INVESTIGATING SWELLING ACROSS SCALES

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KEYWORDS

Unloading, Swelling, Clay, Pore-water chemistry

ABSTRACT

Volumetric expansion of ground formations containing clay minerals occurs at different scales and depends significantly on the pore water composition. This is both a challenge and an opportunity as prediction of deformations becomes complicated but possibilities to influence them arise. The research presented contribute to answer the questions of whether it is feasible to (1) actively control settlements under linear infrastructure in the far future through changes in pore water and (2) use clay rich formations to seal the annular interface that tends to form between them and the casing of wells so that abandonment oil and gas wells may be repurposed for to store carbon and hydrogen. To investigate these possibilities, both the element and micro scale behavior of a Danish Paleogene Clay is studied. A series of one-dimensional unloading oedometer tests represents the element scale while the microscale is studied through Scanning Electron Microscopy to identify the particle arrangement. At the element scale, three conceptually different swell modes were observed which can be described as increased inhibition of swelling. From variation in pore water composition it was shown how KCl inhibits swelling relative to NaCl, which agrees with previous similar observations from loading. Based on the microscopy it was identified that this is based on interaction between particle and their contacts due to the unchanged fabric of the material during unloading.

1. INTRODUCTION

The prediction of the behaviour of soil formations known as the Danish Paleogene Clays is a challenge for both new and existing infrastructure in Denmark (the old and new Little Belt Bridges, Århus harbor, Fehmarn Fixed Link, the Kattegat connection, deep geological storage of CO_2, H_2 or heat). These clays can expand and contract significantly during mechanical loading cycles which makes them very reactive to changes in external boundary conditions. The compression behavior of these and similar formations is well studied (e.g. [A], [B], [C]) however a deeper understanding of their swelling behavior is necessary.

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In addition, the behavior of these formations also depends on their pore water composition as seen from samples of similar smectite dominated mineralogy [D]. To enable accurate prediction of deformations in such formations a deeper understanding of their swelling behavior is necessary that combines information from both the micro and element scales.

2. MATERIALS AND METHODS

The analyzed data represents the Danish Paleogene Clay formation called: Røsnæs Clay. Samples were collected from cores retrieved as part of the preinvestigations for the Fehmarn Fixed Link between Denmark and Germany [E]. The mineralogy of the material was quantified from XRD measurements finding four main components: quartz (17-34%), smectite (8-33%), illite (21-39%) and kaolinite + chlorite (9-25%) as well as trace amounts of other minerals; calcite, dolomite, feldspar and siderite (together: 1-11%). The dominance of clay in the mineralogy and in particular smectite results in the material classifying as high plasticity due to its high liquid limit (w_L), which also agrees neatly with the large specific surface area (SSA) measured. From Table 1 it may also be seen that the material has significant variation in initial state since the initial void ratio (e_i) range from 0.82 to 2.13.

Table 1. Range of classification parameters for Røsnæs Clay [E].

ρ_s	e_i	w_L	w_P	SSA
[g/cm^3]	[-]	[%]	[%]	[m^2/g]
2.68 - 2.87	0.82 – 2.13	84 – 198	26 – 39	55 – 68

All element scale testing was conducted as either Constant Rate of Strain (CRS) or Incremental Loading (IL) oedometer tests following the respective standards ([F], [G]). However, the state of the samples varied from resedimented samples (see [H]), remoulded samples (prepared according to [I]) and natural samples (taken directly from the cores), where these tests are part of those originally published in [J]. The resedimented samples were created based on 0.55M brines either dominated by NaCl or KCl while the remaining tests were carried out with 0.28M (NaCl dominated) brine which represents the in-situ pore water.

The microstructural analysis contains interpretation of SEM images to quantify the orientation of particle edges their amount within a given volume [K]. These SEM images are taken at various stages of loading and unloading.

3. RESULTS AND DISCUSSION

At the element scale the several unloading branches from the CRS and IL tests are compared in Figure 1a by plotting the change in void ratio during unloading (de) against the Unloading Index (UI), defined as the ratio between the effective vertical stress unloaded from ($\sigma'_{v\text{-}max}$) and the effective vertical stress at a given point. Figure 1b illustrates conceptually how the unloading branches displays three different swelling modes as defined in [J]; swell mode one (SM1) has continuously increasing swelling index (C_s, defined as the tangential slope of the unloading branch in the compression plane), swell mode two (SM2) finds a plateau C_s (C_{sp}) after an initial increase, and swell mode three (SM3) displays a subsequent decrease of C_s after C_{sp}. From Figure 1a it may be seen that within each swell mode there is a significant variation in C_{sp} as well as the acceleration of C_s. This was identified by [J] to depend on $\sigma'_{v\text{-}max}$, as illustrated in Figure 2. With increasing $\sigma'_{v\text{-}max}$, C_{sp} increases, however differently for each swell mode. Note that swell mode 1 is not represented in Figure 3 since C_{sp} is not defined for this mode. The evolution of C_{sp} for SM2 and SM3 is compared to the trends from both remoulded samples (intrinsic trend) [M], and a deeper equivalent formation of Ypresian Clay [C]. This comparison shows that all groups of tests display similar trends but at offset C_{sp} values. Taking the remoulded samples as reference the offset from the intrinsic trend may be interpreted as the extent to which swell is inhibited. This fits neatly with the relative positioning of SM2 and SM3 as well as suggesting that the Ypresian Clay contains more swell inhibiting structure.

In order to elucidate the swelling mechanisms, it is worth looking at soil at the microscopic scale through SEM micrographs for samples at two different depths.

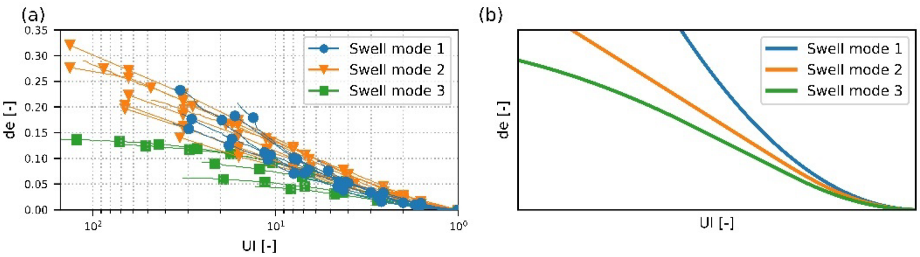

Figure 1: Normalised (change of void ratio since unloading (de) versus Unloading Index (UI)) swelling response under oedometric conditions illustrating the three swelling modes identified by Kinslev et al. 2021 based on (a) the results from oedometer tests and (b) a conceptual more illustrative visualization of the behaviour.

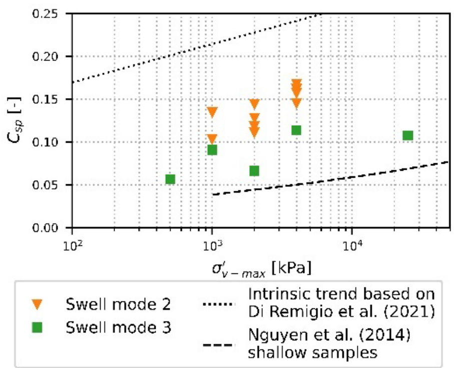

Figure 2: Evolution of the swelling index plateau (C_{sp}) with stress before unloading ($\sigma'_{v\text{-}max}$) for swell mode 2 and 3 compared to remoulded as well as comparable reference trends.

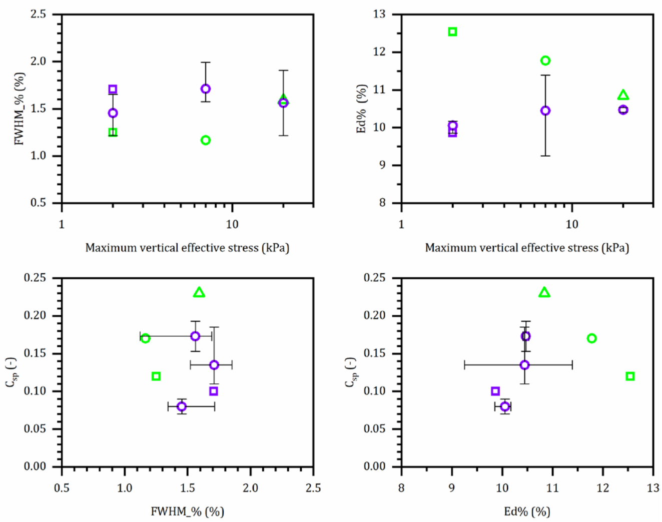

Figure 3: Change in orientation (top left) and amount (top right) of particles within a SEM micrograph as a function of the maximum vertical effective from which the specimens were unloaded from. Change in swelling index with orientation (bottom left) and amount (bottom right) of particles for the same tests.

Figure 3 shows the interpretation of such micrographs, where the top row shows the relative scatter in particle orientation (FWHM) since all images show a unimodal distribution in particle orientation, and the amount of edges (Ed%), both as a function of the maximum stress from which the specimens were unloaded. Note that a higher FWHM indicates less scatter. While this parameter is quite erratic for both samples regardless of the stress applied and there is no clear link to csp, Ed% is more clearly correlated. However for one sample Ed% increases when unloading starts from lower stresses, which corresponds to a lower c_{sp} value, while it is slightly increasing for the other sample and in this case there is no clear link to c_{sp}. Despite the difficulty in the interpretation, it can be stated that the soil fabric is largely unchanged at the microscopic scale since all particles are aligned to the direction orthogonal to loading. This indicates that for Røsnæs Clay the difference in swelling modes observed at the element scale is predominantly dictated by interparticle contacts and spacing.

The reactivity of the interparticle contacts is further backed up by the significant influence of pore water composition on the deformation behavior of Røsnæs Clay. Figure 4 shows the difference in normalized unloading behaviour of resedimented samples in either NaCl or KCl based brines. This data includes both IL and CRS tests, which for each of the two brines compare very well.

From Figure 4 it may be seen that the swelling response of KCl based samples display a larger degree of swell inhibiting structure compared to NaCl samples, which agrees with observations from loading [N]. The variation in the unloading response between NaCl and KCl based samples stems from changes in the electrical double layer on the surfaces of the individual clay particles, which then changes their interaction and assembly. However, these tests are carried out on samples resedimented in KCl and NaCl based brines. It can be expected that when soils are sedimented in the same brine and the pore water is changed after consolidation, chemical diffusion should be stimulated to achieve similar swelling. However, in low stress scenarios (such as for closing of anulus gaps and close to the surface, hence directly below several types of linear infrastructure) the applicability of pore water change might still be viable.

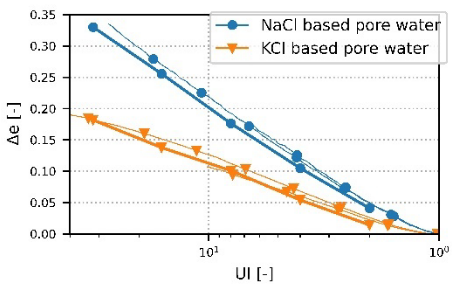

Figure 4: Normalised (change of void ratio since unloading (de) versus Unloading Index (UI)) swelling response for samples resedimented in either NaCl or KCl brines.

4. CONCLUSIONS

The combined interpretation at the element and microscopic scale presented based on oedometric investigation of Røsnæs Clay shows that despite the behavior at the element scale shows three different swelling modes with increasing inhibition of swelling, there is no fundamental difference in particle orientation. Swelling appears therefore to be dominated by face to face electro-chemical interaction between particles. The strong influence of electro-chemistry is confirmed by the significant difference in swellling observed when unloading occurs in specimens having a NaCl or a KCl based pore water composition. While these results represent an ideal scenario and it can be expected that soils sedimented in the same brine, where the pore water is changed after consolidation, will not show such difference in swelling, in low stress scenarios (such as for closing of anulus gaps and close to the surface, hence directly below several types of linear infrastructure) the applicability of pore water change might still be viable if stimulated for example by electro-kinetics.

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