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The effect of salt content on the determination of maximum and minimum dry densities of Marine Sands

L'effet de la teneur en sel sur la détermination de la masse volumique sèche maximale et minimale des sables marins

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ABSTRACT: Challenges have existed with reliably determining the maximum (ρ_{max}) and minimum (ρ_{min}) dry densities of sands. As a result, a set of new methods has resulted in the potential for greater consistency of these measurements. However, is there a potential problem when testing sands from offshore? This paper shows that salt in the porewater of offshore sands can have a significant effect of the measurements of ρ_{max} and ρ_{min}, especially the minimum, when the sample is dried for testing. A laboratory testing programme was completed to look at this effect on 7 sands artificially given saline water and all showed this same response. It was then confirmed with limited offshore samples with and without washing. This behaviour, if ignored, will have significant effects on Relative Density determinations and the reconstituting of samples for laboratory testing and the results there of.

RESUMÉ: La détermination de la masse volumique maximale (ρ_{max}) et minimale (ρ_{min}) des sables sec représente souvent un défi. À cet effet, un ensemble de nouvelles méthodes donne maintenant une plus grande cohérence pour ces mesures. Cependant, y a-t-il un problème pour les sables qui proviennent du domaine marin ? Cet article montre que le sel dans l'eau interstitielle des sables marin peut avoir un effet significatif sur les mesures de ρ_{max} et ρ_{min}, et en particulier le minimum, lorsque l'échantillon est séché pour être testé. Un programme d'essai en laboratoire a été réalisé pour examiner cet effet sur 7 sables ayant reçu artificiellement de l'eau salée et tous ont démontré la même réponse. L'étude a aussi été confirmé avec des échantillons de sable marin avec et sans lessivage. Ce comportement a un effet significatif pour la détermination de la densité relative et la reconstitution des échantillons pour les tests de laboratoire.

KEYWORDS: salt, laboratory tests, standards, maximum and minimum dry densities, density determinations

1 INTRODUCTION

The work described in this paper is a continuation of work originally started as a project to study the consistency and reliability of methods to determine maximum (ρ_{max}) and minimum (ρ_{min}) dry densities of sands.

For nearshore and offshore projects where sand is the dominant soil type, a commonly used approach for obtaining static and cyclic stiffness and strength parameters includes:

- in-situ estimation of relative density (Dr) using the cone penetration test (CPT) combined with empirical correlations
- reconstitution of sand specimens in the laboratory to the estimated D_r value(s) using measured maximum and minimum dry density, and
- static and cyclic triaxial and/or direct simple shear tests as well as resonant columns or bender element tests on the prepared specimens.

An accurate determination of D_r requires reliable methods to determine the maximum (ρ_{max}) and minimum (ρ_{min}) dry densities, but different methods show large variation in measured values. Due to the formulation of the relative density and the relative values of the three soil properties required to compute it, resulting in "a ratio of small differences between large numbers." This implies that small variations in the three basic soil parameters can result in much larger variation in the computed relative density value (Tavenas et al. 1973).

Lunne et al 2019 discuss in detail the potential effects of these errors. They mention as an example, consecutive site investigation campaigns at a North Sea sand site which returned peak friction angles varying within a 15 degrees span for tests performed at a relative density between 95-100 %.

Previous research has shown that there are many factors, other than just the specific test procedure, that influence the values of maximum and minimum dry unit weight and (or) void ratios of sands, e.g., fines content (FC), maximum and mean grain sizes, gradation, particle shape, particle crushability (e.g., Blaker et al. 2015).

2 NEW METHOD DEVELOPMENT

2.1 *Previous Phase 1 study*

The initial work was undertaken by NGI and Geolabs with support from, Ørsted (then Dong Energy) and compared results obtained for maximum (ρ_{max}) and minimum (ρ_{min}) dry densities using a variety of standardised and in-house methods (reported by Blaker et al 2015). The methods studied were:

- British Standard Institute (BS) standards,
- American Society for Testing and Material (ASTM) standards,
- Deutsches Institut für Normung (DIN) standards,
- Dansk Geoteknisk Forening (DGF) guidelines,
- NGI proprietary methods,
- Geolabs proprietary methods, and
- Fugro proprietary methods.

Full details of all methods can be found in Lunne et al 2019.

All methods used for determining the minimum density involved placing dry sand either with the lowest kinetic energy possible to minimize compaction during placement (using a funnel, tube or scoop or by employing agitation/lofting to uncompact/loosen the sand as much a possible after placement (as with gentle inversion within a cylinder). The funnel and tube methods both involve the placement device being steadily raised to be just above the placed level whilst the sand is poured (funnel) or released (from the pre-filled tube as it is raised).

The maximum dry unit weight methods studied all depend on imparting energy to the sand to enable the sand particles to become reoriented to a denser state. The energy can come from vibration (applied either by a vibrating hammer or by vibrating the mould with a surcharge resting on the sand) or from discrete hammer blows (usually flat-faced from above, but also laterally to the mould in the case of the DIN two-prong impactor method). The material can be placed in single or multiple layers. High-energy vibration (such as a vibrating hammer) can come with a greater risk of crushing the particles and changing the grading curve of the sand. The state of the sand tested can vary from dry to saturated, with some methods also using a range of intermediate moisture contents.

Factors investigated included items such as repeatability of results, ease of use, amount of material used, influence of grain crushing - as a result of excessive energy input, the effect of fines content on the results. There were 5 sands used, and the work concluded that significant variations in results were possible and that there was a real need for more reliable tests that were less operator dependent, could be undertaken with less than 2kg of material and gave consistent upper and lower bound values of the two dry densities.

2.2 *Previous Phase 2 work*

The main results of this work were reported in Lunne at et 2019 which completed the work on the sands of the Phase 1 work, added another main sand and complimented this with further targeted testing on a 7th sand, details of all the sands and their mineralogizes can be found in Lunne et al 2019. They concluded that the laboratory determined (ρ_{max}) and ρ_{min} do, to a high degree, depend on the standard or method used. The need for a new consistent method was seen as greatest for ρ_{max} and that any new methods developed should ideally lead to incorporation into international standards.

They concluded that currently (2019) no single set of existing methods could be recommended and that until new methods had been developed then at least two sets of different methods should be used especially for critical projects.

They also set out the requirements that these new methods should take into account.

Most of the sands were predominantly quartz except for the Central American sand which contains significant percentages of Argonite and Calcite.

2.3 *Previous Phase 3 the final development*

Based on the Lunne et al study the work was then taken forward by NGI, Geolabs and Ørsted, with additional support from Innogy, to develop suitable new procedures. It was planned that having developed initial outlines for these new procedures, then additional laboratories at Fugro, Gardline, Geo and University of Massachusetts, who had all had offered their help, would trial the methods and aid further development.

The DIN method (DIN 1996) for minimum dry density and the in-house method of Geolabs for maximum dry density were chosen as the basis for development of the new methods. The former of these uses a funnel to slowly pour the sand in as loose a state as possible into a mould of known volume and weight with the lower end of the funnel always in contact with the sand in the mould. The mould is slightly overfilled, the sand is levelled off and then the mould and sand weighed. The method is repeated 5 times and the average weight value taken to calculate the minimum dry density (there are restrictions of the amount of variation in results that is allowed).

The maximum density method finally developed was based on a method developed at Geolabs to loosely simulate the ASTM method of vibrating a sample of sand under a known surcharge in a saturated state to achieve a maximum density. It used much less sand than the ASTM method, a significant advantage for offshore projects where material is often limited. A sieve shaker (with controllable vertical amplitude) was adopted as the vibration source. This was refined during the project to using a mould of 70 mm diameter, with a top cap and filter paper to limit material losses and the material vibrated for a fixed period of time first without and then with a surcharge. The volume of the sand is calculated based on the height of the sample and diameter of the mould. The dense sample is removed, dried and weighed. The test is performed twice on two separate 500g specimens of the sand. Both a maximum allowable loss of material (2%) and a specified level of repeatability must be achieved if the results are to be acceptable. If not, then the test is repeated.

This work has been reported by Knudsen et al 2020 and the full method statements for the two procedures can be found at https://www.ngi.no/eng/Services/Technical-expertise/Geotechnical-laboratory or https://geolabs.co.uk/downloads.

3 THE PRESENT STUDY

Recently when preparing samples for testing using the new methods, it was noticed when the samples had been dried that one batch, which had had a significant amount of water bagged with it, appeared to develop a white coating over surface of the dried sand. This was found to be salt from the salt water and concern was raised as to potential effects the salt might have on the test results. So, the material was tested both ‘as dried’ and ‘washed’ (washing simply entailed adding distilled water to the sample, mixing it in, allowing it to settle, decanting the excess water and then repeating the process until it was considered most of the salt had been removed). In this way it was hoped that no material would be lost from the sample. The ‘cleaned or washed’ sample was then dried and the ρ_{min} and ρ_{max} testing repeated. The initial test results on the dried ‘as received’ gave average values of ρ_{min} and ρ_{max} of 1.42Mg/m^3 and 1.87Mg/m^3 respectively. These changed to values of ρ_{min} and ρ_{max} of 1.51Mg/m^3 and 1.855Mg/m^3 respectively for the ‘washed’ sand. The significant difference in of ρ_{min} was concerning, a range of ρ_{min} to ρ_{max} of 0.45Mg/m^3 for the sand with salt changes to 0.345Mg/m^3 when ‘cleaned’. For a sample having an in-situ dry density of 1.65Mg/m^3, this would change its calculated Relative Density (D_r) from 52% based on as received to 41% cleaned. Similarly, for a dry density of 1.75 Mg/m^3 the D_r would change from 73% to 69%. It was therefore decided to investigate this further by using the sands from the earlier studies and creating sands with saline water in them.

3.1 *Initial testing*

Three sands from the final stages of the max min study (Knudsen et al 2020) were first trailed, Cuxhaven, Oysand and Taiwan. One set of samples were prepared clean and a second set of each sand left to soak in a 3.1% saline solution (created with sea salt). After soaking, all free saline water was removed from the ‘salted sands’ and they were dried ready for testing. Sets of ρ_{min} and ρ_{max} tests were undertaken on the samples along with repeat tests to ensure consistency in results. As had been found in the earlier studies both sets of the new test methods gave consistent results for any one sand and preparation type (clean or salt). Table 1 summarises the results for these 3 sands.

Table 1. Results for ρ_{min} and ρ_{max} with and without salt for Cuxhaven, Øysand and Taiwan sands.

	Clean		Salt	
	ρ_{max} [Mg/m^3]	ρ_{min} [Mg/m^3]	ρ_{max} [Mg/m^3]	ρ_{min} [Mg/m^3]
Cuxhaven	1.78	1.42	1.81	1.35
Øysand	1.87	1.43	1.88	1.34
Taiwan	1.74	1.3	1.76	1.24

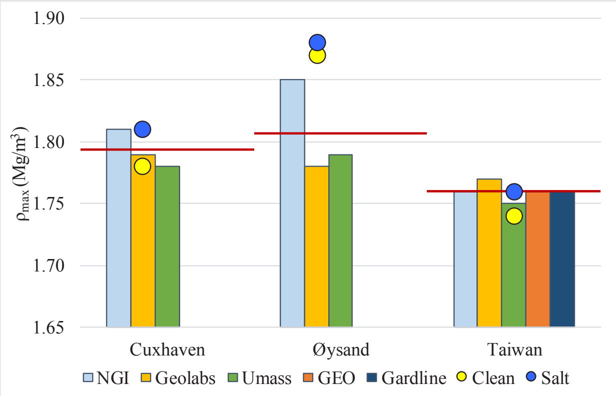


Figure 1a. ρ_{max} For Cuxhaven, Øysand and Taiwan – from Knudsen et al 2020 and the present study, all using new method.

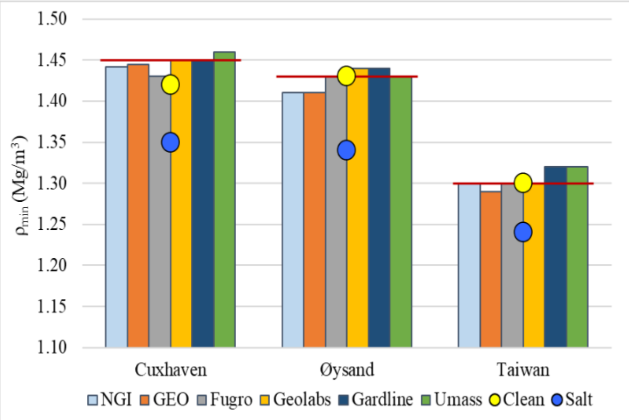


Figure 1b. ρ_{min} For Cuxhaven, Øysand and Taiwan – from Knudsen et al 2020 and the present study, all using new method

It can be clearly seen that for each sand then the ρ_{min} with salt is always lower than that without, just as had been found in the earlier example above. The effect on ρ_{max}, however, is much less in most cases although there is a tendency for the values to be slightly higher 'with salt'. As the ρ_{max} testing is under saturated conditions, then it is likely that the salt may dissolve to some extent during the testing.

Figures 1a and 1b show the data from Table 1 superimposed on data from the Knudsen et al 2020 work. The Knudsen data is shown as a bar chart for the different laboratories using the new methods for ρ_{max} and ρ_{min}, with the horizontal red line showing the mean of their testing. The blobs show the results from this investigation with and without salt. The agreement for the 'clean' sand results matches well with the earlier study with the latest testing matching well with that of NGI for the Øysand. However, as mentioned, the ρ_{max} with salt are slightly higher but the min with salt are significantly lower. The consistency of the ρ_{min} results with the new method on clean sands is particularly encouraging and further enhances the assessment that all results are reliable.

3.2 *Follow on testing.*

As small quantities of some of the other sands from the Lunne et al work, Ticino (TI) LBO, MBO15, and Central America (CA) were still available it was decided to continue the work on those sands also. Table 2 summarises the results from these 4 sands and Figures 2a and 2b present the data on modified plots from Knudsen et al 2020. Here the bars are shown for the other methods as well as the new ones and the red horizontal line indicates the results using the new method statements in the Knudsen work. The blobs represent the testing in this paper. Exactly the same behaviour is seen with the significantly lower values for ρ_{min} with salt compared to the 'clean' versions and

Table 2 Results for ρ_{min} and ρ_{max} with and without salt for TI, CA, LBO and MBO15 sands

	Clean		Salt	
	ρ_{max} [Mg/m^3]	ρ_{min} [Mg/m^3]	ρ_{max} [Mg/m^3]	ρ_{min} [Mg/m^3]
TI	1.74	1.41	1.77	1.31
C/A	1.49	1.16	1.5	1.08
LBO	1.77	1.48	1.82	1.34
MBO15	1.79	1.33	1.82	1.24

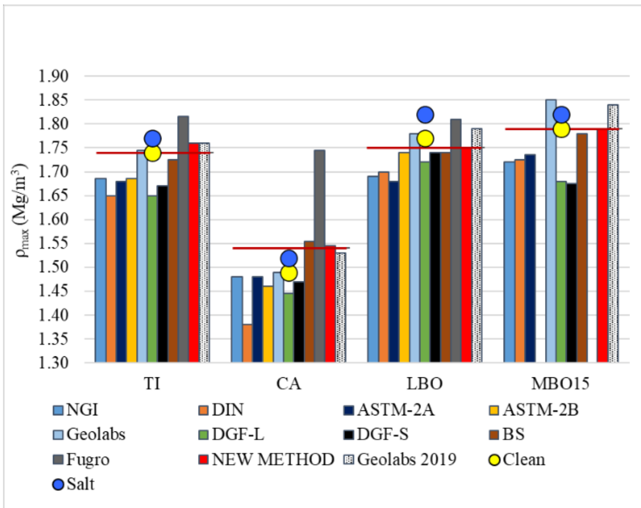


Figure 2a. ρ_{max} For Ticino, CA, LBO and MBO15 sands – from Knudsen et al 2020 and the present study, using various methods.

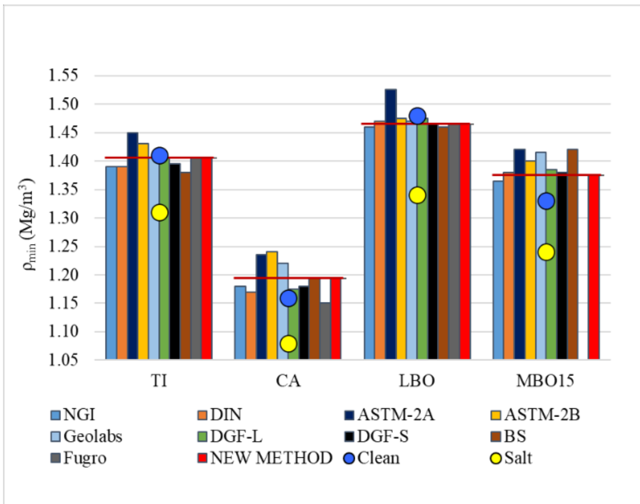


Figure 2b. ρ_{min} For Ticino, CA, LBO and MBO15 sands – from Knudsen et al 2020 and the present study, using various methods.

with slightly higher values for ρ_{max} but matching previous results for the new method.

3.3 *Ensuring consistency.*

To ensure that the behaviour recorded above was consistent further series of ρ_{min} tests were undertaken on all sands with salt in the following sequence:

- dry PSD on clean sample after earlier tests in 2.1 and 2.2, followed by
- wet PSD on same samples
- min test on new salted samples
- dry PSD on salted samples after test

followed by

- wet PSD (all material retained)
- min test on washed salted sample

for the new salted and washed samples both the new method (Knudsen et al 2020) for ρ_{min} and the BS method (BSI 1995) for ρ_{min} were undertaken. Table 3 and Figure 3 present the data.

Table 3. ρ_{min} values for with salt and washed using the NEW and BS methods.

Sand	Salt		Washed	
	New [Mg/m^3]	BS [Mg/m^3]	New [Mg/m^3]	BS [Mg/m^3]
Cuxhaven	1.31	1.33	1.42	1.41
Øysand	1.31	1.33	1.39	1.41
Taiwan	1.18	1.17	1.29	1.29
TI	1.30	1.3	1.39	1.41
C/A	1.09	1.15	1.14	1.16
LBO	1.36	1.38	1.46	1.48
MBO15	1.23	1.25	1.31	1.30

Figure 3 shows this data for all the ρ_{min} results. It can be seen that as with the new method, the BS min method always produces a lower value with salt than without. Furthermore, once a sample has had the salt removed then after wet sieving the ρ_{min} values agree with the clean values from wet sieving. This is reassuring as it shows consistency in the samples and the testing and. that the method is not at fault as these two very different min methods show the same behaviour.

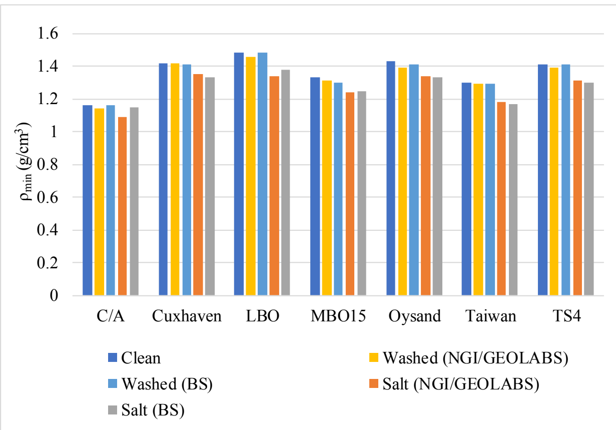


Figure 3. ρ_{min} for all sands, clean and with salt and also after wet (washed) sieving.

4 DISCUSSION

So, what was causing this behaviour? As mentioned in section 3.3, PSDs were run on all samples used in that section of the study. They were run as dry sieves with great care being taken with the salt dried samples, to not break the material down at all. After dry sieving, all samples either clean or with salt were wet sieved. Figures 4a and 4b show examples of these PSDs for the

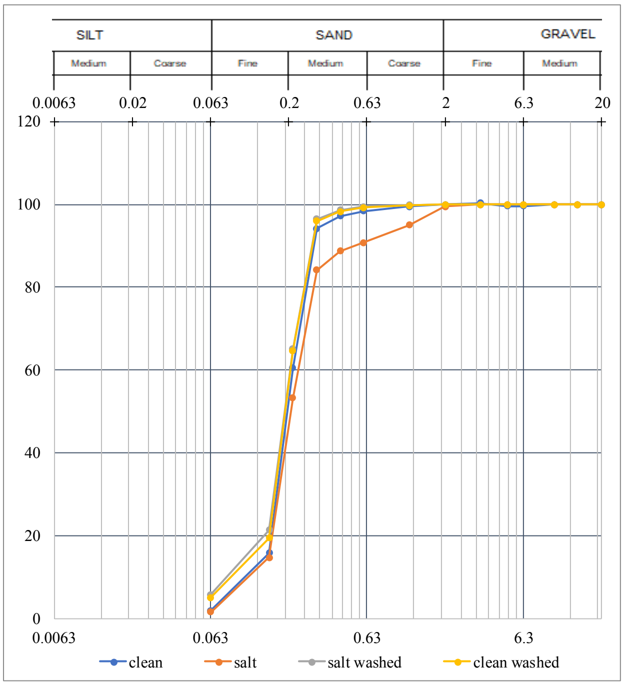


Figure 4a. PSDs for MBO15, clean, with salt, washed clean and washed salt.

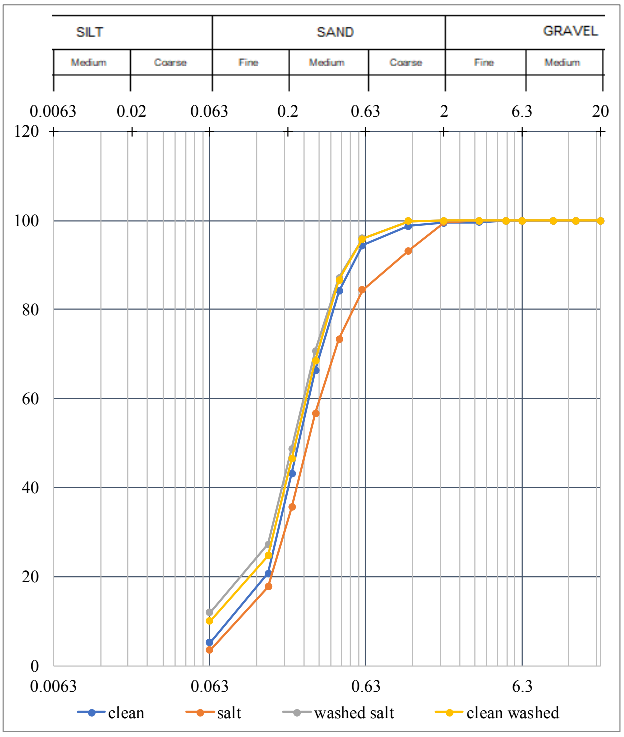


Figure 4b. PSDs for Taiwan sand, clean, with salt, washed clean and washed salt.

MBO15 and Taiwan sands although the pattern was consistent throughout – the dried salted samples always showed a higher percentage of coarser material. However, when wet sieved the PSDs agreed perfectly with the clean sand wet sieves in all cases, even to the extent of the change in fines content on wet sieving the MBO15 as shown in Figure 4a). This seems to imply that the salt might be getting washed off or dissolved in the wet sieving (or bonds breaking?) but it is obviously affecting the grading

percentages when dry! This might also explain why there is closer agreement in the ρ_{max} results which are tested wet.
It should be noted that care was taken throughout that the dry samples for the ρ_{min} testing were never allowed access to moisture before testing as it is well known that sea salt can be hygroscopic and might then absorb water and possibly bulk or flow less freely.

Several series of triaxial tests were conducted on both clean and salted sands reconstituted by under compaction, mainly on Cuxhaven sand, at relative densities of 50% based on the results of both the clean and salted ρ_{min} and ρ_{max} tests (resulting in dry densities of 1.61 and 1.52 Mg/m^3 respectively). Both clean and salted sand were tested at both the aforementioned dry densities. Whist the results varied with consolidation states as might be expected, there were no discernible differences between the results of clean and salted sand when under the same dry density and stress state. It is believed that this is almost certainly due to the fact that during saturation of the samples the salt may well be dissolved out during this process.

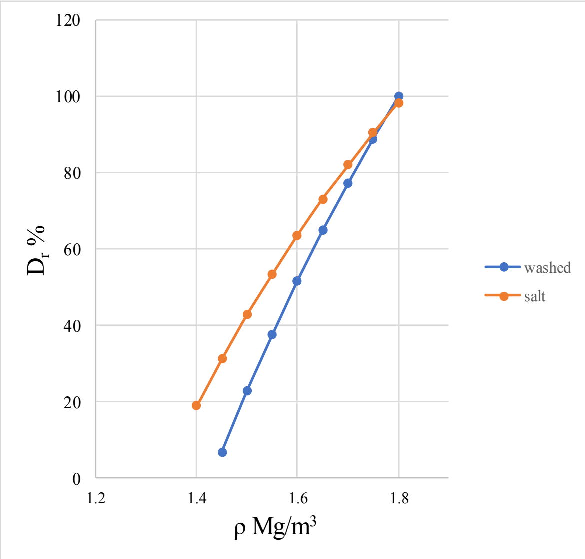
Recently the authors have been given some offshore samples by Ørsted that they could try this comparison with. Table 4 presents the data from these sands (samples 1 and 3 are described as 'fine sand' and samples 2 and 4 as 'fine to medium).

Table 4. ρ_{min} and ρ_{max} values for offshore sands with salt and washed.

	Clean		Salt	
	ρ_{max} [Mg/m^3]	ρ_{min} [Mg/m^3]	ρ_{max} [Mg/m^3]	ρ_{min} [Mg/m^3]
Sample 1	1.8	1.44	1.81	1.33
Sample 2	1.86	1.50	1.87	1.43
Sample 3			1.8	1.34
Sample 4	1.86	1.48	1.86	1.41

It can be seen that exactly the same behaviour as discussed in 3.1 and 3.2 is observed, higher ρ_{min} when washed and slightly lower or equal ρ_{max}. These samples were from vibro cores that had been extruded and placed in bags with no sign of any surplus water and water contents 'as received varying from 7 to 17 % and yet at a water content of 7% still showed signs of salt when dried.

For two of these samples Figures 5a and 5b show the effects of using the washed and 'as received' values for ρ_{min} and ρ_{max} to link Relative Densities (D_r) and dry densities. It is immediately obvious the large differences/errors that can result if the unwashed values are used, especially when looking at lower relative densities.



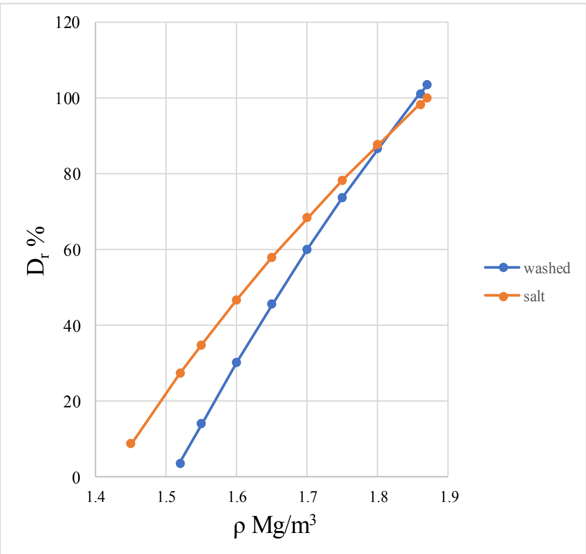


Figure 5a. Dry density ρ and Relative Density for a fine offshore sand.
Figure 5b. Dry density ρ and Relative Density for a fine to medium offshore sand.

5 CONCLUSIONS

The work in this paper has shown that when working with sands where the porewater contains salt (highly likely with offshore samples) then erroneous results can be obtained if the samples are simply dried and then used to determine maximum and minimum dry densities. Minimum density is most affected but there does appear to be an effect on the maximum, but to a much lesser extent. It is recommended that all sands should be first washed (with care to maintain all particles) before being used for the determinations. Failing to do this can result in significant errors in the derived relative density for a known dry density, or incorrect dry density for re-compaction based on a relative density.

Results of triaxial tests when both clean and salted sand were recompacted to the same dry density showed little difference in results. However, as would be expected recompacting to the same % relative densities (different dry densities) but based on the different ρ_{min} and ρ_{max} results did affect the results and would result in incorrect data if the salted sand densities had been used.

6 ACKNOWLEDGEMENTS

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