Structuration in natural clays, dredged sediments, and oil sands tailings

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ABSTRACT

Though creep in clays has received considerable attention in the literature, with several mature semi-empirical models available to practitioners, structuration (or restructuration) has received less attention. Structuration refers to the increase in apparent pre-consolidation pressure in clays that occurs over time without the application of mechanical load, and is often reversible through shearing and recoverable over time. While the difference in structured intact clays and remoulded clays is widely studied, the rate of structuration (or restructuration) less so. From a conventional geotechnical prospective, this makes sense as practitioners are usually faced with predicting settlement in intact undisturbed clays, and how or at what rate the clays achieved their in-situ properties is less important. By contrast, however, in the oil sands industry, where deep deposits of clay dominated tailings are being contemplated, and the performance of such deposits depends on their consolidation, the rate of structuration, if such a phenomenon exists, may substantially affect magnitudes of expected strength gain and settlement. This paper reports on ongoing experiment and numerical studies of structuration in Leda clay and in-line flocculated oil sands tailings, and proposes a preliminary model to describe the rate of structuration in these materials.

RÉSUMÉ

Bien que le fluage dans les argiles ait attiré une attention considérable dans la littérature, avec plusieurs modèles semi-empiriques matures disponibles pour les praticiens, la structuration (ou la restructuration) a reçu moins d’attention. La structuration fait référence à l'augmentation de la pression apparente de pré-consolidation dans les argiles, qui se produit dans le temps sans application de charge mécanique et qui est souvent réversible par cisaillement et récupérable dans le temps. Bien que la différence d'argiles intactes structurées et d'argiles remoulées soit largement étudiée, le taux de structuration (ou de restructuration) l'est moins. D'un point de vue géotechnique conventionnel, cela a du sens, car les praticiens sont généralement confrontés à la prévision d'un tassement dans des argiles intactes non altérées, et la question de savoir comment ou à quelle vitesse les argiles ont atteint leurs propriétés in situ est moins importante. En revanche, dans l’industrie des sables bitumineux, où des dépôts profonds de résidus à prédominance argileuse sont envisagés, et dont la performance dépend de leur consolidation, le taux de structuration, si un tel phénomène existe, peut avoir une incidence considérable sur les ampleurs attendues. gain de force et règlement. Cet article décrit les expériences et études numériques en cours sur la structuration dans les résidus de sables bitumineux en floculation d'argile et de Leda en ligne, et propose un modèle préliminaire pour décrire le taux de structuration dans ces matériaux.

1 INTRODUCTION

The oil sands industry has produced large volumes (~ 300 km^2, with dam heights exceeding 100 m) of clayey tailings from the extraction of bitumen from surface mined ore. The clays tend to be dispersed due to the bitumen extraction process, which results in clayey tailings that have poor consolidation properties. Deposits tend to stabilize at water contents greater than twice their liquid limit – the “natural” water content of these tailings being > 200%, compare to liquid limits typically < 80%. As this state the tailings are termed fluid fine tailings, or FFT. Current regulations dictate the tailings must be rendered “ready to reclaim” within 10 years after end of mine life. Some operators believe that “ready to reclaim” implies that the tailings have strength sufficient to be stable in gently sloped deposits, of similar topography to the surrounding boreal uplands. Simple slope stability calculations suggest that this would require an undrained strength of 20 kPa (McKenna et al. 2016), which in turn requires the tailings to reach their plastic limit, about 40%.

Current dewatering technologies that have been successfully used at commercial scale can achieve water contents of 100% shortly after treating and re-depositing the tailings (< month), bur this is still a long way to go to reach w=40%. Therefore, some deposition plans rely upon a combination of natural dewatering processes (desiccation, freeze-thaw., consolidation) to approach these target water contents.

As some deposits envisage quite deep deposits (> 50 m in thickness), consolidation would be the dominant dewatering mechanism. However, even after polymer induced flocculation treatments, the hydraulic conductivity of the tailings remains relatively low, and substantial settlement is expected over periods of years to decades. In this time scale, time dependent effects, such as creep and ageing (structuration) may become important.

To investigate these effects, Carleton University, , has been studying these processes in different types of treated oil sands tailings since 2017. This paper reviews observed time-dependent behaviours in soils, and then presents experimental and numerical work on such behaviours applied to oil sands tailings. Finally, some evidence of such behaviours from pilot scale data is presented. In this paper, “creep” is defined as any deformation that occurs independently of changes in effective stress, and “structuration” refers to time-dependent changes in the compressibility function.

2. CREEP IN NATURAL CLAYS

Many clays exhibit a viscous component to their deformation, such that they continue to deform under a constant effective stress. This viscous component is evident in rate dependent compressibility curves. Such behaviour is accounted for in engineering projects involving long-term settlements of soft clays. For example, the construction of Kansai International Airport in Japan and similar projects involving construction of other artificial islands on clays (Watabe et al. 2012).

The rate dependency of compression is often treated by considering that the location of the compressibility curve is dependent on strain rate (e.g., Leroueil 2006). A typical example of rate dependent behaviour for a natural clay is shown in Figure 1.

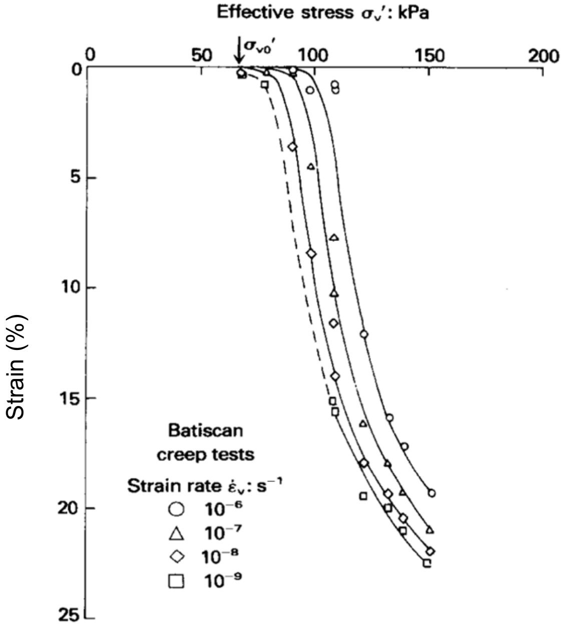

Figure 1. Typical strain rate dependence observed in natural clays (from Leroueil et al. 1985)

Data of the type presented in Figure 1 can be normalized with respect to an apparent pre-consolidation pressure that is related to strain rate. Watabe et al. (2012) proposed a simple relationship to relate the apparent pre-consolidation pressure and strain rate:

$$ln\frac{p'_c - p'_{cL}}{p'_{cL}} = c_1 + c_2\dot{\varepsilon}_{vp} \qquad [1]$$

In which p'_{cL} is a reference pre-consolidation pressure, p'_c is the actual pre-consolidation pressure as a function of strain rate, $\dot{\varepsilon}_{vp}$ is the strain rate, c_1 and c_2 fitting coefficients.

Watabe et al. (2012) analyzed data from around the world, and found strong agreement of many data sets with Equation 1, as shown in Figure 2. The shift in apparent compressibility due to rate effects is relatively well bounded, between 0.7 and 1.5 of a reference pre-consolidation pressure.

There is some debate in the geotechnical literature on the degree of creep that occurs during primary consolidation (Hypothesis A vs Hypothesis B debate). The preceding Equation 1 and associated theory is based on the assumption that creep and primary consolidation occur simultaneously.

Another competing hypothesis is that a substantial amount of creep may be due to delayed consolidation in parts of a test specimen, specifically for those samples with low hydraulic conductivity (Carrier 2017).

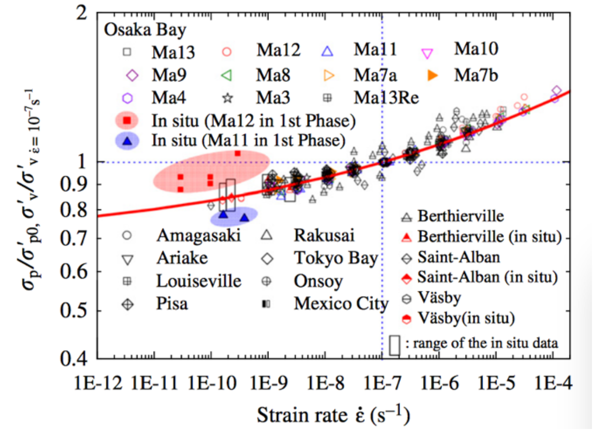

Figure 2. Variation in apparent pre-consolidation pressure with strain rate in large data set on clay compressibility (Watabe et al. 2012).

The well-bounded nature of the magnitude of creep in natural clays appears to be reflected in oil sands tailings as well (Salam et al. 2018b).

3 STRUCTURATION IN NATURAL CLAYS AND DREDGED SEDIMENTS

Natural clays are known to possess a "structure", which is destroyed by remoulding, and is at least partially regained over time. This is evident in from *in-situ* testing or from tests on carefully extracted field samples. In 1 D compression "structure" manifests as an elevated pre-consolidation pressure, which is not seen in the reconstituted specimen. Liu and Carter (1999) compared twenty soils which had compression curves for both their natural and reconstituted states. Over 90% of the structured pre-consolidation pressures were less than 200 kPa, Burland (1990) showed similarly that at or above the consolidation pressure, that most structured soils bore about twice to an order of magnitude of the load at a given void ration in 1D compression tests. Liu and Carter (1999) developed a simple relationship to characterize the difference between reconstituted compression curves and the compression curves of intact natural clays. They found the increase in the void ratio at the pre-consolidation pressure above the void ratio for the reconstituted soil for the same stress could be linearly related to the pre-consolidation pressure, as shown in Figure 3. Liu and Carter (1999) present statistics on the relationship shown in Figure 3.

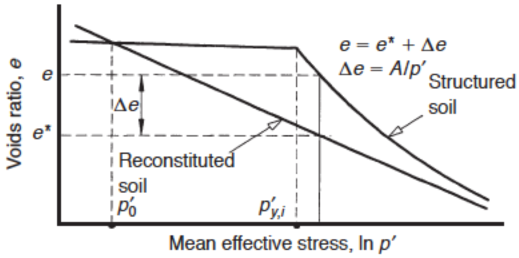

Figure 3. Scheme for analyzing differences in reconstituted and natural clays proposed by Liu and Carter (1999)

Dredged sediments are perhaps a closer analogue to oil sands tailings, as they similarly can stabilize at water contents much larger than their liquid limit. Zeng et al. (2016) studied the influence of ageing on compression curves on dredged sediments from China. As can be seen in Figure 4, ageing the samples under fixed consolidation loads produced significant development of apparent pre-consolidation pressure and changes in the compression curve, though magnitude of the change in pre-consolidation pressure did not approach values seen in natural clays. Zeng et al. (2016), based on their data set of dredged sediments, proposed an empirical equation that predicts the pre-consolidation pressure to develop linearly with log time, strongly dependent on the ratio between the initial water content and the liquid limit, and weakly dependent on the value of vertical effective stress:

$$\frac{\sigma'_p}{\sigma'_v} = 1 + [0.005 - 0.31 \log \sigma'_v + 0.056 \log t]\, e^{\frac{1.55 w_0}{w_L}} \quad (2)$$

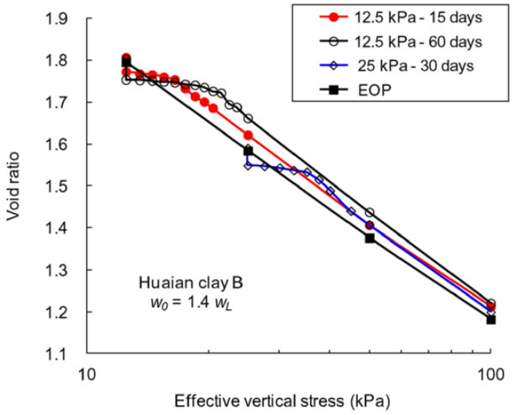

Figure 4. Example of ageing in a dredged sediment (Zeng et al. 2016)

4 STRUCTURATION IN OIL SANDS TAILINGS

Evidence of ageing (structuration) has been reported by Miller (2010) for raw fluid fine tailings, and by Salam et al. (2017, 2018a and b) for polymer amended FFT. Salam et al. (2017) prepared replicate samples in 10 cm tall 10 cm diameter replicate sealed polypropylene columns, of FFT dosed with industry standard polymer and mixing protocol. Salam et al. (2017, 2018) traced structuration in these samples using conventional oedometer tests, oedometer tests with pore-water pressure measurement, and by using fall cone measured undrained strength. Some replicate samples, generally with 10 cm tall samples inside 20 cm diameter polypropylene plastic columns, (Figure 5) were also used to generate density and water content profiles over time. The same authors also performed the same experimental procedure on Leda clay samples, initially prepared at twice their liquid limit. The properties of the raw FFT and the Leda Clay are given in Table 1.

Figure 5. Example of suite of replicate columns.

To summarize these results, some tests showed considerable development of preconsolidation pressure over the testing period (120 days). Figure 6 shows a comparison of a strongly ageing sample, where a preconsolidation pressure of ~70 kPa developed after 100 days, and thereafter did not change appreciably.

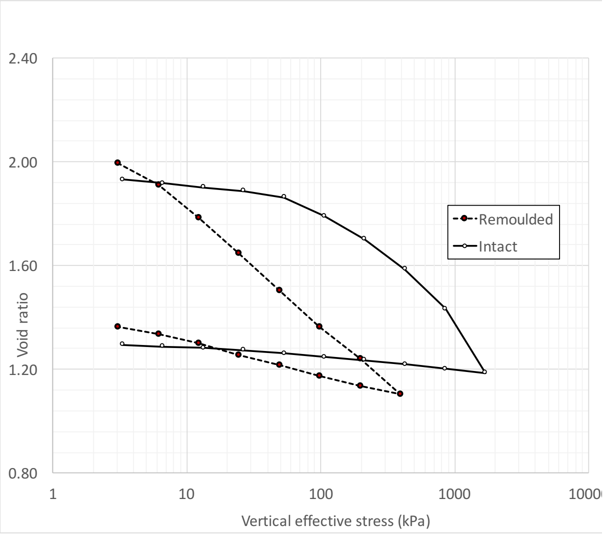

Figure 6 Aged and remoulded compression curves in a polymer amended FFT aged for 112 days

Table 1: Properties of tested materials

Material /Property	**Raw FFT**	**Leda Clay**
Specific gravity	2.2	2.7
d_{90},d_{60},d_{50},d_{10} (μm)	100,11,6,0.8	10, 1, <1, <1
LL, PL	62, 27	55, 25
Mineralogy	Kaolinite (70%) , Illite (30%)	Illite (83%), Kaolinite (11%)

The degree of structuration can also be assessed by fall cone tests on replicate samples. Figure 7 shows an example of correlation of pre-consolidation pressure and fall cone undrained shear strength. This suggests that thixotropy and structuration, in the tailings and at least some clays, are caused by the same physical phenomenon.

In the oil sands tailings, however, the degree of structuration varies considerably, depending on polymer dose and mixing parameters. Figure 8 compares polymer amended FFT prepared at different doses with an aged Leda clay sample. It is interesting that all samples seem to level off at a fairly low shear strength, until about 30 to 40 days, after which the fall cone shear strength begins to substantially increase. As shown in Figure 10, the large increase in shear strength appears to begin towards the end of primary consolidation. This is also borne out by pore-water pressure measurements (Igbinedion et al. 2019, Salam et al. 2018a and b). Samples appear to reach an equilibrium in terms of water content, but then release some additional water co-incident with the development of structuration.

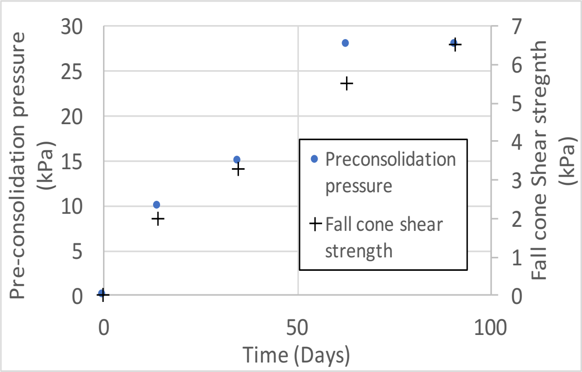

Figure 7. Example of correlation of fall cone shear strength with Casagrande pre-consolidation pressures in polymer amended FFT

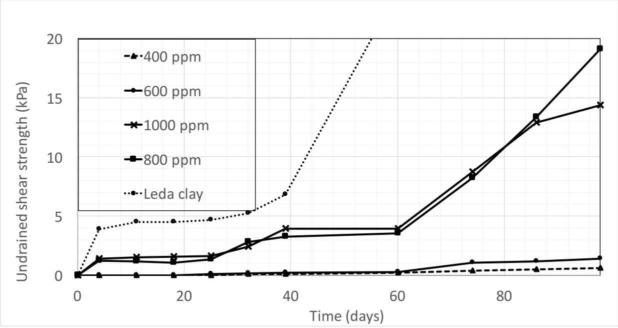

Figure 8. Structuration via fall cone shear strength in Leda Clay and polymer amended FFT at different polymer doses

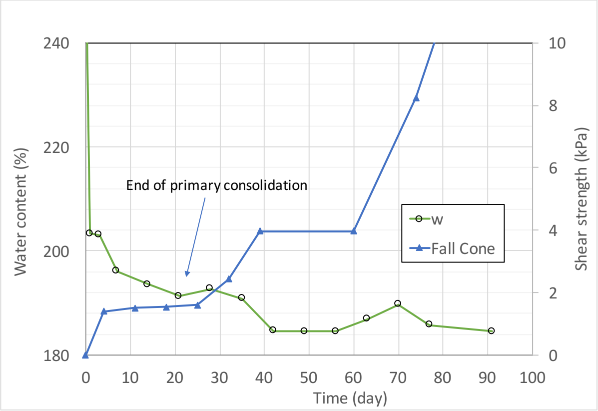

Figure 9. Average water content and fall cone shear strength in replicate columns for a polymer dosed FFT.

Evidence of time dependent compressibility and structuration can be seen in some pilot studies of FFT deposits. The data reported in Figures 10 and 11 is from a pilot study of deposition of FFT in-line flocculated with an anionic polymer. The deposit has wan approximate initial height of 11 m. Figure 10 shows that indeed that *in-situ* measurements of PWP and density suggest time-dependent compressibility effects, similar to observed in laboratory studies of Salam et al. (2017, 2018 a and b) Figure 11 shows the development of sensitivity, or the ratio of peak to remoulded shear strength measured from a field vane. Sensitivity is used as an indicator of structuration in clays (Skempton and Northey 1952, Leroueil and Vaughan 1990).

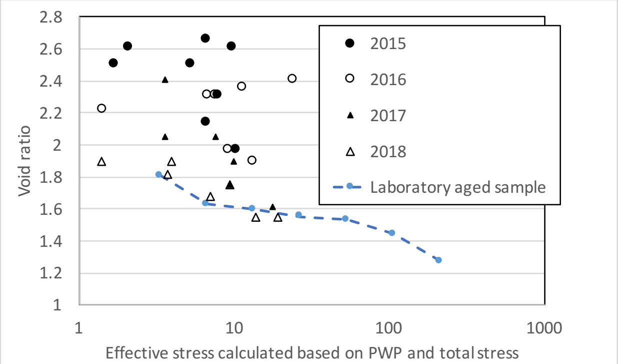

Figure 10. *In-situ* measurements of the compressibility curve in a 11 m deep pilot study of consolidation of polymer amended FFT.

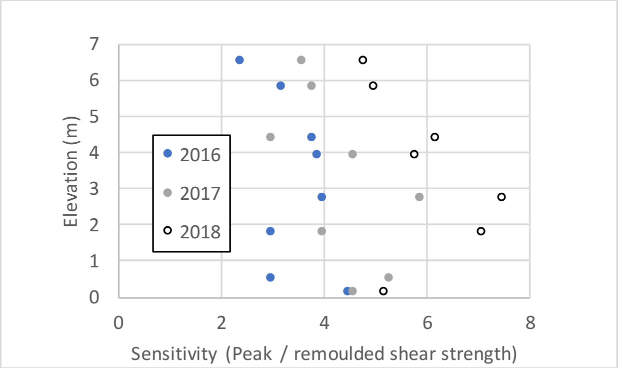

Figure 11. Ratio of peak to remoulded shear strength in a 11 m deep pilot study of consolidation of polymer amended FFT.

5 RATE OF STRUCTURATION

The rate of structuration has been modelled empirically, e.g. as in Zeng et al. (2016) by Equation 2. Data such as Figure 9, however, suggest that at least the onset of ageing may only occur below a critical strain rate. Interestingly, the buildup of thixotropic strength at small time scales is considered in rheology of clay suspensions using viscosity bifurcation models, (E.g. Coussot et al. 2002), which manifest such a critical strain rate. Such models are governed by simple rate laws that balance shear down of the network structure with an ageing term. An example of such a rate law is:

$$\frac{d\lambda}{dt} = a(\lambda_{max} - \lambda) - b\gamma \qquad (3)$$

where λ is the structure parameter, γ is the strain rate, t is time, *a* and *b* are parameters. If we take the pre-consolidation pressure to be linearly related to the structure parameter, Equation 3 will predict a decreasing rate of ageing up to some maximum value, but only above a critical strain rate, which is a function of the ratio of *a* and *b*.

Predictions of pre-consolidation pressure increase by Equation 3 at a constant but low strain rate is compared to Equation 2 and with measured data in Figure 12. The liquid limit and approximate average effective stress are used in Equation 2. Both equations can reasonably replicate the measured data, though Equation 2 will predict an unbounded increase in pre-consolidation pressure (Figure 13). However, Equation 2 and other databases can help guide parameter selection for Equation 3.

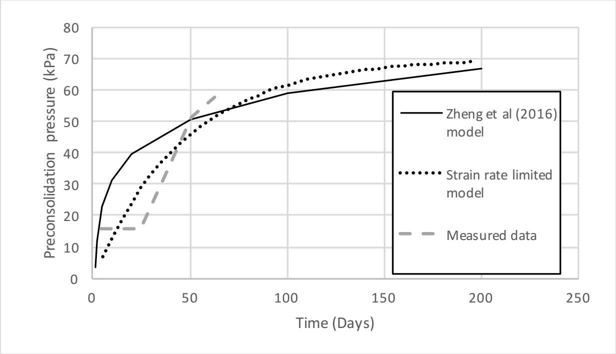

Figure 12. Different models for rate of structuration compared with FFT data

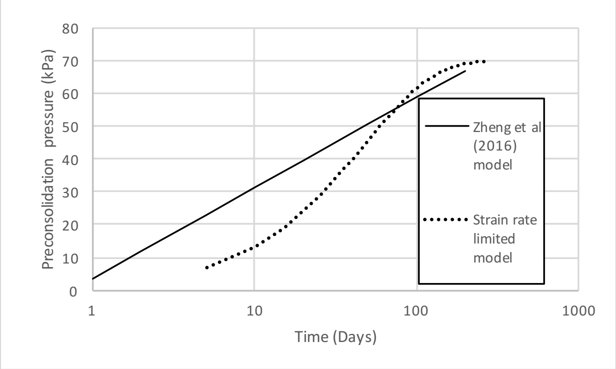

Figure 13. Comparison of Equations 2 and 3 models in log time

6 SUMMARY AND CONCLUSIONS

Structuration occurs in natural clays, dredged sediments, and in at least certain deposits of oil sands tailings. Structuration is important as it may change the compressibility of the deposited material over time, likely reducing settlement and residual strength gain below values expected from a conventional large strain consolidation analysis. Conversely, it will improve the peak undrained strength of the tailings for a given density. This may have positive as well as negative implications for tailings management. Specific conclusions are:

1. The degree of structuration depends on polymer dose and mixing protocol. From the available data, it appears that polymer amended FFT that exhibit the largest short–term dewatering potential also exhibit the largest degree of structuration.
2. Structuration only appears to manifest after initial dewatering / consolidation has decreased below some yet unknown rate.
3. Structuration appears to occur in at least some pilot studies of polymer amended FFT.

The consequence of Conclusion 2, is that appropriate deposition management may allow operators to "escape" from its negative effects, for example by layered deposition, or by using wick drains to shorten drainage paths. Current work on analyzing different deposition schemes using a large strain consolidation model with structuration effects, incorporating the strain rate dependent model discussed in this paper, is ongoing.

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