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GENESIS OF QUICK CLAY: A NANOMETRIC EXPERIMENTAL INVESTIGATION ON GEOLOGICAL ENVIRONMENT

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Abstract: Quick clays are fine-grained soils with high sensitivity that transform into a liquid when remoulded. The deposition history directly impacts the composition and microstructure of natural clays. This study examines the morphology at the nanoscale of two different sensitive Swedish clays (Lödöse and Kärra clay) to establish a connection between the microscopic features and the macroscopic mechanical behaviour observed at their intact and remoulded state. Using in-line holotomography, the nano-scale imaging instrument at the ID16B beamline of ESRF is employed to capture nano-level features in the natural clay specimens. The results illustrate that the size of the silt grains and the macroporosity are smaller for Lödöse clay than for Kärra clay. This might indicate the higher sensitivity of Lödöse clay. Although the macroporosity of Kärra clay reduces by 32% after remoulding, the difference in macropores recorded after remoulding Lödöse clay is negligible.

1. Introduction

Clays vary widely from soft sediments with water-filled pores to highly compressed shale formations. Among these, quick clays stand out as elusive and hazardous due to their potential for abrupt loss of stability, triggering natural and human-induced shallow landslides (e.g. Surte 1952; Tuve 1977; Stenungsund 2023). Quick clay is a meta-stable sensitive clay, often deposited in a marine environment, that shows an irreversible transition from solid to liquid under a hydro-mechanical perturbation [1]. The sensitivity, denoted by the ratio S_t, which compares the undrained shear strength of natural clay in its original, intact condition to its residual state, exceeds 50 for quick clays [2]. These clays are located in areas such as Canada, Alaska, Scandinavia, and northern Russia that were previously glaciated [3].

The emergence of high sensitivity in a natural clay deposit is linked to geological processes controlling the formation of quick clays, which are largely unknown. The deposition history directly impacts the composition and microstructure of natural sensitive clays, such as quick clay [4]. Thus, the mechanical response observed at the macro-scale (metres) is linked to the processes at the nano- and micro-scale. This research takes an integrated approach to unravel the hydro-mechanical behaviour of quick clays by emphasising the crucial link between macro-scale observations and the underlying nano- and micro-scale processes that drive their emerging characteristics. Traditional limitations in experimentally observing the evolution of the microstructure in sensitive clays have obscured our understanding of the mechanisms that underpin the sudden loss of stability. To address this gap, this research advocates for using non-invasive process-monitoring techniques, particularly synchrotron-based nano X-ray Computed Tomography (XCT).

This paper examines the morphology at the nanoscale of two distinct types of natural, saturated, undisturbed sensitive clay sourced from the East Bank and the West Bank of Göta River in Sweden. These sites are 50 km apart and share a similar geological history. Geological unloading, however, has occurred in Lödöse. The primary goal is to identify the influence of geological environment and formation history on the development of sensitivity. Investigations of intact natural quick clays are complemented with observations of saturated remoulded quick clays. The objective is to connect the difference in macroscopic mechanical behaviour observed in intact and remoulded sensitive clay [5] and the distinct nano-scale fabric characteristics, such as the orientation of clay particles, void space, and contacts [6].

2. Material and method

This study examined two samples of natural sensitive clay that were deposited in a marine environment from different locations in south-west Sweden. The first sample was taken from the Chalmers soft soil test site in the Kärra municipality (Gothenburg, Sweden) at a depth of 7 m. The second sample was obtained from Lödöse municipality (Västra Götaland County, Sweden), 50 km away from the Kärra test site at a depth of 5.5 m. Standard geotechnical analysis revealed a sensitivity (S_t = undisturbed strength/remoulded strength [7]) of 20 for Kärra clay and >50 for Lödöse clay (>50).

The nano-scale imaging instrument at the ID16B beamline of ESRF [8] is employed to capture nano-level features in the natural clay specimens using in-line holotomography [9]. The instrument requires miniature samples; thus, the natural clay samples in both intact and remoulded states are carefully placed into cylindrical glass capillaries with a diameter of 300 μm and a wall thickness of 10 μm, which are then securely sealed at both ends using grease paste [10], to preserve the water content. In both cases, the miniature samples were cored from a master sample of 50 mm diameter and 160 mm height, i.e. the middle tube of the Swedish STII 50 mm piston sampler.

Phase contrast imaging is acquired using a conic and monochromatic beam with an energy of 29.6 keV and a flux of 1012 ph/s. Four tomographies are acquired at four different sample-detector distances. For each scan, 2160 projections with a pixel size of 50 nm are recorded, spanning a complete 360° rotation with an exposure time of 15 ms per projection. The field of view (FoV), measuring 128×108×108 μm^3, is smaller than the sample size, hence only covering a central sub-volume within the clay sample. The reconstructed 3D volume of the FoV was obtained using the PyNX software. One representative greyscale horizontal cross-section of each nanotomography is selected, numerically rescaled and converted into a 32-bit 2D array using the Software for the Practical Analysis of Material -spam- toolkit version 0.5 [11].

3. Results and discussion

Figure 1 shows four representative slices from reconstructed nanotomography scans on intact and remoulded natural sensitive clays sampled from Kärra and Lödöse in Sweden. The slices correspond to the horizontal cross-section with the out-of-plane direction of the vertical axis in which the samples are originally deposited and consolidated.

From a visual inspection, both the intact (Figure 1a and Figure 1c) and the remoulded (Figure 1b and Figure 1d) samples present large angular particles (silt grains) embedded in a clay matrix. For both Kärra and Lödöse, the uneven appearance of the clay matrix suggests the presence of a discernible underlying particle network hovering at the threshold of detection. Within this network, the largest assemblies of clay particles, likely composed of kaolinite minerals, manifest as brighter (higher intensity) fibres in 2D (plate-like particles in 3D). The small white angular particles (highest intensity) can represent calcite. The visible pore space, i.e. the black areas with low intensity, can be associated with the macropore structure of natural sensitive clays, as also detected through Mercury Intrusion Porosimetry from [12].

Interestingly, the most evident difference between the intact and remoulded samples of Kärra clay lies in the amount of macroporosity, which reduces by about 32% after the remoulding of the material (from Figure 1a to Figure 1b). The remoulding process at natural water content irreversibly

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modifies the clay microstructure. This microscopic change can be ascribed as one of the possible contributing causes for the observed different macroscopic mechanical responses between intact and remoulded clay samples [5].

Lödöse clay slices, on the other hand, show smaller silt grains for both the intact (Figure 1c) and the remoulded (Figure 1d) sample compared with Kärra clay. This can be one of the reasons why the discerned macropore sizes are also not as large as in Kärra clay samples. Another reason is that Lödöse clay experienced larger mechanical loads due to its location within a valley shaped by an erosional estuary [13]. The gradual buildup of effective stress during glaciation led to a higher level of compaction and, thus, a higher over-consolidation ratio post-deglaciation. Additionally, it is noticeable that the amount of macropores in the intact and remoulded samples is comparable.

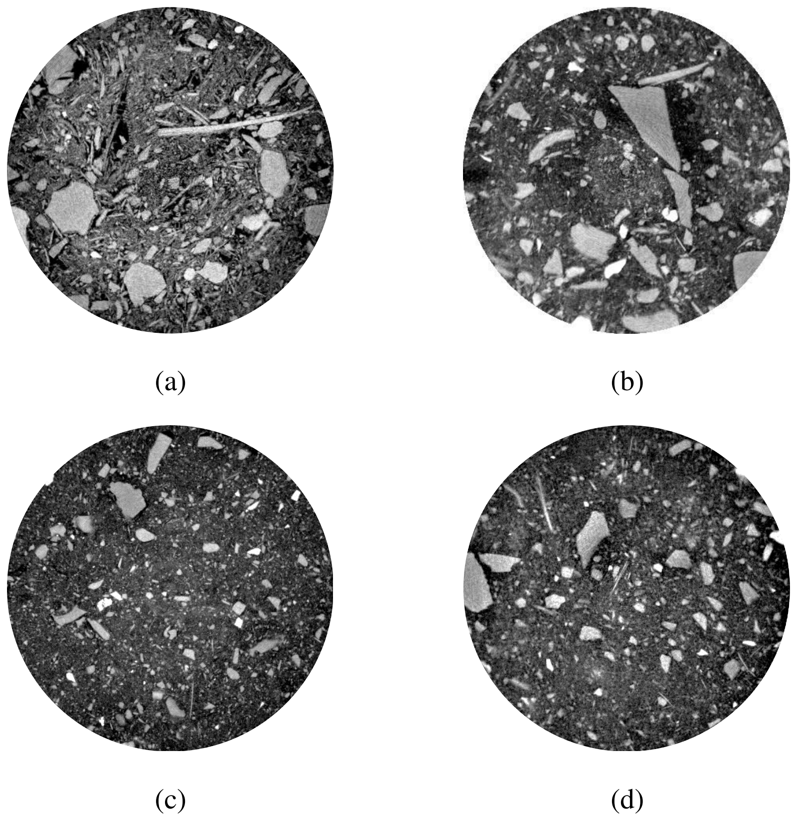

Figure 1. Reconstructed horizontal cross sections from nanotomography scans on (a) an intact and (b) a remoulded sample of Kärra clay, as well as (c) an intact and (d) a remoulded sample of Lödöse clay with normalised colour using SPAM.

Overall, from a particle and pore size point of view, the higher sensitivity of Lödöse clay might be attributed to smaller silt grains and less macroporosity in the clay matrix. Yet, changes in the fabric between the intact and remoulded samples cannot be easily observed. In contrast, there is a noticeable difference between remoulded and intact samples for Kärra clay, which has the lowest sensitivity, especially in macroporosity. Therefore, comparing 2D slices might not be adequate for understanding the difference between the behaviour of intact and remoulded samples of highly sensitive clays. Furthermore, the composition and morphology will not provide sufficient data to support the origin of sensitivity in quick clays without additional data on interparticle interactions.

4. Conclusion

Four representative slices from reconstructed nanotomography scans on intact and remoulded natural sensitive Swedish clay are compared to understand the link between the nano-scale morphological features and the macroscopic behaviour of intact and remoulded samples. The results show that both the intact and the remoulded samples present silt grains embedded in a clay matrix, and both clays contain kaolinite, which can be seen as a brighter fabric in the slices. However, the grain sizes of the silt and macroporosity are smaller for Lödöse clay. This can be one of the reasons why Lödöse clay is more sensitive than Kärra clay. After remoulding, the macroporosity for Kärra clay reduces by about 32%. A 3D study that is ongoing will reveal more quantitative data on the link between the macro and micro behaviour of highly sensitive clays since the slices for intact and remoulded Lödöse clay do not appear to show much difference.

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