Proceedings of the 7th International Conference on Geotechnical and Geophysical Site Characterization
Barcelona, 18 - 21 June 2024

Effects of storage time on sample quality in Ballina clay

Kaiwen Ouyang[1] and *Jubert* Pineda[1#]

[1]*Priority Research Centre for Geotechnical Science and Engineering, The University of Newcastle Australia, Callaghan Campus, 2308, NSW, Australia*
[#]*Corresponding author: Jubert.pineda@newcastle.edu.au*

ABSTRACT

This paper explores the effects of the storage time on the engineering properties of Ballina clay, an estuarine silty clay that represents the soft soil deposits encountered along the eastern and southern Australian coastlines, which serves as foundation material for most of the country's transport and energy infrastructure. An experimental program was carried out to evaluate the variation in soil compressibility and soil shear strength for tube specimens retrieved with an open sampler (Shelby tube) as well as an Osterberg fixed-piston sampler. Mechanical parameters obtained from tests performed immediately after sampling are compared against those measured over a period of 1 year, to assess the influence of the storage time. Results indicate that long-term storage has small influence on the quality of Ballina clay specimens in comparison with the mechanical disturbance caused during tube penetration and extraction, which is controlled by the sampler type.

Keywords: soil sampling, soft clay, storage time, sampling disturbance, Ballina clay

1. Introduction

A typical tube sampling campaign involves several stages which are potential sources for soil disturbance (e.g. Ladd & DeGroot, 2003): drilling, sampler insertion and retrieval, tube sealing, transport, storage, soil extrusion and sample preparation. Some of these effects depend very much on the expertise of the operator, whereas a few relate to the sampling tools and methods. However, there is no easy way to separate the contributions from each source to the global soil disturbance, as all these processes are coupled. If qualified operators and appropriate methods for sealing, transport and sample preparation are used during a sampling campaign then it is plausible to assume that the main sources of disturbance are related to the sampler penetration and extraction, soil extrusion and water content redistribution in the tube (Baligh et al., 1987).

However, experimental evidence has demonstrated that the sample storage method and storage time have a major influence on the behaviour of soft soils (e.g., see Bjerrum & Rosenqvist, 1956). Indeed, sample storage may activate biological processes, such as methane release and the oxidation of organic matter, which can lead to a progressive change in mechanical properties (e.g. Arman and McManis, 1976; Thakur, 2014; L'Heureux & Paniagua, 2014). The alteration of natural soft clays during long-term storage is still an unsolved issue due to the lack of understanding of the key physical-biogeochemical interactions involved. Even small thermal variations may activate or accelerate biogeochemical reactions and alter the hydraulic (permeability) and mechanical (compressibility, strength, stiffness) properties of soft soils (e.g., Mitchell & Santamarina, 2005). Chemical changes may also take place under isothermal conditions if enough oxygen is present.

This paper presents preliminary results obtained from a laboratory testing campaign conducted to evaluate the effects of the storage time on sample quality in Ballina clay from New South Wales (Australia). Emphasis is given to the consequences of storage time on compressibility parameters estimated from oedometer tests. A comparison against published laboratory data covering natural soft soil deposits with variable plasticity is presented to elucidate the effects of soil plasticity on sample quality.

2. Material

The soil investigated is Ballina clay, an estuarine soft clay encountered at the National Soft Soil Field Testing Facility (NFTF) in Ballina, northern New South Wales, Australia (Kelly et al., 2017; Pineda et al. 2019). The soil profile at Ballina site is composed by a shallow alluvial stratum ($z < 1.5$ m), followed by a high-plasticity soft clay layer ($1.5 < z < 11$ m), hereafter Ballina clay. This soft soil stratum may be subdivided into an upper silty clay layer ($1.5 < z < 4$ m) and a lower soft clay layer ($4 < z < 11$ m) where the variation of index properties with depth is not significant. Below 11 m depth, a transition sandy zone is found, followed by a thick stiff clay layer with variable thickness below depth of 17m.

As indicated by Figure 1, the natural water content increases with depth from 20% to 120%. The liquid limit varies between 55% and 135%, whereas the plastic limit ranges from 20% to 55%. Dry density reduces from 1.50Mg/m^3 to 0.70Mg/m^3 with depth. Below 2m, clay content is predominant with maximum values of 82%, while sand content is around 1%. Further details are described in Pineda et al. (2016).

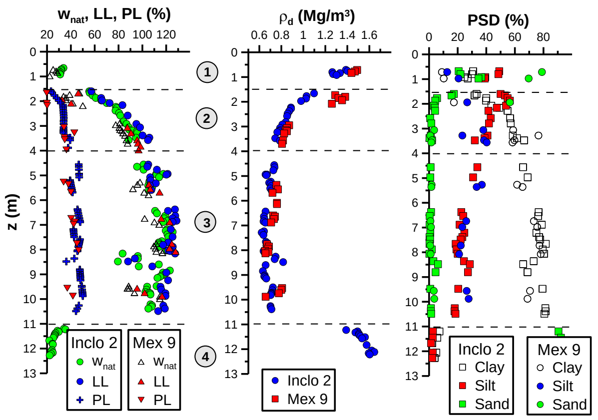


Figure 1. Index properties at the NFTF

3. Soil sampling and sample storage

The study presented in this paper was carried out on tube specimens obtained in a sampling campaign conducted in October 2020 at the NFTF. Drilling and sampling were conducted utilizing a track-mounted rig following the wash boring method to achieve the target depth. A fixed-piston sampler (O89) with 89 mm outer diameter, 1.5 mm thickness, 700 mm total length, 10º cutting angle and 7.1% area ratio, was employed to obtain soil specimens for laboratory testing. Stainless steel tubes were used in this study to retrieve samples from depths between 6.0 – 6.7 m.

After sampler retrieval, tube ends were sealed with plastic film and aluminum foil underlying a 10mm-thick foam plate. A 15mm layer of melted vaseline-wax (50:50) mixture was then poured on top of the foam plate to prevent moisture losses prior to testing (Figure 2a). Tube specimens were placed vertically aligned in sealed plastic containers on a 100 mm-thick sand layer. The sand layer was previously saturated with tap water aimed at producing a high relative humidity environment ($RH \approx 99\%$), thus minimizing moisture losses during transportation and sample storage (Figure 2b) (Pineda et al., 2014). Plastic containers with tube specimens were transported and stored in an industrial fridge under a controlled temperature of T=16ºC.

4. Experimental program and procedures

To assess the influence of the storage time on the quality of tube samples retrieved with the fixed-piston sampler, Constant Rate of Strain (CRS) oedometer tests were performed. Measurements of shear wave velocity (V_s) during CRS tests were also carried out using bender elements transducers located at top and bottom ends of the specimen. Samples used in CRS oedometer tests were tested at: (i) t = 8 days (BH4), (ii) t = 38 days (BH2), (iii) 104 < t < 109 days (BH3), (iv) t = 221 days (BH9), and (v) t =370 days (BH10).

Each tube was first scanned using a medical CT scanner Somaton Confidence CT Scanner (Siemens®) for visual inspection prior to testing. Figure 3 shows longitudinal sections of the tested tubes. This figure includes the variation of the mean CT value within each tube as well as the location of CRS and UCS specimens trimmed after the scans were completed. Tube specimen BH4 was tested in less than 10 days after sampling which gave no time for CT scanning. Boreholes BH2, BH9 and BH10 show a mean CT value around 700 HU (Hounsfield Units) whereas the value for borehole BH3 ranges around 800 HU.

CRS tests were performed according to ASTM D4186. CRS samples were obtained from 40 mm segments, sliced from each tube using a hand grinder (to cut the tube wall) and a wire saw (to cut the soil). Oedometer specimens (48 mm in diameter and 20 mm in height) were trimmed by gentle pushing of a 1 mm-thick oedometer ring into the 40 mm slice. This thin oedometer ring (area ratio around 9%) was designed to reduce soil disturbance during sample preparation. Each CRS test consisted of three main stages: saturation, loading and unloading. Specimens were percolated with synthetic pore fluid prepared at the same electrical conductivity (salinity) as the natural soil. Percolation took place under constant vertical stress ($\sigma_v \approx 20$ kPa) and it was maintained for 2 days to ensure full saturation. A displacement rate of 0.004mm/min was used during the loading and unloading stages. Free drainage was allowed from the top of the sample, while the excess pore water pressure was monitored at the bottom of the specimen. A maximum vertical stress of 1MPa was reached at the end of the loading path.

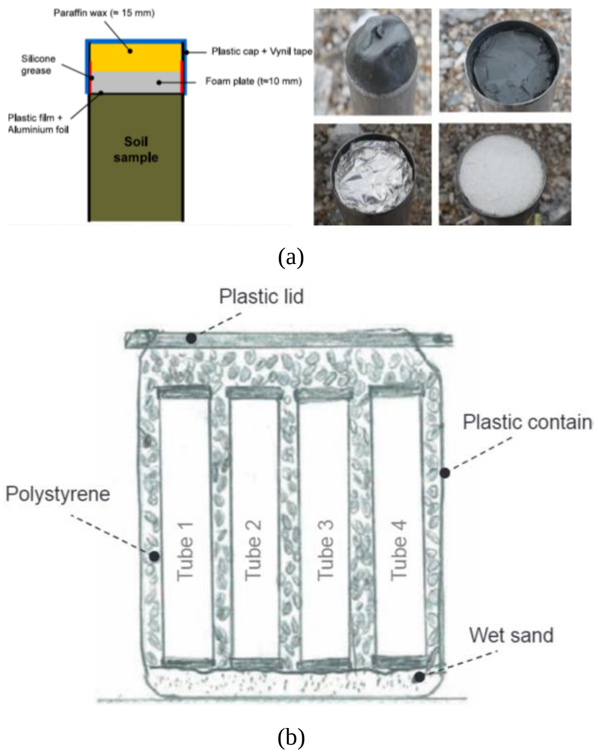


Figure 2. (a) Waxing of tube specimens. (b) Placement of specimens for transport and storage.

5. CRS results

Figure 4(a) shows the evolution of volumetric strain and pore-water pressure during the loading-unloading path measured during CRS tests. The in-situ vertical effective stress at sample depth is indicated in this figure with a vertical dashed line. Similar stress-strain behaviour is observed for most samples except two specimens from borehole BH3 tested between 104 - 109 days. The volumetric strain at $\sigma'_{v(in\text{-}situ)}$ is less than 2% for specimens from boreholes BH4 (t < 10 days), BH2 (t = 38 days), BH9 (t = 221 days) and BH10 (t = 370 days). The larger volumetric strain in specimens from borehole BH3 indicates that important soil destructuration took place before testing. A non-linear excess pore water pressure was measured at the base of the oedometer samples, with maximum values around $\Delta u_b \approx 250$ kPa.

Figure 4(b) shows the compressibility curves, e-log(σ'_v). A highly non-linear response is observed for Ballina clay, a key feature of its structured nature. Consequently, soil destructuration is reflected by linear e-log(σ'_v) plots like those obtained for borehole BH3. Nevertheless, compressibility curves merge at large stresses, after the natural soil structure is erased by mechanical loading.

The evolution of the shear wave velocity, V_S, during loading shows a bi-linear response. Small increase in V_s is observed for vertical effective stresses below $\sigma'_{v(in\text{-}situ)}$. There, V_S ranges around 63-67 m/s which is in agreement with results from a nearby SMDT test ($V_{s\text{-}(SDMT)} \approx 65$ m/s) at the same depth. V_S increased almost linearly with vertical effective stress once yielding takes place. This seems evident for specimens from boreholes BH4, BH2, BH9 and BH10. In the case of BH3, the linear increase in V_S with σ'_v is observed since the beginning of loading.

Figure 5 shows the variation in compression index C_c, obtained as the slope of the e-log(σ'_v) curve, with the vertical effective stress. The non-linear nature of the compressibility curves produces a highly non-linear variation in Cc with the vertical effective stress. Peak values, $C_{c\text{-}peak} \approx 3$, are reached once the yield stress has been exceeded because of soil destructuration. At large stresses, values around $C_c = 1.1$ are observed. Soil destructuration observed in borehole BH3, produces lower values of $C_{c\text{-}peak}$, just slightly higher than that reached at large stresses.

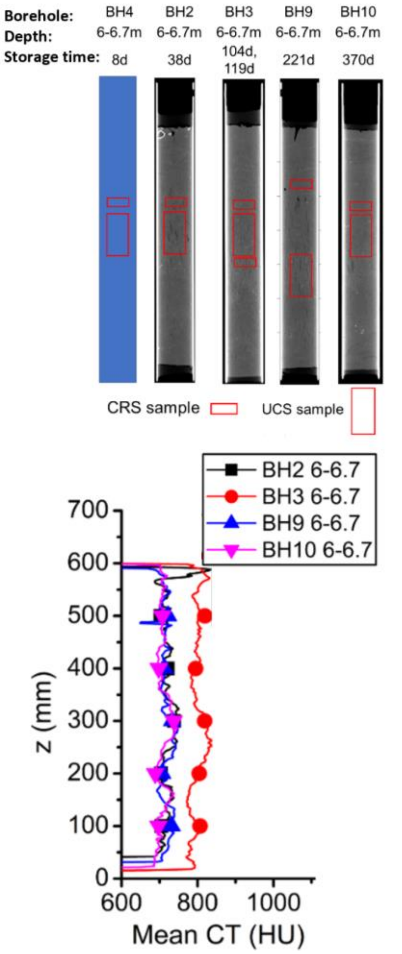
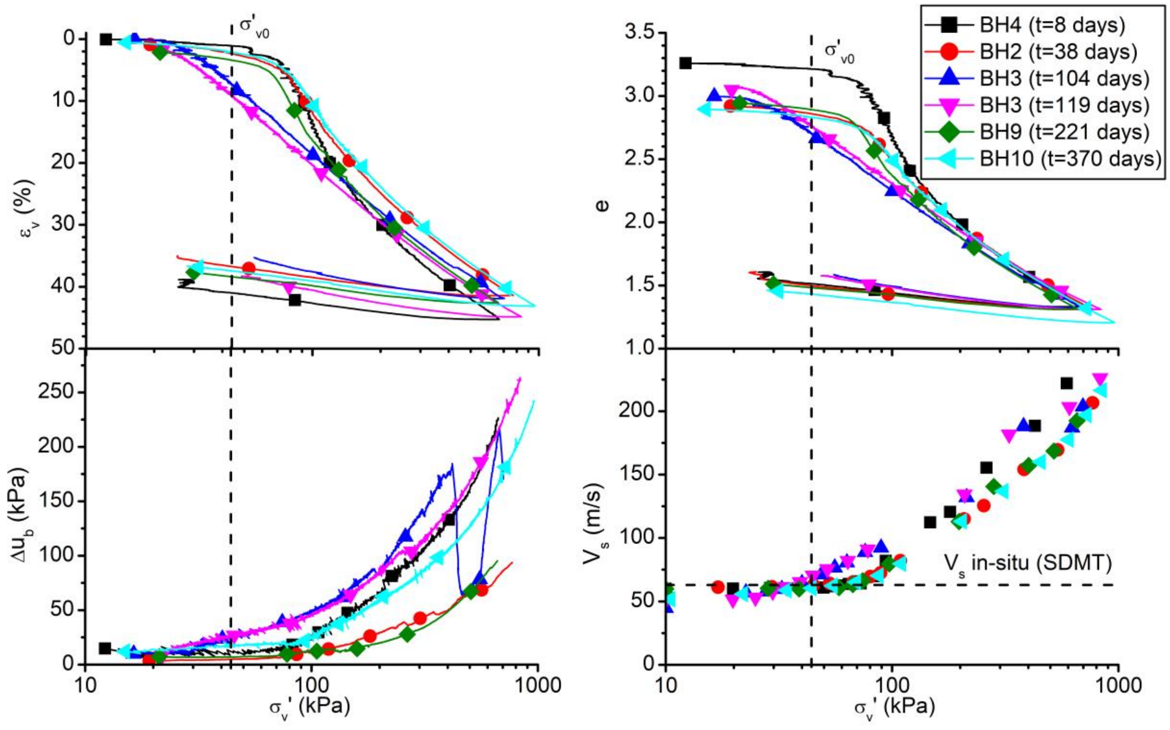


Figure 3. CT scans of tested tube specimens



(a) (b)

Figure 4. CRS test results

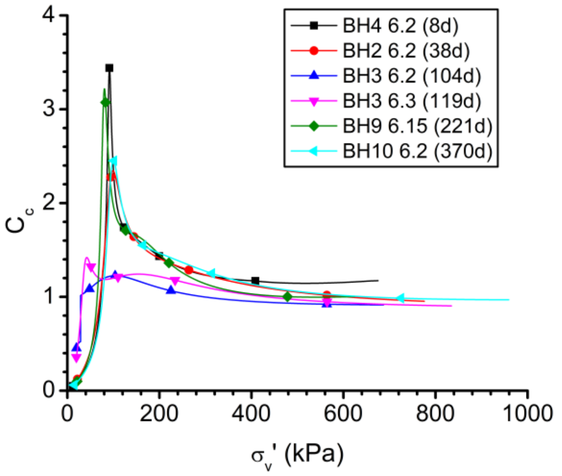


Figure 5. Variation of compression index with vertical effective stress.

6. Influence of storage time on sample quality

The disturbance of natural soils caused by sampling, particularly when tube samplers are used, is the result of several effects such as mechanical disturbance caused by tube penetration and extraction, thermal disturbance due to waxing, chemical disturbance triggered during sample storage and mechanical disturbance caused during soil extrusion and sample preparation prior to testing (Ladd and DeGroot, 2003; Pineda et al., 2018; Ouyang, 2023).

Mechanical parameters estimated from the CRS tests are compared here to evaluate the influence of the storage time on the quality of Ballina clay specimens. The sample quality index $\Delta e/e_0$ (Lunne et al., 1997) is correlated with the estimated mechanical properties and storage time. The sample quality index requires the estimation of the normalized change in void ratio needed to recompress the natural soil to its in-situ vertical stress. For soils with overconsolidation ratio OCR<2, four levels of sample quality are specified from *very good to excellent* ($\Delta e/e_0 < 0.04$), *good to fair* ($0.04 < \Delta e/e_0 < 0.07$), *poor* ($0.07 < \Delta e/e_0 < 0.14$) and *very poor* ($\Delta e/e_0 > 0.14$).

Figure 6 shows the variation of the sample quality index $\Delta e/e_0$ with the storage time. Specimens from boreholes BH4 (t < 10 days), BH2 (t = 38 days) and BH10 (t = 370 days) classify as *very good to excellent* whereas specimen from BH9 (t=221 days) is rated as *good to fair*. The two samples from BH3, tested after 104 days, are rated as *poor*. There is no clear effect of the storage time reflected on the sample quality index $\Delta e/e_0$ apart from the disturbance shown by specimens from BH3 which may be due to ‘short-term’ mechanical disturbance caused during tube penetration and extraction stages.

Figure 7 presents the variation of yield stress, calculated according to the strain energy method (Becker et al. (1987), with the storage time. An average yield stress of $\sigma'_{yield} = 71$ kPa is indicated in this figure using a dashed line. This value represents specimens rated in Figure 6 as *very good to excellent* (BH4, BH2 and BH10) as well as *good to fair* (BH9). Specimens from BH3 show a yield stress around 30 kPa. This value is even lower than the $\sigma'_{v(in\text{-}situ)}$ for this depth (i.e. OCR <1), which confirms the large disturbance experienced by those specimens prior to testing. Storage time has no effect on the yield stress for ‘good quality’ fixed-piston samples.

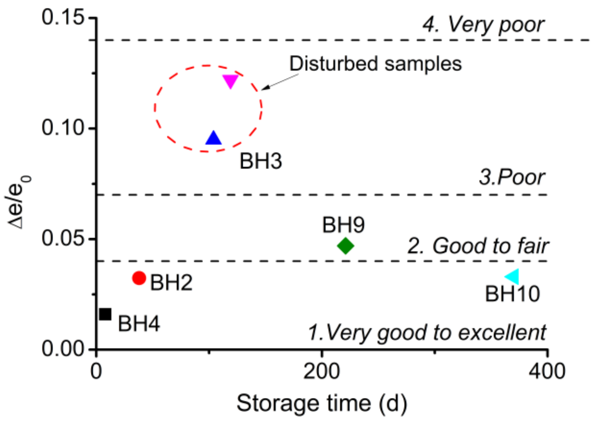


Figure 6. Evolution of sample quality with storage time

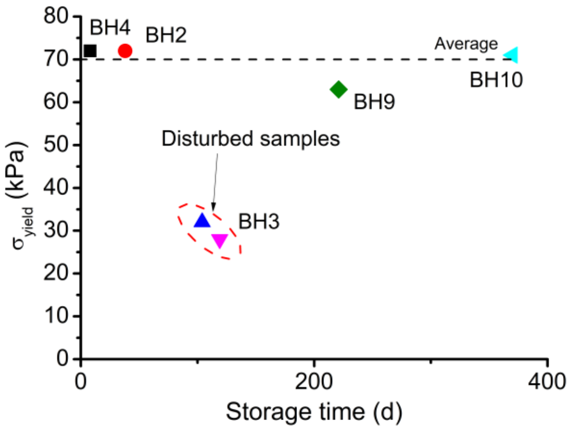


Figure 7. Evolution of yield stress with storage time

The evolution in shear wave velocity, estimated from bender elements tests, with the storage time is shown in Figure 8. Values of Vs reported in this figure, estimated under a sitting load of $\sigma'_{v0} = 10$ kPa, are normalized using the in situ value obtained from the SDMT test reported above. Specimens from boreholes BH4, BH2, BH9 and BH10 show normalized velocities ranging around 0.82-0.90. This range of variation is associated with specimens of *excellent* as well as *good quality* soft soil specimens (e.g., Landon et al., 2007; Arroyo et al., 2015). The normalized velocity reduces to 0.71 for (*poor*) specimens obtained from BH3. Figure 8 shows no influence of the storage time on the shear wave velocity, i.e., small-strain stiffness in Ballina clay.

Although there is no clear trend for the effects of storage time in Ballina clay specimens, mechanical disturbance caused during sampling seems responsible for the *poor* sample quality rating of specimens from borehole BH3. Figure 9 shows the variation of σ'_{yield}, $V_{s0}/V_{s(SDMT)}$ and $C_{c\text{-}peak}$ with the sample quality index $\Delta e/e_0$. Yield stress, shear wave velocity and peak compression index all decrease with $\Delta e/e_0$, i.e. with sample disturbance.

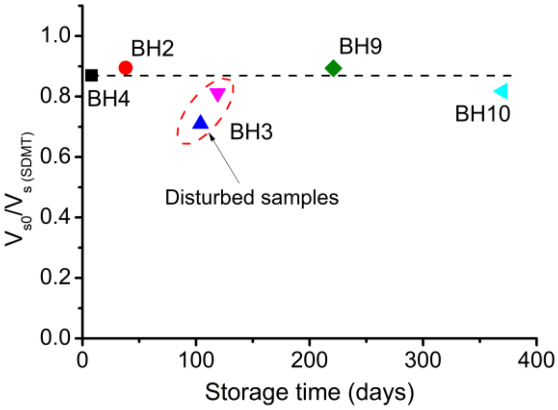
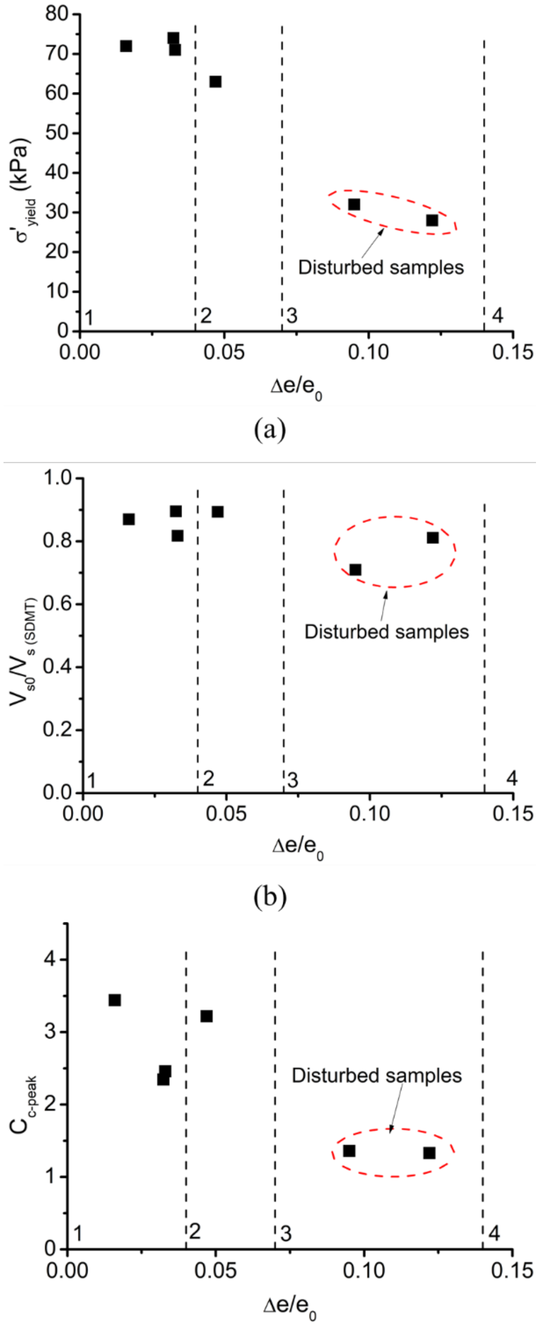


Figure 8. Variation in normalized shear wave velocity with storage time



(a)

(b)

(c)

Figure 9. Variation of σ'$_{yield}$, $V_{s0}/V_{s(SDMT)}$ and $C_{c\text{-}peak}$ with the sample quality index $\Delta e/e_0$.

7. Discussion

The trend shown in Figure 9 is consistent with published data for soft soils (e.g., Landon et al., 2007; Arroyo et al., 2015; Amundsen et al., 2016; Lim et al., 2019). Nevertheless, large values of $\Delta e/e_0$ seems to be caused entirely by mechanical (short-term) effects, due to poor performance of the fixed-piston sampler during tube penetration and extraction in borehole BH3, rather than storage (long-term) effects.

Figure 10 compares the variation in sample quality index $\Delta e/e_0$ with storage time shown previously in Figure 6 with experimental data obtained using tube specimens by Buo et al. (2019), for Perniö and Läpäälla soft clays from Finland, and by Amundsen and Takur (2019), for a Norwegian ‘quick’ clay. Perniö and Läpäälla soft clays have plasticity indexes ranging between 21-41% and 16-41%, respectively. The ‘quick’ clay has a plasticity index around 5-9%. Considering the very high plasticity of Ballina clay, which varies between 67-80%, the results presented in Figure 10 cover a wide spectrum of soft clay deposits. This figure demonstrates that, for specimens obtained using tube samplers, the storage time has an important influence in low plasticity ‘quick’ clay, a moderate influence in the medium plasticity Perniö and Läpäälla soft clays and minor influence in the high plasticity Ballina clay.

Comparison against experimental data reported for block specimens (e.g., Abdellaziz et al, 2019), seems to indicate the superior quality of block specimens even in low-to-medium soft soils. Mechanical tests performed by Adbellazis et al. (2019) on medium plasticity Canadian soft clays have demonstrated negligible changes in compressibility and shear strength parameters between block specimens tested in 1991 and those tested in 2018, after 28 years of storage.

8. Concluding remarks

This paper presented preliminary experimental results, obtained from CRS oedometer tests, aimed to evaluate the effects of storage time on sample quality in Ballina clay. Results suggest that, for tube specimens retrieved with fixed-piston samplers following recommended sampling guidelines, storage time has almost no effect on sample quality, at least for specimens stored up to 12 months prior to testing. Comparison against data for soils reported in the literature indicate that the effects of storage time are important in low plasticity materials and moderate in medium plasticity soils.

Further experimental tests are required to confirm the conclusions obtained from this study. Additional aspects to be explored include: (i) the use of other sampler types (e.g. Shelby tubes and block specimens), (ii) the influence of the storage time on shear strength, permeability, stiffness, and secondary compression behaviours.

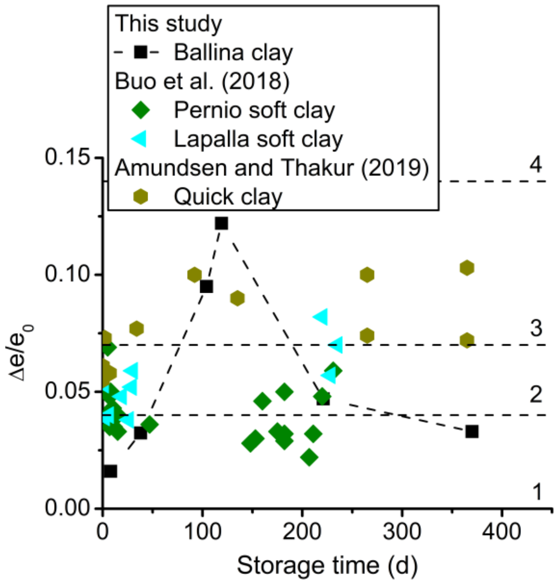


Figure 10. Storage effects on natural soft soils

9. References

Abdellaziz, M., Hussien, M. N., Chekired, M. & Karray, M. (2020) Does long-term storage of clay samples influence their mechanical characteristics? *Canadian Geotechnical Journal, 57(2), 304-309.*

Amundsen, H. A., Thakur, V. & Emdal, A. (2016) Sample disturbances in block samples on low plasticity soft clays. *In Proc. 17th Nordic Geotechnical Meeting, Reykjavik, 159-168.*

Amundsen, H. A., & Thakur, V. (2019). Storage Duration Effects on Soft Clay Samples. *Geotechnical Testing Journal*, *42*(4), 20170426. https://doi.org/10.1520/GTJ20170426

Arroyo, M., Pineda, J.A., Sau, N., Devincenzi, M. & Perez, N. (2015) Sample quality exaination on silty soils. *In Proc. XVI European Conference on Soil Mechanics and Geotechnical Engineering*, Edinburg, UK, 2873-2878.

ASTM. (2006). *Standard Test Method for One-Dimensional Consolidation Properties of Saturated Cohesive Soils Using Controlled-Strain Loading*. ASTM International.

Baligh, M. M., Azzouz, A. S. & Chin, C. T. (1987). Disturbance due to 'ideal' tube sampling. *J. Geot. Engn* 113, No. 7, 739–757.

Becker, D. E., Crooks, J. H. A., Been, K., & Jefferies, M. G. (1987). Work as a criterion for determining in situ and yield stresses in clays. *Canadian Geotechnical Journal*, *24*(4), 549–564. https://doi.org/10.1139/t87-070

Di Buò, B., Selänpää, J., Länsivaara, T. T., & D'Ignazio, M. (2019). Evaluation of sample quality from different sampling methods in Finnish soft sensitive clays. *Canadian Geotechnical Journal*, *56*(8), 1154–1168. https://doi.org/10.1139/cgj-2018-0066

Kelly, R. B., Pineda, J. A., Bates, L., Suwal, L. P., & Fitzallen, A. (2017). Site characterisation for the Ballina field testing facility. *Géotechnique*, *67*(4), 279–300. https://doi.org/10.1680/jgeot.15.P.211

Ladd, C. C. & DeGroot, D. J. (2003). Recommended practice for soft ground site characterization: Arthur Casagrande Lecture. *In Proceedings of the 12th pan American conference on soil mechanics and geotechnical engineering* (eds P. J. Culligan, H. Einstein and A. J. Whittle), Vol. 1, 3–57.

L'Heureux, J.-S., & Paniagua, P. (2014). *"Effect of Storage on Sample Quality-Study on the 54 mm Samples from Onsøy* (Report NIFS-N.6.4.4; pp. 1–20). NGI.

Lim, G. T., Pineda, J., Boukpeti, N., Carraro, J. A. H., & Fourie, A. (2019). Effects of sampling disturbance in geotechnical design. *Canadian Geotechnical Journal*, *56*(2), 275–289. https://doi.org/10.1139/cgj-2018-0016

Lunne, T., Berre, T., & Strandvik, S. (1997). *Sample disturbance effects in soft low plastic Norwegian clay*. Symposium on Recent Developments in Soil and Pavement Mechanics.

Pineda, J. A., Kelly, R. B., Suwal, L., Bates, L., & Sloan, S. W. (2019). The Ballina soft soil field testing facility. *AIMS Geosci*, *5*, 509–534. 10.3934/geosci.2019.3.509

Pineda, J. A., Suwal, L. P., Kelly, R. B., Bates, L., & Sloan, S. W. (2016). Characterisation of Ballina clay. *Géotechnique*, *66*(7), 556–577. https://doi.org/10.1680/jgeot.15.P.181