>
<tr>
<td>c</td>
<td>Cohesion</td>
<td>$kPa$</td>
</tr>
<tr>
<td>D</td>
<td>Diameter</td>
<td>$m$</td>
</tr>
<tr>
<td>$D_f$</td>
<td>Settlements</td>
<td>$m$</td>
</tr>
<tr>
<td>E</td>
<td>Elasticity modulus</td>
<td>$kPa$</td>
</tr>
<tr>
<td>e</td>
<td>Eccentricity</td>
<td>$m$</td>
</tr>
<tr>
<td>e</td>
<td>Void ratio</td>
<td>–</td>
</tr>
<tr>
<td>F</td>
<td>Forces</td>
<td>$N$</td>
</tr>
<tr>
<td>h</td>
<td>Penetration depth</td>
<td>$m$</td>
</tr>
<tr>
<td>i</td>
<td>Slip ratio</td>
<td>–</td>
</tr>
<tr>
<td>j</td>
<td>Shear displacement</td>
<td>$m$</td>
</tr>
<tr>
<td>k</td>
<td>Gradient of the undrained shear strength profile</td>
<td>–</td>
</tr>
<tr>
<td>L</td>
<td>Length</td>
<td>$m$</td>
</tr>
<tr>
<td>Symbol</td>
<td>Description</td>
<td>Unit</td>
</tr>
<tr>
<td>--------</td>
<td>--------------------------------------</td>
<td>--------</td>
</tr>
<tr>
<td>$N$</td>
<td>Cone factor</td>
<td></td>
</tr>
<tr>
<td>$n$</td>
<td>Porosity</td>
<td></td>
</tr>
<tr>
<td>$N_c$</td>
<td>Bearing capacity factor</td>
<td></td>
</tr>
<tr>
<td>$N_c$</td>
<td>Bearing capacity factor</td>
<td></td>
</tr>
<tr>
<td>$N_q$</td>
<td>Bearing capacity factor</td>
<td></td>
</tr>
<tr>
<td>$p$</td>
<td>Ground pressure</td>
<td>$kPa$</td>
</tr>
<tr>
<td>$p_0$</td>
<td>Vertical stress at the seafloor</td>
<td>$\frac{N}{m^2}$</td>
</tr>
<tr>
<td>$Q$</td>
<td>Resistances</td>
<td>$N$</td>
</tr>
<tr>
<td>$q_c$</td>
<td>Cone resistance</td>
<td>$MPa$</td>
</tr>
<tr>
<td>$q_d$</td>
<td>Bearing capacity of the soil</td>
<td>$kPa$</td>
</tr>
<tr>
<td>$r$</td>
<td>The adhesion to cohesion ratio (AC ratio)</td>
<td></td>
</tr>
<tr>
<td>$S_t$</td>
<td>Sensitivity</td>
<td></td>
</tr>
<tr>
<td>$s_u$</td>
<td>Undrained shear strength</td>
<td>$kPa$</td>
</tr>
<tr>
<td>$s_{u_{res}}$</td>
<td>Residual shear strength</td>
<td>$kPa$</td>
</tr>
<tr>
<td>$s_{u_r}$</td>
<td>Remoulded shear strength</td>
<td>$kPa$</td>
</tr>
<tr>
<td>$t$</td>
<td>Plate thickness</td>
<td>$m$</td>
</tr>
<tr>
<td>$V$</td>
<td>Volume</td>
<td>$m^3$</td>
</tr>
<tr>
<td>$v$</td>
<td>Speed</td>
<td>$m/s$</td>
</tr>
<tr>
<td>$V_p$</td>
<td>Total volume of the pores</td>
<td>$m^3$</td>
</tr>
<tr>
<td>$V_s$</td>
<td>Total volume of solids</td>
<td>$m^3$</td>
</tr>
<tr>
<td>$V_t$</td>
<td>Total volume of sample</td>
<td>$m^3$</td>
</tr>
<tr>
<td>$V_{ult}$</td>
<td>Ultimate vertical load on the soil</td>
<td>$N$</td>
</tr>
<tr>
<td>$W$</td>
<td>Submerged weight</td>
<td>$N$</td>
</tr>
</tbody>
</table>
Chapter 1

Introduction

1.1. Project

1.1.1. Background
The Offshore wind industry harvests energy in offshore locations, using large turbines to convert this energy to electrical power. The electricity is gathered and transported to shore via cables. These cables need to be protected from external hazards that could result in damages and thus economic losses. Generally the cables are buried in the seabed or covered with solid objects like rocks or concrete mattresses. For cable burial a trench needs to be created in the seabed, this process is called trenching.

Tideway acquired a trenching vehicle to enable provision of a wider range of cable protection solutions besides rock placement. Instead of more familiar trenching ploughs, this machine is equipped with a track drive and is self-propelling. To create trenches the vehicle has two options, mechanical cutting and jetting.

1.1.2. Problem description
Expected progress rates of the trenching vehicle are to be determined to make a more realistic assessment of the expected project durations in the pre-execution stages. This can only be done if specific knowledge regarding the interaction between seabed soils and track drive is available. Within Tideway this knowledge is only available to a limited extend.

Furthermore it is interesting to look at the most optimal setup of the vehicle for each project. Making the machine work more efficiently and decrease the trenching duration, and thus reducing operational costs.

1.1.3. Project Goal
To develop a model that describes the interaction between a track drive system and the seabed soil, present it together with the governing parameters and processes in a report. Based on the model an analytical tool qualifying and quantifying the impact of these parameters shall be developed.

1.1.4. Project Scope
The boundaries of this thesis are based on the different phases identified in the project. Different deliverables result in varying boundaries. The developed model must be fundamental, not specified for a certain vehicle, but will have certain limitations due to assumptions made. When coding an algorithm a more narrow scope is applied, since it is developed for a specific vehicle. The scope becomes even more focused during the validation process where both vehicle and cable routes are fully specified.

Research
During the research the following items are addressed:

• Required soil mechanics
• Type of track drives
• Behavior of track drives in rest state
Behavior of track drives in driving state

As described earlier the boundaries during stage may be considered wide as the research should be fundamental and generally applicable.

**Modeling**

Based on the research a fundamental model is developed, this model should be open to different applications, including slopes or sand dunes, often encountered in the seabed. The following boundaries are considered for the modeling stage of the project.

- The focus lies on the response of clayey soils
- Only vehicles equipped with a track drive without suspension are considered
- Slopes and sand dunes are taken into account
- Boulders are not taken into account

**Algorithm**

The model developed in the previous phase is to be implemented in a software algorithm. This algorithm can be used in the validation stage to run the model for several cases in a time efficient manner. The algorithm should be programmed in such a way that it furthermore can be implemented by Tideway to asses the progress rate of their trencher along predefined routes. This way the tender and engineering departments can use it to quickly assess a (potential) project. For the algorithm the following boundaries are identified.

- The software algorithm is vehicle specific
- The criteria for mobility of the vehicle is that the speed is equal to or greater than 25 m/h, upper boundaries to the mobility are given by the equipment mounted on the vehicle
- The tool is usable without licensed software

**Validation**

During this stage the scope is very specific. The vehicle is specified as the CBT1100 and the soil as encountered at the project location. The boundary identified here is:

- Validation will be done based on the project 'Westermost Rough', a project executed in 2014.

1.1.5. Outline

This report describes development and validation of the proposed model to solve the problem introduced in section 1.1.2. Based on the text presented in the main chapters the reader is introduced to different aspects of the model. To support certain parts, additional information is added in appendices.

This first section aims to introduce the problem statement, the goal of the thesis and the scope. It presents what problem should be solved, limitations of the thesis and which deliverables are expected. The following section introduces the reader to track driven vehicles. It describes the different types of track belts and the general working principle of a track drive.

For several parts of the proposed model a certain amount of knowledge regarding soil mechanics is required. To provide the reader with this knowledge, chapter 2 is included. The required terminology is explained shortly and references are given to provide the reader with extra information on each subject. Furthermore this chapter contains theories not directly linked to tracked vehicles, but they are implemented in the early stages of developing the model.

After the soil mechanics are introduced, the theory behind rigid track belts is presented in chapter 3. This chapter is divided into two main parts, the rest state being the first part followed by the steady driving state. The rest state describes the ground pressure distributions for several load cases, followed by the bearing capacity and initial settlement of the soil under the tracks. The influences of a slope are
1.2. Track driven vehicles

Vehicles driven by a track drive, examples given in figure 1.1, are also referred to as tracked vehicles or tracked equipment. In contrast to wheel drives, who generate forward thrust through a rotational motion, a track drive generates thrust via a translating motion.

In theory, two different types of track drives are identified: flexible and rigid track belts. The group considered as flexible tracks contain all the rubber track belts but also certain types of steel linked tracks. The rigid track belts are governed by steel linked tracks. The operational behavior of both types is different, so when analyzing a track drive it is important to know how to select the correct type. The main criteria to identify a track belt type, is the ratio between road wheel spacing and track link length. The analysis of both track types is described in depth in this report, chapter 3 is dedicated to the rigid track belts.

Track driven vehicles can be equipped with or without a suspension. If a suspension is applied, it could be one suspension for the entire track frame or a separate suspension for each road wheel. The presence of a suspension has an impact on the interaction between the track and the soil, to what extend depends on a significant amount of parameters. As defined in the scope this project will only take vehicles into account equipped with a track drive without suspension.

1.2.1. Components of a track drive

Before looking at the different types of tracks and their behavior, the main components and some general theory are introduced. As can be seen in figure 1.1 track drives are applied in a wide range of applications. A simple track is shown in figure 1.2, the essential components are:
1. Introduction

Figure 1.1: Examples of tracked vehicles in different applications. (Source: wikipedia.org)

Figure 1.2: The main components of a general track drive (source: tpub.com).

- A track frame
- A track belt assembly
- A sprocket
- An idler
- Road wheels
- Carrier rollers

The frame provides the track drive with structural strength, most of the other components are mounted on the frame. The track belt can differ per application but in general it consists of a chain with pads mounted on it. These pads can be made of steel or heavy-duty plastics. If grousers are applied, they are mounted on the pads of the track belt. In case of a flexible rubber track belt, the track belt assembly is one item. The design of the sprocket depends strongly on the application of the track drive. A track drive can contain one or more sprocket(s), it can be an actual gear or a custom build roller. The sprocket is connected to a drive train, providing the chain attached to the belt with motion. The main function of the idler is to create and maintain sufficient pre-tension in the track. In general the idler is a big roller, via a cylinder connected to the frame. The desired pre-tension can be set by operating the cylinder. The function of the track and carrier rollers is to support the track over the horizontal lengths between the sprocket and idler. In general a track drive contains more track rollers than carrier rollers because the track rollers have to secure the contact area between track and soil.
1.2.2. Track types

The two different types of tracks have been introduced in the previous text. The major difference between the two types is stiffness of the belt in the track assembly. Therefore the two types are called **Flexible track belts** and **Rigid track belts**, see figure 1.3.

**Flexible tracks**

Flexible tracks are mostly used on vehicles operating under relatively high speeds. Also the rubber belts that are often applied on agricultural vehicles are placed in this category. These tracks are characterized by a ratio of road wheel spacing to track link length in the range of 4 to 7.

Flexible tracks can therefore be identified by the curve of the belt in between two adjacent road wheels, see figure 1.3. The stiffness of the belt is not sufficient to keep the track straight when not supported by road wheels. As a result the seabed is not loaded with a constant normal pressure. The normal pressure is build up and peaks at the centers of the road wheels, then the pressure reduces untill the middle of the spacing and then the pressure starts building up again.

**Rigid tracks**

Mounted on vehicles operating on lower speeds are the rigid track belts. Build up by connecting steel links with pins, see figure 1.3. These tracks have a ratio of road wheel spacing to track link length of approximately 1.5, this is a first indication of the behavior of rigid tracks. The track link length approaches the length of the spacing between the road wheels, therefore the track does not curve between the wheels. As a result the normal pressure on the soil does not show high peaks, it is almost a constant load. The response of the soil to repetitive loading has no influence.

**Flat track belts**

Besides a categorization based on belt stiffness, a distinction can be made on the manner the belt is equipped. The track drives presented in figure 1.3 and the top sketch of figure 1.4, are considered flat track belts. In general the consist of a chain mounted with plastic pads or steel strips.
Belts equipped with grousers
In some soils a track drive may generate extra traction by mounting so called ‘grousers’ on the track belt, see the bottom sketch in figure 1.4. More on grousers in appendix A.

1.2.3. General operating principles
A track drive generates thrust via a translational motion. The submerged self-weight of the vehicle creates a normal pressure on the soil, if the track belt starts moving a shear plane is created. Due to the moving belt soil particles experience a force to start moving as well. The soil will resist to this shearing movement, and thus the thrust force is generated. The principle is very similar to a friction force calculation. More on how different types of track belts build up thrust in later chapters.

![Figure 1.5: The simplified working principle of a track. (Source: Wong [24])](image)

1.3. Summary
In the first section if this first chapter the project is introduced. Problem statement describes why the project is needed, project goal quantifies the desired results of the project. The boundaries and other limitations of the project are listed in the subsection describing the scope.

In the second part of this chapter track driven vehicles are introduced for the first time. Based on examples it is shown that there is wide variety in applications of track drives. Two types of track belts are identifiable, rigid and flexible track belts. Even though the main components of each drive are similar, the track belts are different. This difference can be found in looks and sometimes materials, but the most important difference is the soil response to each type. The difference in soil response aside, the working principle for all tracks comes down to creating friction planes. Due to the sticky effect in either the soil/soil interface or the soil/steel (soil/rubber) interface, a force is generated when a track belt is moved through soil.

An introduction to a selection of basic soil mechanics is given in the next chapter. An understanding of this theory is required to increase the reader’s comprehension of the theory and models that follow in chapters 3 and 4.
Chapter 2
Soil mechanics

In the previous chapter an introduction was given into track driven vehicles and their characteristics. When looking into the behavior of such systems in a certain soil, there are two distinguishable main areas of interest. First, the soil trafficability, independent of the type of vehicle and governed by soil properties. Secondly the mobility of a tracked vehicle, governed vehicle specifications and less dependent on the soil type.

This chapter summarizes basic soil mechanics knowledge needed to fully grasp the theories and concepts presented in chapters 3 and 4. Furthermore theories regarding the bearing capacity and penetration resistance of soil under a skirted foundation are introduced. These theories are applied in chapter 4.

2.1. Basics

Soil is defined as an assembly of solid particles which may or may not contain organic matter, the voids between the particles being occupied by water or air. The range of particle sizes encountered in different soils is very wide: from 200mm to less than 0.0001mm.

Classification of soils is based on certain fundamental properties and provides a framework for their systematic description. Most engineering classifications of soils are based on the particle size distribution, since it is measurable and has an important influence on soil behavior. As individual groups boulders, cobbles, gravel, sands, silts and clays are distinguished, their particle size ranges are shown in table 2.1. This thesis will focus mainly on the soils with the finer particle sizes as Sand, Silt and Clay. As presented in section 1.1.4 boulders are excluded from the project scope.

<table>
<thead>
<tr>
<th>Soil type</th>
<th>min. grain size</th>
<th>max. grain size</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clay</td>
<td>0.002mm</td>
<td></td>
</tr>
<tr>
<td>Silt</td>
<td>0.002mm</td>
<td>0.063mm</td>
</tr>
<tr>
<td>Sand</td>
<td>0.063mm</td>
<td>2mm</td>
</tr>
<tr>
<td>Gravel</td>
<td>2mm</td>
<td>63mm</td>
</tr>
<tr>
<td>Cobble</td>
<td>63mm</td>
<td>256mm</td>
</tr>
<tr>
<td>Boulder</td>
<td>&gt; 256mm</td>
<td></td>
</tr>
</tbody>
</table>

Clay may be sorted into classes based on the undrained shear strength.

Unit / Volumetric weight, \( \gamma \): The weight of a specific volume of soil, Verruijt [23] formulated it as equation 2.1. During this thesis the unit weight will be used in several of the sub-models described in chapter 4.
Table 2.2: The classification of clays. (Source: Terzaghi and Peck [21])

<table>
<thead>
<tr>
<th>Class</th>
<th>$s_u$ [kPa]</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Very soft</td>
<td>&lt; 20</td>
<td></td>
</tr>
<tr>
<td>Soft</td>
<td>20 – 40</td>
<td>Easily remolded</td>
</tr>
<tr>
<td>Firm</td>
<td>40 – 75</td>
<td>Remoldable by hand</td>
</tr>
<tr>
<td>Stiff</td>
<td>75 – 150</td>
<td>Cannot be remolded by hand</td>
</tr>
<tr>
<td>Very stiff</td>
<td>150 – 300</td>
<td>Brittle</td>
</tr>
<tr>
<td>Hard</td>
<td>&gt; 300</td>
<td></td>
</tr>
</tbody>
</table>

\[ \gamma = \frac{W}{V} \]  

(2.1)

Where:
- $\gamma$ = Unit weight of the soil [$\text{t/m}^3$]
- $W$ = Submerged weight of the soil [N]
- $V$ = Specified volume [$\text{m}^3$]

Typical unit weight range for saturated clay range from $16 – 22 \text{kN/m}^3$ and for saturated sand from $18 – 20 \text{kN/m}^3$.

**Porosity, $n$:** Soil property that is defined as the ratio of the pore volume to the total volume of the soil:

\[ n = \frac{V_p}{V_t} \]  

(2.2)

Where:
- $n$ = Porosity of the soil [- or %]
- $V_p$ = Pore volume [$\text{m}^3$]
- $V_t$ = Total volume of the soil sample [$\text{m}^3$]

Usually expressed as a percentage, for most soils between 30% and 45%. A small porosity means that the soil is densely packed, a loosely packed soil has a large porosity. (Verruijt [23])

**Void ratio, $e$:** Soil property defined as the ratio of the pore volume to the volume of solids. The void ratio is of significant influence on several phenomena described below. Verruijt [23] formulated is as:

\[ e = \frac{V_p}{V_s} \]  

(2.3)

Where:
- $e$ = Void ratio of the soil [-]
- $V_s$ = Total volume of the solids [$\text{m}^3$]

**Permeability, $\kappa$:** The permeability refers to the ability of a soil to permit fluids to flow through it. Measured in $\text{m/s}$ or $\text{m/day}$ and typical values are $10^{-6} \text{m/day}$ for clay to $10^3 \text{m/day}$ for gravel. During this thesis the permeability is an input value of the cutting model (see chapter 4).

**Cohesion, $c$:** Cohesion refers to the tendency of soil particles to stick together, due to this effect the particles resist to shear loading. The Cohesion is a governing parameter in the cutting and traction models for clayey soils.

**Adhesion, $a$:** In clayey soils the tendency of two different materials (steel/soil or rubber/soil) to stick together is called the adhesion. Inter-molecular forces create an attraction between two materials, making them resist to a shearing motion in the contact surface. Generally the adhesion value of a soil
is lower than the cohesion. The Adhesion is a governing parameter in the cutting and traction models for clayey soils.

**AC ratio, r:** The ratio of the adhesion to the cohesion. Defined as (Miedema [14]):

\[
r = \frac{a}{c}
\]  
(2.4)

Where:

- \( r \) = The AC ratio [-]
- \( a \) = Adhesion value of the interface between soil and the other material [kPa]
- \( c \) = Cohesion value of the soil [kPa]

The AC ratio typically ranges from zero, meaning no adhesion, up till 2. The cutting model uses the AC ratio to define certain parameters.

**Internal friction angle, \( \phi \):** A measure of the ability of a soil to withstand a shear stress. It is the angle measured between the normal force and resultant force that is attained when failure just occurs due to a shearing stress. The internal friction angle can be obtained via the Mohr circle, see figure 2.1. (Allaby [1])

In sands this angle is always present, typically ranging from 20° to 40°. For softer clays this angle is zero. Though for stiffer clays the internal friction angle may build up to a maximum of 20°. It can be considered a governing parameter in the cutting and traction models for sands and stiff clays.

**External friction angle, \( \delta \):** The friction between a soil (mainly sandy soils) and a different material such as steel of a pile or the rubber of a flexible track belt. Different theories and methods to determine the external friction of a soil where derived over to years. Some propose actual values for certain soil/material combinations, others give the external friction as a function of the internal friction. (Terzaghi and Peck [21])

**Bearing capacity, \( q_d \):** The maximum normal load (ground pressure) on a soil before failure occurs. Terzaghi and Peck [21] proved that the bearing capacity in clay may be approximated by:

\[
q_d = N_c \cdot c
\]  
(2.5)

Where:

- \( q_d \) = The bearing capacity [kPa]
- \( N_c \) = Bearing capacity factor [-]

**Consolidation:** Consolidation refers to the slow reduction in volume and an increased density of saturated soil under a load. Rate of consolidation is highly time dependent because it is governed by the rate of pore water flow. Permeability of the soil thus has a significant impact on the consolidation rate of the soil (Allaby [1]). Consolidation is used in the settlement model to be found in chapter 4.

**(un)Drained loading:** When a soil is sheared, potentially the void ratio may change. Water must flow into the soil sample when the void ratio increases. Water must flow out of the sample if the ratio decreases. This process is called drained loading and occurs in highly permeable soils like sands.

If less permeable soils, like clay, are loaded with a high shearing rate, the pore water cannot flow out the soil sample. Since the void ratio does decrease, the pore water pressure increases. This phenomenon is called undrained loading and has a significant impact on the soil strength.

**(Undrained) Shear strength, \( s_u \):** The shear resistance a soil can offer under certain drainage conditions and normal pressure. Defined by Terzaghi and Peck [21] as:

\[
s_u = c \cdot p \cdot \tan(\phi)
\]  
(2.6)

Where:
\[ s_u = \text{Undrained shear strength} \ [kPa] \]
\[ c = \text{Cohesion value of the soil} \ [kPa] \]
\[ P = \text{Ground pressure} \ [kPa] \]
\[ \phi = \text{Internal friction angle of the soil} \ [^\circ] \]

Since in sands the cohesion is assumed zero and in most clays the internal friction angle is assumed to be zero (\( \phi = 0 \) theory, see figure 2.1), the shear stress is governed by different parameters for both soil types (Terzaghi and Peck [21]). As mentioned in clays it equals the cohesion and thus may be considered a governing parameter.

![Figure 2.1: The \( \phi = 0 \) theory, resulting in \( \tau = c \) for clay. (Source: Terzaghi and Peck [21])](image)

**Remolded shear strength, \( s_{ur} \):** The shear strength of a soil peaks, see figure 2.2, at a value defined by equation 2.6. If the soil is shearing continues the shear strength decreases rapidly until the residual shear strength is reached. The process of shearing the soil from maximum shear strength to residual is called remolding the soil. The shear strength during this phase is called the remolded shear strength.

**Residual shear strength, \( s_{ures} \):** The residual shear strength refers to the amount of shear strength after the soil is fully remolded by the shear displacement, see figure 2.2. It can be considered a governing parameter in the traction model, see chapter 4.

**Sensitivity, \( S_l \):** Measure for the decrease in shear strength due to remolding. Defined as the ratio of the undrained shear strength to residual shear strength, see figure 2.2. (Allaby [1])

\[ S_l = \frac{s_u}{s_{ures}} \]

Where:
\[ S_l = \text{The sensitivity of the soil} [-] \]
\[ s_u = \text{Undrained shear strength of the soil} \ [kPa] \]
\[ s_{ures} = \text{Residual shear strength of the soil} \ [kPa] \]
Strain: The deformation of the soil as a result of the applied shear stress. Strain is defined as the ratio of the altered length to the original length.

Stress - strain: The amount of shear stress resistance the soil can generate at a certain point is a function of the shear strain at that point. The shape of this relation is soil specific, but three general shapes are identified, see table 2.3.
Table 2.3: The three main types of shear curves for soils.

<table>
<thead>
<tr>
<th>Description</th>
<th>Curve</th>
<th>Function</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Exponential form</strong></td>
<td><img src="image1" alt="Exponential Curve" /></td>
<td>$\frac{s}{s_{\text{max}}} = 1 - e^{(-\frac{s}{L})}$</td>
</tr>
<tr>
<td><strong>Peak followed by continuous descent</strong></td>
<td><img src="image2" alt="Peak Continuous Descent Curve" /></td>
<td>$\frac{s}{s_{\text{max,k}}} = \left(\frac{f}{K_W}\right) \cdot e^{1 - \frac{f}{K_W}}$</td>
</tr>
<tr>
<td><strong>Peak followed by decent to residual</strong></td>
<td><img src="image3" alt="Peak Decent Residual Curve" /></td>
<td>See below</td>
</tr>
</tbody>
</table>

First there are the soils that have an exponential function. Here the developed shear stress increases with the shear strain and approaches a limit, the function for this curve was developed by Janosi and Hanamoto [12].

Secondly there are soils for which the shear curve peaks in a maximum, after which the shear stress decreases continuously with increasing shear strain. Wong and Preston-Thomas [26] derived the function presented for this curve.

Finally there is a group of soils where the curve peaks in a maximum, after which the shear stress decreases to a constant value of residual shear stress. For this type no final function is established as of yet. Several people proposed functions, below the four most promising are presented. None of these functions are fundamental, all four contain empirical and/or fitting parameters.

- $\tau = \frac{c + p \cdot \tan(\phi)}{\max(f_{Be})} \cdot \frac{e^{\left(-K_2 \cdot \sqrt{K_2^2 - 1} \cdot K_1 \cdot x_B\right)}}{f_{Be}} - e^{\left(-K_2 \cdot \sqrt{K_2^2 - 1} \cdot K_1 \cdot x_B\right)}$ (Bekker [2])

- $\tau = \frac{c \cdot \frac{x_B}{f_B} \cdot e^{1 - \frac{x_B}{f_B}} + p \cdot \tan(\phi) \cdot (1 - e^{\frac{-x_B}{f_B}})}{1 + \left(\frac{1}{(K_r(1 - \frac{1}{\beta}))} - 1\right) \cdot e^{1 - \frac{x_B}{f_{Be}}}}$ (Sela [20])

- $\tau = \tau_{\text{max}} \cdot K_r \cdot \left(1 + \left(\frac{1}{(K_r(1 - \frac{1}{\beta}))} - 1\right) \cdot e^{1 - \frac{x_B}{f_{Be}}}\right)$ (Wong [24])

- $\tau = \left(\tau_R + C_E \cdot e^{-k \cdot x_B} \cdot \frac{1 - e^{-10 \cdot A \cdot x_B}}{1 + A e^{-10 \cdot A \cdot x_B}}\right)$ (Schulte et al. [19])
2.2. Skirted foundations

A skirted foundation is a construction resting on the seabed with vertical bodies attached to it, these bodies penetrate the seabed. An example is given in figure 2.3.

2.2.1. Bearing capacity

The classical recommended approach for predicting undrained bearing capacity of the seabed below a shallow foundation is formulated by Randolph and Gourvenec [17] as:

\[ V_{UI} = A' \left( s_{u0}(N_c + k \cdot B') \cdot F \cdot K_c + p'_0 \right) \]  

(2.8)

Where:
\( V_{UI} \) = Ultimate vertical load on the soil \([N]\)
\( A' \) = effective area of the foundation \([m^2]\)
\( s_{u0} \) = Undrained shear strength at foundation level \([kPa]\)
\( N_c \) = Bearing capacity factor (cohesion) as defined in Terzaghi and Peck [21] 
\( k \) = Gradient of the undrained shear strength profile, equal to zero for homogeneous soils 
\( B' \) = Effective foundation width \([m]\)
\( F \) = Bearing capacity modification factor for soil strength heterogeneity, as defined by Davis and Booker [7] & Randolph and Gourvenec [17] 
\( K_c \) = Modification factor for load orientation, foundation shape and embedment (cohesion) as defined by Randolph and Gourvenec [17] 
\( p'_0 \) = Effective vertical stress at foundation level as defined by Verruijt [23] \([kPa]\)

2.2.2. Penetration resistance

In offshore shallow foundation theory a formula is presented for resistance induced by seabed soil when penetrated by a skirted foundation. A skirted foundation is a flat rectangular or circular horizontal foundation, the ends are mounted with vertical plates, see figure 2.3.

These plates penetrate the seabed when the foundation is installed. Part of the penetration is realized by the self-weight of the foundation, the remainder is realized by creating an under pressure in the space in between the foundation and the seabed.

Figure 2.3 also shows the self-weight sinkage of suction caisson during the installation process. The forces generated by the fact that the seabed resists to being penetrated, are given in the right sketch.

The total resistance is the sum of the tip resistance and the sleeve resistance, \( Q = Q_{tip} + Q_s \). Tip and sleeve resistance are formulated in equations 2.9 and 2.10 (Housby and Byrne [10] & Randolph and Gourvenec [17]).

\[ Q_s = \frac{h \cdot a_q \cdot s_{u1} \cdot (\pi \cdot D_0^2)}{\text{resistance on the outside}} + \frac{h \cdot a_q \cdot s_{u1} \cdot (\pi \cdot D_1^2)}{\text{resistance on the inside}} \]  

(2.9)

\[ Q_{tip} = \left( y' \cdot h \cdot N_q + s_{u2} \cdot N_c \right) \cdot \left( \frac{\pi}{4} \cdot (D_0^2 - D_1^2) \right) \]  

(2.10)

CPT interpretation:

To work with the model presented in chapter 4 knowledge on how to interpret cone penetration tests (CPT) is essential. In appendix C several CPT results are included. Based on these plots the cohesion value of a soil is determined via the following formula:

\[ c = \frac{q_c}{N} \]  

(2.7)

Where:
\( q_c \) = Cone resistance measured during the test \([kPa]\)
\( N \) = Cone factor depending on the stress-strain properties of the soil, ranging from 15 to 20
Figure 2.3: Forces acting on a skirted foundation during installation. (Source: Randolph and Gourvenec [17])

Where:

- \( h \) = Penetration depth \([\text{m}]\)
- \( a_o \) = Outer adhesion factor \([\text{kPa}]\)
- \( D_i \) = Inner diameter \([\text{m}]\)
- \( \gamma' \) = Effective unit weight of the soil \([\text{t/m}^3]\)
- \( s_{u1} \) = average shear strength over the penetration depth \([\text{kPa}]\)
- \( s_{u2} \) = Shear strength at lowest point of the structure \([\text{kPa}]\)
- \( D_o \) = Outer diameter \([\text{m}]\)
- \( N_q \) = Bearing capacity factor (overburden) \([-\text{]}\)
- \( a_i \) = Inner adhesion factor \([\text{kPa}]\)
- \( N_c \) = Bearing capacity factor (cohesion) \([-\text{]}\)
- \( Q \) = Penetration Resistance \([\text{N}]\)

At the point of final penetration due to self-weight, there should be a force equilibrium between the submerged self-weight and the penetration resistance of the seabed (equation 2.11).

\[
Q = W' \tag{2.11}
\]

Where:

\( W' \) = Submerged self-weight of the foundation \([\text{N}]\)

Substitution of equations 2.9 and 2.10 in equation 2.11 results in:

\[
W' = h \cdot a_o \cdot s_{u1} \cdot (\pi \cdot D_o) + h \cdot a_i \cdot s_{u1} \cdot (\pi \cdot D_i) + \left( \gamma' \cdot h \cdot N_q + s_{u2} \cdot N_c \right) \cdot \left( \frac{\pi}{4} \cdot (D_o^2 - D_i^2) \right) \tag{2.12}
\]

2.3. Summary

This chapter starts with an introduction into a selection of basic soil mechanics. An understanding of these presented concepts is a requirement to fully understand the theories introduced in later chapters. The first section starts out with a soil classification, where soil is categorized based on grain size. Furthermore a clay specific classification is presented. Based on shear strength ranges clay is categorized from 'very soft' to 'hard'.

\[ h \]
\[ a_o \]
\[ D_i \]
\[ \gamma' \]
\[ s_{u1} \]
\[ s_{u2} \]
\[ D_o \]
\[ N_q \]
\[ a_i \]
\[ N_c \]
\[ Q \]
\[ W' \]
\[ h \]
\[ a_o \]
\[ D_i \]
\[ \gamma' \]
\[ s_{u1} \]
\[ s_{u2} \]
\[ D_o \]
\[ N_q \]
\[ a_i \]
\[ N_c \]
\[ Q \]
\[ W' \]
2.3 Summary

This is followed by some fundamental concepts like unit weight, void ratio and permeability. These are needed to understand the workings of the drained and the undrained loading principles. These are followed by a list of concepts regarding the shearing behavior of soils (clay or sand).

In the second section skirted foundations are introduced. Formulas regarding the bearing capacity and penetration resistance of soil in combination with a skirted foundation are given. These functions will be used when evaluating the penetration depth of grousers.

In the next chapter the theory behind the rest state and the steady driving state of rigid track driven vehicles is presented. This theory will be applied in chapter 4, where the proposed model is introduced.
In chapter 1 an introduction was given regarding tracked vehicles and a distinction was made between two types of track belts. That was followed by a chapter introducing the required basics of soil mechanics to be able to understand the concepts described in this and the following chapters.

The subject of this chapter is one of track belt types identified in chapter 1, the drives using rigid track belts. Even though there are enough similarities between the two types, some important principles differ for both types.

This chapter is divided into two main sections. In section 3.1 the focus lies on the rest state of the vehicle. Topics as ground pressure distribution, bearing capacity, initial settlements and influences of a slope are discussed. In the second section the steady driving state is analyzed, included are topics like slip, dynamic settlement, the amount of thrust generated, acting resistances and the possible influence of slopes. States of acceleration and deceleration are not in the scope of this thesis. Based on the time frame for this thesis it would be unrealistic to include these effects.

3.1. Rest state

As the name indicates this state is governing when the vehicle is at rest. It is entered primarily when the vehicle is lowered from the vessel onto the sea bottom. Ground pressure, bearing capacity and sinkage become important factors. When the sea bottom has a sloping contour, this should also be taken into account.

The rest state of the vehicle is calculated since these parameters influence the amount of thrust the track drive can generate, and also affect final traction model.

3.1.1. Ground pressure distribution for centric loading

The ground pressure distribution is a function of the distance X from the start point of the contact area. It is strongly influenced by the weight distribution of the vehicle. A center of gravity (COG) that aligns with the middle of the contact area, results in an equally divided weight over the contact area. An increasing distance between the COG and the middle of the contact area, results in an increasingly eccentric ground pressure distribution.

Since these track belts act rigid, their behavior in rest state is similar to that of a strip footing. For a rectangular strip footing on a horizontal seabed, the ground pressure can be determined by:

\[
P = \frac{F}{A_{strip}} = \frac{F}{B_{strip} \times L_{strip}}
\]

(3.1)

Where:

- \( P \) = Ground pressure [Pa]
- \( F \) = Load on the strip footing [N]
- \( A \) = Contact area of the track belt \([m^2]\)
- \( B \) = Effective width of the strip footing \([m]\)
- \( L \) = Effective length of the strip footing \([m]\)

For a flat track belt equation 3.1 may be applied directly. For a track belt with grousers applied this phase is preceded by an initial phase where the grousers penetrate the soil. If this succeeds depends
on the soil, dimensions of the grousers and the weight of the vehicle. In any case before the entire belt is in contact with the soil, relatively high contact pressures may occur locally. This pressure can be determined by substituting the surface in equation 3.1 by the contact surface of a grouser times the amount of grousers in contact with the soil:

\[ P = \frac{F}{\sum A_{\text{grousers}}} = \frac{F}{n \times B_{\text{grouser}} \times t_{\text{grouser}}} \]  

(3.2)

Where:

- \( n \) = Amount of grousers in contact with the soil [-]
- \( t \) = Plate thickness of a grouser [m]

The actual ground pressure distribution thus depends on the presence of grousers. For a flat track belt under centric loading the distribution is horizontal line. When grousers are applied, two phases are identified as described earlier. Figure 3.1 below sketches the flat track belt on the left, on the right both phases of a track belt with grousers are shown.

![Figure 3.1: Ground pressure distributions due to a centric loading (the COG is in the middle of the contact area).](image)

### 3.1.2. Ground pressure distribution for eccentric loading

It is rarely the case that the COG location of a vehicle aligns with the center of the contact area, see figure 3.2, or the original COG location is shifted due to a slope (more on slopes in section 3.1.5). As a result the load is not equally divided of the contact area. The ground pressure distribution as a function of \( X \) will not be a horizontal line.

In an eccentric loading situation equation 3.1 can only be used to get a first indication of the amount of ground pressure. The actual pressure distribution is modeled as a linearly increasing line. The minimum and maximum are at both ends of the strip, see figure 3.2.
Budhu [5] shows that the maximum and minimum pressures can be found through:

\[
P_{\text{max}} = \frac{F}{A} \cdot (1 + \frac{6 \cdot e}{B})
\]

(3.3)

\[
P_{\text{min}} = \frac{F}{A} \cdot (1 - \frac{6 \cdot e}{B})
\]

(3.4)

Where:
- \( P_{\text{max}} \) = Maximum ground pressure [Pa]
- \( P_{\text{min}} \) = Minimum ground pressure [Pa]
- \( F \) = Vertical load [N]
- \( e \) = Eccentricity of the loading [m]
- \( A \) = Contact surface \([m^2]\)
- \( B \) = Width of the strip or track belt [m]

Assuming the ground pressure increases linearly due to the strip, the pressure distribution as a function of \( x \) can be found. Note that it is assumed the load is still centric in the third direction. The reason for this assumption is of an operational nature and is explained in more detail in section 3.1.5.

3.1.3. Bearing capacity soil

As mentioned in the previous section, rigid track belts can be modeled like a shallow strip footing. Several bearing capacity equations have been proposed over the years. Early on Prandtl and Terzaghi developed theories which were used as a base for more recent equations. Terzaghi and Peck [21] proved that the bearing capacity can be found through:

\[
q_d = N_c \cdot c + \gamma \cdot D_f \cdot N_q
\]

(3.5)

Where:
- \( q_d \) = Bearing capacity of the soil [Pa]
- \( N_c \) = Bearing capacity factor [-]
- \( c \) = Cohesion of the soil [Pa]
- \( \gamma \) = Weight of the soil \([N/m^3]\]
- \( D_f \) = Settlement of the foundation [m]
- \( N_q \) = Bearing capacity factor [-]

If \( \phi = 0 \), Terzaghi and Peck derived that the bearing capacity factors, \( N_c \) and \( N_q \), become 5.14 and 1.0 respectively. To be more conservative, in practice the term \( \gamma \cdot D_f \) is neglected. Therefore equation 3.5 can be simplified to:

\[
q_d = N_c \cdot c = 5.14 \cdot c
\]

(3.6)

3.1.4. Initial settlement

The ground pressure distribution due to the submerged self-weight may result in a settlement of the soil beneath the tracks. By substituting \( F = q_d \) into equation 3.6, the threshold cohesion value can be
found where for a certain vehicle settlement will occur. So initial settlement will occur when equation 
3.7 holds.

\[ c \leq \frac{F}{5.14} \]  

(3.7)

### 3.1.5. Influence of a slope

If the vehicle is deployed on a sloped seabed, the situation is different from all described earlier. Due to 
angle of the slope the ground pressure decreases, the weight is now divided into two parts. Only the 
part normal to the slope creates a ground pressure. Since the normal force is smaller than the total 
weight, see figure 3.3, the presence of a slope results in a lower ground pressure.

Though there is another consequence of resting on a slope. Due to the slope the location of the 
COG is no longer above the center of the contact area. But the gravity force does still work vertically, 
see figure 3.3. For this reason, the ground pressure distribution along the track belt is of similar shape 
to the eccentric loaded situation presented in section 3.1.2.

![Figure 3.3: Ground pressure distributions due to deployment on a sloped seabed.](image)

### 3.2. Driving state

One of the most important forces acting on the vehicle is the thrust force generated by the tracks. Due 
to this force the vehicle is able to move forward. Though this is not the only force acting on the vehicle. 
Several other forces act in the opposite direction and act as resistances. Furthermore slip has to be 
taken into account to fully predict the actual traction of the vehicle.

#### 3.2.1. Slip

When a track driven vehicle is moving over a surface, two velocities can be identified. First there is the 
speed over ground of the vehicle, the absolute distance that is covered over a certain amount of time. 
Secondly there is the circumferential speed of the track belt, based on the rotational speed of the motor 
driving the track belt. Both are shown in figure 3.4. Based on these two velocities, Muro and O’Brien [16] 
derived that the slip ratio can be determined through:

\[ i = 1 - \frac{V}{V^r} \]
Which can be rewritten to:

\[
  i = 1 - \frac{V}{V'} = \frac{V'}{V} - \frac{V}{V'} = \frac{V'}{V} - \frac{V}{V'} = \frac{V'}{V} - \frac{V}{V'} = \frac{V}{V'} - V
\]

(3.8)

Where:

- \( i \) = Slip ratio [–]
- \( V \) = The vehicle’s speed over ground \([\text{m/s}]\)
- \( V' \) = The circumferential speed of the track belt \([\text{m/s}]\)

The difference between the circumferential speed of the track belt and the actual speed over ground of the vehicle, is called the slip velocity. This is the amount of forward velocity ‘lost’ to the phenomenon of slip.

![Diagram of driving state](image)

**Figure 3.4:** The different velocities, in blue the shear displacement when \( P \) moved from \( P_0 \) to \( P_1 \) over \( \Delta t \) and below that the overall shear displacement distribution.

### Amount of slippage

As the name suggests, the amount of slippage is directly linked to the slip ratio. The amount of slippage is also referred to as the shear displacement or in more general terms the shear strain. Muro and O’Brien [16] defined the shear displacement as the distance the soil at a random point \( P \) under the track belt is displaced by the track belt, see also figure 3.4. Since the slip velocity is known, the shear displacement can be calculated by taking the integral over time of the slip velocity:

\[
j(X) = \int_{t_0}^{t_1} V_s(X) \, dt = \int_{t_0}^{t_1} (V' - V) \, dt
\]

(3.9)

Here the capital letter \( X \) indicates a distance along the contact area, starting at the front end of this area. It is indicated in green in figure 3.4. This distance does not equal the small letter \( x \), which is related to the general coordinate system of the vehicle. The integral in equation 3.9 can be solved when exact boundaries for \( t \) are identified. The first boundary is defined as \( t_0 = 0 \). For the second boundary it is required to find an expression for the time when \( P \) is at the requested point. The time needed for \( P \) to reach the point is defined as \( t_1 = \frac{x}{V'} \). Substituting this in equation 3.9 results in:

\[
j(X) = \int_{0}^{\frac{x}{V'}} (V' - V) \, dt = (V' - V) \cdot \frac{X}{V'} = \frac{V' - V}{V} \cdot X = i \cdot X
\]

(3.10)

Where:
3.2.2. Dynamic settlement

In section 3.1.4 it was shown that the initial settlement of a subsea tracked vehicle in most soils can be considered zero. Experience learns that ruts are created when moved over the seabed for its full length. It can be concluded that this settlement thus must be the result of the vehicle driving over the soil, this is referred to as the dynamic settlement.

Flat track belts

A fundamental function for dynamic settlement is yet to be determined, in this thesis the amount of settlement is approximated using an assumption used before here. Knowing that the soil responds to a rigid track as it would to a strip foundation, the theory for the settlement of these foundations is used to determine the final settlement of the soil beneath a track. Budhu [5] shows that the amount of settlement is determined through:

$$\zeta = \frac{F}{E_u \cdot 0.5 \cdot L} \cdot (1 - \nu_u^2) \cdot \mu_s \cdot \mu_{emb} \cdot \mu_{wall}$$

(3.11)

Where:
- \( \zeta \) = initial settlement [m]
- \( F \) = Total vertical load [N]
- \( E_u \) = Undr. elasticity modulus [Pa]
- \( L \) = Foundation length [m]
- \( \nu_u \) = Poisson’s ratio (undr.) [-]
- \( \mu_s \) = shape factor [-]
- \( \mu_{emb} \) = embedment factor [-]
- \( \mu_{wall} \) = side wall factor [-]

Flat track belts equipped with grousers

If a track belt is equipped with grousers, the initial contact area is smaller and thus the ground pressure higher. The local initial settlement directly under the grousers must be determined.

A second phase is identified when the grousers fully penetrated the seabed and the contact area increases to the area of the belt. The process where the grousers penetrate the soil is similar to the self-weight penetration of the seabed by skirted suction foundations. The amount of self-weight penetration by a round skirted foundation can be found through the function of total soil resistance defined by Randolph and Gourvenec [17]:

$$Q = Q_{tip} + Q_{sleeve} = \left( y' \cdot D_f \cdot N_q + s_u \cdot N_c \right) \cdot A_{tip} + D_f \cdot \alpha \cdot s_u \cdot A_{outside} + D_f \cdot \alpha \cdot s_u \cdot A_{inside}$$

(3.12)

Where:
- \( D_f \) = Grouser penetration depth [m]
- \( \alpha \) = Adhesion [Pa]
- \( y' \) = Effective unit weight of the soil \([\text{N/m}^3]\)
- \( N_q \) = Bearing capacity factor [-]
- \( N_c \) = Bearing capacity factor [-]
- \( s_u \) = Undrained shear strength [Pa]
- \( A_i \) = Surface \([m^2]\)
- \( Q \) = Penetration Resistance [N]

The soil is penetrated by the skirts if the ground pressure, \( q_d \), due to the self-weight of the foundation, is larger than the penetration resistance, \( Q \). Equation 3.12 can be rewritten in such a way that it can be applied to a track belt equipped with grousers. The surfaces considered are the top, front, back and side surfaces of a grouser plate. The term \( y' \cdot D_f \) is considered to be zero, as described in section 3.1.3. The self-weight penetration \( (D_f) \) is at a maximum when the penetration resistance equals the ground pressure \( (Q = q_d) \). Substituting this, equation 3.12 may be written as:
3.2 Driving state

\[
q_d = \left( \frac{c \cdot N_e}{A_{top}} \right) + D_f \cdot a \cdot c \cdot n \cdot \sum A_{sides} 
\]  

(3.13)

The penetration depth of the grousers can be found by solving equation 3.13 for \( D_f \). The grousers fully penetrate the seabed when this value is larger than the grouser height. In this situation the entire area of the track belt will make contact with the soil, after the grousers reach full penetration depth. The ground pressure will decrease significantly and further settlement is determined through equation 3.7 as for flat track belts.

3.2.3. Thrust force

As mentioned in the introduction of this section, is the thrust the force that provides the vehicle with a forward motion. The principle of thrust generation depends on how the track drive is equipped. Both principles are based on the creation of a friction plane(s), they will be discussed in more detail below. The major difference between both principles is that one activates the cohesion/internal friction of the soil, where the other activates the adhesion/external friction of the soil.

Flat track belts

As showed below in equation 3.14, the thrust force is heavily dependent on the shear stress - shear displacement function of the particular soil. This function can take several shapes, as described in chapter 2. Due to this in certain soils remolding also influences the thrust generated by a track belt. As the shear displacement increases, the available shear resistance can increase or decrease. For highly sensitive soils this results in a significant fluctuation in the generated thrust force by a point moving along the contact length.

A flat track belt generates thrust by creating a friction plane at the interface between the track belt and the soil. The total thrust force developed along the main parts of a track belt is derived by Muro and O’Brien [16]. As the shear stress - shear displacement function defines the available shear stress over the length of the contact area, the thrust force is then determined by integrating this function over the contact length and multiplying it with the contact width (Muro and O’Brien [16]):

\[
T_1(j) = 2 \cdot B \cdot \int_0^{L_{track}} \tau(j) \, dX 
\]

(3.14)

Where:

- \( T_1(j) \) = The thrust force developed along the length of the track \([N]\)
- \( \tau(j) \) = The available shear resistance along the length of the track (shear stress - shear displacement relation) \([Pa]\)

Since the friction plane is located at the interface between track belt and soil, the available shear resistance is dependent shear stress - shear displacement relation as introduced in chapter 2. The maximum shear resistance is found via equation 3.15 (Terzaghi and Peck [21]).

\[
\tau = a + P \cdot \tan(\delta)
\]

(3.15)

Where:

- \( a \) = Adhesion \([Pa]\)
- \( P \) = Ground pressure distribution \([Pa]\)
- \( \delta \) = External friction angle \([deg]\)

Track belts equipped with grousers

A rigid track belt equipped with grousers develops thrust slightly different. When the grousers have penetrated the soil and start loading it with a shear load, the friction plane is no longer located at the interface between belt and soil. Due to the presence of the grouser a soil column directly below the
belt is mobilized and friction planes are created. In these friction planes there is moving soil sliding over soil at rest, and thus activating the cohesion forces. The resulting thrust force generated by the bottom of the soil column is calculated by equation 3.14 but the maximum available shear resistance is (Terzaghi and Peck [21]):

\[ \tau = c + P \cdot \tan(\phi) \]  

(3.16)

Where:
- \( c \) = Cohesion value [Pa]
- \( \phi \) = Internal friction angle [deg]

Muro and O’Brien derived that the thrust generated by the sides of the moving soil column is defined as:

\[ T_2(j) = 2 \cdot 2 \cdot G_{\text{length}} \cdot \int_0^{L_{\text{track}}} \tau'_e \, dX \]  

(3.17)

Where:
- \( T_2(j) \) = Thrust force generated by the sides of the mobilized soil column [N]
- \( D_f \) = Grouser penetration depth, if grousers fully penetrate it equals grouser height [m]
- \( \tau'_e(j) \) = Shear resistance acting on the sides of the belt or mobilized soil column, as defined in Muro and O’Brien [16] and used with the cohesion value [Pa]

Lastly Muro and O’Brien derived that the thrust generated by the sides of the grousers is defined as:

\[ T_3(j) = 2 \cdot n \cdot D_f \cdot B_g \cdot \sum \tau'_a(j) \]  

(3.18)

Where:
- \( T_3(j) \) = Thrust force generated by the sides of the grousers [N]
- \( n \) = Number of grousers in contact with the soil [–]
- \( B_g \) = Grouser width [m]
- \( \tau'_a(j) \) = Shear resistance acting on the sides of the belt or mobilized soil column, as defined in Muro and O’Brien [16] and used with the adhesion value [Pa]

**Total thrust**

The total thrust, \( T(j) \), generated by a track belt is the sum of all thrust forces generated by the friction planes (Muro and O’Brien [16]):

\[ T(j) = T_1(j) + T_2(j) + T_3(j) \]  

(3.19)

For flat track belt both \( T_2 \) and \( T_3 \) are considered to be zero.

### 3.2.4. Resistances

Aside from the thrust force, during operation also resistant forces act on the vehicle. By definition these forces act in the opposite direction as the thrust force. Several resistant forces can be identified, but the most important are the motion resistance and the cutting resistance. Since currents and boulders are outside the scope and internal mechanical resistance is negligible small, these resistant terms are not taken into account during this thesis.

The tracks undergo an amount of sinkage into the seabed. Regardless whether this is due to the initial settlement or the dynamic settlement, this amount of soil needs to be compacted by the track during the driving motion. Though since the soil resists to this compaction, a force is acting on the vehicle in the opposite direction of the thrust force. This force is called the motion resistance. The motion resistance is calculated using the principle of work done. The work done by the track belt is defined as (Cathie et al. [6]):

\[ W = R_{\text{mot}} \cdot L_{\text{track}} \]  

(3.20)

Schulte et al. [19] defined work done as:

\[ W = q_d \cdot W_{\text{track}} \cdot L_{\text{track}} \cdot \zeta \]  

(3.21)
If the bearing capacity is considered as is done in equation 3.6, then the motion resistance becomes a function of the settlement by rewriting equations 3.20 and 3.21 as:

\[ R_{\text{mot}} = c \cdot N_c \cdot W_{\text{track}} \cdot \zeta \]  

(3.22)

Where:

- \( W \) = Work done \([Nm]\)
- \( R_{\text{mot}} \) = Motion resistance \([N]\)
- \( L_{\text{track}} \) = Contact area length \([m]\)
- \( q_d \) = Bearing capacity of the soil \([Pa]\)
- \( W_{\text{track}} \) = Contact area width \([m]\)
- \( \zeta \) = Total settlement \([m]\)

The second resistant term is the force generated by the operation of the vehicle. In this case the creation a trench. The calculation of these forces is part of the model developed in this thesis and will be presented in section ??.

**Effective driving force**

It can be stated that if the effective driving force is zero or negative, the vehicle will not be moving since the force propelling the vehicle forward is smaller than the forces holding it back. The effective driving force is defined by Muro and O’Brien \([16]\) as:

\[ F_{\text{eff}} = F_{\text{thrust}} - F_{\text{resistance}} \]  

(3.23)

Thus it is concluded that a tracked vehicle can only be in operation if the generated thrust force exceeds the resistances acting on the vehicle.

Based on previous sections the thrust force propelling the vehicle forward is defined, but also the resistances holding the vehicle back are known. Though a valid prediction of the progress rate of the vehicle cannot be given yet. The slip ratio at which the track drive operates is still to be determined.

The solution lies in the function that links the shear stress - shear displacement. So far it has been used as the name states, the available shear stress was a function of the shear displacement. But as the beginning of the section states the shear displacement itself is also a function: \( j = i \cdot X \). Using iteration equation 3.14 should be solved for the entire range of slip ratio’s 1% up to 99%. If the current combination of soil and vehicle parameters are viable, the iteration will result in an interval of slip ratio’s where the generated thrust is larger than the resistance. Based on these numbers a working area or working point of the operation can be determined, corresponding to certain slip ratio.

Using this slip ratio and the chosen circumferential track belt velocity, the speed over ground of the tracked vehicle can be predicted. Thus the model is able to predict a progress rate, or production, of a known tracked vehicle based on simple soil data.

**Influence of a slope**

The presence of a slope along the driving direction, influences the ground pressure distribution as discussed at the end of the previous section. This creates a negative effect on the thrust force that can be generated by a track belt since this is a function of the shear resistance of the soil, which is a function of ground pressure. The other part of the gravity force now works parallel to the slope, i.e. in the opposite direction of the slope. This means there is an extra resistance term when driving up a slope.

If the vehicle is tracking up the slope the ground pressure distribution shifts its focus to the last part of the contact length, i.e. there will be less ground pressure at the beginning of the contact length. Less ground pressure equals a lower thrust force in the area where the vehicle needs a high thrust force. Since in the later parts of the contact length the thrust force is already lower due to remolding of seabed soil.

When the vehicle arrives at the top of a slope, the ground pressure could spike locally. Depending on the location of the COG, different situations may arise. The situation sketched in figure 3.5 is an example of what may happen when the COG is shifted backwards in reference to the middle of the contact area. As long as the COG did not pass the top, the contact area continues to decrease resulting
in an increasing ground pressure. What happens next depends on which state is reached first, either the COG passes the top and the vehicle topples due to gravity. Or the bearing capacity of the soil is reached and due to soil failure the vehicle sinks in, resulting in an increasing contact area and a decreasing ground pressure. Which options occurs depends on several variables, like soil properties, slope properties and vehicle properties.

Figure 3.5: When the vehicle arrives at the top of a slope, the ground pressure increases locally due to a decreasing contact area.

3.3. Summary

This chapter illustrated that for tracked vehicles several states can be identified. Rest state, where the vehicle is at rest, and a steady driving state are considered in this thesis. States of acceleration or deceleration are outside the scope.

An important conclusion is that while at rest the soil response to a rigid track belts is very similar to the response to a strip foundation. Important processes here are the ground pressure distribution developed under the contact length of the track, the bearing capacity of the soil and the initial settlements. Governing parameters are the geometric properties of the track belt and the cohesion value and/or internal friction angle of the soil.

Besides the forces acting on the vehicle, slip is an important process to take into account when analyzing the driving state of a track driven vehicle. Due to slip and the cutting process more settlement can be expected, increasing the resistance acting on the vehicle. Take into account that the thrust generation principle is different for a flat track belt then for a track belt equipped with grousers. Governing parameters for the driving state of a flat belt are the geometric variables of the track belt and the adhesion value or external friction angle between the soil and the belt material. For a track belt equipped with grousers the driving state is governed more by grouser variables, cohesion value or internal friction angle of the soil and to a lesser extend the track belt geometric variables.

The presence of a slope will, in either state result in an asymmetric ground pressure distribution, just like an eccentric location of the vehicle’s COG would. Depending on the slope angle and the angle of approach this could result in a far from optimal thrust generation. And thus the operational window
is narrowed.

In the next chapter the theory presented in chapter 2 and this chapter is applied in a model. This model will derive the progress rate of a tracked subsea vehicle based solely on CPT results and general vehicle specifications.
Chapter 4
Modeling

This chapter is left out for confidentiality reasons.
This chapter is left out for confidentiality reasons.
This chapter is left out for confidentiality reasons.
Appendices
Chapter A

CBT1100 Trencher
CBT 1100 CABLE TRENCHER
CBT 1100 CABLE TRENCHER

Main data

**MAIN FEATURES**
- 2 x 400kW (1072hp) Electro-Hydraulic power packs
- 1750 mm wide heavy duty track gear for minimum ground pressure
- Heavy duty chain cutter system capable of cutting 2.3m deep trench @ 4m MER in 40MPa rock
- Rear mounted dual jetting swords provide trench depth of 3m @ 3m MER
- TSS Dual track cable tracking system
- Fully instrumented for simultaneous or post lay burial survey
- Instrumented 7 function Manipulator Crane with water jetting tool
- Fully integrated LARS capable of operating in up to sea state 5

**Twin Water Jetter**
- 500kW Dual Sword jetter operating at 7-15bar with switchable top sword supply and rear backwash
- Spoil backfill rubber lined, load limited blades (optional fitment)
- Variable cable path between swords 150-400mm
- Detachable 3m deep x 3m MBR depressor with adjustable MBR for reduced depth
- Jetting swing frame for 40m radius trenching

**Tractor**
- 1072hp (800kW) with power sharing between cutter and jettter
- Maximum trench depth: 2.3m cutting mode / 3.0m jetting mode
- 75kW Front mounted dredge pump with backwash function
- Jetting system for tool cleaning
- Dual cable loading grapple
- Positioning thrusters

**Chain Cutter**
- 400kW heavy duty 600mm wide chain cutter with up to 4.0m MBR trough

**Manipulator crane**
- Instrumented Boom/Jib/Slew Telescopic cylinders
- 7 function, slew, boom, jib x 2, grab tilt
- Instrumented arm (4 function)
This appendix is left out for confidentiality reasons.
Chapter C

Westermost Rough

This appendix is left out for confidentiality reasons.


