SAMPLING DISTURBANCE IN SOFT GROUND: IMPLICATIONS IN GEOTECHNICAL DESIGN

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ABSTRACT

This paper discusses the main mechanisms of sampling disturbance in soft ground and their implications in geotechnical design. In addition to the mechanical disturbance associated with the type of sampler, the influence of other factors frequently overlooked in practice such as thermal loading due to waxing as well as biological effects due to long-term storage, are evaluated. The paper discusses three methodologies for assessing sample quality in soft soils, which may be easily incorporated in practice. In the last section, mechanical soil properties derived from specimens retrieved using four different samplers are used in the prediction of the total settlement and excess pore water pressure underneath an embankment. The results of the prediction exercise demonstrate the negative effects of poor sampling in geotechnical design. It demonstrated that reliable and cost-effective predictions of geotechnical infrastructure are possible with minimum improvements to the current practice for sampling and testing of soft clays.

1. INTRODUCTION

Safe and cost-effective geotechnical design is critically dependent on the precise determination of soil parameters, as these effect the accuracy of the associated numerical analysis (which is now ubiquitous in geotechnical practice). Laboratory tests are a key to the characterization process, especially to measure input parameters for numerical soil models, but they need high quality samples which are often hard to obtain in soft and problematic soils. Poor quality sampling changes the state and properties of the soil, and hence the representativeness of the *in situ* material. This, in turn, has been shown to affect safe and cost-effective designs for much of civil infrastructure (e.g., Rowe, 1972; Clayton, 2001; Tor Lim et al., 2018a).

Despite of being a very old problem in geotechnical engineering, sampling disturbance is a common issue observed in current practice worldwide. The answers to the sampling issues are local, because they need to be grounded in the local practice of drilling and sounding and be adapted to suit the local geological and geochemical conditions. In Australia, where light geotechnical structures are frequently located along the east coast on soft estuarine clays, rigorous guidelines for undisturbed sampling in soft soils are still not available.

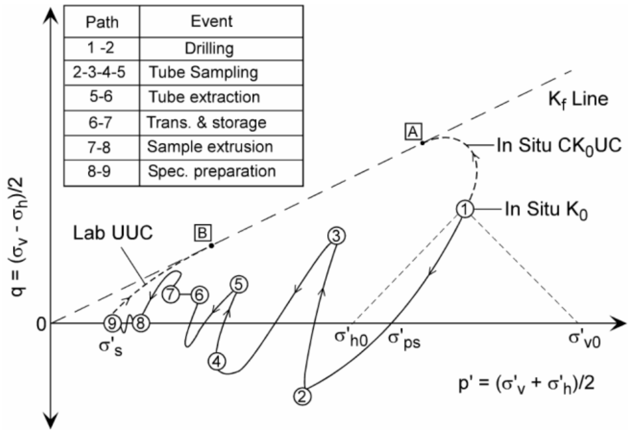
A typical soil sampling process is composed of eight stages as follows: (i) drilling, (ii) sampler penetration or block trimming, (iii) sampler extraction or block retrieval, (iv) tube/block sealing, (v) tube/block transport, (vi) tube/block storage, (vii) soil extrusion (only tube specimens) and, (viii) sample preparation. Figure 1 shows a schematic representation of the stress path followed by a soil specimen subjected to tube sampling. As observed in this figure, soil sampling reduces the *in situ* mean effective stress, $p'_{\text{in-situ}}$, even if soil disturbance is 'avoided'. Every stage of the sampling process may cause some degree of disturbance that changes further the stress state as well as the structure of natural soils. Some of the interactions that occur during different steps in a tube sampling campaign are represented in Figure 2. The degree that each stage of the sampling process contributes to the total disturbance in a given soil is, even nowadays, largely unknown. One of the main reasons for this is the profound lack of knowledge about the coupled phenomena that occur during each stage of sampling. Stress relief, undrained compression and extension paths, suction effects, thermal gradients, time-dependent dissipation phenomena and biogeochemical processes take place during and/or after soil sampling. According to Hight (1986) soil disturbance is associated with:

- Changes in the soil stress state (i.e. reduction in p' and q)
- Mechanical deformation

- Moisture content redistribution
- Chemical reactions
- Mixing and segregation of soil constituents

Clearly, soil disturbance is not solely associated with the mechanical deformation caused by each sampler type, an aspect that has been extensively investigated over last decades. Other effects like tube penetration and tube extraction rates, sealing methods, transport and storage methods, rarely described and frequently ignored in geotechnical practice, may also adversely affect measured soil properties in a major way.

The aim of this paper is to identify the negative effects of sampling disturbance in geotechnical design. Emphasis is given to Australian soft soils (clays and silts), particularly to the estuarine soft soil deposits from the National Soft Soil Field Testing Facility located in Ballina (NSW) (Kelly et al., 2017). These deposits represent the natural soft soils commonly encountered along the eastern and southern Australian coastlines. The consequence of poor sampling in practice are evaluated in the last part of the paper via a prediction exercise of surface settlements and excess pore water pressure underneath an embankment built on estuarine soft clay. It is important to remark here that although laboratory testing procedures are also key to obtaining reliable soil parameters this topic is beyond the scope of this paper.



Path	Event
1 -2	Drilling
2-3-4-5	Tube Sampling
5-6	Tube extraction
6-7	Trans. & storage
7-8	Sample extrusion
8-9	Spec. preparation

Figure 1: Hypothetical stress path during tube sampling in low OCR clay (Ladd & DeGroot, 2003)

2. MECHANICAL DISTURBANCE: EFFECT OF THE SAMPLER TYPE

The open sampler (Shelby tube) is the most common sampling method in soft soils due to its simple operational principle (Figure 3). However, specimens retrieved using Shelby tubes are significantly influenced by mechanical deformation as a consequence of the entrance of disturbed soils from the bottom of the borehole. Baligh et al. (1987) studied the undrained penetration of a rigid open sampler (S-sampler) in saturated clay using the strain path method (Baligh, 1985). Neglecting the differences in the geometry of the cutting edge between the S-sampler and open (Shelby) tubes, it was shown that: (i) large shear strains (and strain non-uniformity) take place in the outer zone of the tube, mainly at the soil-tube interface, and (ii) the vertical strain component is dominant at locations closer to the centreline. Three deformation stages were identified for soil located at the centreline of the sampler: (a) compression, ahead of the sampler, (b) extension, near to the cutting edge and (c) compression, inside the sampler. Clayton et al. (1998) complemented the work done by Baligh and co-workers by considering more realistic geometries for the cutting edge of the sampler. The results were analysed in terms of the geometric descriptors introduced by Hvorslev (1949) to quantify the effects of tube sampling caused by different tools. They showed that the area ratio (AR = area of the annulus of the tube sampler divided by the area of the tube specimen), as well as the angle of the cutting edge (α), dominate the compression component ahead of the sampler (see Figure 4(a) and (b)). The axial compression increases with the increasing of AR and α. On the other hand, the inside clearance ratio (ICR), which refers to the enhancement of the internal tube diameter behind the cutting edge, has a strong influence on the extension component inside the sampler.

Another issue with Shelby tubes is the difficulty of the check valve to maintain the vacuum during sampler retrieval which affects the total recovery (e.g., Clayton et al., 1995). This phenomenon is associated with suction created at the bottom of the sampler during retrieval. Figure 5 shows the key role of sampler retrieval on soil disturbance (Tor Lim et al., 2018b). The Authors took advantage of the symmetry of the problem to push in half Shelby tubes in reconstituted calcareous silt against a transparent Perspex window. Three mechanisms may be recognized: (i) the progressive development of a shear plane at the sampler tip, (ii) the soil heave at the bottom of the borehole (due to the interaction between the uplift force and soil suction), and (iii) the creation of tension cracks, due to the loss of lateral support for the soil located at the bottom of the sampler, which leads to low soil recovery.

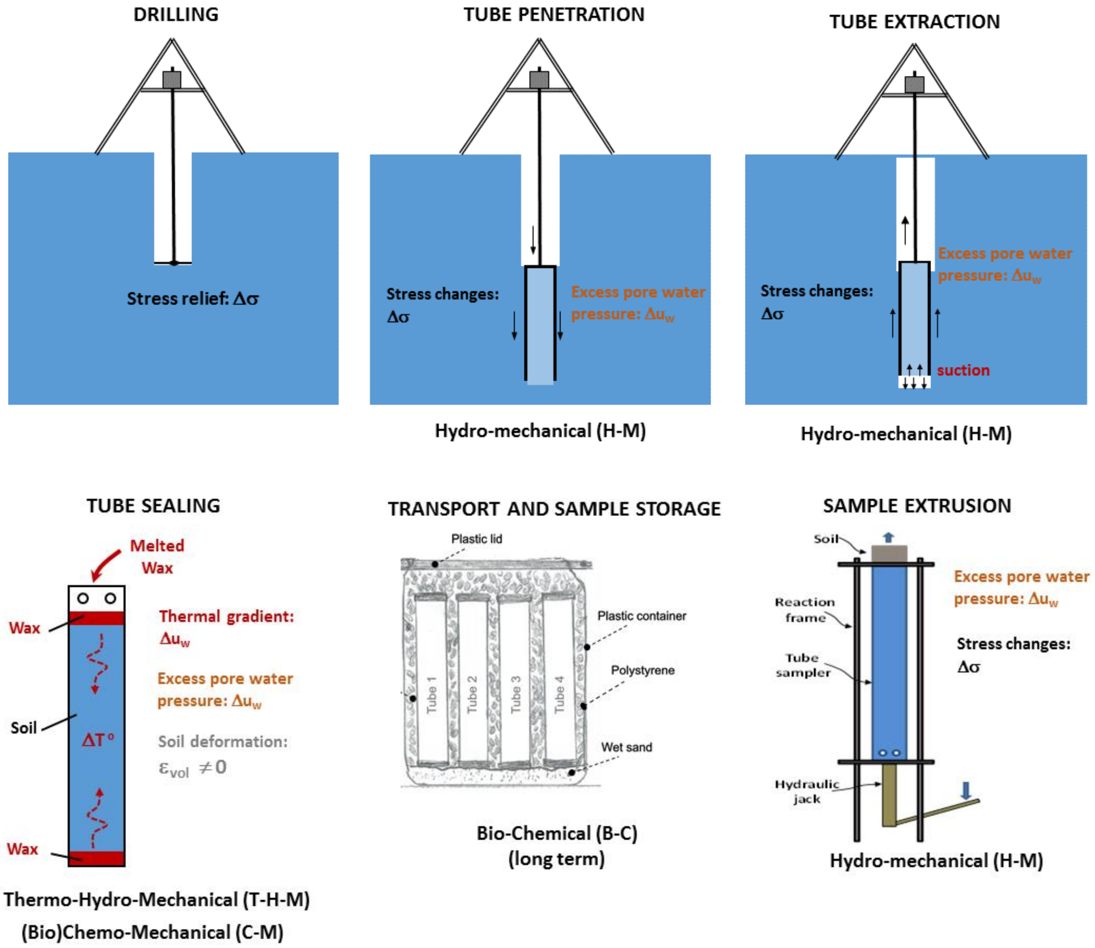


Figure 2: Physical and (bio)chemical processes that may occur in a tube sampling campaign

To overcome those issues, Österberg (1973) designed the hydraulic fixed-piston sampler which has catalysed the development of several devices of its kind during subsequent decades. Although the working principle of the hydraulic fixed-piston sampler is a bit more complicated than the Shelby sampler, it is still simple enough to be adapted to conventional practice without major modifications (Figure 3). The main differences between these two samplers are: (i) the presence of an internal fixed piston to prevent the entrance of disturbed soil during lowering to the sampling depth, (ii) the presence of an internal thin-walled tube sampler that is pushed into the ground using a floating piston via hydraulic pressure. After full penetration, the hydraulic fluid flows up (through the hollow piston rod) and down (through the cutting toe) to ensure the same static pressure inside the sampler and at the bottom base. It helps to minimize suction at the bottom of the sampler during withdrawn. The NGI 54-mm sampler (Andersen & Kolstad, 1979) and the JPN 75-mm sampler (e.g., Tanaka et al., 1996) are examples of hydraulic fixed-piston samplers that have been incorporated into practice in Norway and Japan, respectively.

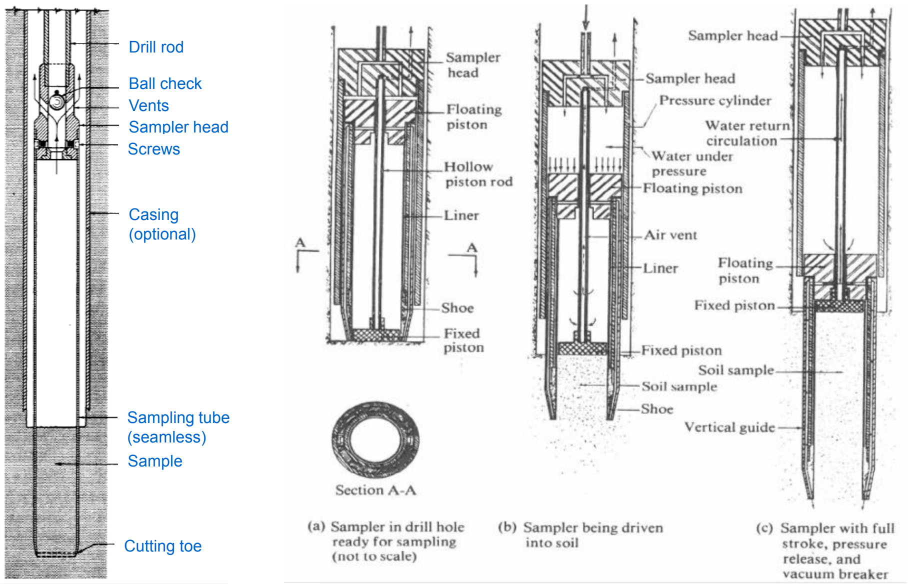
Fixed-piston samplers are known for providing specimens of better quality compared with other tube sampling techniques (e.g., Andersen and Kolstand, 1979; Lacasse et al., 1985; Tanaka et al., 1996; Lunne et al., 1997; Ladd & DeGroot, 2003; Lunne et al., 2006; Landon et al., 2007; Donohue & Long, 2010; Pineda et al., 2016b; to name a few). Despite their well-documented advantages, the use of fixed piston samplers is still not well established in practice. In Australia, for instance, Shelby tubes (50 – 75 mm in diameter) are the typical choices, mainly due to their simple operational principle. However, mechanical parameters obtained from laboratory tests performed on Shelby tubes in most cases do not represent the *in situ* conditions. Laboratory testing is expensive and involves long testing times, so additional sampling and laboratory campaigns tend to be avoided in practice, even if the quality of soil specimens does not fulfil the recommendations given in the literature. Therefore, there is a concern about the influence of soil disturbance as a result of sampling on predicted soil behaviour for typical geotechnical infrastructure.

A set of recommendations to select the proper tube sampler and minimize mechanical disturbance was given by Ladd & DeGroot (2003) (see Table 1). They suggest the use of sampler tubes with ratio B/t (B: outer diameter and t: thickness of the tube wall) higher than 40, area ratio lower than 10%, no inside clearance ratio and angle of the cutting shoe lower than 10 degrees. Moreover, they suggest avoiding top and bottom ends in tube specimens (≈ 1.5 B each) for mechanical testing due to the large degree of soil disturbance. Soil from top and bottom ends should be used for characterization purposed only.

Even if fixed-piston samplers are used in practice, the quality of the retrieved sample is also influenced by the skills of drillers. Tanaka (2008) reported a benchmark exercise carried out to assess by how much driller skills may affect the undrained shear strength of a soft clay from Japan found in a site with an homogeneous soil profile up to 20 m depth devoted to port construction works. Seven drilling companies (A to G) were requested to obtain tube specimens using the JNP sampler, a 75-mm fixed-piston sampler recommended in the specifications given by the Japanese Geotechnical Society (JGS). Figure 6 compares the undrained shear strength profiles obtained by each company. There is a clear effect of the driller's skill on the measured undrained shear strength, even in homogeneous soil profiles. Although it is commonly overlooked, results shown in this figure highlight the importance of good training for drillers and technicians in order to obtain high quality soft soil specimens for laboratory testing.

Table 1: Recommended criteria for the selection of tube samplers (Ladd & DeGroot, 2003)

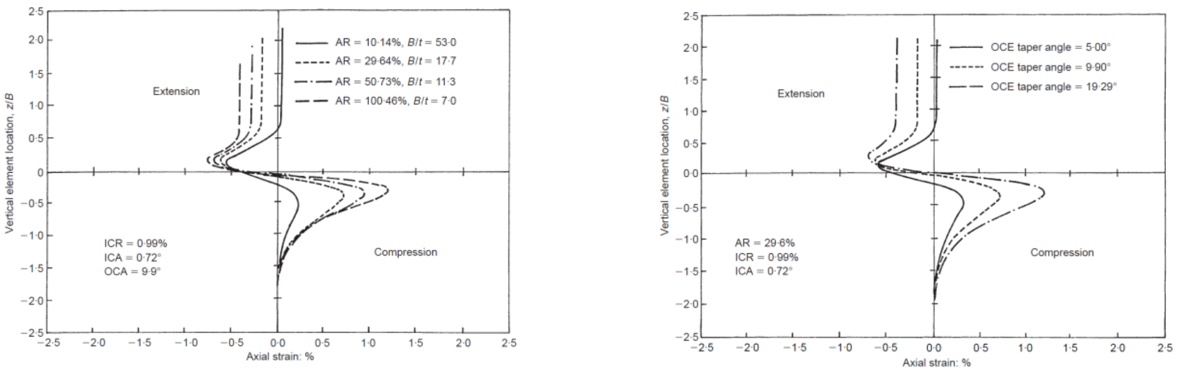
B/t	Area Ratio AR (%)	Inside Clearance Ratio ICR (%)	Angle of the cutting shoe α (°)
> 40	< 10	0	< 10



Open sampler

Hydraulic fixed-piston sampler

Figure 3: Shelby tubes and hydraulic fixed-piston sampler (from Clayton et al., 1995)



(a) (b)

Figure 4: Deformations during undrained tube sampling in saturated clay. (a) Influence of AR on centreline vertical strains. (b) Influence of ICR and a on centreline vertical strains (from Clayton et al., 1998)

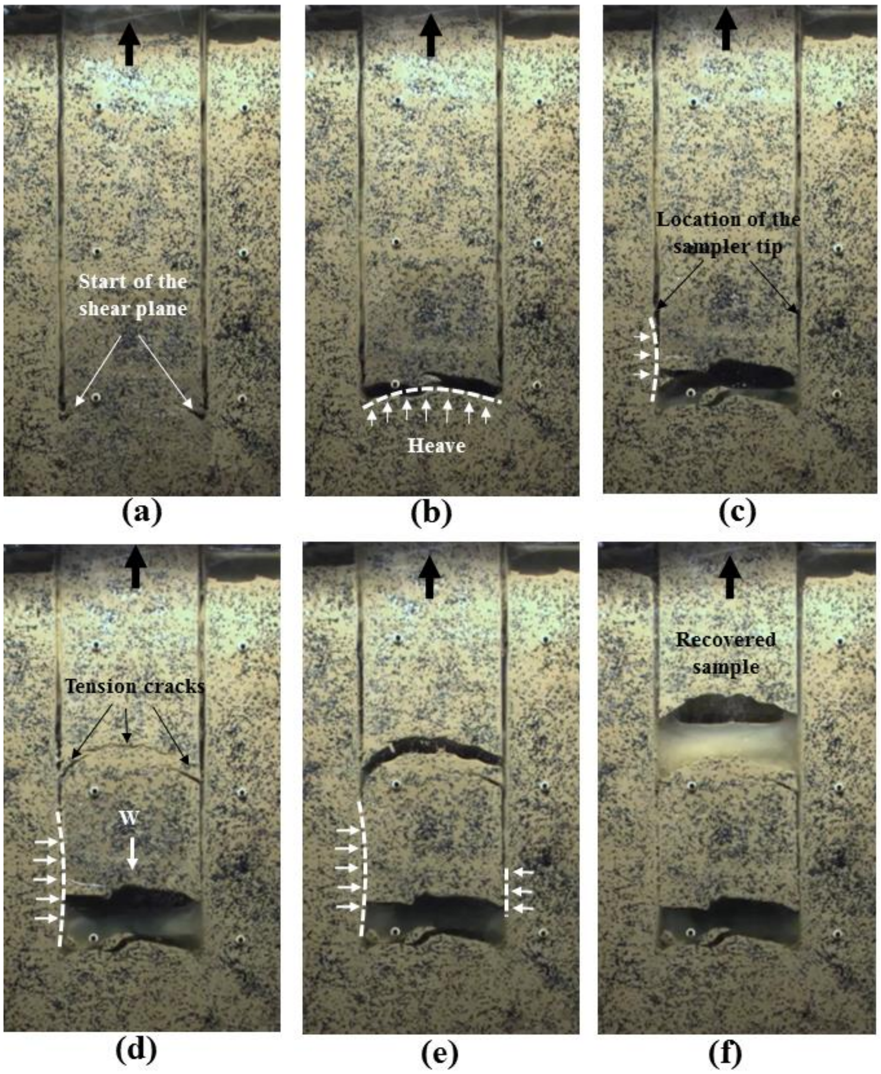


Figure 5: Effects of sampler retrieval in calcareous silt

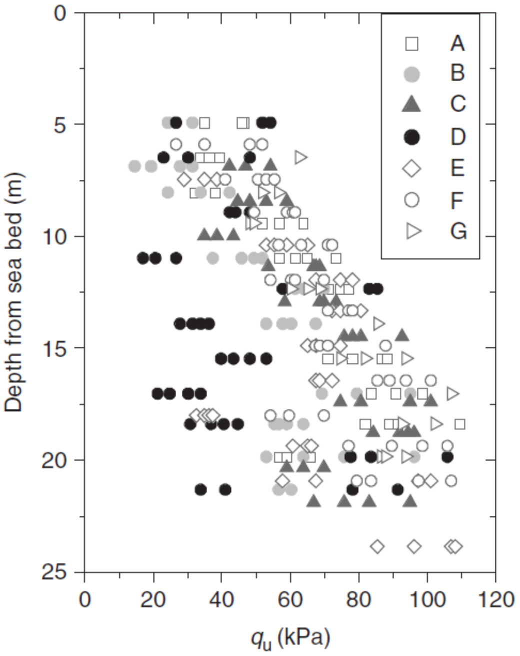
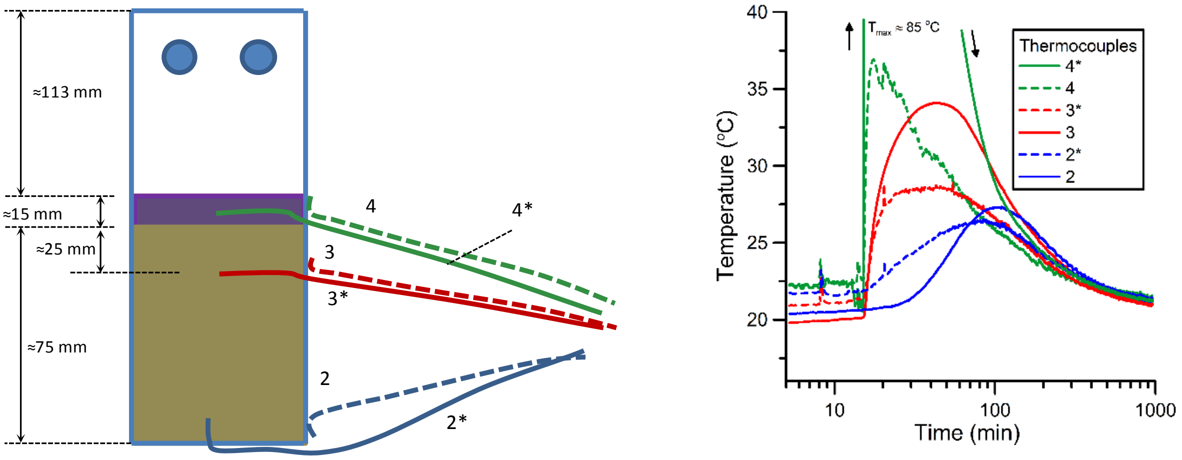


Figure 6: Effects of driller's skills on the measured undrained shear strength of a soft clay from Japan (Tanaka, 2008)

3. THERMAL DISTURBANCE: EFFECTS OF WAXING

Little attention has been given in the past to the influence of the thermal gradients generated by waxing when sealing tubes and block specimens after sampling. This was recognized by Hvorslev (1949) as a potential problem and led to complementary work (Lefebvre & Poulin, 1979; La Rochelle et al., 1986) that focused almost exclusively on the performance of the wax composite in avoiding moisture losses. However, soil disturbance caused by the thermal gradient was neglected. This gradient dissipates with time as wax hardens, but generates excess pore water pressure under undrained conditions as the pore water is not allowed to drain out. This may lead to significant moisture redistribution within the clay. Biological processes (e.g., methane release) and chemical reactions may also be triggered by thermal fluctuations, but are rarely evaluated in practice.

A pilot test was carried out on Ballina soft clay from the National Field Testing Facility (NSW, Australia) to highlight the importance of the thermal gradients caused by waxing in soft soils. The upper slice of a tube specimen, previously waxed and stored for six months in a controlled relative humidity room, was used. To perform the experiment, the layer of solidified wax applied *in situ* was first removed. Then, thermocouples were inserted into the soft clay to monitor variations in temperature along the specimen (see Figure 7a). Additional thermocouples were attached externally to the sampler wall to monitor the changes in temperature along the tube. Melted wax was then poured onto the top of the sample to reproduce the procedure used *in situ*, and created a final layer thickness of around 15mm. As observed in Figure 7(b), the temperature of the wax reached 85ºC after pouring and then reduced slowly with time. The soil located closer to the top boundary cooled to around 34ºC in less than 1h, while soil at the bottom of the specimen (75mm from the heat source) reached 28ºC after 2h. It took about 1 day for the temperature to come back to room conditions. This specimen was re-opened after one week and a clear oxidation front could be observed.



(a) (b)

Figure 7: Thermal test in Ballina clay. (a) Experimental set up. (b) Temperature variations with time

To get a better understanding of the evolution of the thermal gradient generated by waxing in tube samples, a simple numerical modelling of the thermal loading was performed using the finite element analysis program ABAQUS FEA 6.14. For the sake of simplicity, it was assumed that conduction is the only factor that controls the temperature field within the sample. Therefore, the basic energy balance equation is given by

$$\int_V \rho \dot{U} dV = \int_S q dS - \int_V r dV \qquad (1)$$

where V is the volume of the solid material with surface area S, ρ is the density of the material, $\dot{U}$ is the rate of inertial energy; q is the heat flux per unit area of the body; r is the heat supplied internally into the body per unit volume. The heat flux and the variation of the internal energy are computed via Fourier's law and the internal energy equation as follows:

$$q = -\lambda \nabla T \qquad (2)$$

$$dU = c \cdot dT \qquad (3)$$

where λ is the thermal conductivity of the material, ∇T is the thermal gradient and c is the heat capacity of the material. The latent heat of the wax was also considered in the calculation of the internal energy to account for the phase change that occurs as wax hardness. Table 2 summarizes the set of parameters used in the numerical simulations.

Table 2: Thermal parameters for the materials

Material	Heat capacity (10^3J/kg · K)	Thermal conductivity ($W/(m \cdot K)$)	Density (kg/m^3)	Latent Heat (10^5J/kg)
Wax[1]	2.9	0.25	900	2
S.S. tube	0.502[2]	16[3]	7480[3]	-
Soil[3]	1.381	1	1348	-

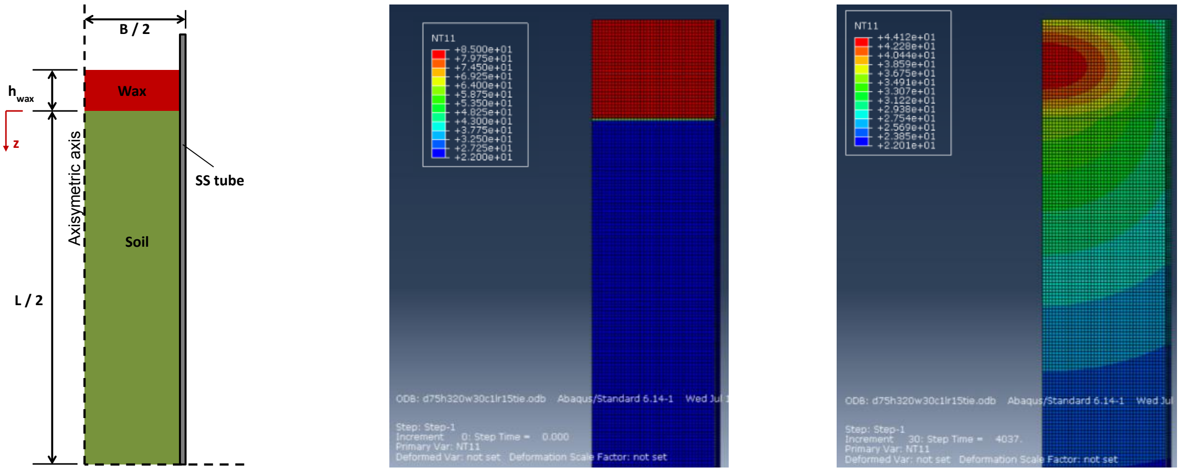
[1] Haji-Seik et al. (1982) [2] https://www.engineersedge.com [3] https://www.engineeringtoolbox.com

In practice, there is a heat loss starting as soon as the wax is poured as a consequence of the difference in temperature between the system (wax+tube+soil) and the environment. This scenario was simulated by introducing a convection-type boundary condition. The heat flux at the boundary is given by

$$q = c_{conv}(T - T_0) \qquad (4)$$

where q is the heat flux at the boundary; c_{conv} is the convection coefficient at the boundary, T is the temperature of the boundary surface and T_0 is the temperature of the environment. Figure 8(a) shows the geometry and set up used in the numerical simulations. The experimental results described in Figure 7 were used here to calibrate the numerical model.

A back-analysis procedure was followed to estimate the convection coefficient for Ballina clay which controls the heat loss during the experiments. 2D axisymmetric analyses were carried out using 4-node linear heat transfer elements. The boundary condition at the axisymmetric axis was set as zero heat flux boundary, while other boundaries were set as convection-type. The contact conditions between the wax, soil and sampler were set as "tie" as suggested by (Fiedler et al., 2015). Figures 8(b) and (c) show screenshots that correspond, respectively, to the thermal fields at the beginning of the simulation (t=0) and after a reduction of about 50% in the initial wax temperature. The convection coefficient obtained from the back analysis was equal to 10 W/m^2.K.



(a) (b) (c)

Figure 8: Modelling of thermal effects in tube samples. (a) Model set up. (b) and (c) Generated thermal profiles

A parametric analysis was then performed in order to evaluate: (i) the influence of the amount of heat applied to the system, which is controlled by the height of the wax layer, and (ii) the thermal field generated in samples of different sizes. The second aspect was studied by applying the same volume of heat to tube specimens of different diameters.

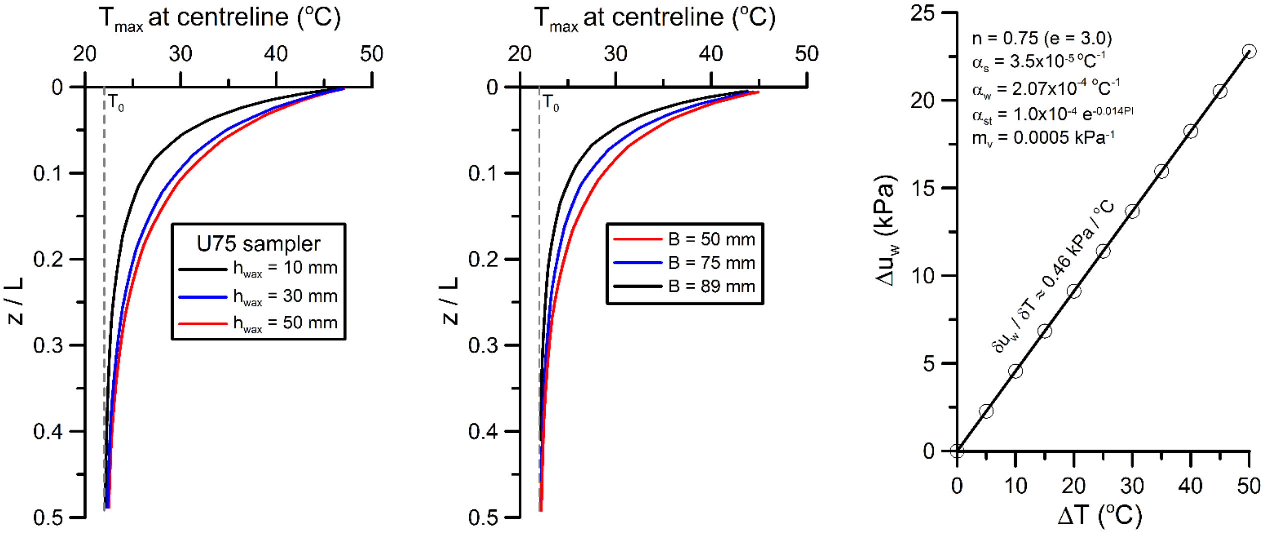
Figure 9(a) shows the variation of the maximum temperature, T_{max}, estimated at the centreline of a U75 tube specimen (commonly used in Australian practice), with the sample depth. The three profiles observed in this figure represent thicknesses of the wax layer of 10 mm, 30 mm and 50 mm. As expected, the influence of the thermal loading on the soil mass enhances with h_{max}. At the wax/soil interface, the soil reach temperatures up to 45°C which dissipates at different rates depending on h_{max}. There is a zone affected by the thermal loading which varies from $0.15 < z/L < 0.25$, depending on the thickness of the wax layer. For $h_{max} \geq 30$ mm, the numerical results presented in Figure 8(a) indicate that around 50% of the sample is (directly) affected by the thermal gradient. Therefore, only about 250 mm of the tube (assuming full recovery) could be used in advanced laboratory testing (e.g., triaxial, consolidation). The results presented in Figure 9(b) indicate that, if the same volume of heat is applied to the system, the zone affected by the thermal loading reduces with increasing the sampler diameter. Hence, specimens retrieved using U50 samplers are more prone to be affected by waxing.

One of the limitations of the numerical analysis described above is the lack of information regarding to the excess pore pressure generated by the thermal loading. Waxing is used to avoid moisture losses in soil samples. This implies that undrained conditions prevail during the thermal loading as the pore water is not allowed to drain out. A rough estimate of the maximum excess pore water pressures generated by the thermal load was carried out here by using the following expression (e.g., Mitchell & Soga, 2005)

$$\Delta u_w = \frac{n\Delta T(\alpha_{solids}-\alpha_{water})+\alpha_{st}\Delta T}{m_v} \tag{5}$$

where n is the soil porosity, α_{solids}, α_{water} and α_{st} refer to the thermal expansion coefficients of solids, water and soil structure, respectively, whereas m_v is the volumetric compressibility of the soil. $\alpha_{st} = 1.x10^{-4}\ e^{-0.014PI}$, where PI is the plasticity index of the soil. Figure 9(c) shows the estimated excess pore water pressure caused by an increase in temperature in Ballina clay. Values of n, PI and mv were obtained from laboratory data given in Pineda et al. (2016b) and Tor Lim et al. (2018a) whereas α_{solids} and α_{water} were selected from values reported by Mitchell and Soga (2005). The rate of excess pore water pressure due to thermal heating is around 0.46 kPa/°C. Maximum temperatures estimated from the numerical modelling at the top boundary of the tube sample lies around 40-45°C, i.e., $\Delta T_{max} \approx 20\text{-}22$ °C. According to Eq. 5 such an increase in temperature would generate a maximum excess pore water pressure of 10 kPa (from top and bottom ends), travelling towards the centre of the tube sample. For a natural soft clay with values of undrained shear strength between 10-15 kPa (see Pineda et al., 2016) an increase in excess pore pressure of that amount may cause the failure of the soil located closer to the heating source but also modifications in soil fabric (due to moisture redistribution) along the entire specimen.

The results of the numerical analyses remark the need of using insulating materials to separate the soil from the wax. This approach was intuitively adopted by Pineda et al. (2014, 2016b) who used a foam plate (10 mm in thickness) to minimize the effects of waxing on tube specimens of Ballina clay. Preliminary numerical analyses including the foam plate suggest that the effects of the thermal loading on tube specimens may reduce by around 40-50%. This simple approach could be adopted in practice. Further research is still required in order to get a proper understanding of the effects of waxing in natural soft soils.



(a) (b) (c)

Figure 9: Thermal effects in Ballina clay; (a) Effects of the volume of wax and (b) Effects of the sample diameter. (c) Estimated excess pore water pressure

4. (BIO)CHEMICAL DISTURBANCE: EFFECTS OF THE SOIL STORAGE

The sample storage method and storage time have a major influence on the behaviour of soft soils (e.g., see Bjerrum & Rosenqvist, 1956; Thakur, 2014). Indeed, sample storage may activate biological processes, such as methane release and the oxidation of organic matter. This may lead to a progressive change of the undrained shear strength and preconsolidation pressure as reported by Arman and MacManis (1976) for clay and silty clay specimens from Louisiana (USA) (Figure 10). A reduction about 50% in undrained shear strength is observed after 4 months of storage. Preconsolidation pressure decreases drastically after only three months of storage. Unfortunately, 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., see Mitchell and Santamarina, 2005). Chemical changes may also take place under isothermal conditions if enough oxygen is present. This aspect is frequently neglected in practice, despite its major effect on the mechanical response of natural soils. Therefore, it is recommended to test soil specimens soon after sampling in order to minimize the aforementioned effects. Regarding to the laboratory testing techniques, it is important to use pore water with similar salinity to natural water in order to minimize changes in the mechanical behaviour of the soil as a consequence of chemical reactions.

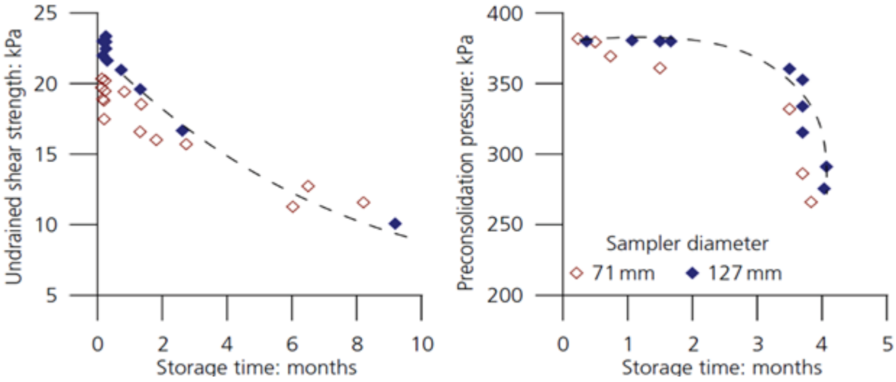


Figure 10: Effects of storage time on undrained shear strength and preconsolidation pressure in soft soils (Arman and MacManin, 1976)

5. SAMPLE QUALITY ASSESSMENT

A key issue in the characterization of natural soft soil deposits lies in the selection of 'representative' soil specimens for laboratory testing. Sampling disturbance as well as the natural soil variability along tube/block specimens, may affect the results of laboratory tests and lead to considerable discrepancies between *in situ* and laboratory data. Non-destructive methods as well as conventional laboratory tests have been used over the last decades to assess sample quality in soft soils. The most common approaches are based on:

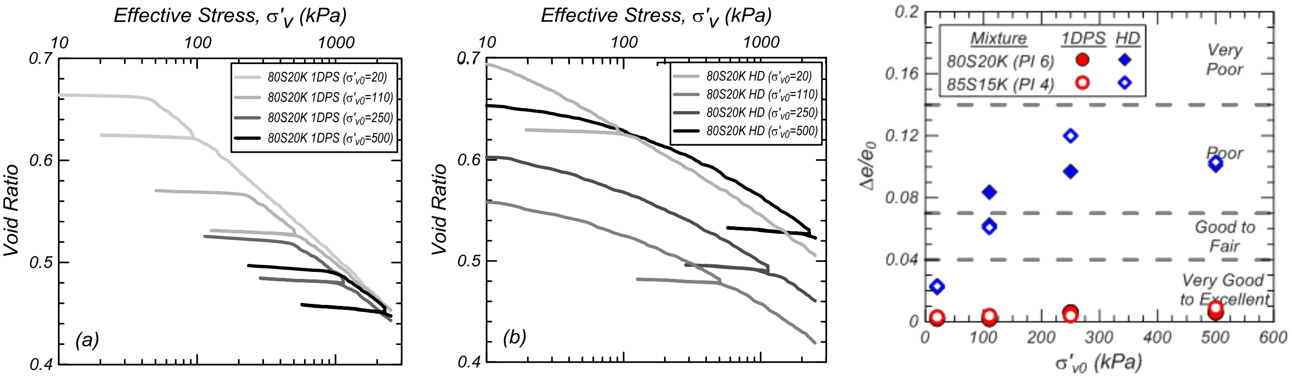
- Volume change due to soil recompression to the *in situ* effective stress
- Image analysis (X-ray analysis and CT scanning)
- Shear wave velocity measurements

The proposals by Andersen & Kolstad (1979) (see also Terzaghi et al., 1996) and more recently by Lunne et al. (1997) have a good track record as indicators of sample quality in soft soils. Both approaches are based on the recompression deformation (ε_v or $\Delta e/e_0$) required to bring the sample to the *in situ* vertical effective stress. Sample quality is ranked using four levels (see Table 3): (1) very good to excellent, (2) good to fair, (3) poor and (4) very poor. The method by Lunne et al. (1997) also considers the influence of OCR and therefore it has become popular in the assessment of sample quality in soft soils.

Table 3: Methods for sample quality assessment based on ε_v and void ratio

Level	Andersen & Kolstad (1979)		Lunne et al. (1997)		
	ε_v (%)	Rating	$1 < OCR < 2$ $\Delta e/e0$	$2 < OCR < 4$ $\Delta e/e0$	Rating
1	< 1	Very good to excellent	<0.04	<0.03	Very good to excellent
2	1-2	Good to fair	0.04-0.07	0.03-0.05	Good to fair
3	2-4	Poor	0.07-0.14	0.05-0.10	Poor
4	4-8	Very poor	>0.14	>0.10	Very poor

Nevertheless, both approaches were developed using laboratory results obtained primarily for marine clays (6% < PI < 43%) retrieved from relatively shallow depths (< 25 m). Although the influence of OCR is accounted for by Lunne et al. (1997), no correction is considered for the recompression to *in situ* stress in specimens with high overburden stresses, subjected to large stress relief due to sampling. This issue was evaluated by Krage et al. (2016) using reconstituted specimens made of silica silt-kaolin mixtures with PIs ranging from 0 to 31%. Oedometer specimens were subjected to a wide range of overburden stresses ($20 < \sigma'_{v0} < 500$ kPa) to establish a depositional stress history. Two levels of disturbance were then induced as follows: 1D 'perfect sampling' (1DPS) and highly disturbed (HD) states. 1D 'Perfect sampling' condition was achieved via removal of the deviatoric stress to get K_0=1. Highly disturbed specimens were produced by applying a freezing-thawing cycle under unstressed conditions. HD samples were subsequently loaded beyond the preconsolidation stress, followed by unloading until achieve K_0=1, as imposed to 1DPS specimens. Finally, both 1DPS and HD samples were loaded further to a vertical effective stress of 2500 kPa. Figure 11(a) and 11(b) shows the compressibility curves obtained from 1DPS and HD specimens, respectively. It can be seen the strong influence of the previous freezing-thawing cycle on the compressibility of HD specimens which also affects the preconsolidation stress. Figure 11(c) shows the variation of the normalized void ratio ($\Delta e/e_0$) against the overburden stress obtained from 1DPS and HD specimens. The quality of HD specimens ranges from *very good to excellent* to *poor* sample quality. These results are clearly inconsistent with level of disturbance induced to each specimen and highlight the need for considering the influence of the stress relief (overburden stress) on $\Delta e/e_0$. Therefore, caution should be taken when using these methodologies to assess sample quality in low plasticity silty deposits.



(a) (b) (c)

Figure 11: Sample disturbance in low-plasticity soil. (a) Compressibility curves of 1DPS specimens. (b) Compressibility curves of HD specimens. (c) Sample quality rating for 1D perfect sampled (1DPS) and highly disturbed (HD) specimens (Krage et al., 2016)

The main drawback of the volume change-based sample quality methods is the testing time which, in some cases, makes them unsuitable for a quick assessment of sample disturbance. This fact has prompted interest on non-destructive sample quality examination techniques. X-Ray or Computer Axial Tomography (CAT) analysis are becoming popular in geotechnical engineering due to their non-destructive nature and simple procedure. The main drawback of the X-Ray technique is that all features of the specimen are superimposed into a 2D image whereas a 3D reconstruction is obtained from CAT analysis. It gives a 3D picture of the sedimentary structures but also natural heterogeneities (fissures, inclusions, cavities) and allows selection of high-quality specimens for laboratory testing.

The maximum energy of medical CT scanners ranges between 120 – 140 keV. These devices are designed for use on human subjects to image soft tissue and bones. Human bones have similar density as natural soft soils (~ 2 Mg/m^3) and therefore it might be reasonable to use them on soft soil deposits. CT scanning is nowadays common practice at the University of Newcastle (Australia) to examine qualitatively the internal structure of tube samples. Figure 12 shows the vertical sections of two tube specimens, retrieved from two near-by boreholes at the National Soft Soil Testing Facility using a fixed-piston sampler as well as a Shelby tube. Both tube specimens were retrieved from a depth of 7.5 m - 8.1m. The fixed-piston sampler has an outer diameter of 89mm, 5-degree cutting edge and area ratio equal to 9%. The U75 (Shelby), commonly used in Australian practice, has an outer diameter of 75mm and an area ratio of 8%. The cutting edge is 15 degrees. The inside clearance ratio is zero in both cases. Particular emphasis was made here on the detection of possible heterogeneities and their potential influence on laboratory testing. The free software Gimias® (Gimias, 2011) was employed for image post-processing. The attenuation scale shown in Figure 13 varies from white (maximum attenuation or high material density) to black (minimum attenuation or low density).

The comparison of the vertical sections shows clear differences between the two tube specimens. The specimen retrieved using the fixed-piston sampler seems quite homogeneous with a few sub-horizontal cracks observed at top and bottom ends. A highly disturbed specimen is obtained with the Shelby tube. Sub-horizontal cracks as well as vertical fissures and cavities are clearly identified along the 75-mm Shelby tube caused by the absence of a fixed-piston, which helps to compensate suction effects created at the bottom of the sampler during retrieval as discussed above. Figure 12 also shows cross-section images obtained at different depths along the tubes. It can be noted that the presence of fissures, cavities and shells in the Shelby tube which makes difficult to obtain representative specimens for laboratory testing (i.e., oedometer and triaxial tests). The black hole located at the top of the tube represents a cavity, which is assumed to be induced during sampling. In the case of the specimen retrieved with the fixed-piston sampler, the inspection of Figure 12 suggest that soil from slice 2 to 7 could be used for laboratory testing whereas top and bottom ends should be employed only for characterization purposes as suggested by Ladd & DeGroot (2003). Overall, CT images indicate that open sampler U75 induces higher soil disturbance than fixed-piston samplers despite its lower area ratio.

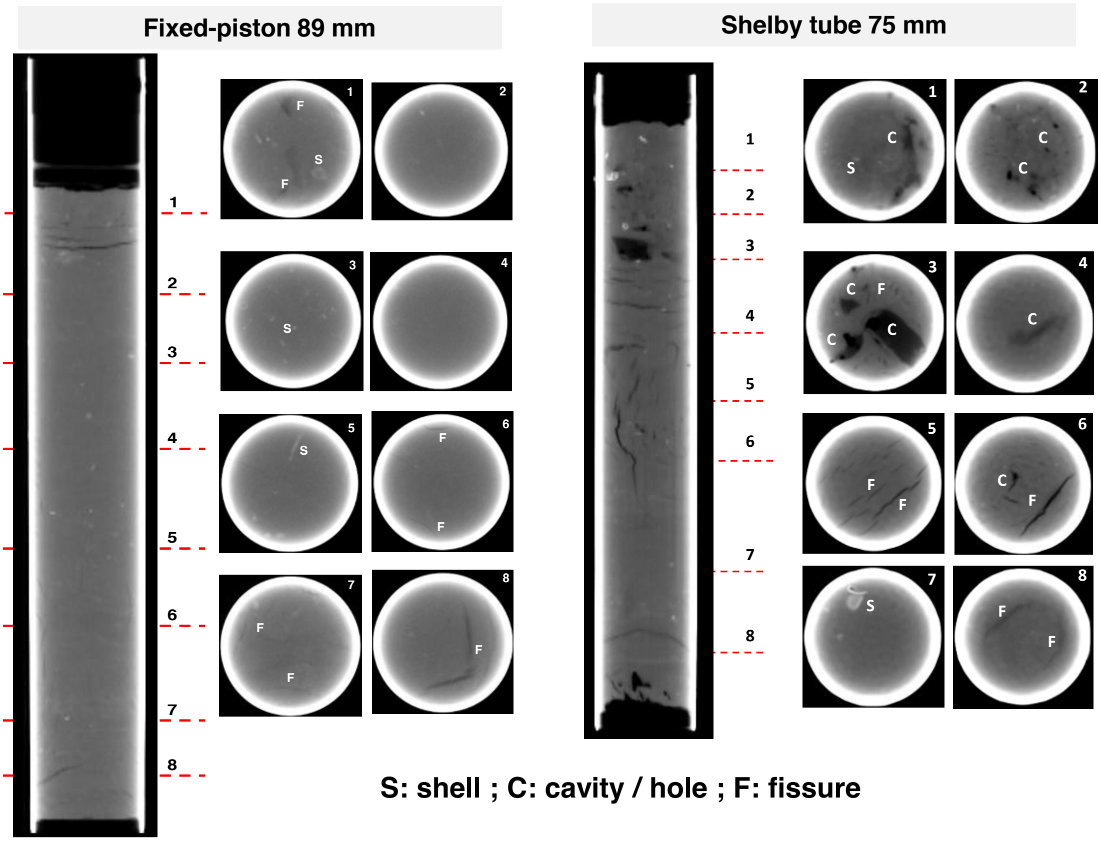
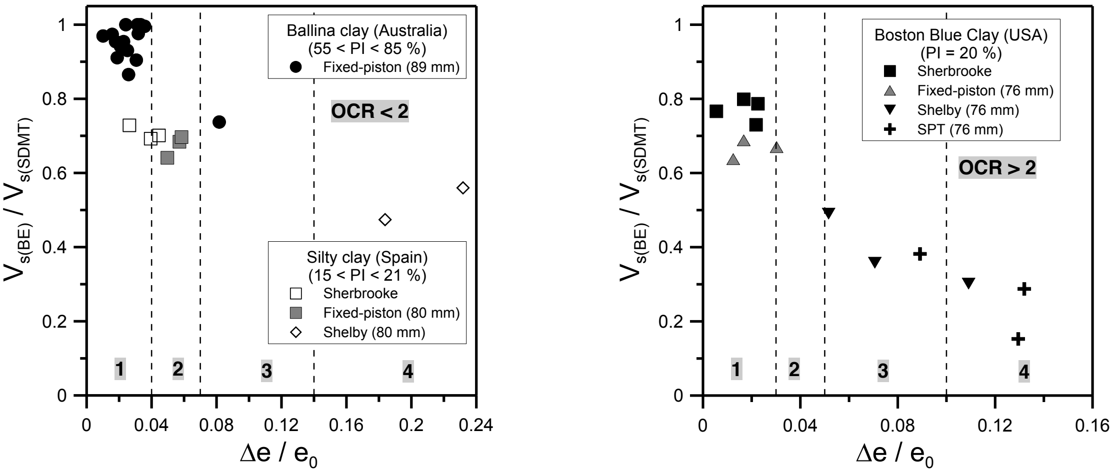


Figure 12: Qualitative CAT analysis in Ballina clay (Australia)

Sample quality assessment via shear wave propagation is becoming a common procedure in several laboratories worldwide. Shear waves, Vs, are preferred against compressional waves, Vp, as they can only propagate through the soil skeleton and therefore they provide useful information about changes in soil fabric, like those caused by sampling. Laboratory measurements are conveniently normalized against *in situ* values (e.g. CPTu, SDMT) in order to have an estimation of the reduction in soil stiffness due to sampling. Values of shear wave velocity measured at unconfined conditions (e.g., Landon et al., 2007; Donahue & Long, 2010) as well as at *in situ* stress conditions (e.g., Arroyo et al., 2015; Pineda et al., 2016b) are the two procedures followed in laboratory to check variations in soil stiffness due to sampling. Both have shown good correlation with sample quality descriptors ε_v and $\Delta e/e_0$ for a wide variety of soils.

Figure 13 shows V_s estimates for three natural soils: low plasticity Boston Blue clay (USA) (Landon & DeGroot, 2007), low plasticity silty deposits from Spain (Arroyo et al., 2015) as well as high-plasticity Ballina clay (Pineda et al., 2016). Block (Sherbrooke) specimens as well as tube samples (fixed-piston, Shelby tube and SPT samplers) are included in this figure. Good correlation between shear wave velocity, normalized against *in situ* values obtained from seismic dilatometer tests, $Vs_{(BE)}/Vs_{(SDMT)}$, and sample quality indicator $\Delta e/e_0$ is observed. Results shown in Figure 13(a) correspond to Vs estimates after recompression to the *in situ* vertical effective stress in CRS tests. Values of Vs measured at unconfined conditions are shown in Figure 13(b). Sherbrooke specimens show the lowest reduction in shear wave velocity followed by fixed-piston samplers and Shelby tubes. Recompression to the *in situ* stress in high-plasticity Ballina clay gives shear wave velocities close to the *in situ* measures. In the case of the low plasticity silty deposits, recompression bring the shear wave velocity to 0.80 $Vs_{(SMDT)}$ for $\Delta e/e_0=0$. Arroyo et al. (2015) observed that the normalized shear wave measurements showed a better correlation with sample quality when taken after recompression than when taken after re-saturation. Values reported by Landon et al. (2007) for Boston Blue Clay show a clear ordering of Vs with sample quality, with the Sherbrooke rating above the piston tubes, those above the Shelby and SPT. Vs reduces to $0.35Vs_{(SDMT)}$ and 0.15 $Vs_{(SDMT)}$ in specimens retrieved with Shelby tube and SPT sampler, respectively.

Despite the simplicity of the shear wave propagation technique, it is important to recognize that sampling may affect the soil stiffness in two opposite ways. Whereas soil stiffness may decrease due to soil destructuration it may increase if soil destructuration causes a reduction in porosity (compression). The latter has been reported in silty deposits (e.g. Long, 2006; Tor Lim et al., 2018b).



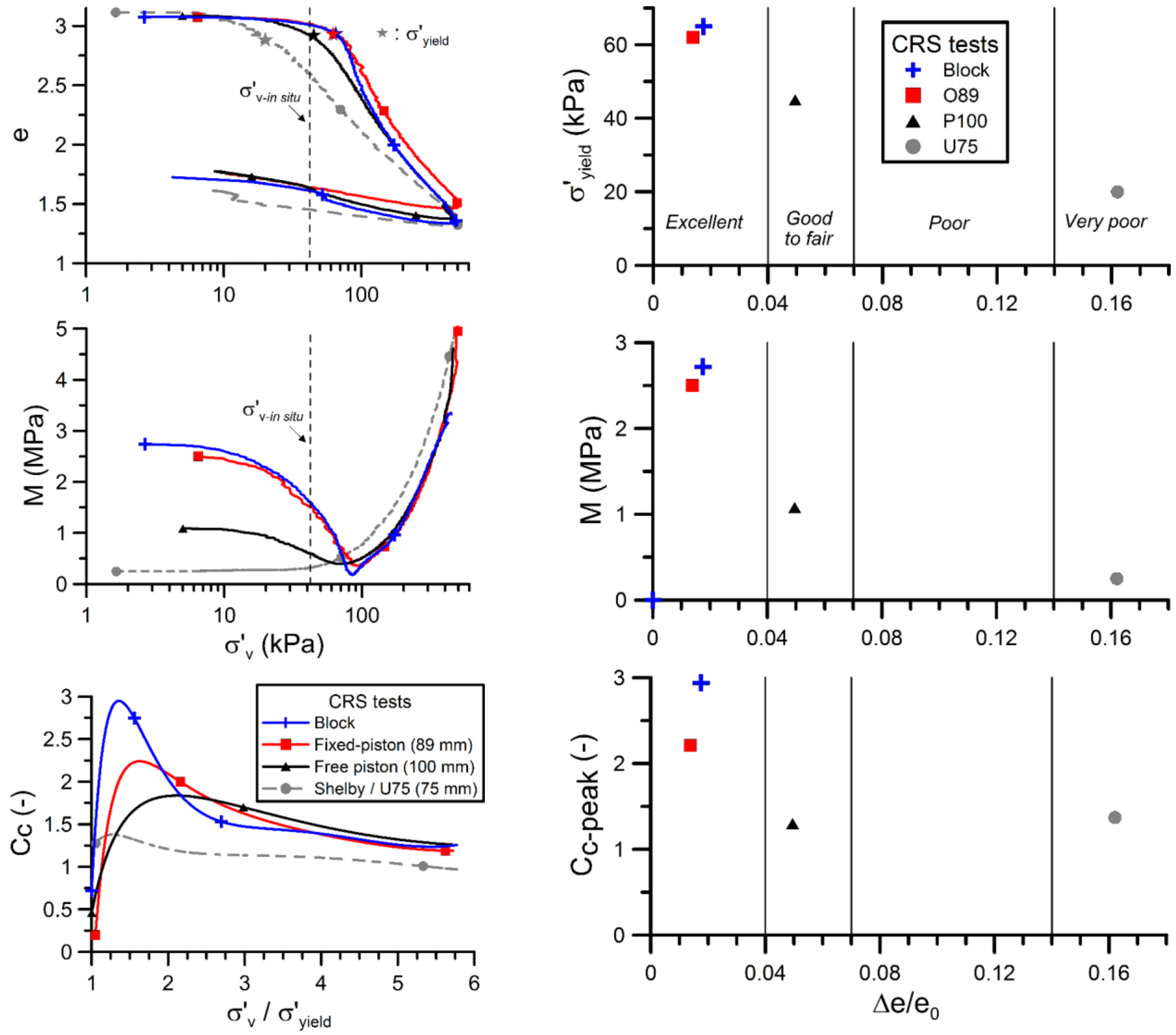
(a) (b)

Figure 13: Normalized shear wave velocity vs Lunne's et al. sample quality indicator. (a) Ballina clay (Pineda et al., 2016b) and silty deposits (Arroyo et al., 2015). (b) Boston Blue Clay (Landon et al., 2007)

6. IMPLICATIONS OF SAMPLING DISTURBANCE IN GEOTECHNICAL DESIGN

Recently, Tor Lim et al. (2018a) evaluated the effects of sampling disturbance on the predicted behaviour of geotechnical infrastructure. Laboratory tests were performed on Ballina clay specimens retrieved from the National Soft Soil Testing Facility in Ballina (NSW) using four different samplers: (i) the U75 Shelby sampler (commonly used in Australian practice), (ii) the 100 mm free-piston sampler, (iii) the 89 mm hydraulic fixed-piston sampler and (iv) the 250 mm Sherbrooke (block) sampler. Block specimens were used to obtain reference soil parameters as the Sherbrooke sampler is recognized to provide specimens of the highest quality in soft soils (e.g., Terzaghi et al., 1996; Lunne et al., 1997). Results obtained from 1D Constant Rate of Strain (CRS) compression tests are shown in Figure 14(a). The inspection of the compressibility curves (e-log σ'_v) shows two main trends. Block and O89 specimens have the lowest volumetric deformation at $\sigma'_{v\text{-in situ}}$ followed by the P100 and U75 specimens. The small deformation that has been required to reach $\sigma'_{v\text{-in situ}}$ implies less degree of soil destructuration. This is consistent with the larger yield stress σ'_{yield} as well as the steeper slope of the compressibility curve post-yielding observed in block and O89 specimens. σ'_{yield} ranges from 20 kPa to 65 kPa. The value obtained from the U75 specimen, which is even lower than the $\sigma'_{v\text{-in situ}}$ (i.e. OCR<1), is incompatible with the stress history of the marine deposits at the Ballina site. Specimen P100 shows a σ'_{yield} slightly higher than $\sigma'_{v\text{-in situ}}$, thus, much lower than the level of overconsolidation ratio ($1.5 < OCR < 1.6$) reported by Pineda et al. (2016b). The oedometric modulus, $M=\delta\sigma'_v/\delta\varepsilon$, reduces from 2.72 MPa (block sample) to 0.25 MPa (U75 sample) in the overconsolidated range. Block and the O89 specimens show a similar trend which is followed by the P100 specimen only at larger stress levels. The variation of the compression index, $C_c=-\partial e/\partial \log(\sigma'_v)$, with σ'_v is highly non-linear, characterized by a peak value reached between 1.20 – 2.0 σ'_{yield}. As expected, strong non-linearity is observed in the block and O89 specimens, with a peak Cc values of 2.95 and 2.25, respectively. Lower peak values of C_c are reported for P100 and U75 specimens (1.83 and 1.38, respectively) for which a more gentle post peak reduction in C_c is observed. The post peak value seems to be similar for all specimens tested ($C_c \approx 1.30$), except for the U75 sample ($C_c \approx 1.0$).

Laboratory results were used to estimate the ratio $\Delta e/e_0$ used by Lunne et al. (1997) as sample quality descriptor (see Table 3). Figure 14(b) compares the estimated σ'_{yield}, M and $C_{c\text{-peak}}$ against $\Delta e/e_0$ obtained from CRS tests. The trend shown in this figure is qualitatively consistent with published data, i.e. the estimated σ'_{yield}, initial M and $C_{c\text{-peak}}$ decrease with reducing sample quality. σ'_{yield} reduces 30 % and 67 % in P100 and U75 specimens respectively. The reduction of M and $C_{c\text{-peak}}$ is even more dramatic. It may be noted that the P100 specimen has a good to fair quality according to the adopted sample quality criterion. This would imply that results from this specimen could be used with confidence in design, which would appear to be a misleading outcome judging by the comparison against mechanical properties measured in either block or O89 specimens.



(a) (b)

Figure 14: (a) CRS test results on Ballina clay specimens. (b) Sample quality assessment

Compressibility parameters estimated from CRS tests were used by Tor Lim et al. (2018a) to assess the effects of sampling disturbance on the predicted surface settlement and excess pore pressure underneath an embankment built on Ballina clay. The geometry of the trial embankment constructed at Ballina site by the ARC Centre of Excellence for Geotechnical Science and Engineering (CGSE) was adopted here (Kelly et al., 2018) (see Figure 15). With the aim of emphasizing the effects of sampling disturbance on predicted soil behaviour, a few simplifications were made in the predictions presented below. Vertical drains, included in the trial embankment constructed at Ballina site, were neglected in the predictions described below. Moreover, a single layer soil profile was adopted. The predictions made include: (i) the end-of-primary consolidation settlement due to the weight of the embankment using 1-D consolidation theory, and (ii) the time variation of excess pore water pressure, degree of consolidation and consolidation settlement due to the construction of the embankment via the Finite Difference Method (FDM). Only total settlements are discussed here.

Figure 16 compares the predicted surface settlements using the set of parameters determined from CRS tests for each sampler type. Larger total settlement is predicted when using parameters obtained from block or O89 specimens, which had sample quality indexes of *excellent*. The settlement curve predicted for the P100 specimen is similar to those obtained for the block and O89. Although this result would be considered in agreement with its sample quality index of *good to fair*, it may be noted the important differences in soil properties between this sample and block and O89 specimens shown in Figure 14(a). Total settlement is mainly controlled by σ'_{yield} and C_c. The ‘good’ prediction obtained for the P100 specimen is attributed here to the counterbalance effects of a lower compression index (that reduced the predicted total settlement) and a lower yield stress (that increased the predicted total settlement). Figure 16(a) also shows an important underestimation of total settlement when soil parameters are obtained using disturbed specimens such as those obtained with the U75 sampler. In this case, the reduction in C_c had more effect on the predicted total settlement than the reduction in σ'_{yield}. Underestimation of total settlement caused by embankment construction on soft clay has been commonly observed in Australian practice. This result is likely, to a large extent, due to the use of inappropriate sampling techniques, such as the U75 Shelby tube.

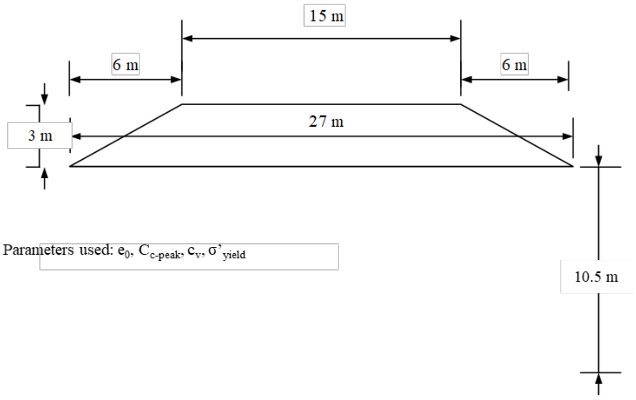


Figure 15: Embankment geometry

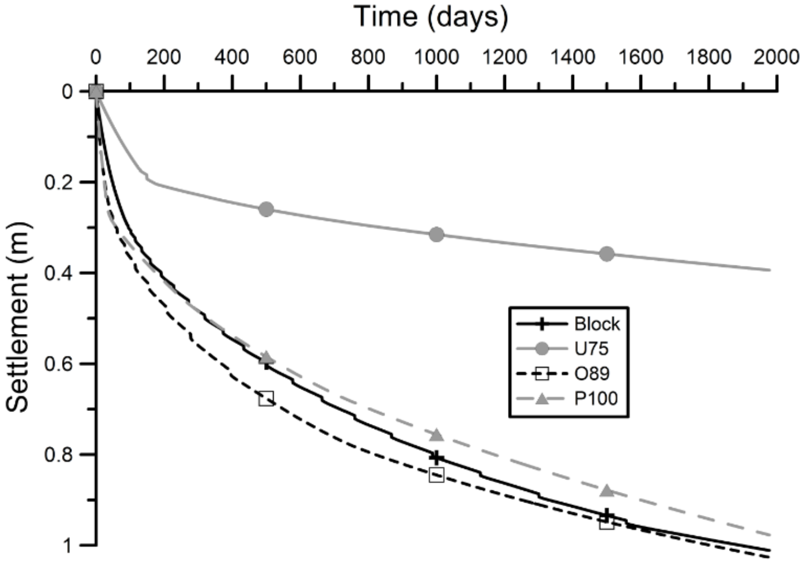


Figure 16: Predicted embankment surface settlement

7. CONCLUDING REMARKS

The paper discussed the factors influencing sampling disturbance and its consequences on the predicted behaviour of geotechnical infrastructure. It was showed that total settlement prediction underneath an embankment is strongly affected by sampling disturbance as a consequence of the important variation in σ'_{yield} and Cc (but also the cv which controls the excess pore pressure dissipation). Practitioners have to be aware of the fact that there are cases where correct predictions can be achieved, but for the wrong reasons, which by no means reflects good practice. It may occur, for instance, when the reduction in C_c is largely compensated for by the reduction in σ'_{yield}.

Relatively simple, relatively low cost steps can be taken to improve the quality of tested samples and hence the reliability of soil properties measured in the laboratory. It is recommended that these steps, below, be incorporated into routine practice.

- Use fixed-piston samplers for sampling soft soils (Shelby tubes should be avoided).
- The diameter of the tube sampler should be ≥ 63 mm. (50 mm tube diameters should be avoided).

- Use insulating materials, such as polystyrene plate, to separate the soil from the wax. In the case of block samples, aluminium foil and plastic film could be used as insulating materials.
- Tube/block specimens should be tested soon after sampling. In organic soils, storage for more than 3 months seems problematic.
- When possible, use either X-Ray or (conventional) medical CT scanning to assess sample quality and select the best zone of the tube for (mechanical) laboratory testing.
- Check sample quality using volume change relationships (either ε_v or $\Delta e/e_0$) and potentially laboratory shear wave velocity measurements (e.g. bender elements) correlated with $V_{s\text{-in situ}}$. This allows engineers to make judgement on the sensitivity of analysis to laboratory test inputs
- Regarding to the laboratory testing techniques (not discussed here), it is important to use pore water with similar salinity to natural water as it plays a key role on the mechanical behaviour of the soil.

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