Effect of seawater on marine deltaic cohesive soft soils from Llobregat River (Barcelona, Spain)

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ABSTRACT: The effect of salt solutions on some geotechnical properties of clayey soils depends, among other parameters, on clay mineralogy and plasticity. Thus, as previously pointed out by many authors, compressibility behavior of swelling clays is highly affected when exposed to salt solutions while slight influence was reported on non-swelling clays. In this paper the results of a laboratory campaign on marine deltaic soft cohesive sediments from Llobregat River (Barcelona, Spain) are presented. Undisturbed samples were recovered from rotary boreholes operated from a jack-up located up to 20m water depth. The effect on consistency limits and compressibility characteristics of cohesive samples when exposed to different water solutions such as distilled water and seawater was studied. Results were also compared with previous research, confirming them, and contribute to increase the knowledge of the effect of saline waters on geotechnical parameters of cohesive soils, reaching the conclusion of a low effect of the seawater on low plasticity soils.

Keywords: cohesive soils; consistency limits; consolidation; seawater.

1. Introduction

Cohesive soils show considerably different engineering behavior depending on their mineralogical and chemical composition. Pore fluid chemistry may affect significantly the engineering properties of clays in most cases. Hence, the performance of earth structures such as impermeable clay liners changes may change depending on the pore fluid chemistry of the system. On the other hand, variations in the pore fluid do not affect significantly the performance of earth structures composed of non-swelling clays.

There are several studies reporting variations in engineering behaviour of cohesive soils upon testing samples saturated with different salt solutions, such as [1-9]. These studies reported that inorganic salt solutions have a strong impact on the engineering behaviour of clays, especially on swelling clays. However, the effects of saline waters on the compressibility and/or swelling behaviour of soils are not known well. The effects of saline waters on the engineering behaviour of soils need to be determined, especially for offshore and nearshore structures since they are settled on seawater saturated soils. The aim of this study is to determine the rate of change in some of the geotechnical engineering properties of the marine deltaic soft cohesive sediments from Llobregat River, located in the south of Barcelona city, when exposed to seawater with respect to distilled water. For this purpose, seven soil samples where tested and subjected to the consistency limits and incremental loading oedometer tests both with distilled water and seawater from the nearshore zone of Llobregat Delta.

2. The Llobregat Delta

Intensive geotechnical investigations have been carried out in the Llobregat Delta Quaternary sediments during the last two decades for the numerous infrastructures that have been developed in this area (extensions of the port, new terminal at El Prat airport, highways, high-speed train, etc.). Most of these surveys were executed by means of core drilling with undisturbed sampling and SPT tests, as well as advanced geotechnical in situ tests such as CPTU, DMT, SCPTU, SDMT, pressuremeter tests, field vane tests, etc. Numerous laboratory tests have always complemented these field investigations.

The stratigraphic sequence of the delta body and its geotechnical characterization is well defined and has been the subject of numerous publications, such as [11], [12] and [13], where a high resolution stratigraphy study of the delta body using CPTU data and core boreholes were presented. Several papers which help to increase knowledge about this area are also presented at ISC'6 Conference [14-16].

The general stratigraphy of the Llobregat Delta is presented in Fig.1. Schematically, the soil profile is made up of a thick layer of fine sediments, mainly clayed silts, sandwiched between two granular soils, the so-called lower aquifer and upper aquifer. The entire sequence is topped by recent Quaternary soils and, in turn, rests on the Pliocene blue clays and shales basement. The fine grained soils, which correspond to the sedimentological pro-delta facies (E unit in Fig.1), are the ones studied herein. Fig.2 shows works during the site soil description and a SEM-EDS image of the silty clay used for this study.

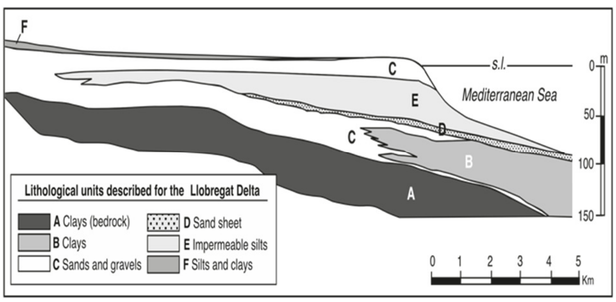

Figure 1. Sedimentary sequence of Llobregat Delta body. Adapted from [17]

Figure 2. Detail of samples being logged on site

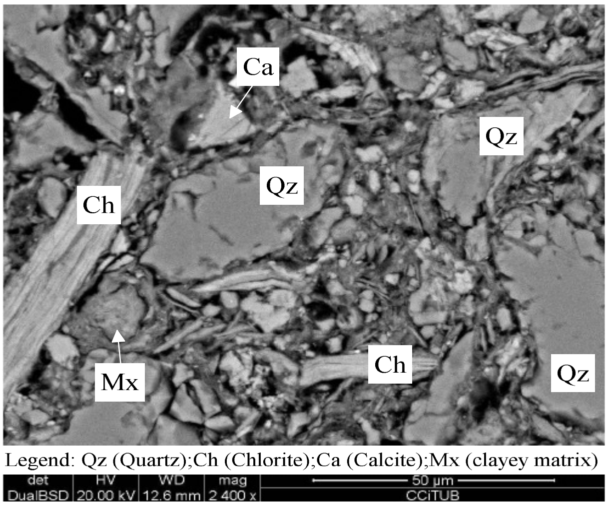

Figure 3. Detail of the pro-delta silty clay from a SEM-EDS analysis

3. Previous Studies on Saline Solutions

The effect of inorganic salt solutions on the engineering properties of clays or clayey soils was extensively investigated by many researchers, such as [2, 5, 10, 17 and 19]. The published data shows that clay structure undergoes changes in the particulate levels when clayey soils are exposed to artificial seawater. Rao et al. [10], Sivapullaiah and Savitha [20], Sridharan et al. [21] and Ören and Kaya [4], among others, reported the effects of inorganic salt solutions on consistency limits of clayey soils. Some of these studies reported slight increase in the Liquid Limit of non-swelling clays such as kaolinitic and mixed clay minerals when exposed to strong salt solutions [4 and 21].

On the other hand, the Liquid Limit of montmorillonitic clays decreases when exposed to salt solutions, as was reported by [10, 2, 22, 23 and 19]. This decrease gets more significant in clays with a Liquid Limit higher than 110% [5]. The seawater effect on compressibility characteristics of clays is more pronounced for bentonites [2 and 19]. Furthermore, the consolidation behavior of a marine clay and kaolinite is similar when they are exposed to both still water and seawater [19]. Ören et al. [18] performed consolidation tests on five different clays having Liquid Limit values up to 110%. The results showed that compression indices of clays do not change significantly when the clayey soils are tested with distilled water or seawater. After that, they reported [5] that Na bentonites showed a very pronounced seawater effect.

4. Materials and methods

For this study, seven cohesive soil samples collected from different boreholes in the nearshore area of Llobregat Delta were used in order to determine their changes in behaviour iwhen tested with distilled and seawater. Some X-Ray Diffractions and SEM-EDS analysis were performed in order to determine the dominant minerals in the area. Results were quite similar among all samples and are summarized in Table 1.

Table 1. Main minerals present in samples used for this study

Mineral	**Min. content (%)**	**Max. content (%)**	**Av. Content (%)**
Illite / Montmorillonite	24.87	37.53	31.20
Calcite	16.44	28.07	22.26
Quartz	16.03	25.86	20.95
Muscovite	2.50	10.49	6.50
Albite	2.83	8.46	5.65
Dolomite / Ankerite / Aragonite	3.08	5.96	4.52
Kaolinite	2.88	5.45	4.17
Microcline	1.80	4.24	3.02
Chlorite	0.82	2.03	1.43

Samples are classified as CL, ML and ML-CL based on the USCS classification, with Liquid Limit (LL) ranging from 33.3 to 44.3%, Plastic Limit (PL) from 19.4 to 25.1% and Plasticity Index (PI) from 6.5 to 14.9%. An exensive particle size distribution by sieve and hydrometer has been carried out. Results suggest that this marine soils are classified as silty clays (siCl) in the particle size ISO classification, with the following range values: 0 to 2.8% of gravel, 1.1 to 15.8% of sand, 55 to 69% of silt and 26.4 to 37.9% of clay.

All consistency limits were ovendried (60 °C), crushed and sieved through the 0.4 mm sieve. Liquid and Plastic Limit were determined according to ISO 17892-12.

Compressibility characteristics of the samples were determined using incremental loading oedometer test according to ISO 17892-5. Samples were tested at their undisturbed state, adding distilled water and seawater in two different specimens. Each load was maintained for, at least 24 h. The swelling characteristics of the samples were observed by unloading the sample after the completion of the loading process.

Natural seawater from the nearshore zone of Llobregat Delta and distilled water were used as fluids.

The chemical composition of the seawater was determined by IPROMA laboratories in Spain and is shown in Table 2.

Table 2. Chemical composition of the seawater used for this study

Element	**Content (mg/l)**
Cl^-	22.101
Na^+	11.830
SO_4^{2-}	3.059
Mg^{2+}	1.457
K^+	423
Ca^{2+}	420
CO_3^{2-}	<20
Al^{3+}	<0.1

Cu	<0.05

5. Results

The consistency limits of the seven samples were determined using both distilled water and seawater. Results are shown in Fig. 4, Fig. 5 and Fig. 6.

As it is showed in Fig. 4, a clear but not too significant reduction of the Liquid Limit between 2% and 10% with seawater was obtained.

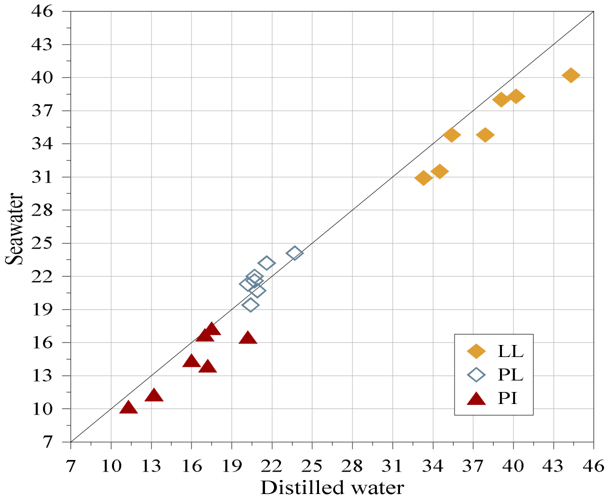

Figure 4. Liquid Limit, Plastic Limit and Plasticity Index results for samples tested with distilled water and seawater

All tests results were on the same way, although no trend related to the increase of LL was reported, as it is shown in Fig. 5.

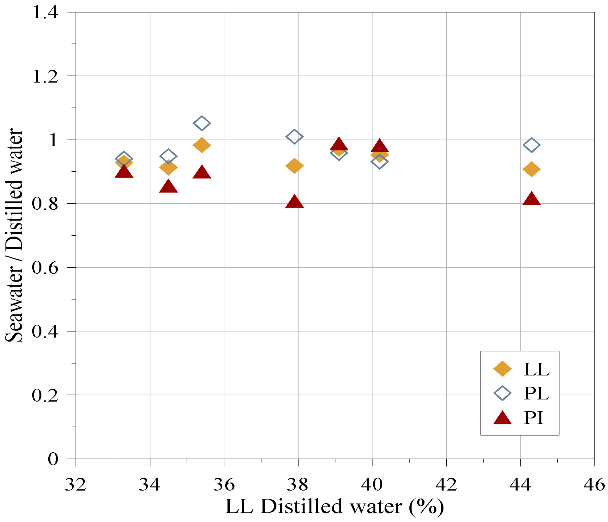

Figure 5. Seawater/distilled water relationship for Liquid Limit, Plastic Limit and Plasticity Index

On the other hand, the Plastic Limit was not affected significantly when different salt solutions were used. It was reported increments of about 5% and reductions of the 7% when seawater was used instead of distilled water. The relationship between seawater/distilled water results for Liquid Limit, Plastic Limit and Plasticity Index related to the Liquid Limit with distilled water is shown in Fig. 5. Results plot falls between 0.8 and 1. Moreover, no trend was observed with Liquid Limit variations.

Taking into account the results of the Consistency Limits, and based on the Casagrande chart, the estudied soil is classified as low plasticity clay, without any significant variation when seawater was used, as it is shown in Fig. 6.

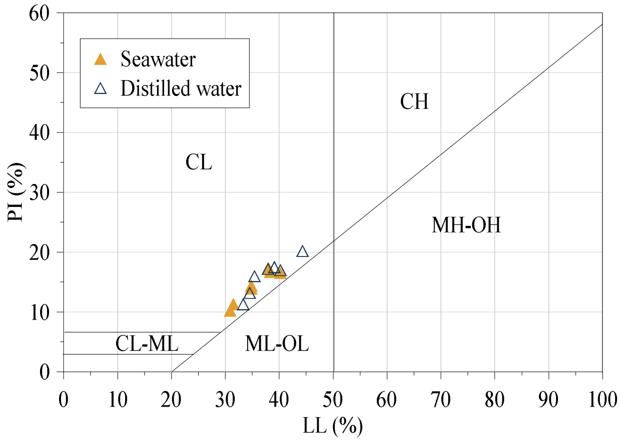

Figure 6. Consistency limits for seawater and distilled water plotted in a Casagrande chart

Oedometer tests were also conducted using seawater and distilled water. The results of consolidation also show a reduction of the compression coefficient. In this case, the reduction is more significant than in the Liquid Limit, as it reaches values up to 14 %. Some other samples, however, not only does not show a reduction of this parameter but a very low increment of less than 2 %. Results are shown in Fig. 7 and Fig. 8.

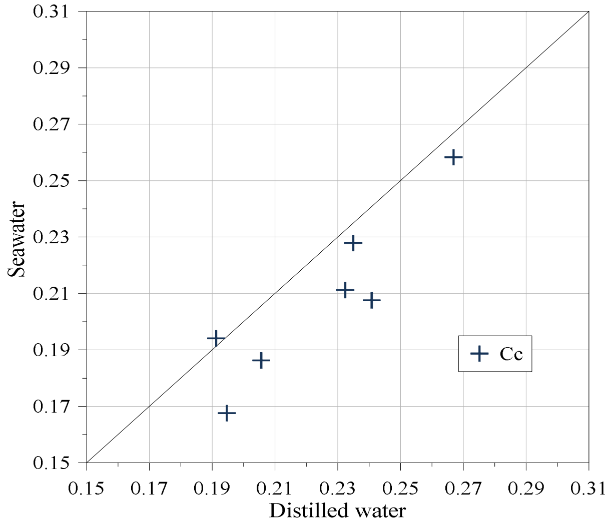

Figure 7. Cc values for samples tested with distilled water and sea-water

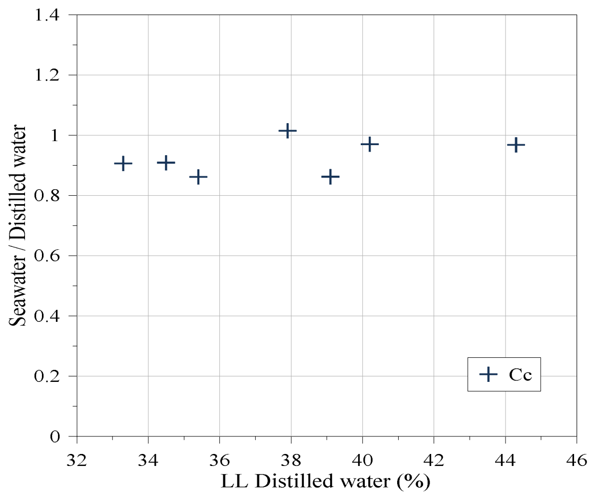

Figure 8. Seawater/distilled water relationship for Cc.

The results of the oedometer tests are shown in Fig. 9, Fig. 10, Fig. 11, Fig. 12, Fig. 13, Fig. 14 and Fig. 15. It is significant that some samples, such as samples #1, #3, #5, #6 and #7 present a higher void ratio when tested using seawater but, additionally, some other samples, such as #2 and #4, present a lower void ratio in this case.

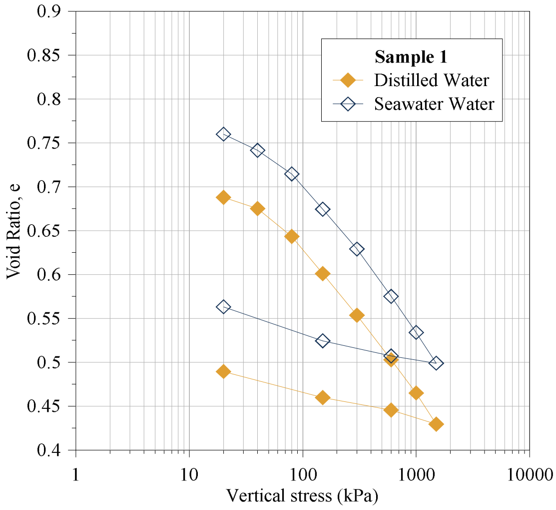

Figure 9. Oedometer results for Sample 1.

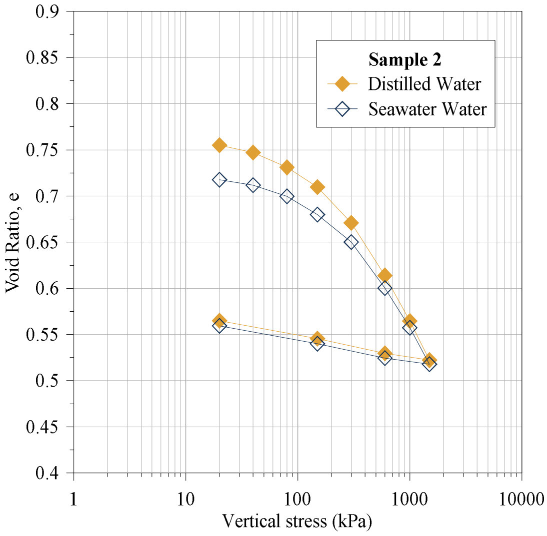

Figure 10. Oedometer results for Sample 2.

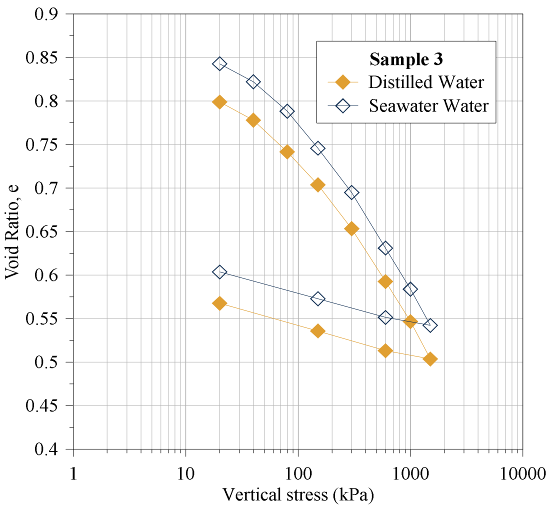

Figure 11. Oedometer results for sample 3.

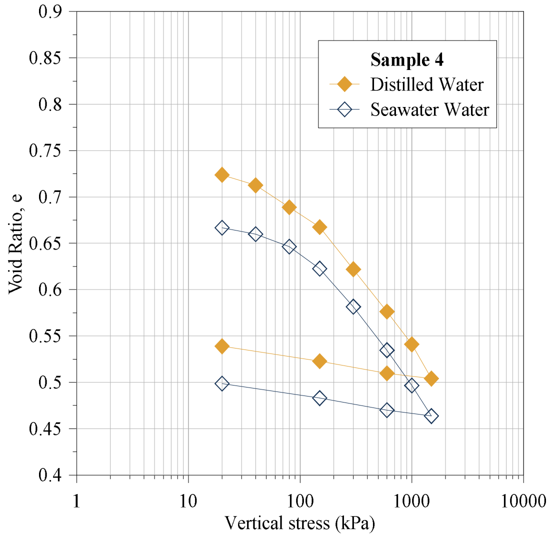

Figure 12. Oedometer results for Sample 4.

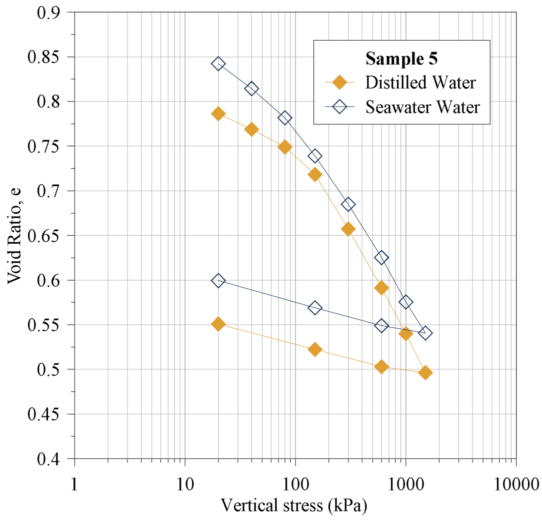

Figure 13. Oedometer results for Sample 5.

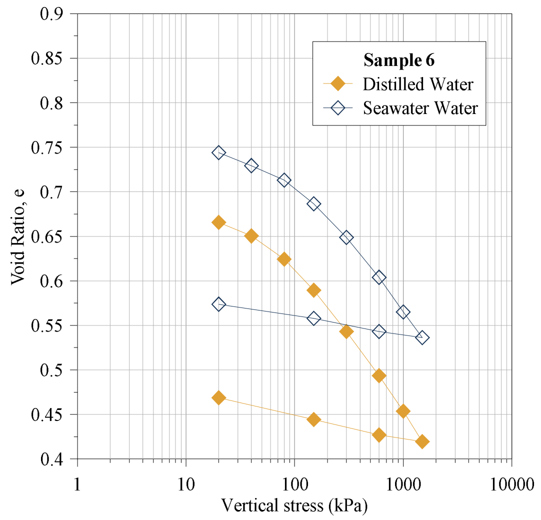

Figure 14. Oedometer results for Sample 6.

As it is shown with all these results, neither the Liquid and Plastic Limits nor the consolidation coefficient present significant variations that could affect critically the engineering properties of this soil. Nevertheless, clear differences were reported in the void ratio in some samples when using seawater instead of distilled water. No reasonable explanation has been found yet, although a more detailed study will be carried out in the future.

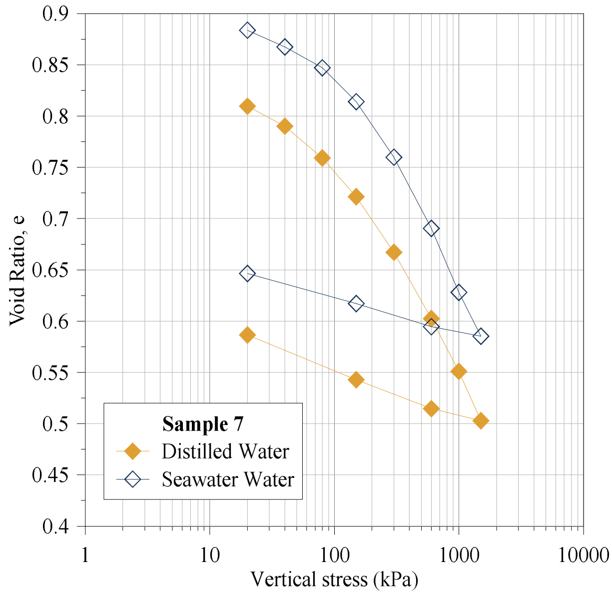

Figure 15. Oedometer results for Sample 7

Although there is consensus among researchers that consistency limits of soils composed of mostly montmorillonite minerals decrease with seawater, there is no agreement on how seawater affects the consistency limits of kaolinitic soils.

Most of the data in the previous study plots around the unity line up to Liquid Limit of 110%; then, the index and the compressibility properties of soils decrease linearly on log–log graph, as seen in Fig. 16, Fig. 17 and Fig. 18. This effect is more pronounced for highly active clayey soils. Therefore, an extensive comparison can be made only for the Liquid Limit and Plasticity Index of clayey soils.

Most of the Liquid Limit data of the Canadian glacial deposits reported in [24 and 25] plot above the unity line. However, the data reported in [26] for glacial deposits of Canada plot below the unity line. The data of Ariake marine clays of Japan reported [21 and 27] plot slightly above the unity line as well. Fig. 17 show that normalized Plastic Index has a similar trend as Liquid Limit with somewhat increased scatter.

The effect of seawater on the compression indices is evaluated as a function of Liquid Limit in Fig. 16 and Fig. 17. Results of this study are in good agreement with those of previous researchers, filling an empty zone around 30 to 45 % of Liquid Limit. According to existing bibliography, the seawater effect is significantly pronunciated above the Liquid Limit of 110%. Therefore, no influece was expected in soils with Liquid Limit less than 110%, as all tests carried out in this study have confirmed.

Furthermore, although there is less bibliography related to the influence of seawater on the Compression Index, it seems that it is similar to the one well described for consistency index, as it is shown in Fig. 18. Results of this study are in line with previous results in both Consistency Limits and Compression Index, and increase the knowledge of the effect of seawater on the behavior of cohesive marine soft soils.

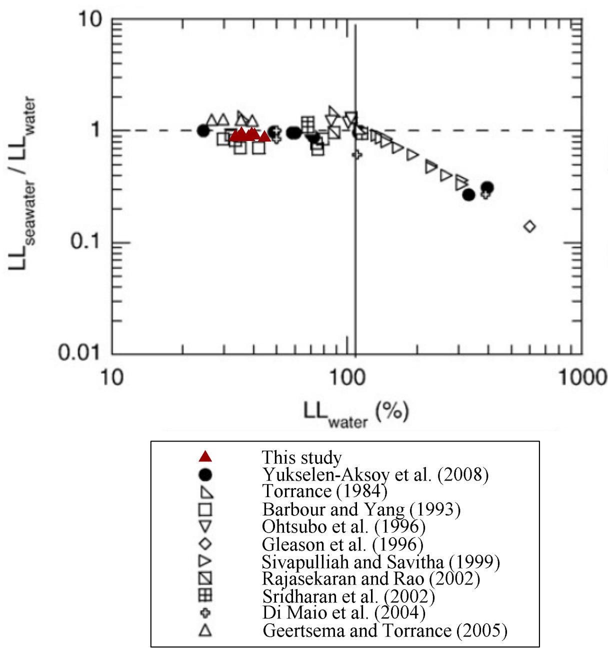

Figure 16. Normalized Liquid Limit versus Liquid Limit. Results of previous and current study

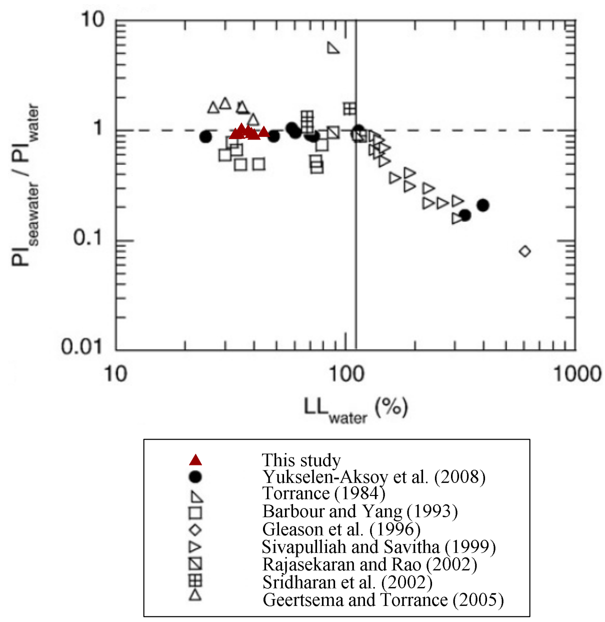

Figure 17. Normalized Plastic Limit versus Liquid Limit. Results of previous and current study

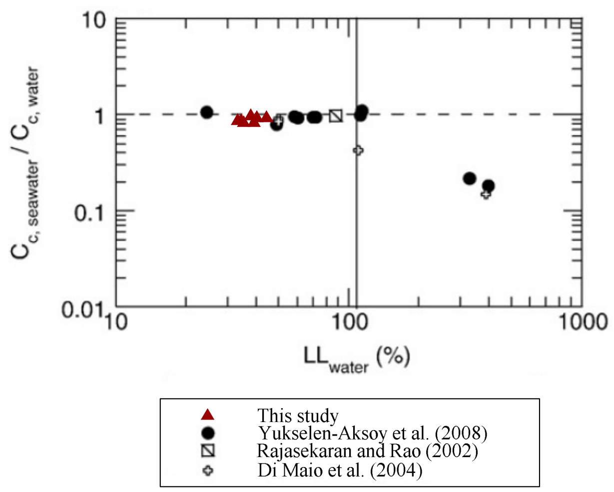

Figure 18. Normalized Compression Index versus Liquid Limit. Results of previous and current study

6. Conclusions

Consistency Limits and Compression Index have been estimated with both distilled water and seawater on a marine deltaic cohesive soft soil from Llobregat River, (Barcelona, Spain).

A reduction of the Liquid Limit between 2% and 10% when seawater was used for tests was reported. Furthemore, Plastic Limit was not clearly affected, as increments of 5% and reductions of 7% were reported. Thus, based in the Casagrande chart, the studied soils did not change its classification when seawater was used instead of distilled water.

On the other hand, a reduction up to 14% of Compression Index was reported with seawater when oedometer tests were performed.

Based on these results, it might be concluded than there is a low effect on geotechnical parameters of low plasticity marine soils when seawater is used as salt solution for laboratory tests.

Results of this study are in line with previous research in both Consistency Limits and Compression Index, and increase the knowledge of the effect of seawater on the behavior of cohesive marine soft soils.

7. Acknowledgements

The authors wish to thank the Port Authority of Barcelona (APB) for their support during the development of this paper.

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