ON THE LIQUID LIMIT OF SENSITIVE CLAY

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KEYWORDS

Quick clay, Kaolinite, Clay properties, Liquid limit, NaCl

ABSTRACT

Quick clays are ubiquitous materials in Sweden, Norway, and Canada. When disturbed, these sensitive clays transform into a liquid, losing all its strength, and cause natural disasters. Both mineralogy and salinity have a major impact on quick clay behaviour. Liquid limit is one of the determining properties for quick clays since the water content in this type of clay is usually higher than the liquid limit. In this study, two different types of commercial kaolinites, and natural Kärra clay were utilised to determine how mineralogy affects the liquid limit. In addition, a 1M NaCl solution was added to the clays to understand the impact of salinity on the liquid limit. The results showed that although the liquid limit for Kärra clay increases with an increase in salinity, adding NaCl solution to kaolinite causes a drop in the liquid limit. Therefore, kaolinite cannot be the determining mineral for the emerging liquid limit of sensitive clay.

1. INTRODUCTION

In Sweden, Norway, and Canada nearly all shallow landslides have taken place in regions with quick clay [1], such as Stenungsund landslide in September 2023. Quick clays are sensitive fine-grained sediments that can permanently transform into a liquid upon anthropogenic and environmental loading [2]. In Sweden, clay that has a sensitivity of 50 or above and a fully remoulded shear strength of less than 0.4 kPa is referred to as quick clay [3, 4]. These clays are found in regions that were originally covered by glaciers such as Canada, Alaska, Scandinavia, and northern Russia [3, 5].

The mechanisms in quick clay that govern the sudden liquefaction are mainly unknown. However, a number of factors have been reported to affect the sensitivity of clays, such as mineralogical composition, particle size distribution, concentration of salt in the pore fluid (marine sediments), pH of the pore fluid, and organic content [6].

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The concentration of electrolytes in the water, as well as the type and amount of fine minerals, have a significant impact on clay properties such as liquid limit (LL). In quick clays, the amount of water content is usually much higher than the liquid limit [6]. Extensive research has been conducted to determine the effect of pore water salinity on the liquid limit of different clays. It has been shown that adding NaCl to illite-rich marine clay causes an increase in the amount of the LL [6]. Song et al. [7] studied the impact of NaCl on two different types of illite-rich coastal clay and concluded that the LL increases with an increase in the salinity of pore water. Palomino & Santamarina [8] demonstrated that the LL of Wilklay RP-2 kaolin decreases as NaCl concentration increases. Sridharan and Prakash [9] concluded that adding a 0.5M NaCl solution to Kundra clay (kaolinitic clay) causes a decrease in the LL. However, Di Maio et al. [10] stated that adding NaCl up to 6M has no significant impact on the LL of kaolin clay.

The studies referenced show that pore fluid chemistry has a profoundly different effect on the LL of clay depending on clay mineralogy. Quick clay, however, has a diverse mineralogical composition that have been reported to affect its sensitivity [11]. According to Cabrera and Smalley [12], high sensitivity develops when non-expanding inactive clay-sized particles of quartz and feldspar are present. On the contrary, the presence of high-swelling minerals such as smectite decreases the sensitivity of clay [13].

The influence of salinity on a mixture of different minerals has not been studied extensively. In this study, two different monogranular monomineral industrial kaolin clays, as well as natural quick clay, composed of multiple minerals, were analysed to better understand how salinity affects the liquid limit of sensitive clays. The macroscale tests included a series of fall cone test at different ionic strength. Following the idea of Cabrera and Smalley [12], the intent is to understand if the inactive kaolinite fraction could be the determining mineral for this sensitive clay behaviour.

2. MATERIALS AND METHODS

Soil samples

Natural clay samples were collected from the Chalmers soft soil test site in Kärra municipality (Gothenburg, Sweden) from a depth of 4.5 to 5.5 m. The natural water content for this clay was 80%. X-ray diffraction analysis was also conducted in ALS Scandinavia AB laboratory to determine the minerals in this natural clay. The result of XRD analysis is demonstrated in table 1. Moreover, Speswhite kaolin clay (produced by IMERYS France), and Acros Organics kaolin clay were tested. The average particle size for Speswhite is 1.3 μm and the particle size for Acros Organics is 1.8 μm. Therefore, the main difference between the two kaolinite clays is the particle charge, which is controlled by the particle size. The specific gravity (G_s) of both kaolin is 2.6 [14, 15].

Table 1. XRD results for natural Kärra clay.

Mineral	Result (%)
Quartz	51.3 ± 1.5
Albite	10.8 ± 1.0
Microcline	8.3 ± 1.0
Cordierite	0.2
Calcite	17.3 ± 1.0
Halit	1.8 ± 0.5
illite	6.4 ± 1.0
Kaolinite	3.9 ± 0.5

Salts

To determine the effect of salinity on the liquid limit, sodium chloride (NaCl) was used in this study. The salt was purchased from Sigma-Aldrich USA with a purity of ≥ 99.0%.

Method

Natural Kärra clay samples were dried, ground, and sieved. Soil passing through a 500 µm sieve was then used to determine the liquid limit using the fall cone method (BS 1377-2, [16]). Demineralised water was added gradually to the sieved soil so the average depth of cone penetration in the sample was in the range of 15 to 25 mm. After each penetration in this range, a small amount of the sample was dried for 24 hours at 110 ºC, and the water content was calculated. At least four samples with different water content were considered for the determination of the LL.

In the next step, Kärra clay was washed until the electrical conductivity reached below 100 µS to ascertain that there was negligible amount of ions left in the pore fluid [8]. Both kaolin clays did not need to be washed since the original electrical conductivity was found to be negligible (<40 µS). The whole procedure was repeated with the washed Kärra clay, and the liquid limit was measured. Then, the impact of salt on the LL of each clay was investigated. To do so, the 1M salt solution, instead of demineralised water, was added gradually to the washed Kärra clay, Speswhite, and Acros Organics.

3. RESULTS AND DISCUSSION

The results of the fall cone test for each type of clay, as well as the liquid limit, are illustrated in Figure 1. A linear regression was used to determine the liquid limit.

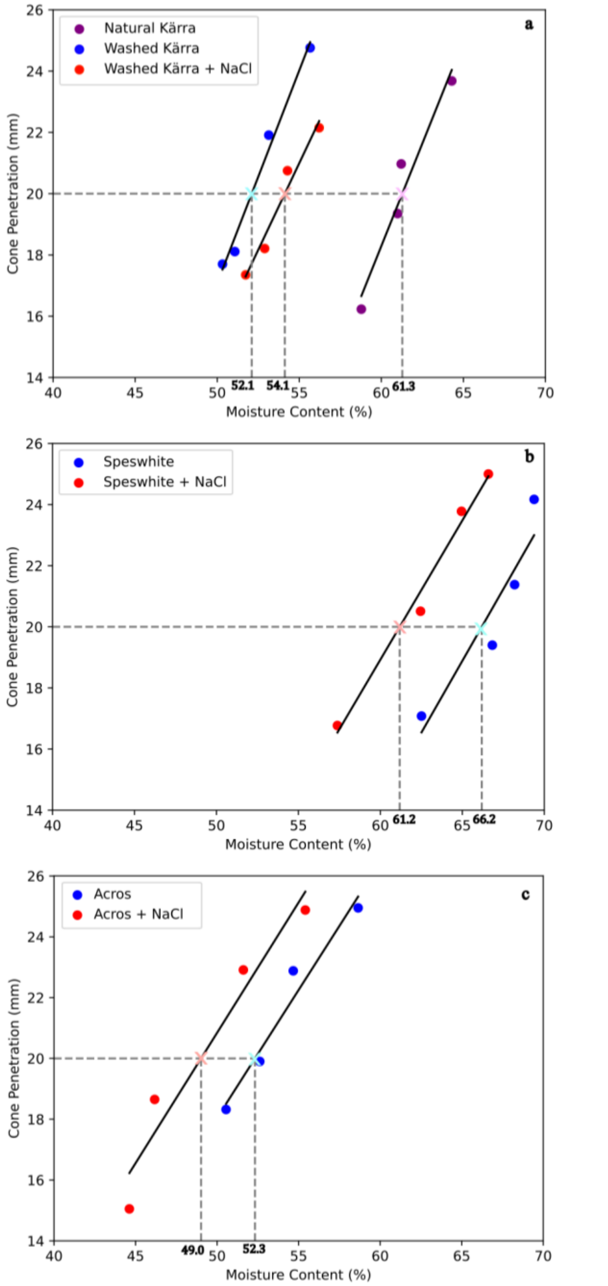

Figure 1. Cone penetration test results, and the liquid limit based on British standards for a) Kärra clay, b) Speswhite kaolinite, and c) Acros kaolinite.

Following the definition of British Standards, the liquid limit is equal to the water content when the cone penetration is 20 mm. The slope of the linear regression for cone penetration vs. moisture content can indicate the sensitivity of clay to pore fluid. A steeper slope shows higher sensitivity to the salinity of the pore fluid [8]. As can be seen, Kärra clay, which is a quick clay, was more sensitive to salinity than both kaolinites. Speswhite kaolinite, also, had the highest LL at 66.2% while Acros kaolinite had the lowest at 52.3%.

Figure 1a demonstrates the liquid limit for three different conditions of Kärra clay. The liquid limit was higher (61.2%) in the natural condition and was reduced substantially when there was a negligible amount of ions in the pore fluid. After adding 1M NaCl solution to the washed clay, the liquid limit increased by 2% reaching 54.1%, which was still less than the liquid limit in the natural condition. The reduction in the liquid limit with salt leaching was reported in a few studies [6, 17]. This phenomenon, however, contradicts the diffuse double layer theory. Based on this theory, higher ion concentrations in the pore fluid reduces the thickness of the double layer, hence, the interparticle distance. Therefore, the capacity for holding water is reduced with higher salinity, resulting in a decrease in the liquid limit. The change in LL of sensitive clay at higher ion concentrations, however, can be attributed to changes in the soil fabric.

The liquid limits of Speswhite and Acros kaolinite are shown in Figure 1b and 1c respectively. After the addition of 1M NaCl solution, the liquid limit for Speswhite decreased by 5% while for Acros this reduction was approximately 3%. This is aligned with the result of Palomino & Santamarina [8] for Wilklay kaolinite. In contrast to the Kärra clay, the behaviour of both commercial kaolinites can be explained by the diffuse double layer theory. In other words, the reduction in the diffuse double layer thickness causes a decrease in interparticle repulsive forces, resulting in a smaller interparticle distance. Therefore, the liquid limit decreases at higher ion concentrations in the pore fluid.

Overall, the behaviour in terms of LL for Kärra clay contrasts with that of both kaolinites. While with an increase in salinity, the liquid limit increases for Kärra clay, it decreases for both kaolinites. Therefore, kaolinite does not seem to impact the LL of Kärra clay.

4. CONCLUSION

The liquid limits of a natural sensitive clay from Kärra, Speswhite kaolin clay, and Acros kaolin clay were determined in natural and saline environments to investigate the effect of salinity on clay behaviour. The main results are summarised below:

- The sensitivity to the ionic strength of the pore fluid for Kärra clay was higher than for Speswhite and Acros.

- An increase in salinity caused an increase in the liquid limit of Kärra clay while Speswhite and Acros kaolinite experienced a reduction in the liquid limit after a 1M NaCl solution was added.
- The change in LL of Kärra clay cannot be explained by the diffuse double layer theory but can be attributed to the change in soil fabric.
- Although the liquid limit of Speswhite is higher than Acros, the behaviour of both kaolinites agrees with the diffuse double layer theory.
- Kaolinite does not seem to impact the liquid limit of Kärra clay.

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