Specialization: Transport Engineering and Logistics

Report number: 2016.TEL.8083

Title: Developing a test method to investigate effect of compaction on penetration resistance of moist iron ore and coal

Author: F.M. Sickler

Title (in Dutch) Het ontwikkelen van een testmethode om het effect van verdichting op de indringingsweerstand van vochtig ijzererts en steenkool te onderzoeken.

Assignment: Research assignment

Confidential: No

Initiator (university): dr. ir. Dingena Schott & ir. M. Javad Mohajeri

Supervisor: dr. ir. Dingena Schott & ir. M. Javad Mohajeri

Date: May 24, 2017

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Subject: Developing a test method to investigate effect of compaction on penetration resistance of moist iron ore and coal

The focus of our current research is on understanding behaviour of consolidated bulk materials, such as cohesive iron ore and coal. Penetration resistance is one of the main properties of solid bulk materials which is dependent to different parameters, such as state of compactness, moisture content and cohesion strength.

The aim of this project is to develop a test method to study penetration resistance of iron ore and coal under effect of compaction, moisture content and changes in penetration velocity. The experimental results will be used to calibrate Discrete Element Method (DEM) model of cohesive bulk materials. The DEM model will be coupled with the Multi Body Dynamics (MBD) of grab to study interaction of grab with cohesive iron ore and coal.

The assignment is to develop an experimental test to investigate penetration of wedge tools into different types of iron ore and coal. The research should cover the following tasks:

1. Study principles of penetration into cohesive bulk solids
2. Determine range of consolidation levels required to replicate realistic behavior of bulk materials that are stored inside bulk carrier
3. Design a box to hold the bulk materials during the test. Stresses created by compaction force/impact should be considered in the design.
4. Develop a method to compact bulk materials in different consolidation levels. State of compactness of the material should be measurable.
5. Record resistance force on the wedge tool during penetration into the bulk material
6. Show reproducibility of the result by retesting dry and moist materials
7. Systematically log the experiments in a log book
8. Present test procedure in a technical report

The report should comply with the guidelines of the section. Details can be found on the website.

The mentors,

Ir. M.Javad Mohajeri and Dr. ir. Dingena Schott
ME2130 Research Assignment

Developing a test method to investigate effect of compaction on penetration resistance of moist iron ore and coal

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Specialization
TEL

Creditpoints (EC) 15
Assignment type Research
Report no. 2016.TEL.8083
Confidential No
Preface

I would like to express my gratitude to all the people that assisted in the completion of this research project. First of all with ir. M. Javad Mohajeri and dr. ir. Dingena Schott who gave me insightful criticism and excellent support. I would especially like to thank ir. M. Javad Mohajeri for designing this project with great learning opportunities, his confidence in me, his patience by explaining everything and the weekly meetings which sometimes even took place in the weekends and after work hours just to get to the best result for the project.

Secondly I would like to thank Arno Mulder, the senior technician of the faculty of civil engineering and geosciences who provided me with very useful information, allowing me to conduct the experiments in his laboratory, arranging the test facility and the assistance he provided me.

Thirdly I would like to thank Nemag, the company who assisted with the production of the container. Especially I would like to express my gratitude to Wilbert de Kluijver who was the main contact person.

Fourthly I would like to acknowledge all the other members who assisted on this project, Dr. A. Askarinejad for providing useful information on the particle trajectory experiment and Leon Roessen for the production of the connection part between the wedge and the apparatus on very short notice.

Delft, 12th May 2017
Femke Sickler
Summary

Iron ore has the largest dry bulk trading volume per year due to its high demand. Iron ore is often transported using cargo ships due to its high weight and abrasive nature. As this seaborne voyage often takes a longer period of time the iron ore is subjected to many factors such as wave motions and the vibrations of the ship’s engine. At arrival at the port the state and compactness of the iron ore is often unknown. When unloading the iron ore the grab must be able to penetrate the iron ore. Nemag, a company that designs and produces grabs are constantly innovating their designs. However the testing and evaluation of new grabs is an expensive and time consuming process and therefore simulation models are used to show the interaction between the grab and the material. Previous research performed by Lommen [2011] and Lommen [2016] focused on the penetration of iron ore investigating the impact of type of iron ore, penetration velocity, compaction, size of the container and tip of the tool. However the conclusions of the research were that there is a high sensitivity of the penetration resistance to the consolidation level of the material and it was difficult to consolidate the sample for each measurement consistently Lommen [2011]. The main purpose of this research assignment is to develop a test method to investigate the effect of compaction on the penetration resistance for moist iron ore. The method will be developed based on research performed by other researchers, own calculations and existing NEN standards. The results of the experiment will be used to calibrate Discrete Element Method (DEM) model of cohesive bulk materials. The DEM model will be coupled with the Multi Body Dynamics (MBD) of grab to study the interaction of the grab with cohesive iron ore.

A static, laboratory, vertical wedge penetration test was performed using hydraulic servo controlled test frame. Iron ore (classified heritage) from the TUDelft was used with a fine particle size distribution. The sample of iron ore was prepared with 5% moisture content and during the test a penetration velocity of 6 mm/s would be used. The iron ore would be compacted in 3 layers followed by the penetration test using a wedge. The compaction stress levels were; 0 kPa, 13.3 kPa, 66.6 kPa, 133.3 kPa, 266.7 kPa and 533.3 kPa respectively. These compaction levels were calculated using cargo hold design. A connection pin and container was designed for this test set up with dimension of 300 x 250 x 200 mm to ensure that no significant wall effect will be present during the penetration test. One wall of the container is fabricated from plexiglas such that the movements of the particles can be observed during the testing. The existing penetration tool developed by Lommen [2011] was used with dimensions of 200 mm length, 40 mm width and 75 mm depth and a blunt tip.

The results of the force-displacement measurements were adjusted to the height of the material in the test setup. Several tests were performed among them, the determination of the density, 3 layer vs. 1 layer compaction, influence of the laboratory environment and the penetration test. First, the density of the material was calculated showing that with increasing compaction force the density of the material would increase, as expected. In addition with higher density the penetration resistance encountered by the wedge increased. Second the 3 layer compaction showed a small difference with the 1 layer compaction. In view of time and money it was decided that the remainder of the experiments will be performed with a 1 layer compaction. Thirdly the influence of the exposure of the material to the air in the laboratory was tested, this did not have a
significantly large effect. The penetration resistance showed that the resistance increased with increasing compaction levels. The penetration resistances were compared based on the maximum penetration resistance encountered and the penetration resistance at 90 mm penetration depth. An interesting phenomenon occurred at from the 5kN and higher penetration measurements. A small bump also known as the shear failure of the material was encountered. With higher compaction forces this bump appeared more frequently and with greater magnitude. Each experiment was performed 3x to ensure that it would qualify as a repeatable experiment. In conclusion it could be stated that this is a repeatable method for the study of penetration resistance of iron ore under the effect of compaction, moisture content and penetration velocity.
Samenvatting


Een statische, in situ, verticale wigpenetratie test wordt uitgevoerd door het hydraulisch servo gestuurde test frame. Ijzererts van de TUDelft is gebruikt met een hele fijne korrel. Het ijzererts is geprepareerd met 5% vochtgehalte en gedurende de test wordt een penetratiesnelheid van 6 mm/s gebruikt. Het ijzererts wordt in 3 lagen worden samengeperst, gevolgd door de penetratietest met een wig. De verdichtingsniveaus zijn; Los, 1kN, 5kN, 10kN, 20kN en 40kN. Deze verdichtingsniveaus zijn berekend met behulp van het ontwerp van de ship containers. Een aansluitpin en container zijn ontworpen voor deze test. De container heeft een afmeting van 300 x 250 x 200 mm om ervoor te zorgen dat er tijdens de penetratietest geen wandwrijving zal plaatsvinden. Een wand van de container is gemaakt van plexiglas, zodat de bewegingen van de deeltjes tijdens het testen kunnen worden waargenomen. Het bestaande penetratie wig ontwikkeld door Lommen [2011] is her-gebruikt met een afmeting van 200 mm lengte, 40 mm breedte en 75 mm diepte en een stompe punt.

De resultaten van de krachtverplaatsingsmetingen zijn aangepast aan de hoogte van het materiaal in de testinstelling. Er zijn verschillende tests uitgevoerd, de bepaling van de dichtheid, 3 lagen verdichting versus 1 laag verdichting, invloed van de omgeving en de wigpenetratie test. Ten eerste is de dichtheid van het materiaal berekend, waarbij blijkt dat bij toenemende verdichtingskracht de dichtheid van het materiaal toenemt, zoals verwacht. Daarnaast zorgt dit voor een verhoogde penetratieweerstand van de wig met hogere dichtheid. Ten tweede is het resultaat van de 3-laags verdichting klein vergeleken met de 1-laag verdichting. Tijd en geld in acht nemend is besloten dat vol-
gende testen van het experimenten uitgevoerd worden met een 1-laagse verdichting. Ten derde is de invloed van de blootstelling van het materiaal aan de buitenlucht in het laboratorium getest, dit heeft geen significant groot effect op de penetratieweerstand. De penetratieweerstand toont aan dat de weerstand verhoogd wordt met toenemende verdichtingsniveaus. De penetratieweerstanden werden vergeleken op basis van de maximale penetratieweerstand en de penetratieweerstand bij 90 mm penetratie diepte. Een interessant fenomeen kan worden waargenomen in de resultaten van 5kN en hoger. Een kleine heuvel, ook wel bekend als de schuif weerstand van het materiaal. Bij hogere verdichtingskrachten verscheen deze heuvel vaker en in grotere mate. Elk experiment is 3x uitgevoerd om ervoor te zorgen dat het een herhaalbaar experiment is. Concluderend kan worden vastgesteld dat dit een herhaalbare methode is voor de studie van de penetratieweerstand van ijzererts door het effect van verdichting, vochtgehalte en penetratie snelheid.
## Abbreviations

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
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<tbody>
<tr>
<td>AoR</td>
<td>Angle of Repose</td>
</tr>
<tr>
<td>CPT</td>
<td>Cone Penetration Tests</td>
</tr>
<tr>
<td>DEM</td>
<td>Discrete Element Model</td>
</tr>
<tr>
<td>DWT</td>
<td>Dead Weight Tonnage</td>
</tr>
<tr>
<td>IOF</td>
<td>Iron Ore Fines</td>
</tr>
<tr>
<td>L</td>
<td>Liters</td>
</tr>
<tr>
<td>MT</td>
<td>Metric Ton</td>
</tr>
<tr>
<td>OMC</td>
<td>Optimal Moisture Content</td>
</tr>
<tr>
<td>PFT</td>
<td>Proctor - Fagerberg Test</td>
</tr>
<tr>
<td>TML</td>
<td>Transportable Moisture Limit</td>
</tr>
<tr>
<td>TWG</td>
<td>Technical Working Group</td>
</tr>
</tbody>
</table>
# List of Symbols

The symbols with description and units can be used throughout the report unless stated otherwise.

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Unit</th>
</tr>
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<tr>
<td>A</td>
<td>area</td>
<td>$[m^2]$</td>
</tr>
<tr>
<td>$b_f$</td>
<td>breadth of hold</td>
<td>[m]</td>
</tr>
<tr>
<td>$C_v$</td>
<td>coefficient of consolidation</td>
<td>$[m^2/yr]$</td>
</tr>
<tr>
<td>e</td>
<td>void ratio</td>
<td>[-]</td>
</tr>
<tr>
<td>$e_v$</td>
<td>water content</td>
<td>[%]</td>
</tr>
<tr>
<td>F</td>
<td>Force</td>
<td>[kN]</td>
</tr>
<tr>
<td>H</td>
<td>height</td>
<td>[m]</td>
</tr>
<tr>
<td>$h_c$</td>
<td>height of material in cargo hold</td>
<td>[m]</td>
</tr>
<tr>
<td>$l_h$</td>
<td>length of hold</td>
<td>[m]</td>
</tr>
<tr>
<td>M1</td>
<td>mass of material</td>
<td>[kg]</td>
</tr>
<tr>
<td>M2</td>
<td>mass of tray</td>
<td>[kg]</td>
</tr>
<tr>
<td>M3</td>
<td>mass of dry material</td>
<td>[kg]</td>
</tr>
<tr>
<td>$M_{container+ironore}$</td>
<td>mass of container filled with iron ore</td>
<td>[kg]</td>
</tr>
<tr>
<td>$M_{di}$</td>
<td>mass of material after drying for 24h</td>
<td>[kg]</td>
</tr>
<tr>
<td>$M_{di}$</td>
<td>mass of material after drying consequent measurements</td>
<td>[kg]</td>
</tr>
<tr>
<td>$M_{empty}$</td>
<td>mass of empty container</td>
<td>[kg]</td>
</tr>
<tr>
<td>$M_{sample}$</td>
<td>mass of 1 layer of material</td>
<td>[kg]</td>
</tr>
<tr>
<td>$m_v$</td>
<td>coefficient of compressibility</td>
<td>$[m^2/MN]$</td>
</tr>
<tr>
<td>$\rho$</td>
<td>density</td>
<td>[kg/m$^3$]</td>
</tr>
<tr>
<td>$\rho_{ironore}$</td>
<td>density of iron ore</td>
<td>[kg/m$^3$]</td>
</tr>
<tr>
<td>$\rho_{loosebulk}$</td>
<td>density of loose iron ore material</td>
<td>[kg/m$^3$]</td>
</tr>
<tr>
<td>$\rho_{water}$</td>
<td>density of water</td>
<td>[kg/m$^3$]</td>
</tr>
<tr>
<td>P</td>
<td>pressure</td>
<td>[kPa]</td>
</tr>
<tr>
<td>$q_c$</td>
<td>cone tip resistance</td>
<td>[MPa]</td>
</tr>
<tr>
<td>$q_{lim}$</td>
<td>limiting penetration resistance</td>
<td>[MPa]</td>
</tr>
<tr>
<td>$\sigma$</td>
<td>consolidation pressure</td>
<td>[kPa]</td>
</tr>
<tr>
<td>$\sigma_c$</td>
<td>unconfined yield strength</td>
<td>[kPa]</td>
</tr>
<tr>
<td>$V_{container}$</td>
<td>volume of container</td>
<td>$[m^3]$</td>
</tr>
</tbody>
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1 Introduction

Bulk materials such as iron ore are transported all over the world due to its high demand. During the transportation between countries, often per ship, the iron ore is stored for a longer period of time and is influenced by many factors such as the wave motions and the vibrations of the ship’s engine. When arriving at the port of destination the iron ore is often encountered in a compacted dense form in the cargo hold. The exact state of the iron ore remains unknown as each iron ore may have a varying moisture content and varying forces acted upon the iron ore. When unloading the iron ore a grab is lowered into the cargo hold and this grab must be able to handle the iron ore. Nemag produces grabs among other machines for the handling of bulk goods. The testing and evaluation of new grabs is an expensive and time consuming process and therefore models are used to simulate the interaction between the grab and the material. Previous research performed by Lommen [2011] and Lommen [2016] focused on the penetration of iron ore investigating the impact of type of iron ore, penetration velocity, compaction, size of the container and tip of the tool. However the conclusions of the research were that there is a high sensitivity of the penetration resistance to the consolidation level of the material and it was difficult to consolidate the sample for each measurement consistently Lommen [2011].

The main purpose of this research assignment is to develop a test method to investigate the effect of compaction on the penetration resistance for moist iron ore and coal. The method will be developed based on research performed by other researchers, own calculations and existing NEN standards. The results of the experiment will be used to calibrate Discrete Element Method (DEM) model of cohesive bulk materials. The DEM model will be coupled with the Multi Body Dynamics (MBD) of grab to study the interaction of the grab with cohesive iron ore and coal.

To answer the main question of this report, the problem setting will be discussed first in Chapter 2. In this chapter background information about iron ore shipping and the previous research done by the TU Delft is discussed. Second a literature study will be performed on compaction, moisture contents, the grab, penetration resistance and penetration velocity in Chapter 3. Thirdly, in Chapter 4 the iron ore material that will be tested is presented, the design of the container (the technical drawings can be found in Appendix A), criteria for the selection of the experiment apparatus, selection of the experiments and the determination of the penetration force is elaborated. Next in Chapter 5 the steps that will be performed during the experiment are described in detail. Chapter 6 describes the results from the experiments presented in Chapter 5. These experiments are the preparation of the iron ore with 5% moisture content, the compaction of the iron ore with loose, 1kN, 5kN, 10kN, 20kN and 40kN respectively. Finally in Chapter 7 the conclusions from the experiment and the recommendations for further research are stated.
2 Problem Setting

This chapter describes the problem setting of this assignment. Iron ore has the largest dry bulk trading volume per year. The transportation between countries is often done by ship, requiring the iron ore to be stored for a longer period of time in cargo holds. The characteristics of the bulk material often change during this journey due to the various forces acting upon the iron ore. When arriving in the port of destination the iron ore has to be un-loaded by terminal handling equipment. The various stages of the journey, the relevant forces and equipment needed to successfully transport the iron ore from its exportation destination to the importing destination are described in this chapter including the challenges that are faced.

2.1 Iron Ore Exporting and Importing

Iron ore is a dry bulk cargo with the largest trading volume per year. Iron ore is found in the form of rocks, usually mixed with other elements. After processing it is sold to steel companies. Some countries have large deposits while other countries have a high demand for iron ore, resulting in shipping of this dry bulk material. Large trades of bulk flow exist in the world; in 2015 a total of 4,553 million Metric Ton (MT) of dry bulk was shipped. 1,354 MT accounted for iron ore [OpenSea.org, 2016]. This is almost 30% of the total dry bulk shipped annually as can be seen in Table 6.4. The top 5 countries for exporting can be found in Table 2.2 and for importing in Table 2.3.

Table 2.1: Annual iron ore shipping vs. total dry bulk shipping [OpenSea.org, 2016]

<table>
<thead>
<tr>
<th></th>
<th>2010</th>
<th>2011</th>
<th>2012</th>
<th>2013</th>
<th>2014</th>
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<tr>
<td>Iron Ore (million MT)</td>
<td>991</td>
<td>1,053</td>
<td>1,110</td>
<td>1,189</td>
<td>1,337</td>
<td>1,354</td>
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<tr>
<td>Total Dry Bulk (million MT)</td>
<td>3,605</td>
<td>3,841</td>
<td>4,099</td>
<td>4,333</td>
<td>4,553</td>
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<tr>
<td>% Iron Ore</td>
<td>27.5</td>
<td>27.4</td>
<td>27.1</td>
<td>27.4</td>
<td>29.4</td>
<td>29.7</td>
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Table 2.2: Top 5 iron ore exporting countries [Workman, 2016a]

<table>
<thead>
<tr>
<th>No.</th>
<th>Country</th>
<th>billion US$</th>
<th>%</th>
</tr>
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<tbody>
<tr>
<td>1</td>
<td>Australia</td>
<td>36.7</td>
<td>51.7</td>
</tr>
<tr>
<td>2</td>
<td>Brazil</td>
<td>14.1</td>
<td>19.8</td>
</tr>
<tr>
<td>3</td>
<td>South Africa</td>
<td>4.3</td>
<td>6</td>
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<tr>
<td>4</td>
<td>Ukraine</td>
<td>2.8</td>
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</tr>
<tr>
<td>5</td>
<td>Canada</td>
<td>2.8</td>
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Table 2.3: Top 5 iron ore importing countries [Workman, 2016b]

<table>
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<td>China</td>
<td>57.9</td>
<td>63.5</td>
</tr>
<tr>
<td>2</td>
<td>Japan</td>
<td>9.3</td>
<td>10.2</td>
</tr>
<tr>
<td>3</td>
<td>South Korea</td>
<td>4.9</td>
<td>5.4</td>
</tr>
<tr>
<td>4</td>
<td>Germany</td>
<td>2.8</td>
<td>3</td>
</tr>
<tr>
<td>5</td>
<td>Netherlands</td>
<td>2.1</td>
<td>2.3</td>
</tr>
</tbody>
</table>

The Netherlands is the 5th largest importer of iron ore in the world accounting for 2.3% of the world iron ore import as can be seen in Table 2.3. Most of the iron ore is imported through the largest port of the Netherlands, the port of Rotterdam. Almost 50% of all iron ore throughput in Northwest Europe takes place in Rotterdam. The
The port of Rotterdam is the only port in Northwest Europe that is 23.65 m deep and can thus accommodate the largest dry bulk vessels such as the Valemax bulk carriers Port of Rotterdam [2016].

2.2 Iron Ore Shipping

Iron ore has to be shipped from the exporting countries to the importing counties, which is often done using bulk carrier vessels. The various types of dry bulk carrier vessels including their dead weight tonnage (DWT) are listed in Table 2.4. DWT is used to measure how much weight a ship is carrying or can safely carry.

Table 2.4: Types of dry bulk vessels [Ariston, 2016]

<table>
<thead>
<tr>
<th>Category</th>
<th>Capacity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Very Large Ore Carriers (Valemax)</td>
<td>&gt; 200 000 DWT</td>
</tr>
<tr>
<td>Capesize</td>
<td>110 000 - 199 000 DWT</td>
</tr>
<tr>
<td>Post-Panamax</td>
<td>80 000 - 109 999 DWT</td>
</tr>
<tr>
<td>Panamax</td>
<td>60 000 - 79 999 DWT</td>
</tr>
<tr>
<td>Handymax / Supramax</td>
<td>40 000 - 59 999 DWT</td>
</tr>
</tbody>
</table>

During shipping the iron ore is stored in the cargo holds. The cargo holds come in many different shapes and sizes, as shown in Figure 2.1. As shipping, depending on the origin and destination may well take over a month the iron ore is subjected to many forces during the journey for a longer period of time. Some of them are, but not limited to: the iron ore is fixed from the bottom and the sides, resulting in wall friction, the movement of the ship due to wave motions, it’s own weight, time, the vibrations of the ship and the ships’ engine.

Figure 2.1: Types of cargo holds [Ghosh, 2015]

The forces acting on the iron ore during shipping have a compacting effect on the material. With increasing time and vibration this compaction increases. By the time the ship arrives at the harbor it is often unclear how the material has developed and in which
state it is. However the unloading process must continue and the grab has to grab the material from the cargo hold to unload the bulk carrier. Depending on how the material has developed during the journey the penetration resistance encountered by the grab may vary. For different penetration resistances different grabs are required. Therefore this research assignment will aim at developing a test method to study the penetration resistance of iron ore under effect of compaction, moisture content and changes in the penetration velocity.

2.3 Iron Ore as a Material

Different types of iron ore are mined, having different material characteristics. The material characteristics can be identified using the bulk density, cohesion strength, dry density, moisture content, particle shapes, particle size distributions and particle sizes. Other terms that might often be used in iron ore handling are consolidation, cohesion, compaction and penetration resistance. First the definitions of the various concepts are presented followed by a more in depth explanation of consolidation.

2.3.1 Definitions

Bulk density
Bulk density is defined by the ratio of the mass, m, of an amount of bulk solid to its volume, V, often presented in units $[kg/m^3]$ Schulze [2008]. The void spaces in the material may be filled with air and water.

Cohesion (strength)
Cohesion is the component of shear strength of a rock or soil that is independent of inter-particle friction. For cohesive soils the dry state is not considered as this is only a temporary state. A cohesive soil becomes more compressible under the same load when moisture is added Murthy [2003].

Consolidation
Consolidation is the term used to describe the increase in granule density caused by closer packing of primary particles as liquid is squeezed out as a result of collisions Rhodes [2008].

When a saturated material is subjected to a pressure, the pressure is initially taken by the water in the pores, creating an excess pore water pressure. When drainage is permitted, the water flows out of the material, resulting in compression. A portion of the applied pressure is allowed to be mineral skeleton reducing the pore water pressure. Consolidation may occur due to:

1. External static loads
2. Self-weight of the soil

Consolidation can be divided in primary consolidation and secondary consolidation. Primary consolidation: compression of the material solely determined by the resistance of flow of water under the applied pressure. Secondary consolidation: compression after the primary consolidation is finished, that is, the excess pore water pressure approaches 0. Often is assumed that secondary consolidation proceeds linearly with the logarithm
of time Murthy [2003].

**Compaction**
Compaction is the densification - reduction of void ratio - of a soil through the expulsion of air Budhu [2011].

**Compressibility**
The compressibility of a soil mass can be due to any combination of:

1. Compression of the solid matter
2. Compression of the water and air within the voids
3. Escape of water and air from the voids

Under the applied loads the solid matter and the water within the voids can be assumed relatively incompressible. Therefore the change in volume of a mass is often due to the escape of water in case of a saturated matter. In the case of a partially saturated or dry matter it can be assumed that the change in volume of a mass is due to the compression and escape from air from the voids or dissolution of air in the pore water Murthy [2003]

**Dry density**
The bulk density of a sample when all the moisture has evaporated. The voids in the sample are filled with air.

**Moisture content**
The portion of a representative sample consisting of water, ice or other liquid expressed as a percentage of the total wet mass of that sample International Maritime Organization [2002].

**Particle shapes**
The shape of the individual iron ore particles in the iron ore sample. The particle shapes are often not uniform.

**Particle sizes**
The sizes of the individual iron ore particles in the iron ore sample. The particle sizes are often not uniform. A sample often contains large lumps as well as fines.

**Particle size distribution**
A distribution (percentage) of how many particles within a certain size range exist in one iron ore sample.

**Penetration Resistance**
The resistance of the iron ore sample to penetration. e.g. How easy or difficult is the cutting of the material.

**Wet density**
The bulk density of a sample including the moisture content. The voids in the sample are filled with air and / or water.
2.3.2 Iron Ore Handling Equipment

For cargo (un-)loading there are many handling equipment types. The equipment used is dependent on the nature of the cargo and the type of storage. Dry bulk cargoes such as iron ore are often handled by conveyor belts or grabs. As a result of the weight and abrasive characteristics of the iron ore the conveyor belt would be the least favorable option as this would result in large wear of the belt. The significant wear would require the belt to be often repaired or replaced. For reparation or replacement the entire operation would have to be stopped resulting in delays and loss of income Faculty of Maritime Studies [2013].

The Nemag grabs are manufactured from the highest possible quality steels, such as Dillidur 400, Hardox 400, Dillimax 690 and Weldox 700 resulting in less wear than conveyor belts. In addition if the grabs need maintenance or replacement this can be quickly done be replacing the grab with other grab, enabling the continuation of the (un-)loading process Nemag [2016].

2.4 Previous Research

Lommen [2011] has researched in his master thesis "The penetration of iron ore: calibrating discrete element parameters using penetration tests"; the penetration of tools in iron ore in order to calibrate DEM simulations. This research investigated the impact of the type of iron ore, penetration velocity, compaction, size of the container and tip of the tool.

The compaction of the material is studied by comparing the loose state of the material, compaction through shaking and compaction through shaking and applying pressure. The shaking was realized by impacting all sized of the container with an approximate fixed amount of energy. The pressure that was applied was an 800N steel plate lying on the material which was twisted to improve the compaction effort Lommen [2011].

His conclusions regarding consolidated iron ore are: "Experiments using consolidated ore showed a penetration resistance four times higher than loosely packed ore. This high sensitivity to consolidation made measurements with consolidated ores hard as it was difficult to consolidate the sample for each measurement consistently". In this research assignment it is researched how to consolidate the sample for each measurement consistently.
3  Literature Study

Nemag, a company specialized in the handling of bulk goods worldwide designs grabs. To optimize this design an insight is needed in the material characteristics of the bulk material. In this chapter the relevant literature regarding compaction of iron ore, how to estimate the density of the bulk material in the cargo hull, the influence of moisture, grabbing the bulk material will be discussed. Finally the relevant literature regarding penetration resistance will be presented.

3.1  Compaction

To investigate the effect of the state of compactness on the penetration resistance of iron ore, penetration tests have to be performed with different bulk densities. In this section the available literature on the density of iron ore in a cargo hull is discussed.

3.1.1  Influence of compaction

Schwedes [2002] found that the strength and flow properties of bulk solids can be determined by measuring the shear strength. The shear strength depends on the way and degree of consolidation. During consolidation a stress history is impressed on the bulk solid sample which only vanishes after steady state flow. The strength depends on the direction of stress application.

Fagerberg and Stavang [1971] found in a very early stage that the rolling, pitching and vibrations of a vessel that is loaded with granular loosely packed ore concentrate has an influence on the material characteristics of the ore. The material will gradually get compressed especially with rough weather.

3.1.2  Field Experience

The iron ore technical working group (TWG) have performed extensive research on iron ore in cargo hold in the reports Iron Ore Technical Working Group [2013a], Iron Ore Technical Working Group [2013b], Iron Ore Technical Working Group [2013c], Iron Ore Technical Working Group [2013d] and Iron Ore Technical Working Group [2013e]. The research is done regarding the adequacy of current methods for determining the Transportable Moisture Limit (TML) for Iron Ore Fines IOF, the characteristics of vessel motions and forces imposed on the IOF, adjustments to the existing tests to better reflect the actual in-hold shipping conditions and observations and finally performed some extra tests to verify that their adjustments are valid.

Drop Tower Test

Drop tower tests were conducted to estimate the range (minimum and maximum) of bulk densities that can possibly occur in a cargo hold. IOF fines (sample = 20 kg) at a certain moisture content were dropped from a height of 20 m in a container of known volume. Following the bulk density was determined. Tests were conducted as single and multiple drops to mimic the ship loading characteristics.
The average bulk density determined from the drop tower test is 2230 kg/m$^3$ as shown in Figure 3.1. Key findings are that the bulk density is not significantly influenced by the drop height from drop heights greater than 5 m and that the number of drops does not significantly influence the average bulk density. The average bulk density in the cargo hold is mainly determined by the initial drop of material from the ship-loader into the hold Iron Ore Technical Working Group [2013a].

Figure 3.1: Bulk density versus drop height results from drop tower test [Iron Ore Technical Working Group, 2013a]

**Cone Penetration Test**

The Cone Penetration Tests (CPT) were conducted in the holds of the vessel to investigate the characteristics after loading and upon arrival at the port after sea transportation. The tests were performed using a cylindrical penetrometer with a conical tip (cone) penetrating the ground (i.e. the stow in the cargo space) at a constant rate. Three cape size bulk carriers in total were selected and for each vessel two holds were tested - Hold 1 nearest the bow which experiences the largest wave-induced motions and Hold 9 nearest the engines, which experiences the most engine and propeller induced vibrations. Cone penetration testing was carried out in the centre of the cargo stow after loading and upon arrival at the destination port.

The results suggest that the material is in a relatively loose state, but increases in density or become cemented during the voyage. Increases in cone penetration resistance, i.e. cone tip resistance ($q_c$), occurred as a result of seaborne transportation. This is considered to be the effect of cementing and compaction. An increase in relative density is generally observed between the commencement and end of transportation and the increase in observed relative density is equivalent to an increase in bulk density of 4%. Bulk density varies with depth on loading, however the profile determined is not uniform as can be seen in Figure 3.2 and Figure 3.3.
Laser Monitoring

Laser scanning units were installed within each of the monitored holds to record detailed data on the intensity of changes in the cargo stow geometry during sea transportation. The cargo was scanned every 15 minutes throughout each separate voyage. Figure 3.4 below shows a typical laser scan image of a cargo inside one of the holds of the capsize vessels monitored.

Laser surveying images from the cargoes suggest a reduction in height of around 4%. A distinct difference is seen between the image at loading and the image at arrival; with the corners and side of the hold having been ‘levelled’ out. Whilst the cargo has clearly undergone a change of shape around the corners of the hold during the voyage, the bulk of the cargo remains approximately as loaded.

Figure 3.2: Cone tip resistance IOF prior and after transportation for Hold 1 [Iron Ore Technical Working Group, 2013a]

Figure 3.3: Cone tip resistance IOF prior and after transportation for Hold 9 [Iron Ore Technical Working Group, 2013a]

Figure 3.4: Laser scan image inside a hold of a cape size vessel [Iron Ore Technical Working Group, 2013a]
Conclusion Field Experience

The data consistently shows a small net consolidation of the cargo over the seaborne voyage associated with small increases in global bulk density of the material as a whole. Overall, the cargo settles globally during the seaborne voyage, but in the order of only circa 0.6m. Average increases in bulk densities for the measured investigations give an increase of on average 1% - 4% with a maximum of 10% between the loaded and unloaded conditions as shown in Figure 3.5.

<table>
<thead>
<tr>
<th>Compaction %</th>
<th>Hold 1</th>
<th>Hold 9</th>
<th>Hold 1</th>
<th>Hold 9</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average</td>
<td>1.9</td>
<td>0.7</td>
<td>3.8</td>
<td>2.6</td>
</tr>
<tr>
<td>Maximum</td>
<td>10.2</td>
<td>3.2</td>
<td>10.3</td>
<td>7.3</td>
</tr>
<tr>
<td>Minimum</td>
<td>0.0</td>
<td>0.0</td>
<td>0.5</td>
<td>0.1</td>
</tr>
</tbody>
</table>

Figure 3.5: Cargo compaction from cargo height measurements [Iron Ore Technical Working Group, 2013a]

Typically the IOF in Hold 1 was more compacted than in Hold 9, however this was not always the case. A small correlation between the sea condition and the compaction degree was found during the voyage. Most of the compaction of the cargo is due to the loading process (dropping from a greater height than 20 m). Measurements on partially loaded cargoes show similar bulk densities to the fully loaded bulk densities so the weight of the material above has minimal effect.

Figure 3.6: Laser scanning summary [Iron Ore Technical Working Group, 2013a]

In Figure 3.6 the laser scanning summary of all hold results for cargo compaction and bulk density can be found. The results are for three IOF products that are shipped from Australia, they show that the compaction determined from laser scanning compared closely with the compaction determined by cargo height measurements. The bulk density of the cargo increased due to the compaction that occurs during the voyage, although the average increase was small. Also, from laser scanning the angle of repose (AoR) for all three IOF products was similar, at 35° to 37°.

3.1.3 Maximum compaction level

The field experience indicated that the average bulk density of the cargo in hold will increase over the seaborne transportation. If the particle size is very small, the compaction achieved is much higher. The transportation of very fine iron ore particles may lead to tight compaction and if too much moisture is added liquification may occur, this phenomenon is explained in Section 3.2. Therefore before compacting the material the
material needs to be sieved to ensure that the particle size distribution is known. In
the field situation all particle sizes are loaded in the cargo ship and therefore in the
experiment design all particle sizes should be included.

When compacting the fines of iron ore there is a maximum to which the iron ore can
be compacted as shown in Figure 3.7. Höganäs [2012] has conducted research on the
possibilities and limitations of powder compaction. For each sample with a different
particle size distribution and moisture content there is a maximum compaction that has
to be determined. This maximum compaction can be determined by measuring the bulk
density with increasing compacting pressure. At a certain point the pressure is so large
that the process will not be compacting but crushing, at this point the measurements
will stop.

![Figure 3.7: Density pressure curve [Höganäs, 2012]](image)

3.1.4 Time

Time is a very important factor in the consolidation of bulk material. Schulze [2008]
describes that the unconfined yield strength $\sigma_c$ increases with increasing storage time.
For some bulk solids it is the case that a few hours result in a large increase in unconfined
yield strength but that for longer storage periods the unconfined yield strength does not
increase any more. The aspect of time consolidation will not be taken into account.

3.2 Moisture

Fagerberg and Stavang [1971] stated that moisture has a large influence on the be-
avour of the iron ore. When the material in the cargo hold is compacted this results
in a decrease of the voids or spaces between the mineral grains in the concentrate. If the
material is fine grained, with high moisture content the entire compressive stress may
momentarily be carried by the water in the voids. An "excess pore pressure" is created,
which means that the mineral grains do not come in proper contact with each other.
As a result the internal friction and cohesion forces, and consequently also the shear
strength disappear. This phenomenon is called liquefaction.
Munro and Mohajerani [2016] has researched the liquefaction phenomena of iron ore. If a partially saturated material is under (cyclic) loading the shear strength may decrease to 0, causing the material to liquefy. If the material liquefies the counter ballast of the ship will no longer be able to counteract the weight of the moving bulk cargo, resulting in capsizing of the ship. The parameters that influence the liquefaction are the void ratio, dry density, degree of saturation and the angle of repose.

A safe moisture content in a granular ore concentrate must be accordingly that the water can be accommodated in the voids even at the highest compaction attained during shipment. The Proctor test is a test used for finding the Optimum Moisture Content (OMC) for compaction of the material being tested. Compaction curves are plotted, relating dry density and moisture content. From these curves, the OMC can be identified at the point of maximum compaction (maximum dry density) as shown in Figure 3.8. This point corresponds to the minimum void ratio or the maximum compaction condition (i.e. maximum dry bulk density) for the given compaction energy.

![Figure 3.8: Example of a Proctor-Fagerberg compaction curve [Fagerberg and Stavang, 1971]](image)

All compaction curves have the same general shape. When the tested material is completely dry, a small void ratio, i.e. a dense compaction is obtained. The individual mineral grains easily move towards each other during compaction. If a small amount of water is added, lumps are formed due to capillary forces. These lumps hamper compaction. These lumps are gradually broken down when still more water is added. The density increases with moisture content, but only to a certain point. Optimum compaction marked by the minimum point on the compaction curve, is obtained when the voids are so small that they can not accommodate more water.

At moisture contents higher than the optimum, no further compaction is possible since the compression pressure is counteracted by excess pore pressure. Since more water is required to wet a finer material, the critical water content generally increases with the product fineness.
3.3 The Grabbing Process

A grab is a type of hoisting equipment which is designed to pick up a type of bulk solid material. In our case study the grab is used for the removal of the material from the bulk cargo of a ship to drop it on the quay. An example of a grab (in this case the Clamshell grab) is shown in Figure 3.9. Preferably to operate the grab in the most efficient manner the grab is maximally filled, reducing the amount of cycles and time needed to (un)load the ship. To ensure that the grab is most efficiently used the material has to be studied.

![Figure 3.9: Clamshell grab [Lommen, 2016]](image)

The filling of the grab is dependent on how much material can be scooped in the bucket (nr. 7 in Figure 3.9). The grab is lowered into the bulk solid material causing the bucket knifes (nr. 8 in Figure 3.9) to penetrate the material.

3.3.1 Influencing factors

1. Tool: The tool used to penetrate the material has to mimic the bucket knife of the grab.
   (a) **Size**: the size of the tool must be sufficiently large to have a similar impact on the sample as it would have in situ. In addition the size of the tool has to fit in the apparatus.
   (b) **Shape**: the shape of the tool is of great importance. The effect of a wedge-shaped, concave, flat, convex or ball shaped tool has a large impact on the results as researched by Medvedev [2009].
   (c) **Roughness**: the roughness of the tool influences if the tool penetrates the material sample smoothly or if it faces a lot of resistance.
2. Material
   (a) **Density**: the density of the material determines if the particles are packed closely together and thus are harder to penetrate or if they are loosely packed, thus having more air in between the particles allowing for easier penetration.
(b) **Moisture content**: the moisture content determines the degree to which the particles stick together and thus to which degree the material is easy or more difficult to penetrate.

(c) **Particle size**: the particle size has an influence on how tightly the particles can be packed together when compacted. Larger particles allow for larger voids between the particles and thus a less tight compaction. Smaller particles are packed closer together and are therefore more difficult to penetrate.

### 3. Interaction

(a) **Friction**: the friction between the particles also determine how much resistance is encountered when trying to penetrate the material.

(b) **Internal friction**: internal friction depends on the normal stress between the grains Miedema [2013].

(c) **External friction**: external friction depends on the normal stress between the grains and another material Miedema [2013].

(d) **Adhesion**: The sticky effect between two different materials Miedema [2013].

(e) **Cohesion**: The sticky effect between two surfaces of the same material before any failure has occurred Miedema [2013].

### 4. Path

(a) **Angle**: The angle of the penetration tool entering the material, especially in a small experiment set-up can influence the penetration resistance due to the wall friction that may occur.

(b) **Path**: The path of the penetration tool has an effect when the path is not straight; increasing the penetration resistance. Therefore it must be ensured that the penetration tool enters the material perpendicular.

(c) **Velocity**: The velocity of the penetration tool influences the penetration resistance as will be explained in Section 3.5.

### 3.4 Penetration resistance

Penetration resistance is the resistance of a material against an object separating the material. Medvedev [2009] describes it as the penetration resistance by a body with a particular shape (wedge, cone, ball or flat disk). The penetration resistance can be measured by pushing a shaped item into the material at a constant rate and during the penetration the force on the tip is measured and related to the strength of the material. The penetration stress is measured in kPa or $N/m^2$.

Various penetration tests exist, often developed in the field of geosciences and soil mechanics researching the compaction of soils and rocks. This was needed to analyze vehicle mobility problems and agricultural related problems. Yu and Mitchell [1998] has researched the available theories for the analysis of cone resistance and made comparisons among them. The main theories for penetration resistance are 1) bearing capacity theory; 2) cavity expansion theory; 3) steady state deformation; 4) incremental finite element analysis; 5) calibration chamber testing.

A typical penetration resistance profile as a function of depth for a homogenous specimen is shown in Figure 3.10. When the penetration cone enters the material the penetration resistance increases due to the development of the yield zone in the surrounding material. The yield zone increases as the cone enters the material deeper due to decreasing influence.
of the free surface. Eventually the yield zone will become fully developed and will reach a steady-state (for very deep depths). In the steady state a the maximum penetration resistance is reached and will remain constant, also known as the limiting penetration resistance ($q_{lim}$) Janda and Ooi [2016].

![Figure 3.10: Typical penetration resistance profile with depth for a homogeneous material [Janda and Ooi, 2016]](image1)

![Figure 3.11: Typical penetration resistance profile with depth for a homogeneous material [Janda and Ooi, 2016]](image2)

Janda and Ooi [2016] modeled the penetration resistance using DEM simulation software as a function of the depth for a soil. This experiment used a uniaxial confined compression to mimic the consolidation process of real soils. Following the compression was performed by moving the top plate down with a constant velocity. Once the vertical stress reached the desired consolidation stress, the top plate was moved upward until the sample was completely unloaded. The resulting penetration resistance can be found in Figure 3.11.

The penetration tests can be split in static tests, dynamic tests, laboratory tests, real-life tests with various penetrating velocities and penetrating tools. In this section the differences between the penetration tests are described.

### 3.4.1 Static vs. Dynamic test

Lommen [2011] has researched the advantages and disadvantages of static and dynamic penetration tests. With a static test the bulk material is penetrated with a constant velocity. The force needed to achieve a certain depth is measured. The result is the cone index: the resistance force per unit area. With a dynamic test the penetration tool is dropped from a certain height into the bulk material. The depth achieved by the impact is measured. The result is the resistance in terms of energy per unit depth.

A static test is chosen as it can be controlled by an actuator. This actuator can be controlled by the machine ensuring a constant downward velocity of the tip of the penetration tool. The machine that can be used for this is the hydraulic servo controlled test frame available at the laboratory of geosciences and engineering at the Delft University of Technology.
3.4.2 Laboratory vs. in situ test

The test can either be performed in the laboratory or in a real-life in the field situation also called an in situ test. The advantage of an laboratory test is that it is performed in a controlled environment. This means that there are no influences of environmental conditions such as wind, snow, ice, rain, hot, cold or sunny weather conditions. These environmental conditions could influence the measurements as these conditions can influence the density and moisture content of the material.

An advantage of an in situ test is that it gives similar results to what a grab in the field would also experience. A laboratory experiment is limited to a much smaller scale sample, penetration tool, compaction and moisture methods than would occur in the field. For this experiment a laboratory test is chosen as it is easy to perform in a controlled environment thus more likely to gain re-producibility of the testing result.

3.4.3 Horizontal vs. Vertical penetration tests

A horizontal penetration test is where the bulk material is penetrated from the side. The side being 90° from where the sample is loaded. As an example, the bulk sample is loaded from the top while the penetration is done at either the left or the right side of the sample. A vertical penetration test is that the bulk material is penetrated from the top, the same side of which it is loaded. U.S. Department of Commerce [1969] has conducted some experiments with both horizontal and vertical penetration tests. For this experiment only a vertical penetration test is chosen as this mimics the grab unloading the cargo carrier.

3.4.4 Wedge penetration vs. Cone penetration

In soil mechanics studies often cone penetration is used to measure the penetration resistance of the soil. Standard test for cone penetration are the (pocket)penetrometer or the cone penetration test (CPT). However in the field the grab grabbing the iron ore, does not penetrate the material as a cone but has more resemblance with wedge penetration. Occasionally cone penetration is used to initiate the separation of the material by adding cones to the knife of the grab, however as these are subject to large abrasion most often line contact is preferred.

Cone penetration results in material being moved to all sized while wedge penetration results in plane stress. Mohamed [2003] and Yong et al. [1972] researched the effect of cone penetration versus wedge penetration and concluded that in order to achieve a plane stress effect, a relatively large length of plate and wedges (instead of a cone) were required. In Figure 3.12 and Figure 3.13 the difference between a cone penetration and a wedge penetration is shown. In Figure 3.12, cone penetration is shown, the grey circle in the middle represents the cone penetrating the bulk material (brown). Figure 3.13 shows wedge penetration with the grey rectangle represents the wedge penetrating the bulk material. Notable in the wedge penetration is that the wedge does not come in close contact with the walls of the container holding the sample material, this is to minimize the friction between the wall and the wedge as explained in more detail in Section 4.2. The influence of the shape of the penetration tool is explained in more detail in Section 4.5.1.
3.5 Penetration Velocity

The penetration velocity during a penetration test has a large influence on the penetration resistance with depth due to the drag of the material. The penetration velocity will not be part of the experiment and therefore this parameter will be a constant. To determine the constant value of the penetration velocity a literature research is conducted.

Lommen [2011] has attempted to find a relation between the penetration velocity and the penetration resistance. The velocities used for his penetration tests are 0.67 mm/s, 3.33 mm/s, 8 mm/s, 16 mm/s and 32 mm/s. His findings were that only for the two highest velocities an increase of 15% of the penetration force is observed as shown in Figure 3.14. However as literature is inconclusive and his research remains uncertain whether this 15% increase is due to a margin error of a machine error no conclusion can be drawn about the penetration velocity.

Yong et al. [1972] researched the effect of penetration rates into sand. The penetration velocities varied from 0.04 mm/s to 2.55 mm/s. His findings are that no significant
change in penetration resistance is observed. Asaf et al. [2007] also researched the influence of penetration velocity and found that according to Bekker [1969] (quoted in Asaf et al. [2007]), the influence of the velocity in penetration tests is negligible until the deformation rate reaches a value of 740 mm/s. This would agree with Fowkes et al. [1973] (quoted in Asaf et al. [2007]) who also discovered that the penetration velocity did not show a significant influence on the penetration resistance.

Figure 3.15: Penetration velocity [Janda and Ooi, 2016]

Figure 3.15 shows the variations in penetration resistance based on the DEM simulations performed by Janda and Ooi [2016]. From these DEM simulations it can be concluded that the penetration velocity only has a small impact on the penetration resistance. As the depth of the measurement increases the influence of the penetration velocity becomes more clear, however in the first 0.02 m there is little to no difference.
4 Experiment Selection

In this chapter the experiment parameters are selected and explained. First the iron ore material that will be used for the experiment will be presented, secondly the design of the container that will hold the material during the experiment is explained. Next the selection of the experiment apparatus, thus the machine that will perform the penetration resistance test is elaborated. Following it is explained how the compaction levels are determined. A small recap based on the previous literature study on the moisture content and the penetration velocity is provided. Finally the penetration tool, including the selection of the penetration tool shape, the design of the connection pin from the penetration tool to the test apparatus and the expected penetration force is discussed.

4.1 Iron Ore Material Characteristics

The type of iron ore that will be tested in this experiment is from the laboratory of Civil Engineering at the TUDelft. For confidentiality reasons the specific material and it’s heritage can not be named. In Table 4.1 the specifications of the iron ore based on Van Paassen and Mulder [2012]. They also determined the grain size distribution for the iron ore which can be found in Table 4.2.

<table>
<thead>
<tr>
<th>Moisture content as received</th>
<th>Particle density</th>
<th>Moisture content at TML</th>
<th>Void ratio at TML</th>
</tr>
</thead>
<tbody>
<tr>
<td>%</td>
<td>kg/m$^3$</td>
<td>%</td>
<td></td>
</tr>
<tr>
<td>16.00</td>
<td>4 182</td>
<td>14.1</td>
<td>0.81</td>
</tr>
</tbody>
</table>

Table 4.1: Iron ore characteristics [Van Paassen and Mulder, 2012]

<table>
<thead>
<tr>
<th>d50</th>
<th>d10</th>
<th>gravel</th>
<th>sand</th>
<th>fines</th>
</tr>
</thead>
<tbody>
<tr>
<td>mm</td>
<td>mm</td>
<td>%</td>
<td>%</td>
<td>%</td>
</tr>
<tr>
<td>0.088</td>
<td>0.001</td>
<td>11</td>
<td>46</td>
<td>43</td>
</tr>
</tbody>
</table>

Table 4.2: Iron ore characteristics - grain size distribution [Van Paassen and Mulder, 2012]

Van Paassen and Mulder [2012] also performed a hydrometer test to determine more accurately the grain size of the material sample. The results of this hydrometer test can be found in Figure 4.1. According to Look [2007] the particle size for gravel has to be between 2 mm - 60 mm, for sands 75 $\mu$m - 2 mm and for fines the particle size is < 75 $\mu$m.
In Figure 4.1 a picture of the used iron ore from the side and in Figure 4.3 a picture of the used iron ore from the top can be found. As can be concluded from the pictures and the particle size distribution in Table 4.2 the iron ore has very fine particles.

4.2 Design of the container

The design of the container which will hold the iron ore sample while testing has to fulfill certain requirements. First of all the container should be as small as possible, reducing the amount of material needed for the experiment. However care has to be taken that the tests are unaffected by an adjacent-, side- or bottom wall of the container. U.S. Department of Commerce [1969]. This is called the wall effect, representing the friction between the wall of the container and the material. For cone penetration a rule of thumb to avoid the wall effect for fine-grained soils is to maintain a minimum spacing of twice the diameter of the largest cone.
The length of the penetration tool is 200mm as shown in Figure 4.14. Based on Figure 3.13 to achieve plane stress the material only has to move to the sides, basically splitting the material. The material does not have to move up or down. Therefore the width of the box can be as wide as the wedge; 200mm with a small space between the wedge and the edge of the box. The small space between the wedge and the wall should be large enough to avoid wall friction. This can be achieved by applying some silicon grease between the wall and the wedge Schwedes [2002]. In practice however it is hard to achieve this. Therefore the width of the box is selected to be 250 mm. This allows more space for the material between the container wall and the wedge. To still be able to visually observe the wedge, the wedge can be placed on the side of the container near the Plexiglas wall.

The dimensions of the container are limited by the apparatus to be used for the penetration test. The penetration tool has a length of 75mm. Therefore the depth of the box should be at least \( 75\text{mm} \cdot 2 = 150\text{mm} \), to avoid the wall effect of the bottom of the container. As some room is needed for compaction of the material, the depth of the container is chosen to be 200 mm.

The length of the container is of importance because as the material is penetrated the material will move to the sides. The width of the penetration tool is 40 mm. To ensure enough space on both sides at least 80 mm on each side is needed, resulting in a total width of \( 80 + 80 + 40 = 200 \text{ mm} \). As the container has to be re-usable for future tests, with maybe larger wedges, the length of the container is chosen to be 300 mm as shown in Figure 4.4.

The volume of the container is \( 0.015 \, \text{m}^3 \). As 15 L of material is required and there is a limited amount of material available, the material will be reused. The produced design of the container can be seen in Figure 4.5. The technical drawings of the container can be found in Appendix A.

### 4.2.1 Plexiglas Wall

One wall of the container is to be made from plexiglas. Asaf et al. [2007] performed a wedge penetration test using a Plexiglas container with the dimensions 0.2 m x 0.2 m x 0.2 m. The use of Plexiglas enables visual observation what happens during the experiment. Yong et al. [1972] researched that the particle trajectories from the penetration can be determined as shown in Figure 4.6. The zone of disturbance can indicate how much each particle moves and if there is a large particle movement near the wall,
indicating wall friction. The particle movements that can be found in Figure 4.6 only show one side of soil movement due to the wedge penetration.

Figure 4.6: Particle movement with a wedge penetration [Yong et al., 1972]

Although not part of the initial research plan, the movement of the particles would lead to an interesting verification for the DEM simulation which will result from this test. By using a normal camera a video can be made of the particles and using GeoPIV-RG the particles can be analyzed. GeoPIV-RG is an image analysis module for MATLAB designed for geotechnical research applications University of Western Australia and Queens’ University Canada.

4.3 Criteria for Experiment Apparatus

Based on the following criteria the apparatus for the experiment is selected. The goal is to create conditions similar to the in situ conditions.

4.3.1 Compaction Apparatus

- The apparatus must be able to supply the required force.
- The deviation in the apparatus must be reasonably small.
- The apparatus must be available at the TUDelft.
- The room for the experiment must be sufficiently large to hold the container.
- The apparatus must not absorb water.
- The apparatus must produce repeatable measurements.
- The experiment must be performed within a reasonable timespan.
- The apparatus can be used with different materials.
- The apparatus must be able to produce a force-displacement curve.
- The apparatus must be the same apparatus as the apparatus for the penetration test as the container filled with iron ore is too heavy to be transported according to the Arbo-wet.
4.3.2 Penetration Apparatus

- The deviation in the apparatus must be reasonably small.
- The apparatus must be available at the TUDelft.
- The deformation of the shaft must be at least 200 mm.
- The room for the experiment must be sufficiently large to hold the container.
- The existing wedge must be able to be attached to the apparatus.
- The apparatus must not absorb water.
- The apparatus can be used for material with varying moisture contents.
- The apparatus must be able to penetrate the material with the required velocity.
- The apparatus can be used with varying penetration velocity.
- The apparatus must produce repeatable measurements.
- The experiment must be performed within a reasonable timespan.
- The apparatus can be used with different tools and materials.
- The apparatus must be able to produce a force-displacement curve.
- The apparatus must be the same apparatus as the apparatus for the compaction as the container filled with iron ore is too heavy to be transported according to the Arbo-wet.

4.4 Selection of Experiments

The apparatus selection, determination of the compaction levels, including the compaction methods, moisture content and velocity are discussed in this section.

4.4.1 Compaction

To determine the compactness levels for the penetration tests, the iron ore shipping situation from Section 2.2 is analyzed. In Figure 4.7 two types of cargo hold designs can be found. The left illustration shows a typical cargo hold for an ore carrier and the right illustrates a typical cargo hold for a general bulk carrier. As only an estimation of the compactness of iron ore is needed, the left configuration is chosen. The design of the cargo hold must comply with the Rules for Classification of Ships Pt.3 Ch.1 Sec.12 as explained by Det Norske Veritas [2003]. The definitions of the symbols can be found in Table 4.3.

![Cargo hold design](image)

Type: ore carrier

Type: general bulk carrier

Figure 4.7: Cargo hold design [Det Norske Veritas, 2003]
Table 4.3: Design parameters for the cargo hold Det Norske Veritas [2003]

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>b_f</td>
<td>Breadth of hold in m at level 0.3 H (0.4 H for ore carriers) above inner bottom at hold midlength.</td>
<td>45 m</td>
</tr>
<tr>
<td>h_c</td>
<td>Assumed height of cargo surface above the inner bottom in hold. For ore carriers, it is to be taken 0.4 H + 0.2 bf within 60% of the middle breadth of hold, and linearly reduced to a level 0.4 H at hold sides.</td>
<td>21 m</td>
</tr>
<tr>
<td>H</td>
<td>Height of hold (including hatchway) above plane part of inner bottom in m.</td>
<td>30 m</td>
</tr>
<tr>
<td>l_h</td>
<td>Length of hold above lower stool in m, measured to the middle of corrugation depth.</td>
<td>45 m</td>
</tr>
</tbody>
</table>

The assumption is made that the height (H) and the width (l_h) of the cargo hold are both 30 m. Using the equations given in Table 4.3 the values for h_c and b_f are calculated as shown in the right column of Table 4.3. To verify that this design is stable, the angle of the material slope is calculated to ensure that this is not larger than the angle of repose (AoR). The material slope is 19.3°, which is smaller than the AoR of iron ore.

For simplification of the calculation 1 column is taken with a width of 1 m instead of the entire width of 30 m. This simplification is shown in Figure 4.8. In the cargo hold the material’s own weight pushes down on the material below it, causing pressure in the material. The height difference is each time taken 1 m and following the corresponding pressure in kN is calculated using equation 4.1. \( \rho \) is the assumed density of iron ore (2600 kg/m\(^3\)), \( h \) the height of the material, varying from 0 - 20 m, \( g \) the gravitational acceleration (9.81 m/s\(^2\)) and \( A \) the area (1 m\(^2\)). Figure 4.9 shows the corresponding pressure at each height, this can also be found in Table 4.4.

\[
\sigma = \frac{\rho \cdot h \cdot g}{A \cdot 1000}
\]  

\[ (4.1) \]
Table 4.4 shows the resulting stress in kPa and the corresponding force needed to be applied to the material in the container to obtain the same stress as predicted for the cargo hold. The force required to mimic the pressure can be calculated using equation 4.2. \( F = \sigma \cdot A \) (4.2)

Table 4.4: Stresses in the material on 0, 5, 10, 15 and 20 m respectively

<table>
<thead>
<tr>
<th>Height [m]</th>
<th>Corresponding Stress [kPa]</th>
<th>Corresponding Force [kN]</th>
<th>Actual Applied Force [kN]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>25.5</td>
<td>1.91</td>
<td>1</td>
</tr>
<tr>
<td>5</td>
<td>127.5</td>
<td>9.56</td>
<td>5</td>
</tr>
<tr>
<td>10</td>
<td>255.1</td>
<td>19.13</td>
<td>10</td>
</tr>
<tr>
<td>15</td>
<td>382.6</td>
<td>28.70</td>
<td>20</td>
</tr>
<tr>
<td>20</td>
<td>510.1</td>
<td>38.26</td>
<td>40</td>
</tr>
</tbody>
</table>

The pressure calculated is reviewed in the literature. Munro and Mohajerani [2016] performed research on the TML of iron ore and used several consolidation pressures to achieve the properties of iron ore under these pressures. As can be seen in Figure 4.10 the consolidation pressures that were used range from 1 kPa to 600 kPa. These results are corresponding to the 0 - 500 kPa levels that are calculated for the cargo hold situation in Table 4.4. Janda and Ooi [2016] modeled the penetration resistance using DEM simulation software as a function of the depth for a soil and also used a vertical uniaxial stress ranging from 0 kPa to 500 kPa as can be seen in Figure 3.10. This range corresponds to the situation calculated in Table 4.4.

<table>
<thead>
<tr>
<th>Consolidation pressure (( \sigma ))</th>
<th>Void ratio (( e ))</th>
<th>Coefficient of compressibility (( C_{v} ))</th>
<th>Coefficient of consolidation (( C_{c} ))</th>
<th>Hydraulic conductivity (calculated) ( (L) )</th>
<th>Hydraulic conductivity (direct measurement) ( (L) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>(kPa)</td>
<td>(m(^3)/MS)</td>
<td>(m(^3)/yr)</td>
<td>(m/s)</td>
<td>(cm/s)</td>
<td>(cm/s)</td>
</tr>
<tr>
<td>1</td>
<td>1.14</td>
<td>43.22</td>
<td>20</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>10</td>
<td>0.99</td>
<td>12.41</td>
<td>139</td>
<td>5E-07</td>
<td>5E-05</td>
</tr>
<tr>
<td>50</td>
<td>0.81</td>
<td>2.13</td>
<td>2481</td>
<td>2E-09</td>
<td>2E-04</td>
</tr>
<tr>
<td>100</td>
<td>0.80</td>
<td>0.24</td>
<td>3789</td>
<td>3E-07</td>
<td>3E-05</td>
</tr>
<tr>
<td>200</td>
<td>0.71</td>
<td>0.15</td>
<td>4092</td>
<td>2E-07</td>
<td>2E-05</td>
</tr>
<tr>
<td>400</td>
<td>0.71</td>
<td>0.04</td>
<td>4222</td>
<td>3E-08</td>
<td>3E-06</td>
</tr>
<tr>
<td>600</td>
<td>0.67</td>
<td>0.02</td>
<td>4055</td>
<td>2E-08</td>
<td>2E-06</td>
</tr>
</tbody>
</table>

Figure 4.10: Rowe cell results [Munro and Mohajerani, 2016]

In the right column of Table 4.4, ‘the actual applied force’: the forces that will be applied during the experiment can be found. The applied forces do not correspond directly with the calculated force necessary as shown in the 3rd column ‘corresponding force’. The values are rounded off for easy set-up of the penetration machine. However the minimum and maximum required force are taken into account, but the steps in between are doubled each time to see if there is a relation between the increase in applied force and the measured penetration resistance.
Compaction method

Many compaction methods such as the proctor-fagerberg test compact the material in layers. As we wish to mimic the field situation, the material in the cargo hold of the ship will only be compressed by loading the cargo hold (drop height as explained in Section 3.1.2) and by its own weight. Therefore it is chosen to also compact the material in layers to achieve this uniform compaction.

4.4.2 Moisture

In Section 3.2 the influence of moisture content for the penetration resistance is explained as well as the importance to prevent liquefaction while shipping iron ore. In Table 4.1 the moisture content of the received iron ore can be found. The received moisture content of the iron ore is 16% and the moisture content at the TML is 14.1%, thus indicating that liquefaction is at risk when compacting the material. Liquefaction, as explained in Section 3.2 is a phenomenon in which a soil-like material is abruptly transformed from a solid dry state to an almost fluid state. This especially happens when compaction takes place. As high forces are used in this experiment the moisture level of the sample is taken at 5%, to prevent liquefaction under all circumstances. The moisture factor will be a constant parameter in this experiment. The procedure for preparing the material sample at a 5% moisture level follows the NEN-EN 1097-5 standard Delft University of Technology [2008] and is explained in Section 5.1.

4.4.3 Velocity

The maximum velocity of the hydraulic servo controlled test frame is unknown. However tests are often performed at very low speeds. Therefore it is chosen in collaboration with the senior technicians of the faculty of geosciences and engineering of the Delft University of Technology that the velocity will be set at 6 mm/s.

This speed is based on the literature study performed in Section 3.5. All sources stated that the penetration velocity has a little to no influence on the penetration resistance. Only at greater depths the penetration velocity might have a small influence. The penetration depth of the experiment is limited, only 10 cm, therefore it is not expected that the penetration velocity will have a significant influence. A study on the sensitivity of the penetration velocity on the penetration resistance, by varying the penetration velocity is not part of the experiment. Therefore the penetration velocity will be set as a constant parameter.

4.4.4 Machine type selection

Based on the laboratory equipment of the TUDelft Delft University of Technology [2016] a selection of suitable equipment can be made based on the availability of equipment. For compaction the machine has to be able to provide a minimum of 500 kPa equal to 40kN compression force as stated in Table 4.4. Based on the dimensions of the container the travel length of the shaft should be at least 200 mm. There are several compression benches available at the TUDelft as shown in Table C.1 in Appendix C.

The difference between a hydraulic press and a mechanical press is that a hydraulic press relies on fluid pressure while a mechanical press transforms the rotational force
of a motor into a translational force vector that performs the pressing action. As the energy in mechanical presses comes from the motor these presses are generally faster than hydraulic presses.

The machine that is selected is the hydraulic servo controlled test frame with a maximum force of 200kN at the faculty of civil engineering and geosciences. This machine is selected based on it’s characteristics and availability on short term. The maximum deflection of the hydraulic servo controlled test frame is 300 mm. The space in the test frame is large enough to contain the container and the wedge and is able to produce a force-displacement curve. The hydraulic servo controlled test frame is shown in Figure 4.11 and the controller in Figure 4.12.

![Figure 4.11: The hydraulic servo controlled test frame](image1.jpg)

![Figure 4.12: The operating panel of the hydraulic servo controlled test frame](image2.jpg)

The hydraulic servo controlled test frame indicated in Figure 4.11 has an error at the starting point. This error is 0.56 kN as indicated in Figure 4.13. This error must be taken into account when analyzing the results.

![Figure 4.13: Error for the apparatus at starting point](image3.jpg)
4.5 Penetration resistance

The penetration resistance test is based on the test performed by Lommen [2011]. Vertical penetration tests will be conducted. The penetration tool is attached to a steel shaft of a much smaller diameter than the penetration tool. The shaft is connected to a force-measuring load cell. The shafts are strong enough to ensure straight alignment and small enough to prevent soil drag.

For repeatability of the experiment at least 3 penetration tests will be performed for each compaction level according. This is in accordance to U.S. Department of Commerce [1969], so that an average value relatively unaffected by soil uniformities can be obtained.

4.5.1 Penetration tool

The same penetration tools that Lommen [2011] and Lommen [2016] will be used. Figure 4.14 shows these 3 wedges. The study regarding the dimensions and shape of the penetration tool shall not be included in this research. A small summary of the design choices made by Lommen shall be given as these parameters to a large extent influence the penetration resistance.

The tool is chosen to be symmetric to minimize the bending stress in the experimental apparatus. The 40mm width of the penetration tool is based on manufacturing requirements stating a minimum of 30mm and a maximum of 50mm and the characteristics of a real grab. Ideally the width of the penetration tool should be as thick as the bucket and knives of a grab. The tool angle has been chosen to be 30° as this is the most standardized angle used by other researchers such as Asaf et al. [2007], Fowkes 1973. Mohamed [2003] and Yong et al. [1972] have researched several tool angles (30°, 60°, 90°, 120° and 150°) and concluded that only 30° and 90° were sufficient for the penetration resistance tests. Yong et al. [1972] researched that with increasing tool angle the penetration resistance will increase as shown in Figure 4.16. Lommen also researched the effect of a sharp tip and blunt tip on the penetration resistance of iron ore. The blunt tips are expected to increase the penetration resistance compared to the sharp tip. However blunt tips are often used with grabs as a sharp tip would not be able to withstand heavy loads and the abrasive nature of iron ore. For this experiment penetration tool B will be used. Research by Baligh and Scott [1976] showed that the smoothness or roughness of the penetration tool also as a large effect on the penetration resistance as shown in Figure 4.17. It can be seen that the shape and texture of the wedge influences greatly the penetration resistance.
Other researchers such as Medvedev [2009] researched the types of penetration tools. The tools displayed in 4.18 show differences in soil resistance to compression as shown in Figure 4.19. Although the shape of the wedge is not taken into account in this research it is an interesting aspect to consider in future research.
4.5.2 Design of connection pin penetration tool

The penetration tool B has to be connected to the selected penetration apparatus. Based on the connection of the wedge and the connection of the penetration apparatus a connection pin was designed. The design has to take into account the force it had to transfer to the wedge.

In Figure 4.20 the left picture displays the dimensions of the connection pin to the penetration apparatus. The connection to the apparatus has a diameter of 30 mm with a thread of 1.5 mm. The pin was designed to be 50 mm in length so that any slight inclinements or declinements of the tool would not affect the connection pin. In addition as the connection only has to transfer a pushing load, the connection did not have to be any longer. In Figure 4.20 the center picture displays the already available penetration tool. This tool connection has a diameter of 12 mm with a standard thread size. The length of the wedge connection is 25 mm. Next the part in between was designed. This was designed so that it would connect perfectly to the wedge, so that the forces are directly transferred through this middle bolt instead via the thread connection with the wedge. In the right picture the final produced connection pin can be found. The technical drawings for the connection pin can be found in Appendix B.
4.5.3 Penetration Force

The penetration force required to penetrate the compacted iron ore has to be estimated to determine which apparatus is suitable to use in the experiment. Yong et al. [1972] researched the penetration resistance of sand and clay for different tool angles. 93.84 Pcf is equal to around 1503 kg/m³ and the largest force measured for a wedge angle of 30° is 52.5 lb equal to 233N. Lommen [2011] researched the penetration resistance of iron ore in several states (loose, medium and dense). These results can be found in Figure 4.21. Based on these results it can be concluded that the ‘dense’ compaction has a maximum penetration resistance of 1000 N (1kN).

The research of Janda and Ooi [2016] predicts a higher penetration force. Figure 3.11 shows the penetration resistance predicted with the depth. For a vertical compaction stress of 500 kPa the modeled penetration resistance is 1 Mpa. With an area of 0.075 m² this results in a penetration force of 75 kN for our container. However it must be noted that for this simulation the depth at which this force was required is 0.03 m and this is already in the steady-state. Our experiment will require 0.1 m penetration and will probably not reach the steady state. In addition in the simulation of Janda and Ooi [2016] a penetration velocity of 0.03 m/s was used were in our case a penetration velocity of only 0.006 m/s will be used. Therefore the penetration resistance can be expected to be lower. In any case the hydraulic servo controlled test frame is able to provide 200 kN of force and therefore the expected penetration resistance will be able to be provided.
5 Experimental Plan

In this chapter the three phases of the experiment and the steps that will be performed during these phases will be explained. The first phase is the preparation of the test material, preparing it with 5% moisture content. The second phase is the compaction of the material to the required stress level and the third phase is the penetration resistance of the iron ore.

5.1 Phase 1: 5% Moisture Content

The material is delivered in plastic bags loaded in crates. It is unknown what the current moisture content of the sample is. Therefore the iron ore will be loaded into large containers which will be placed in a drying oven according to the standard NEN-EN 1097-5: Test for mechanical and physical properties of aggregates - Part 5: Determination of the water content by drying in a ventilated oven Delft University of Technology [2008].

The procedure that will be as follows:

1. Clean and dry the tray.
2. Weight and record the mass of the tray (M2).
3. Spread the test portion out on the tray.
4. Weigh the tray containing moist test portion.
5. Determine mass of the test portion (M1).
6. Place the tray in the oven at 110 degrees for 24 hours.
7. Cool the tray to room temperature.
8. Determine the mass of the test portion (M\text{d1}).
9. Return the tray with test portion to the oven for at least 1 hour.
10. Cool the tray to room temperature.
11. Repeat the determination of the mass of the test portion (M\text{d1}).
   (a) If M\text{d1} < 0.1% of Md1 constant mass is assumed to be achieved.
   (b) If M\text{d1} > 0.1% of Md1 repeat procedure.
12. Determine final mass (M3).

Using the final mass, 5% moisture content is calculated using equation 5.1. 1 kg is equal to 1 liter (L) water. The water is now mixed with the material. The mixing will take place in the mixing apparatus at the faculty of civil engineering and geosciences. The water and iron ore will be mixed for 5 minutes.

\[ L = 0.05 \cdot M3 \] (5.1)

5.2 Phase 2: Compaction of the material

Before compacting the material, the material is loosened to ensure that no compaction remaining from the mixing or transportation. Following the iron ore will be loaded in 3 stages in the designed container. Each stage will be compacted using a predetermined force. The hydraulic servo driven test frame will apply force until the requested force is
reached. Following the load will be released from the material.

When loading the material in the container, each time 1/3 of a full container weight will be added: 8 kg. During each compaction step, the force is determined by the hydraulic servo driven test frame indicating how much the material is compacted. Using the displacement the new density can be calculated. This process is illustrated in Figure 5.1 and Figure 5.2.

![Diagram of compaction process](image)

Figure 5.1: Steps 1-3 in the compaction process

![Diagram of compaction process](image)

Figure 5.2: Steps 4-6 in the compaction process

The compaction forces used to compact the material are based on Table 4.4 and are re-calculated for the applied forces as shown in Table 5.1.
Table 5.1: Force for compacting the material

<table>
<thead>
<tr>
<th>Actual Force [kN]</th>
<th>Equivalent Pressure [kPa]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>13.3</td>
</tr>
<tr>
<td>5</td>
<td>66.6</td>
</tr>
<tr>
<td>10</td>
<td>133.3</td>
</tr>
<tr>
<td>20</td>
<td>266.7</td>
</tr>
<tr>
<td>40</td>
<td>533.3</td>
</tr>
</tbody>
</table>

After the completed compaction phase (3 layers) the penetration resistance of the material is tested. After the penetration tests are finished the material is loosened and mixed. Following the material is compacted again with the next force level. To avoid crushing (e.g. breaking of the particles) as soon as a crushing noise is registered (which is not expected), the material will not be tested any further. As a consequence of crushing the remaining higher forces will not be tested. Each compaction & penetration resistance experiment will be repeated 3 times to examine if it is a repeatable experiment.

The procedure will be as follows:

1. Clean and dry the container
2. Weight and record the mass of the container
3. Determine the amount of sample to be added
   (a) Determine the bulk density of the loose material \( \rho_{\text{loosebulk}} \).
   (b) The container volume is \( 0.3 \cdot 0.25 \cdot 0.2 = 0.015m^3 \) \( V_{\text{container}} \).
   (c) The mass of one layer is \( M_{\text{sample}} = 0.3 \cdot \rho_{\text{loosebulk}} \cdot V_{\text{container}} \).
4. Repeat for 3 layers (stages):
   (a) Add the sample to the container and spread out in container.
   (b) Weight and record the mass of the container + stage X.
   (c) Apply required pressure.
   (d) Weight and record the mass of the container + stage X compacted.
   (e) Measure the displacement of the material (manually + force displacement curve).

5.3 Phase 3: Penetration Resistance

The penetration resistance will be performed using the same machine as the compaction experiment. The servo controlled test frame is programmed for the penetration of the material to obtain a constant velocity of 6 mm/s. This will not be achievable when operated manually. As it is uncertain what the maximum deflection of the servo controlled test frame is and because it is hydraulically controlled a safety limit is imposed on the test set-up so that under no circumstances the bottom of the container is reached. The maximum deflection is set at 5 mm, equivalent to 5 cm from the bottom as can be seen in Figure 5.3.
In Figure 5.3 the measurement set-up can be seen. The servo controlled test frame is able to measure from -150 mm till 150 mm. When the wedge is positioned on the upmost position the measurement reads -150 mm. When the wedge is in the downmost position the measurement reads +150 mm. The safety limit is set at +5 mm, this 50 mm above the bottom of the container. At the top of the container there is a small space between the wedge and the container of 5 mm to move the container in and out of the servo controlled test frame to prepare the material sample.

The results of the measurements are translated such that the height of the material is set as the 0-line. As the compaction force decreases the height of the material decreases, the deflection of the wedge that the machine measures does not say anything about how far the wedge has penetrated the material. By taking the material height as the 0-line the various measurements can be compared based on how far they penetrated the material and what forces were required to reach this depth in the material.

![Figure 5.3: Measurement Set-up](image)

After the penetration test the wedge will be moved upward again with the same speed. Each experiment will be repeated at least 3 times to examine that the experiment will produce repeatable results.
6 Results

In this chapter the results of the 3 phases of the experiments will be presented. First the results of the drying of the material and adding the 5% moisture content are presented followed by the results of the compaction of the material. Finally the penetration test results are shown.

6.1 Phase 1: 5% Moisture Content

In this section the results of the 5% moisture content phase of the experiment are presented. First the material is dried, following the dry bulk density is determined followed by the adding of the 5% moisture content.

The scale that has been used for the measurement of the amount of iron ore material and the amount of water to be added is located at the faculty of Geosciences and Civil Engineering. This is a Mettler PM30-K calibrated scale. The latter referring to the fact that the scale has been calibrated using calibration weights. The scale has a significance of 3 digits and therefore has an error of 1 gram. The used scale is shown in Figure 6.1.

6.1.1 Drying the material

In Section 5.1 the procedure for drying the material is described. The material was divided into 3 trays. After 24 hours of drying the material was weighed and the results can be found in Table 6.1. In Table 6.1 the 0.1% change in weight is calculated in the last column, indicated in green. If the difference in mass of the material is smaller than 0.1%, the material is considered dry. The mass of the material after 24 hours of drying is larger than 0.1% and therefore the material is not dry yet.

<table>
<thead>
<tr>
<th>[kg] Container</th>
<th>Mass of tray M1</th>
<th>Mass of sample M2</th>
<th>Mass after drying Md1 (24h)</th>
<th>0.1% Md1</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3.336</td>
<td>27.684</td>
<td>24.164</td>
<td>0.0242</td>
</tr>
<tr>
<td>2</td>
<td>3.325</td>
<td>28.969</td>
<td>26.155</td>
<td>0.0262</td>
</tr>
<tr>
<td>3</td>
<td>1.129</td>
<td>9.246</td>
<td>8.483</td>
<td>0.0085</td>
</tr>
</tbody>
</table>

After 48 hours of drying the material only reduced a little in weight compared to the 24 hours of drying as can be seen in the last column of Table 6.2. The difference however is still too large compared to the 0.1% of Md1 (indicated in the last column of Table 6.1. Therefore it may not be assumed that there is a constant mass, indicated by the red color in the last column in Table 6.2.
Table 6.2: Iteration 2: 48 hours drying

<table>
<thead>
<tr>
<th>Container</th>
<th>Reference 24h Md1 (24h)</th>
<th>Iteration 2 Md2 (48h)</th>
<th>Difference 24h and 48h</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>24.164</td>
<td>24.603</td>
<td>-0.439</td>
</tr>
<tr>
<td>2</td>
<td>26.155</td>
<td>25.800</td>
<td>0.355</td>
</tr>
<tr>
<td>3</td>
<td>8.483</td>
<td>8.243</td>
<td>0.240</td>
</tr>
</tbody>
</table>

After 49 hours of drying the material mass change was smaller than 0.1% as can be seen in the 4th column in Table 6.3. The change in mass is smaller than 0.1% of Md1 and therefore constant mass may be assumed, indicated by the green color in the 3rd column of Table 6.3. Following the final dry material mass is calculated using equation 6.1. Finally the dried iron ore is cooled down and stored at in a dark dry place in containers wrapped in cling film to prevent any evaporation or adding of moisture by the environment from or to the iron ore.

\[ M3 = Md3 - M1 \]  

(6.1)

Table 6.3: Iteration 3: 49 hours drying

<table>
<thead>
<tr>
<th>Container</th>
<th>Iteration 2 Md1 (24h)</th>
<th>Iteration 3 Md3 (49h)</th>
<th>Difference 48h and 49h</th>
<th>Material Mass M3</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>24.603</td>
<td>24.604</td>
<td>-0.001</td>
<td>21.268</td>
</tr>
<tr>
<td>2</td>
<td>25.800</td>
<td>25.800</td>
<td>0.000</td>
<td>22.475</td>
</tr>
<tr>
<td>3</td>
<td>8.243</td>
<td>8.242</td>
<td>0.001</td>
<td>7.113</td>
</tr>
</tbody>
</table>

6.1.2 Dry bulk density

To calculate the dry bulk density an arbitrary container was selected. The empty weight of this container was determined. Following the container was filled with water and the mass of the container with water was determined. Using this knowledge the volume of the container was calculated using equation 6.2. Next the container was filled with iron ore and the mass of the iron ore is weighted. The dry bulk density of the iron ore can now be calculated using equation 6.3.

\[ V_{container} = (M_{container+water} - M_{empty})/\rho_{water} \]  

(6.2)

Table 6.4: Parameters for calculating dry bulk density

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Empty weight container</td>
<td>1.952 kg</td>
</tr>
<tr>
<td>Weight container with water</td>
<td>3.756 kg</td>
</tr>
<tr>
<td>Weight container with iron ore</td>
<td>4.829 kg</td>
</tr>
<tr>
<td>Density of water</td>
<td>1000 kg/m³</td>
</tr>
<tr>
<td>Volume container</td>
<td>1.804 L / 0.001804 m³</td>
</tr>
<tr>
<td>Density of iron ore</td>
<td>1595 kg/m³</td>
</tr>
</tbody>
</table>
6.1.3 Adding moisture

The weight of the empty mixing bowl is measured. Following the scale with the mixing bowl on top of it is put again to 0.000 kg. Next the mixing bowl is filled with 10.000 kg of Iron ore, shown in the left picture in Figure 6.1. 5% is water is calculated using Equation 5.1. The scale is set to 0.000 kg again and 0.5 kg of water is added as shown in the middle picture in Figure 6.1. Following the iron ore is mixed for 5 minutes using the mixer as shown in the right picture of Figure 6.1. After mixing the iron ore is weighed to 8 kg, equivalent to 1/3rd of the material for a full test up container and stored in a container in a dry and dark place. The container is wrapped in cling film to prevent water from evaporating, due to environmental conditions, as shown in the right picture in Figure 6.2.

![10 kg iron ore, 0.5 kg water, Mixing for 5 min](image)

Figure 6.1: The mixing process

![Iron ore before and after mixing, Stored iron ore](image)

Figure 6.2: The mixing process continued

The left image in Figure 6.2 shows the iron ore before and after the mixing. Interesting
to see is that before mixing there are several large pieces of iron ore present in the material (agglomerates). After mixing these pieces have been broken down into smaller pieces.

6.2 Phase 2: Compaction of the Material

In this section the results of the second phase of the experiment: compaction of the material are presented. First the general compaction process is described. Secondly the change from 3 layer compaction to 1 layer compaction is explained and evidence is presented why this is more convenient. Finally the material densities for all the experiments are presented.

6.2.1 General compaction

The material is compacted as explained in Section 5.2. The material is compacted in layers of 8 kg. First 8 kg of the sample material is added. Following the material is compacted with the predetermined force and following the second layer of 8 kg is added and again compacted with the predetermined force. Finally the 3rd layer of 8 kg of the material is added and again compacted with the predetermined force.

The material is compacted using the top sheet that is fabricated by Nemag. This top plate is used so that the force of the hydraulic servo controlled test frame is uniformly divided over the test sample. In Figure 6.3 the process is shown. In the left figure the material is compacted using the top plate and in the right figure the result is shown.

The compaction of the material is done manually by the senior technician Arno Mulder. The force can be increased by lowering the apparatus. By real-time measurement of the force the force can be increased until it reads the required force on the measurement computer. However as it is operated manually the force is often overshoot (e.g. 10 kN is required but 10.5 kN is applied). In addition as the material becomes more compact and the machine has a measurement error, the force than can be read on the measurement computer is slowly decreasing, thus the senior technician has to constantly adjust the force. This however induces some uncertainty in the amount of time that the force is applied to achieve the compaction.

Preferably this compaction process would have been done automatically by the hydraulic servo controlled test frame. However this would double the time required for each experiment as the settings of the machine would have to be manually entered after each experiment. This would have required significantly more time and money.
6.2.2 Results 3 layer compaction vs. 1 layer compaction

For the 5kN compaction it was tested if compacting in 1 layer or in 3 layers would make a significant difference. In Figure 6.4 the penetration resistance for 5kN compaction in 1 layer and 3 layers can be found. The detailed information can be found in Table 6.5.

Figure 6.4: Penetration resistance 5kN Compaction
Table 6.5: Maximum Penetration Resistance 5kN Compaction

<table>
<thead>
<tr>
<th>5kN</th>
<th>Displacement [mm]</th>
<th>Force [kN]</th>
</tr>
</thead>
<tbody>
<tr>
<td>3layer Rep1</td>
<td>97.74</td>
<td>4.24</td>
</tr>
<tr>
<td>3layer Rep2</td>
<td>98.33</td>
<td>4.55</td>
</tr>
<tr>
<td>3layer Rep3</td>
<td>97.73</td>
<td>4.02</td>
</tr>
<tr>
<td>1layer Rep1</td>
<td>98.92</td>
<td>4.30</td>
</tr>
<tr>
<td>1layer Rep2</td>
<td>98.91</td>
<td>4.15</td>
</tr>
</tbody>
</table>

In Table 6.5 the maximum penetration displacement and corresponding force can be found. This maximum penetration resistance is based on the settings of the penetration machine. Due to the manual filling of the material the height and therefore the displacement in the material is not always identical. In Table 6.6 this is corrected to show a comparison to a 90 mm penetration into the material. From these results it can be seen that there is a small difference between the results. Compared the average result the difference with the other values in percentages is acceptably small. Rep 1, 3layer) 5% Rep 2, 3layer) 5%, Rep 3) 3% Rep 4, 1layer) 1% and Rep 5, 1 layer) 6%. As this difference is relatively small it is decided that due to the small difference in results and the time constraint a 1 layer compaction is performed for further experiments.

Table 6.6: Penetration Resistance 5kN Compaction at 90mm Displacement

<table>
<thead>
<tr>
<th>Layer</th>
<th>5kN</th>
<th>Displacement [mm]</th>
<th>Resistance [kN]</th>
<th>Difference [kN]</th>
<th>Percentage [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>3layer Rep1</td>
<td>90.08</td>
<td>3.44</td>
<td>0.00</td>
<td>5%</td>
<td></td>
</tr>
<tr>
<td>3layer Rep2</td>
<td>90.08</td>
<td>3.43</td>
<td>-0.01</td>
<td>5%</td>
<td></td>
</tr>
<tr>
<td>3layer Rep3</td>
<td>90.08</td>
<td>3.18</td>
<td>-0.26</td>
<td>3%</td>
<td></td>
</tr>
<tr>
<td>1layer Rep1</td>
<td>90.08</td>
<td>3.25</td>
<td>-0.19</td>
<td>1%</td>
<td></td>
</tr>
<tr>
<td>1layer Rep2</td>
<td>90.08</td>
<td>3.10</td>
<td>-0.34</td>
<td>6%</td>
<td></td>
</tr>
</tbody>
</table>

An interesting phenomenon that can be seen in Figure 6.4 is that at the start of the measurements there is a sudden increase in the penetration resistance around 0 mm displacement and then it drops again. This bump can either be a measurement error or a failure phenomenon. With increasing compaction forces it can be observed that this bump increases in size. This phenomenon will be explained in the 40kN compaction section.

6.2.3 Results material density calculations

As can be seen in Figure 6.7 there is a lot of noise at the beginning of the measurements. This is due to the fact that the measurements were not all started at the same height. In addition as the material is compacted with a greater force e.g. 1kN vs. 40kN the height of the material is also lower.

To calculate the density of the material the data is calibrated to determine where the wedge experiences resistance for the first time. When the penetration resistance reaches 0.1 kN for the first time is considered as the material height. Based on the material height and the bottom of the container the height of the material can be determined.
Using the volume of the container the density of the material can be calculated. In Figure 6.5 the density of the material can be found.

![Figure 6.5: Density of the material](image)

Keeping in mind that this is an estimate of the density of the material, it can be seen that there is a pattern in the density. As the force applied to achieve the density is not without uncertainty (manually operated and time) the density varies. The pattern that is clear in the measurements is that the more force is applied for compaction the higher the density is.

![Figure 6.6: Relationship between bulk density and penetration resistance](image)

The relation between the bulk density and the penetration resistance can be found in Figure 6.6. There is a trend that the higher the bulk density the higher the penetration
resistance required. This result is as expected. Figure 6.6 shows the same pattern as the pressure at different levels in the ship in Figure 4.9.

6.3 Phase 3: Penetration Resistance

During the penetration test the force and displacement were measured. During the first stages of the measurement the machine only measured noise. This noise has to be filtered from the data, so that an estimate of the material density and the penetration resistance can be made.

The penetration resistance measured for all measurements can be seen in Figure 6.7. In Figure 3.11 it is shown what the expected increase in penetration resistance with depth for various different uniaxial confined compression levels was. The results from the experiment shown in Figure 6.7 show that the higher the uniaxial confined compression level (e.g. 40 kN vs. 1 kN) the higher the penetration resistance. This result is as expected. As the experiment performed was limited by the test apparatus the steady state of the material (where the yield zone is fully developed) is not reached due to the limited penetration depth (only 10 cm).

6.3.1 Particle Trajectory

In Section 4.2.1 it was explained that one wall of the container was made from plexiglas so that the particles could be traced using the GeoPIV-RG program. To perform this experiment different color stones (white) were selected to be added to the material so that the camera would have distinct particles to trace. In addition as the wedge would be located very close to the plexiglas to that the material deformation would be clearly visible. To prevent any damage to the plexiglas a plastic sheet was added between the
Unfortunately due to the very fine particles present in the iron ore, it was not possible to measure the particle trajectory. The iron ore particles were too fine to perform this experiment. The white stones added to the iron ore were covered in the fine particles, making them the same color as the iron ore. In addition, the particles were so fine that the very fine particles attached as dust to the plexiglas wall, making it hard to see the exact particles. The container can in the future be used particle trajectory recognition for iron ore with a larger particle size distribution.

6.3.2 Penetration Resistance Loose Material

![Penetration Resistance Loose](image)

Figure 6.8: Penetration resistance Loose

<table>
<thead>
<tr>
<th>Loose</th>
<th>Displacement [mm]</th>
<th>Penetration Resistance [kN]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rep2</td>
<td>97.12</td>
<td>1.37</td>
</tr>
<tr>
<td>Rep3</td>
<td>101.24</td>
<td>1.42</td>
</tr>
<tr>
<td>Rep5</td>
<td>101.75</td>
<td>1.60</td>
</tr>
</tbody>
</table>

In Table 6.7 the maximum penetration resistance and the corresponding depth is presented. The difference between the lowest penetration resistance measured (1.37) and the highest penetration resistance (1.60) is 0.23 kN. In Figure 6.8 it can be observed that the penetration resistance of the 3 measurements are all increasing with the same speed. The measurements pattern is similar except at the end, where the measurements differ in the maximum displacement and the maximum force.
When examining at the penetration resistance measured at the depth of 90 mm, as shown in Table 6.8 it can be observed that the difference between the penetration resistances is very small; Rep 1) only has a 2% decrease compared to the average result, Rep 2) only has a 8% decrease compared to the average result and Rep 3) 10% increase compared to the average result. Taking into account that the data set for the loose material is very depending on external conditions, it can be concluded that this is a repeatable experiment for the loose condition.

For the loose material the compaction is highly dependent on the external conditions. The iron ore consists of very fine particles and therefore the slightest vibrations and disturbances will result in a different density and therefore a different penetration resistance. Even the impact of filling the container with the material can have an influence on the compaction.

6.3.3 Penetration Resistance 1kN Compaction

Figure 6.9: Penetration resistance 1kN Compaction
Table 6.9: Maximum Penetration Resistance 1kN Compaction

<table>
<thead>
<tr>
<th>1kN</th>
<th>Displacement [mm]</th>
<th>Resistance [kN]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rep1</td>
<td>101.25</td>
<td>2.70</td>
</tr>
<tr>
<td>Rep2</td>
<td>100.66</td>
<td>2.63</td>
</tr>
<tr>
<td>Rep3</td>
<td>102.43</td>
<td>2.43</td>
</tr>
</tbody>
</table>

In Table 6.9 the maximum penetration resistance and the corresponding depth is presented. The difference between the lowest maximum penetration resistance measured (2.43) and the highest maximum penetration resistance (2.70) is 0.17 kN. However this measure does not indicate if the experiment is reproducible as the penetration depth varies. Depending on the displacement and the compaction of the displacement the maximum penetration resistance has a contribution. This will be explained in Figure 6.10. In Figure 6.8 it can be observed that the penetration resistance of the 3 measurements are all increasing with a similar pattern. The measurements pattern is similar except at the end, where the measurements differ in the maximum displacement and the maximum force.

Table 6.10: Penetration Resistance 1kN Compaction at 90mm Displacement

<table>
<thead>
<tr>
<th>1kN</th>
<th>Displacement [mm]</th>
<th>Resistance [kN]</th>
<th>Difference [kN]</th>
<th>Percentage [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rep1</td>
<td>90.06</td>
<td>1.82</td>
<td>0.00</td>
<td>-3%</td>
</tr>
<tr>
<td>Rep2</td>
<td>90.06</td>
<td>1.85</td>
<td>0.02</td>
<td>-5%</td>
</tr>
<tr>
<td>Rep3</td>
<td>90.06</td>
<td>1.62</td>
<td>-0.20</td>
<td>8%</td>
</tr>
</tbody>
</table>

When examining at the penetration resistance measured at the depth of 90 mm, as shown in Table 6.10 it can be observed that the difference between the penetration resistances is very small: Rep 1) only has a 3% decrease compared to the average value, Rep 2) only has a 5% decrease compared to the average value and Rep 3) 8% increase compared to Rep 1. As these differences are small compared to the high stresses that they represent and the machine error taken into account it can be concluded that the measurement is repeatable for the 1kN compaction case.

6.3.4 Penetration Resistance 5kN Compaction

The penetration resistance results for 5kN compaction have already been explained in Section 6.2.2.
6.3.5 Penetration Resistance 10kN Compaction

Figure 6.10: Penetration resistance 10kN Compaction

<table>
<thead>
<tr>
<th>10kN</th>
<th>Displacement [mm]</th>
<th>Resistance [kN]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rep1</td>
<td>94.22</td>
<td>5.38</td>
</tr>
<tr>
<td>Rep2</td>
<td>93.04</td>
<td>5.88</td>
</tr>
<tr>
<td>Rep3</td>
<td>94.21</td>
<td>4.74</td>
</tr>
<tr>
<td>Rep4</td>
<td>93.03</td>
<td>4.90</td>
</tr>
<tr>
<td>Rep5</td>
<td>95.98</td>
<td>4.62</td>
</tr>
</tbody>
</table>

Table 6.11: Maximum Penetration Resistance 10kN Compaction

In Table 6.11 the maximum penetration displacement and corresponding force can be found. This maximum penetration resistance is based on the settings of the penetration machine. Due to the manual filling of the material the height and therefore the displacement in the material is not always identical. In Table 6.12 this is corrected to show a comparison to an 90 mm penetration into the material. From these results it can be seen that there is a small difference between the results. Compared the average result the difference with the other values in percentages is acceptably small. Rep 1) -5%, Rep 2) -16%, Rep 3) 8% Rep 4) 0%, Rep 5) 13%.
Table 6.12: Penetration Resistance 10kN Compaction at 90mm Displacement

<table>
<thead>
<tr>
<th>10kN</th>
<th>Displacement [mm]</th>
<th>Resistance [kN]</th>
<th>Difference [kN]</th>
<th>Percentage [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rep1</td>
<td>90.09</td>
<td>4.79</td>
<td>0.00</td>
<td>-5%</td>
</tr>
<tr>
<td>Rep2</td>
<td>90.09</td>
<td>5.32</td>
<td>0.53</td>
<td>-16%</td>
</tr>
<tr>
<td>Rep3</td>
<td>90.08</td>
<td>4.21</td>
<td>-0.58</td>
<td>8%</td>
</tr>
<tr>
<td>Rep4</td>
<td>90.09</td>
<td>4.56</td>
<td>-0.22</td>
<td>0%</td>
</tr>
<tr>
<td>Rep5</td>
<td>90.09</td>
<td>3.98</td>
<td>-0.81</td>
<td>13%</td>
</tr>
</tbody>
</table>

The experiment of 10kN has been used to test whether the drying of the material by the surrounding air has a significant influence on the experiment. All material was prepared in the same batch following the procedure as explained in Section 5.1. During the experiments of loose material, 1kN and 5kN compaction the same material was used. As each experiment takes between 30-45 minutes including preparation, testing and breaking down the experiment the iron ore 5% moisture content is exposed for a significant amount of time to the environment. As the temperature and moisture content of the room is not controlled it is uncertain what effect this has on the iron ore. Rep 1, Rep 2 and Rep 3 of the 10kN experiment are used for testing with the iron ore batch which has been exposed for a longer period of time to the environment (also for loose, 1kN and 5kN tests). Rep 4 and Rep 5 are iron ore samples which are taken ‘fresh’ from the storage containers. From Figure 6.10 and Figure 6.12 the difference in penetration resistance is present but there is no pattern which could exclusively assign this to the difference in moisture content of the iron ore.

6.3.6 Penetration Resistance 20kN Compaction

![Figure 6.11: Penetration resistance 20kN Compaction](image-url)
In Figure 6.11 the penetration resistance with the penetration depth can be found. The bump which was also seen in a smaller manner for 5kN and 10kN is now more significantly present. In addition it can be seen that a second bump is also formed in the graph. In Section 6.3.7 this phenomenon will be explained.

Table 6.13: Maximum Penetration Resistance 20kN Compaction

<table>
<thead>
<tr>
<th>20kN</th>
<th>Displacement [mm]</th>
<th>Force [kN]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rep1</td>
<td>93.06</td>
<td>7.49</td>
</tr>
<tr>
<td>Rep2</td>
<td>92.47</td>
<td>7.68</td>
</tr>
<tr>
<td>Rep3</td>
<td>90.12</td>
<td>7.69</td>
</tr>
</tbody>
</table>

In Table 6.13 the maximum penetration displacement and corresponding force can be found. This maximum penetration resistance is based on the settings of the penetration machine. Due to the manual filling of the material the height and therefore the displacement in the material is not always identical. In Table 6.14 this is corrected to show a comparison to an 90 mm penetration into the material. From these results it can be seen that there is a small difference between the results. Compared the average result the difference with the other values in percentages is acceptably small; Rep 1) 5% Rep 2) 1%, Rep 3) -6%.

Table 6.14: Penetration Resistance 20kN Compaction at 90mm Displacement

<table>
<thead>
<tr>
<th>20kN</th>
<th>Displacement [mm]</th>
<th>Resistance [kN]</th>
<th>Difference [kN]</th>
<th>Percentage [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rep1</td>
<td>90.11</td>
<td>6.96</td>
<td>0.00</td>
<td>5%</td>
</tr>
<tr>
<td>Rep2</td>
<td>90.12</td>
<td>7.22</td>
<td>0.25</td>
<td>1%</td>
</tr>
<tr>
<td>Rep3</td>
<td>90.12</td>
<td>7.69</td>
<td>0.73</td>
<td>-6%</td>
</tr>
</tbody>
</table>
6.3.7 Penetration Resistance 40kN Compaction

In Figure 6.12 the penetration resistance with the penetration depth can be found. The bump which was also seen in a smaller manner for 5kN, 10kN and 20kN is now very clearly present. In addition it can be seen that a second bump is also formed in the graph. This can be explained by the shear failure.

Ucgul et al. [2014] performed a penetration test with a circular disk into 100 mm deep washed beach sand with 0.5% moisture content. Figure 6.14 shows the results of the penetration test. These results show the same pattern as the results above. There is a hump present due to that the stress first increases and suddenly decreases. Ucgul et al. [2014] states that this is the point where the yield strength can be measured. Schulze [2008] has analyzed the shear stress vs. time, as shown in Figure 6.13 and stated that if

![Figure 6.12: Penetration resistance 40kN Compaction](image)

![Figure 6.13: Shear stress vs. time](image)

![Figure 6.14: Failure pattern](image)
a “consolidated specimen is sheared under normal stress it will start to flow (fail) when a sufficiently large shear force” is applied. This phenomenon can be seen in the results with higher compression forces. The 40 kN compaction force results in a penetration resistance which fails after a certain force is reached. This happens multiple times in a penetration measurement as can be seen by the multiple bumps in Figure 6.12.

Table 6.15: Maximum Penetration Resistance 40kN Compaction

<table>
<thead>
<tr>
<th>40kN Displacement [mm]</th>
<th>Force [kN]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rep1 90.14</td>
<td>9.14</td>
</tr>
<tr>
<td>Rep2 88.39</td>
<td>10.22</td>
</tr>
<tr>
<td>Rep3 88.37</td>
<td>9.29</td>
</tr>
</tbody>
</table>

In Table 6.15 the maximum penetration displacement and corresponding force can be found. This maximum penetration resistance is based on the settings of the penetration machine. Due to the manual filling of the material the height and therefore the displacement in the material is not always identical. In Table 6.16 this is corrected to show a comparison to an 90 mm penetration into the material. From these results it can be seen that there is a small difference between the results. Compared the average result the difference with the other values in percentages is acceptably small; Rep 1) -3% Rep 2) -2%, Rep 3) 5%.

Table 6.16: Penetration Resistance 1kN Compaction at 90mm Displacement

<table>
<thead>
<tr>
<th>40kN Displacement [mm]</th>
<th>Resistance [kN]</th>
<th>Difference [kN]</th>
<th>Percentage [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rep1 90.14</td>
<td>9.14</td>
<td>0.00</td>
<td>-3%</td>
</tr>
<tr>
<td>Rep2 89.63</td>
<td>9.05</td>
<td>-0.09</td>
<td>-2%</td>
</tr>
<tr>
<td>Rep3 89.69</td>
<td>8.38</td>
<td>-0.76</td>
<td>5%</td>
</tr>
</tbody>
</table>
6.3.8 90 mm Displacement Penetration Resistance

In Figure 6.15 the summary of the penetration resistance forces in kN at 90mm of penetration into the iron ore can be found for the various compaction levels. The green circles indicate the average of the measurements done. Following the trend line of the ‘average’ circles it can be concluded that the penetration resistance increases as the compaction level increases. Although there are slight variations in the measured penetration resistances for one type of compaction level the overall result shows that there is an increase with compaction force. These variations can be accounted to the manually operation by the senior technician for the compaction of the iron ore. The amount of time and force that is applied to the iron ore is therefore approximate and not definite.
7 Conclusion & Recommendation

The aim of this project was to develop a test method to investigate the effect of compaction on the penetration resistance. 6 research questions were formulated, being:

1. Study principles of penetration into cohesive bulk solids.
2. Determine range of consolidation levels required to replicate realistic behavior of bulk materials that are stored inside a bulk carrier?
3. Design a box to hold the bulk materials during the test. Stresses created by compaction force / impact should be considered in the design.
4. Develop a method to compact bulk materials in different consolidation levels. State of compactness of the material should be measurable.
5. Record resistance force on the wedge tool during penetration into the bulk material.
6. Show re-producibility of the result by retesting dry and moist materials.

7.1 Conclusion

This research showed that this method is capable of performing repeatable penetration tests in iron ore. Previous research has shown that on this topic has indicated that it is difficult to consolidate a sample for each measurement consistently. Several factors that influence the penetration resistance of iron ore are the material characteristics such as: density, cohesion (strength), consolidation, compaction, compressibility, moisture content, particle shapes and particle sizes. Also the tool shape, size and roughness, interaction between particles such as friction, adhesion and cohesion and the path of the penetration have a large influence on the penetration into cohesive bulk solids.

Iron ore is shipped over large distances in cargo holds subjected to wave motions and vibrations of the ship’s engine among other forces. Studies have been performed to determine the behavior of the material in the cargo hold. A drop tower test, cone penetration test and laser monitoring has been performed inside the cargo hold. Based on these results and the compaction prediction calculations made for a general cargo hold design several consolidation layers have been determined at different depths in the cargo hold. For 0, 1, 5, 10, 15 and 20 m depth they are respectively 0, 15, 127, 255, 383 and 510 kPa. These values were compared with studies on penetration resistance published in literature, which had quite similar values.

A container was designed based among other requirements on the length of the existing penetration wedge. This wedge has the dimensions of 200 mm length, 40 mm width and 75 mm depth. To ensure that no wall friction is present the container is designed at 250 mm length, 300 mm width and 200 mm depth. As an additional test it was considered to perform a particle trajectory test, which can follow the particle movement during the penetration to determine if there is wall friction and how the material reacts to penetration. Therefore a plexiglas wall was designed on one side of the container to allow for visual observation. The machine that was selected for the experiment is the hydraulic servo controlled test frame. Due to the already existing test frame and wedge a connection pin had to be designed able to transfer the applied forces to the wedge.
For the test set-up it was chosen to perform a static test, thus the material would be penetrated with a constant velocity. The vertical penetration test would be performed in a laboratory setting to ensure that limited influences of environmental conditions. In addition wedge penetration was chosen as plane stress is required as this resembles the penetration of a grab in the iron ore most. The penetration velocity selected for the experiment is 6 mm/s. The test will be performed with 5% moisture content in the iron ore to ensure that no liquefaction would take place. 3 Penetration tools were available for the experiment. The tool with a blunt tip has been selected as this resembles the grab in the field situation. A tool with a sharp tip would result in fast wear of the tip or breakage due to the large forces of the iron ore.

The test method that was designed to obtain a repeatable penetration test is that the material would be compacted in 3 layers to ensure that the entire soil is compacted and not only the top layer. The compaction would be performed by applying pressure to the top sheet designed by Nemag. This top sheet has a weight by itself and in addition force is applied by lowering the apparatus. This application of the force is done manually by a senior technician. During the application of the force a force and displacement is shown based on which the operator can determine the applied force to the material. Following the plate is released and a new layer of material is added and compacted until the container is filled. Following the penetration resistance is performed by lowering the wedge with constant speed into the material. This is done automatically and a force-displacement curve is produced.

The results of the measurements are based on the force-displacement curves. The moment that the wedge first experiences 0.1 kN of resistance this is considered the penetration of the material. Based on the height of the material and the weight of the material the stress level inside the material can be determined. Besides the stress level also the density, compaction method, usage of the material and particle trajectory was tested. First, based on the height of the material and the volume of the container the density of the tested material can be calculated. The results showed that with increasing compaction force the higher the density of the sample. In addition it was also measured that with higher density the penetration resistance increases. Second, an experiment was performed to identify if the 3 layer compaction would show significant differences in penetration resistance compared to 1 layer resistance. As the difference showed to be minimal and it would reduce time and cost it was decided to perform the remainder of the experiments with only 1 layer compaction. Thirdly it was tested if material that had been exposed to the environment for a significant longer time would have an influence on the penetration resistance due to influence of the environment on the moisture content. The results showed that this was not the case. Finally an attempt was made to perform the particle trajectory test using the GeoPIV-RG program. However due to the very fine particle size distribution this was not possible as the white tracing particles were covered in iron ore, thus turning the same color and the fine particles sticked to the plexiglas like ‘dust’ thus blurring the view.

The penetration resistance was measured for loose, 1 kN, 5 kN, 10 kN, 20 kN and 40 kN of compaction. With increasing compaction the penetration resistance increased. The maximum penetration resistance that was encountered was measured and the penetration resistance at 90 mm depth for all compaction levels. An interesting phenomenon that was encountered at 5 kN was that a small bump would appear in the results. With higher compaction levels the magnitude of this bump would increase and the bump would
occur multiple times in the measurement graph. This bump can be explained due to the shear failure of the material. Schulze [2008] explained this if a “consolidated specimen is sheared under normal stress it will start to flow (fail) when a sufficiently large shear force” is applied. Each of the compaction level penetration resistance experiments is performed at least 3 times to ensure that the different tests can be compared. It can be stated that the maximum deviation between results was small, indicating that the tests are repeatable.

### 7.2 Recommendation

The following recommendations for further research can be made:

- **Operation by senior technician**: the compaction of the experiments was done manually by the senior technician assisting on the project. Due to the manual operation uncertainty was introduced on the exact amount of force that was applied to the sample. In some cases the desired force (e.g. 10 kN) was crossed and 10.5 kN was applied. In addition as the force was applied by lowering the apparatus, not a consistent force was applied and this force had to be adjusted every second. Therefore it is also uncertain for which amount of time the force was applied to the sample. This introduced high uncertainty in the experiment. Further research can be performed on this aspect. It is recommended that for future research the same apparatus can be used, however the compaction of the iron ore sample should be performed automatically by the apparatus, resulting in a more accurate result. In addition it can be analyzed what the effect of the initial 0.56 kN error of the machine is and how this affects the results.

- **Particle trajectory**: it was attempted to trace the particle trajectory during the experiment using a video camera and the GeoPIV-RG program. Due to the very fine particle size distribution of this iron ore sample, it was not possible to perform this experiment. For further research it can be interesting for the validation of the DEM model to research the particle trajectory during a penetration test.

- **Vibrations of the ship**: in this experiment the vibrations and ship motions of the ship have not been included. Only the compaction due to the drop height and the material’s own weight. For further research the effect of the ship motion (e.g. heavy storm) and vibrations of the engine on the iron ore compaction can be studied.

- **Time consolidation**: during this experiment the time consolidation aspect of the compaction of iron ore was neglected. However the sea voyage of the iron ore takes a significant amount of time and thus can have a large influence on the compaction of the iron ore. For further research the influence of time consolidation on the compaction can be researched.

- **Strain gauges**: during the set-up of the experiment the usage of strain gauges was discussed with the senior technicians. Due to the already very complex experiment it was decided that this aspect would not be included in this experiment. However for further research it can be interesting to measure the wall effect by placing strain gauges on the walls and measuring the presence and influence of the penetration resistance.
• **Tool shapes and sizes**: There is a great influence of the shape, roughness and size of the tool on the penetration resistance. In this experiment only one tool was tested. For completeness in the future the shape, size and roughness of the tool can be varied to determine the influence on the penetration resistance.

• **Penetration velocity and angle of penetration**: The penetration velocity for this experiment was set at 6 mm/s. However as studied by various tests the penetration velocity can have an influence on the penetration resistance. For further research the penetration velocity of a grab in the field situation can be measured and following the penetration velocity in the experiment can be adjusted as such to investigate the influence on the penetration resistance.

• **Particle size distribution**: In this experiment the particle size distribution of the iron ore was very small. This resulted in limitations with the particle trajectory test. In addition very small particles are difficult to model in a DEM simulation. For further research the influence of a larger particle size distribution can be researched.

• **Moisture content**: The moisture content was set for this experiment at 5%. However the iron ore in the cargo hold varies in moisture content. Therefore in further research a range of moisture levels can be tested to see the influence on the compaction and penetration resistance. Especially the moisture content near the TML can be of great importance.

• **In situ conditions**: For further research the conditions on site can be measured. The moisture content of an iron ore sample, the velocity of the grab grabbing the iron ore out of the cargo hold, the external factors, rain, wind, sun, ice etc. This experiment can be done for multiple samples (different cargo ships) and research the influence of these factors. Based on these factors the parameters such as penetration velocity, moisture content, compaction level can be determined. According to Asaf et al. [2007] the parameters of a sample measured in a lab are based on remolded material and do not always are a good prediction of the sample in situ.
Bibliography


Faculty of Maritime Studies. Cargo-handling equipment on board and in port. Technical report, Faculty of Maritime Studies, Rijeka, 2013.


A  Design of container
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<th>QTY.</th>
<th>Title</th>
<th>Artikelcode</th>
<th>Weight</th>
<th>Dimensions</th>
<th>Material</th>
<th>Length</th>
<th>Remarks</th>
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<td>1</td>
<td>Plate</td>
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<td>5.355 JR</td>
<td>5</td>
<td>250</td>
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<td>A</td>
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<td>SLR08ST</td>
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<td>H8</td>
<td>Standard</td>
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<td>-</td>
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<td>A</td>
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<td>Side plate</td>
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<td></td>
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<td>3</td>
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<td>B</td>
<td>1</td>
<td>Top plate away</td>
<td>9</td>
<td>-</td>
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<td>1</td>
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<td>Plate 8 mm</td>
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Note: 
- Container penetration test bulk
- STEEL STRUCTURE: SHARP EDGES TO BE REMOVED
- TITLE: Container penetration test bulk
- REV.: 0050032
- SCALE: 1:3
- SHEET: 1 / 1
- TYPE: A3

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B Design of connection pin
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**STEEL STRUCTURE:**
Sharp edges to be removed

**TITLE:**
Verbinding wedge machine

**SCALE:**
1:1

**SHEET:**
1 / 1

**FORM:**
A4

---

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C  Available Apparatus at the TUDelft

Table C.1: Available compression benches at the TUDelft [Delft University of Technology, 2016]

<table>
<thead>
<tr>
<th>Machine</th>
<th>Location</th>
<th>Load</th>
<th>Movement</th>
<th>Contact</th>
</tr>
</thead>
<tbody>
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<td>2000 kN</td>
<td>-</td>
<td>van Rhijn, Arjen</td>
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<tr>
<td>Instron tensile and compression press 1195</td>
<td>Civil Engineering</td>
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<td>Scharp, Edwin Hr.</td>
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<td>Biaxial test setup</td>
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<tr>
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<td>Amsler Hydraulic Testing Machine</td>
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</table>

The highlighted machine was selected for the test set-up. As explained in Chapter 7 this machine was suitable for the experiment as the deflection and required force were high enough. However during the compaction phase of the experiment the machine was manually operated by the senior technician. This compaction can also be performed automatically however this would require significantly more time. As a recommendation it can be stated that if an easier operatable apparatus can be found this should be selected for the experiment however this new apparatus should not compromise on the required deflection and force.