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A Consolidation-Penetration Test for Wedge-Shaped Penetration Tools

Grabs are often used for unloading bulk carriers that deliver iron ore cargoes. The grabbing process starts with cutting the free surface of the bulk iron ore. For that reason, the initial penetration depth of the grabs' knives into the material is an important success factor in their filling ratio. The resistance to penetration is influenced by the consolidation process of the cargo which occurs during ship loading and sailing. In this study, a test method is developed to mimic the penetration process of the grabs' knives into material, and to determine the relationship between the level of consolidation stress and the penetration resistance. The test results show that when the consolidation stress increases, the penetration resistance, and the bulk density also increase. The results obtained from these measurements will be used in further research for improving the design of iron ore grabs.

Keywords: penetration test, consolidation, moist bulk material, grab, iron ore fine.

1. INTRODUCTION

Iron ore is a cargo with the largest dry bulk trading volume per year due to its high demand in industry, above coal and grains [1]. The two main exporters of iron ore are Australia and Brazil, with more than 70% share of the global market in 2015 [2], while the top 5 importing countries are located in Asia and Europe, resulting in its intercontinental shipping. In 2015, for example, a total of 4553 million tons of dry bulk was shipped, of which 1354 million tons was iron ore [1]. Approximately 9000 Capesize bulk carriers are required to transport the annual demand of the iron ore global market.

Due to the high specific weight and abrasive nature of iron ore, a discontinuous unloading system is preferred. For that reason, grabs are usually employed to unload bulk carriers, which offer a time- and cost-efficient service at destination ports.

When bulk carriers arrive at the port of destination, the iron ore cargo is often in a partially consolidated form in the cargo hold. However, the exact state of the iron ore cargo remains unknown, as many factors are involved in its production, loading and transportation. For instance, the varying forces that acted upon the cargo during loading and sailing can lead to different states of compaction [3]. The state of compaction or the relative density compares the current packing with both the densest and the loosest packing conditions.

Furthermore, as the unloading of a ship's hold starts and proceeds, the cargo height will be reduced gradually. Consequently, when the grab's knives touch the bulk material that was stored at greater depths, an over-consolidated condition is present. Over-consolidation

means that the current existing vertical stress is less than the historical maximum stress. The historical maximum, which is referred as the pre-consolidation stress, is the maximum vertical overburden stress that a particular sample has sustained in the past [4].

Since the grabs' performance is influenced by the initial penetration depth of their buckets into bulk materials, it is expected that a higher pre-consolidation stress results in a lower grab payload by reducing its initial penetration depth.

In [5], a penetration test was used to calibrate the Discrete Element parameters of iron ore pellets in interaction with grabs. Due to the low sensitivity of pellets to consolidation, no significant influence on the penetration resistance could be identified. However, the majority of the iron ore products are iron ore fines (IOFs), which are expected to have a higher penetration resistance in the over-consolidated condition.

The influence of pre-consolidation on the penetration resistance of soil material has been investigated by a number of researchers; some examples are [6], [7] and [8]. To the best of our knowledge, though, no one has studied the influence of pre-consolidation on the penetration resistance of IOFs.

Therefore, the aim of this paper is to develop a test method to investigate the effect of pre-consolidation stress on the penetration resistance of moist IOFs, with a focus on the grab design application.

The test method is discussed first in Section 2. Section 3 describes the test results and discusses the effect of pre-consolidation stress on the penetration resistance as well as the bulk density. Finally, Section 4 states conclusions from the experiment and ideas for future research.

2. TEST METHOD

Current section, first discusses the IOF cargo characteristics, including its particle size, its particle

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density and an estimation of its consolidation pressure along the ship's hold depth. The second sub-section, 2.2, describes the experimental hardware, their specifications and our assumptions behind these specifications. Then two stages of the experiment, consolidation and penetration, are discussed in the experimental procedure sub-section. Finally, the last sub-section, 2.4, presents the designed experimental, which investigates the effects of pre-consolidation stress, number of consolidated layers and test repetitions on the test results.

2.1 Cargo (IOF) characteristics

Iron ore products are produced in three different particle size ranges: pellets, sinter feed and pellet feed. The first ore, pellets, are marble-sized, heat-hardened balls of iron and have a particle size between 8 and 18 mm [5]. The other two groups have a particle size usually smaller than 6.3 mm [9]. Figure 1 displays three samples, one of each iron ore category, indicating the difference in their particle size range.



Figure 1. Iron ore products with different particles sizes

Pellets are out of the scope of the current study, since consolidation does not play a role in their resistance against grabs knives' penetration [5]. Therefore, we used a pellet feed type of iron ore in this experiment. Table 1 shows the particle size and density characteristics of the iron ore sample. 50% of the sample weight consists of particles smaller than 0.88 mm, and 80% of the particles have a diameter between 0.001 and 6.3 mm, indicating a wide particle size distribution.

Table 1. Characteristics of the iron ore sample [10]

Particle size distribution (mm)	d_{10}	0.001
	d_{50}	0.088
	d_{90}	6.3
Particle density (kg/m^3)		4182

IOF cargoes are often transported in a wet state, and their bulk properties, such as bulk density and compressibility, are different in wet and dry states [11]. To create this wet state, first the iron ore sample was dried in an oven device according to the procedure described in [12], and then water was added to the dry sample.

Since cargo moisture should be always low enough to prevent any hazardous cargo liquefaction [13], the sample was prepared with only 5% dry-based moisture content. Dry-based moisture content is the portion of a representative sample consisting of water, expressed as a percentage of the total dry mass of that sample [4]. This parameter can be expressed as follows:

$$\text{Dry-Based Moisture Content (\%)} = \frac{\rho_b - \rho_d}{\rho_d} \quad (1)$$

where ρ_b and ρ_d are the bulk density in wet and dry states respectively.

A mixing machine was used to combine the water with the dry iron ore to create a homogeneous moisture distribution. Figure 2, which shows the iron ore before and after the mixing, indicates that prior to mixing there are several relatively large agglomerated particles present in the material. Most of these agglomerates are created during the drying process of the IOF sample in the oven. During mixing, these pieces are broken down into smaller pieces.

Next, to create an over-consolidated sample, representing the cargo's in-hold situation, an estimation of this cargo condition is required. This is a challenging job, since a combination of both deterministic and non-deterministic forces act upon the cargo, such as the weight of the cargo itself, the drop height during the cargo loading and the waves' impact during sailing. Additionally, it is nearly impossible to identify which of these forces are more influential on the grabs' performance during the unloading of cargo.

Therefore, we used the design guideline for bulk carriers [14], as well as [15], to estimate a range of consolidation stresses required to replicate the IOF cargo condition in a laboratory environment. Based on the design guideline, the maximum height of the IOF pile inside the hold of a typical Capesize bulk carrier should be limited to 15 m; this complies with the measurement data of [16]. However, based on [15], the height of an IOF cargo pile can be up to 20 m in practice. Therefore, the maximum height of an IOF cargo is assumed to be 20 m, to cover the whole range.

Since the aim of the current study is to investigate the relationship between vertical consolidating pressure and penetration resistance of the cargo, a range of pre-consolidation stresses are determined to replicate the confining pressure acting on IOF cargoes at different layers. Figure 3 displays a 3D view of an IOF cargo pile

in the ship's hold. The geometrical profile suggests different levels of vertical pressure along the pile depth.

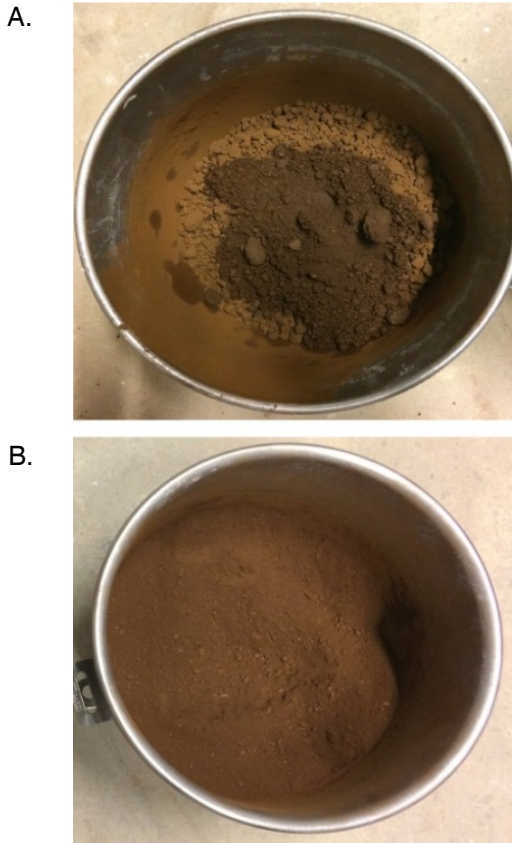


Figure 2. The iron ore sample before (A) and after (B) mixing with the mixer machine [10]

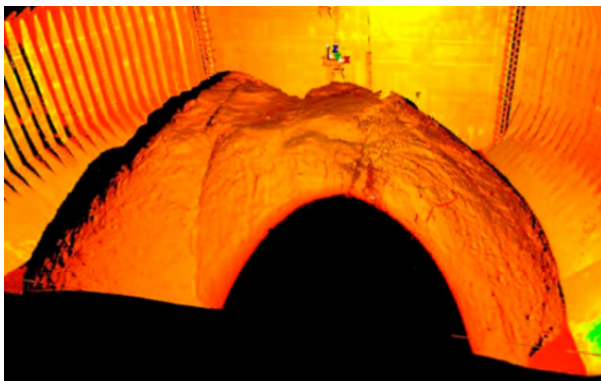


Figure 3. Laser scan of a ship's hold containing cargo of iron ore fine [16]

2.2 Experimental hardware

A column of iron ore with the height of 20 m and the area of 1 m² approximately weighs 55 tons, corresponding to vertical confining pressure of 540 kPa at the bottom of the column. In order to replicate this pressure, we selected a hydraulic servo-controlled test frame with a maximum force of 200 kN and a starting point error of 0.56 kN. This error was considered when analyzing the results.

Figure 4 displays the schematic cross section of the penetration tool selected for this study. This is the same tool that [5] used to study the penetration of a grab into the iron ore pellets. Using the same tool aids in producing comparable results, which will be used for the grab design application.

A wedge-shaped penetration tool is chosen, as plane stress is required to resemble the penetration of a grab in iron ore. The tool is chosen to be symmetric to minimize the bending stress in the experimental apparatus. The 40 mm width of the penetration tool is based on manufacturing requirements; this specifies a minimum of 30 mm and a maximum of 50 mm as the characteristics of a real grab. The tool angle was chosen to be 30° as this is the standard angle used by other researchers such as [17] and [18], as well as in the existing industrial scale grabs. The wedge length is 200 mm.

The ideal penetration tool tip shape for minimizing penetration resistance is a sharp one. However, due to the abrasive nature of iron ore, in practice a sharp tip wears off quickly; therefore, a blunt tip is often used.

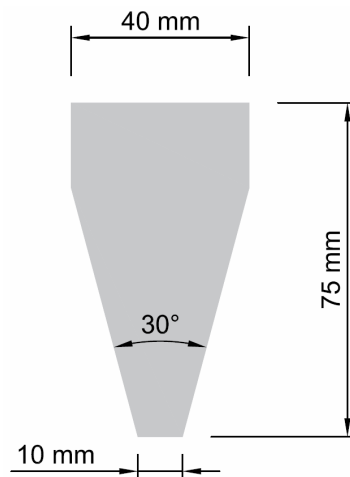
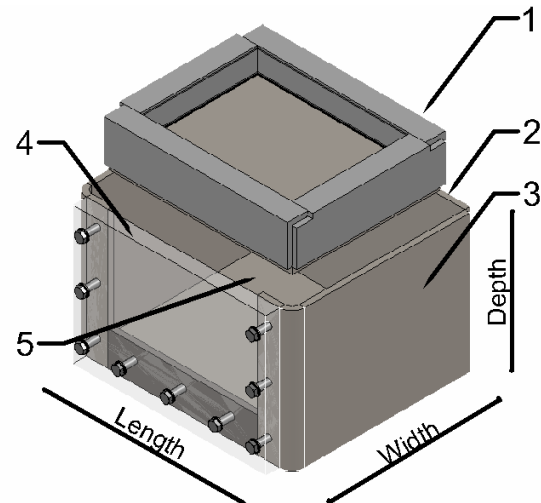


Figure 4. Cross section of the wedge penetration tool [5]



Item No.	QTY.	Title	Material	Function
1	1	Top plate	-	Consolidation
2	1	Back plate	S355 J2+N	N.A (fixed)
3	2	Side plate	S55 J2+N	N.A. (fixed)
4	1	Transparent plate	Plexiglas	Capture flow
6	1	Bottom plate	S355 JR	N.A (fixed)

Figure 5. Details of the test container

Figure 5 displays details of the test container. The dimensions of the container are limited by the apparatus

to be used for the penetration test. The penetration tool has a depth of 75 mm. Care has to be taken that the tests are unaffected by the adjacent sides or bottom wall of the container [19]. To avoid this wall effect, the depth of the container should be at least $75 \text{ mm} \cdot 2 = 150 \text{ mm}$. The length of the container is of importance because as the material is penetrated the material will displace to the sides. For the cone penetration into sand, the ratio used of the nearest wall to the cone diameter is larger than 2 [20]. To ensure that enough space on both sides of the wedge is available, at least 80 mm of space on each side of the penetration tool is required, resulting in a total container width of $80+80+40 = 200 \text{ mm}$. These dimensions result in a container with a volume of 15 liters. 24 kg of the iron ore sample is used to fill the container.

2.3 Experimental procedure

Before starting the consolidation phase, the sample of the iron ore is loosened to ensure that almost no consolidation remains from mixing or transportation. Then the iron ore is loaded in the designed container, and the bulk surface is leveled out manually.

In order to create a homogeneous sample, the state of compaction should be uniform along the depth. One of the factors that could affect the state of compaction is the layer thickness [21]. To study the influence of this factor on the test results, consolidating in one layer and three layers are considered in the test procedure. In both cases, each layer is consolidated using the same compressive force. A rigid top plate (1, in Figure 5) is placed between the hydraulic jack and the bulk surface to distribute pressure uniformly on the sample.

For the experiment of consolidating in one layer, 24 kg of the iron ore sample is poured into the container using a small shovel. After creating a levelled-out surface, the sample is consolidated by applying the predetermined force of 5 kN on the top plate, equivalent to 66.7 kPa consolidating pressure on the sample. Next, in a separate experiment, the sample is consolidated in three layers of 8 kg each by applying the same consolidating pressure.

In the next phase, the penetration phase, the reaction force on the wedge tool during penetration into the iron ore sample is measured. Since previous research, [5] and [17], have stated that the penetration velocity has little to no influence on the penetration resistance, a constant velocity of 6 mm/s is used.

Figure 6 displays the consolidation phase, as well as the material condition before starting the penetration phase. After the penetration phase, the wedge is moved upward to the initial position with the same velocity (6 mm/s). After each experiment, the container is emptied and the sample is loosened.

To calculate the bulk density, the material depth is determined by using the elevation where the wedge tool touches the bulk surface, and a force of 0.1 kN is measured.

Figure 7 shows the schematic set-up for determining the vertical displacement of the wedge tool relative to the material depth. Since the test apparatus does not record the displacement data relative to the material depth, the sample surface is adjusted with +10 mm.

Therefore, the penetration resistance can be compared consistently in the prospective diagrams.



Figure 6. Consolidating the iron ore sample: top) consolidating iron ore with the top plate, bottom) starting point of the penetration phase

2.4 Experimental plan

The two dependent variables measured in this experiment are, I) the recorded reaction force on the wedge during penetration into the sample, the so-called *penetration resistance*, and II) the *bulk density* of the sample after the consolidation phase. The effect of three independent variables on them are measured: I) number of consolidated layers, II) applied consolidation stress and III) number of repetitions.

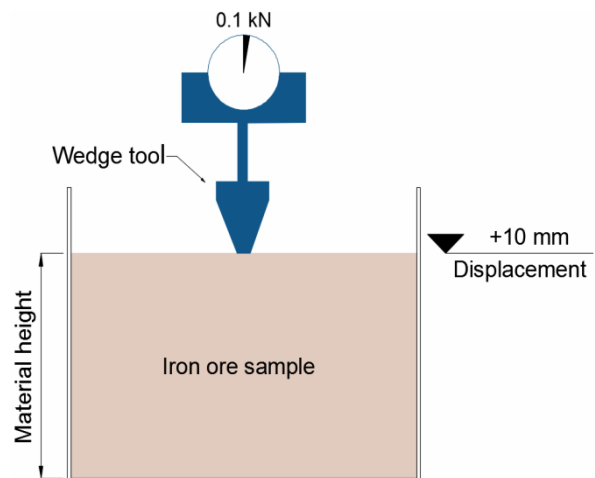


Figure 7. Schematic view of the set-up for measuring the displacement of the wedge tool over material depth

In the first experiment, the sensitivity of the penetration resistance to the number of consolidated layers is

investigated. The experiment determines whether consolidating the iron ore sample in one layer or in three layers influences the penetration resistance significantly.

For the second experiment, the effect of increasing consolidation stress on the penetration resistance is investigated. Table 2 shows the range of forces and the corresponding consolidation stress to be applied on the iron ore sample. As explained in Section 2.1, several levels of consolidation stress are determined to represent a range of possible vertical confining pressure in ships' holds, at different depths in the iron ore cargo.

Each test is repeated at least three times. This makes it possible to measure the penetration resistance and the bulk density in at least three test repetitions, and to plot the confidence interval of the results.

Table 2. Levels of applied consolidation stress

Applied force (kN)	Equivalent consolidation stress (kPa)
0	0
1	13.3
5	66.7
10	133.3
20	266.7
40	533.3

3. Results and discussion

Figure 8 illustrates the effect of the consolidation strategy, one layer versus three layers, on the penetration resistance. For a stress level of 66.7 kPa, the average penetration resistance, as well as the 95% confidence intervals (CI 95%), are shown for both cases. Even though at the initial depths, with the displacement smaller than 40 mm, the recorded reaction forces in both cases are similar, they start to diverge as the tool penetrates deeper. To quantify the difference, we calculate the ratio of the average penetration resistance at the 100 mm wedge displacement in the case of consolidating in one layer over the other case; this ratio is 0.91.

The difference at the greater depths is likely to be caused by applying more consolidating energy to the second and third layers; this results in a slightly stiffer bulk material, and thus more resistance to penetration. Comparing the bulk density supports this idea; in the case of consolidating in three layers, the bulk density (average) is 11 kg/m³ higher than the other case. However, considering the similarity in the trend of the penetration resistance in both cases, the overlapping confidence intervals, and the small difference in the bulk density, the second set of experiments are conducted by consolidating the sample in one layer.

A major objective of this study was to determine the relationship between penetration resistance and consolidation stress. Their relationship is illustrated in Figure 9, which presents the penetration resistance at 100 mm of the wedge displacement for all the applied levels of consolidation stress. The circles indicate the average of the measurement, and the 95% confidence interval for each consolidation level is displayed using vertical error bars. The variations in the measured

penetration resistance can be explained by the manual operation of the consolidation phase.

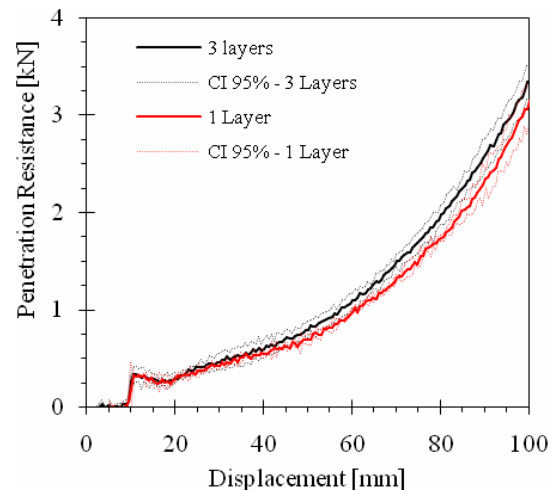


Figure 8. The effect of number of consolidation layers on the penetration resistance; consolidation stress: 66.7 kPa

As expected, with increasing consolidation stress, the penetration resistance increases as well. However, the rate of increasing the penetration resistance decreases when the consolidation stress increases. For instance, applying the first level of consolidation (13.3 kPa) increases the penetration resistance by 67% compared to the loose condition. On the other end of the diagram, increasing the applied consolidation stress by 100% (266.7 kPa), resulted in only a 22% increase in the penetration resistance.

To quantify this non-linear behavior, a quadratic regression (dashed line in Figure 9) with $R^2=0.9976$ is fitted on the data. R^2 , the coefficient of determination, is commonly interpreted as the proportion of total variance explained by the independent variable [22]. When $R^2 = 1$, all the variance is explained by the regression model. A linear regression can only fit the data with $R^2=0.9038$. Therefore, the quadratic regression model with a R^2 of 0.9976 demonstrates the accuracy of the fitted non-linear model.

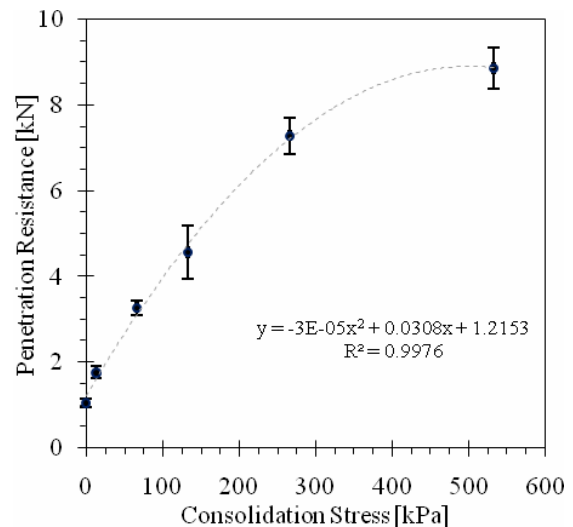


Figure 9. The penetration resistance at 100 mm wedge displacement for each compaction level (as stated in Table 2); Included is a non-linear regression line (dashed) equation and its R^2 value

Figure 10 displays another non-linear behavior; a sudden increase in the penetration resistance at initial depths of consolidated material is observed. After this, the measured penetration resistance decreases again. With an increasing consolidation stress, this peak increases in magnitude and repetition over depth, which can be explained due to the shear failure mechanism of the bulk material. Schulze [19] explained that if a consolidated specimen is sheared under normal stress it will start to flow (fail) when a sufficiently large shear force is applied. For instance, comparing the initial peak for different levels of consolidation indicates that a higher state of compaction requires a higher (shear) force to initiate particle flow.

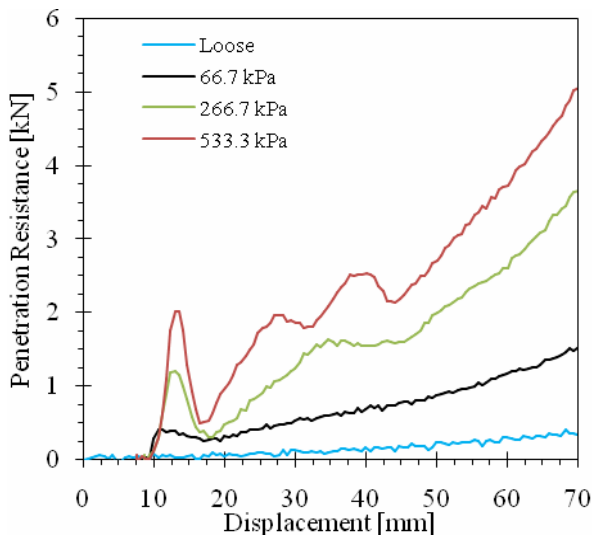


Figure 10. Effect of consolidation stress on the failure pattern

One of the major bulk material factors affecting penetration resistance is bulk density [24]. A higher relative bulk density often results in a higher penetration resistance. In what follows, first, the relationship between bulk density and consolidation stress is described; next, the relationship between penetration resistance and bulk density is illustrated.

Figure 11 displays the relationship between the applied consolidation stress and the measured bulk density. The approach used to measure the bulk density, explained in subsection 2.4, might have introduced some level of error into the result. For instance, the average bulk density of the sample in the loose condition is higher than that of the next consolidation level (13.3 kPa), which is not as expected. In addition, the confidence interval of the average bulk density in the loose condition is larger, than that of other consolidation levels. This is probably caused by leveling out the bulk surface manually; it is difficult to create a repeatable and perfectly flat surface in this way.

A clear trend is that the higher the consolidation stress, the higher the resulting bulk density. For example, the average bulk density in the loose condition is 2109 kg/m³, and this increases to 2275 kg/m³ at the highest consolidation stress (533.3 kPa). This relation was expected, since applying consolidating stress reduces the voids in the sample, and thus, makes it denser. To quantify the relationship between the bulk

density and the consolidation stress, a non-linear regression model is fitted, with a high level of accuracy ($R^2=0.9614$).

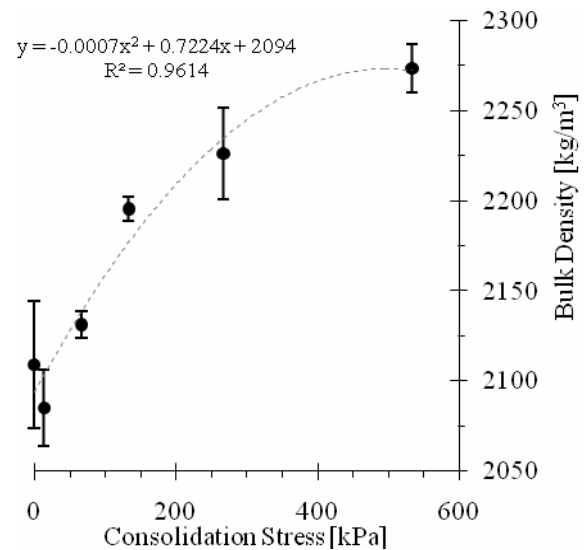


Figure 11. Average bulk density at different levels of consolidation; Included is a non-linear regression line (dashed) equation and its R^2 value

The bulk density result can be used to link the test results to the iron ore condition in the ship's holds during the unloading. For example, by measuring the relative bulk density of the cargo, the required energy for the initial penetration of the grab's knives can be estimated. This value is useful for finding a design that requires the least amount of energy, allowing the grab a greater initial penetration.

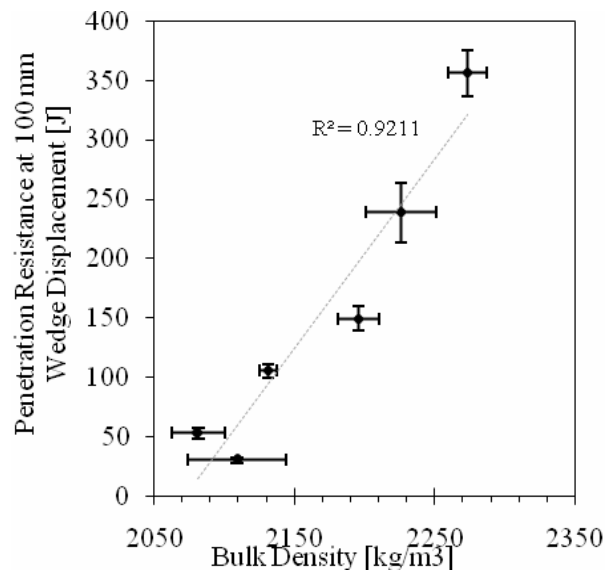


Figure 12. Relationship between bulk density and penetration resistance; Included is a linear regression line (dashed) equation and its R^2 value

By integrating the resulting force (in N) over the depth (in m), the penetration resistance in Joules is obtained. Figure 12 displays the relationship between the penetration resistance at 100 mm wedge displacement and bulk density. The circles indicate the average of the measurement done at different levels of consolidation stress. The 95% confidence of interval of

the penetration resistance and bulk density are displayed using vertical and horizontal error bars respectively.

As was expected, a higher energy is required for cutting a denser sample. However, this is with exception of the test results in the loose condition, in which the recorded bulk density is higher than the next level of consolidation stress. The result can be fitted using a linear regression model with a $R^2=0.9211$, suggesting a linear relationship between the penetration resistance and bulk density. However, since there are overlaps between the 95% confidence intervals of the bulk density data, caution in interpreting the relationship is advised.

4. CONCLUSION AND OUTLOOK

The test method developed in this study has been successfully used to investigate the effect of consolidation stress on the penetration resistance of a wedge-shaped tool. We observed an increasing, non-linear relationship between them. Regarding the experimental procedure, a one-layer strategy was adequate for creating a consolidated sample of iron ore fine. The results are repeatable, with only one exception, the results of bulk density in the loose condition.

In future research, the test method will be used to characterize the penetration resistance of other materials sensitive to consolidation, such as the sinter feed type of iron ore. Furthermore, particle tracking can be used to qualitatively and quantitatively describe how different types of iron ore react during penetration. Future work will also focus on moisture content, which is known to affect the penetration resistance and compressibility of fine granular materials.

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**ТЕСТ ПЕНЕТРАЦИЈЕ И КОНСОЛИДАЦИЈЕ
КОД КЛИНАСТИХ ПЕНЕТРАЦИЈСКИХ
АЛАТА**

М. Мухајери, Ф.М. Сиклер, Ц. Ван Ри, Д.Л. Шот

Грејфери се често користе за истовар расутог терета са теретног брода, који довози руду гвожђа. Радни

процес грејфера започиње сечењем слободне површине расуте руде гвожђа. Зато је почетна дубина пенетрације ножева грејфера у материјал важан фактор процента успешног пуњења. Отпорност пенетрацији се јавља услед процеса консолидације терета, која се врши за време утовара и пловидбе. У раду је развијен метод за опонашање процеса пенетрације ножева грејфера у материјал и одређивање односа између нивоа напона консолидације и отпора пенетрацији. Резултати тестова показују да се са повећањем напона консолидације повећава отпорност пенетрацији и запреминска маса. Резултати мерења ће се користити при пројектовању грејфера за руду гвожђа.