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Electrically induced deformations of a bentonite slurry

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Abstract. Dewatering of soft clayey soils through Electrokinetic Treatment (EKT) is explored in several engineering applications. Hydrodynamic consolidation, a hydro-mechanical coupled mechanism, is now a electro-hydro-mechanical one, in which the total flow of fluid extracted is due to the superimposition of hydraulic and electrical gradients. Oedometer tests were performed in modified cells to study the effects of electrical current on deformations, measured for different vertical stresses. Instantaneous volume changes caused by electrical current were investigated on samples of consolidated slurries of bentonite, and during 3 cycles of EKT. In all cases constant electrical potential was applied after more than 90% of settlement had occurred, to distinguish electrical from mechanical effects. The same stress paths were applied in tests performed without electrical potential, for comparison. It was observed that the sign of vertical deformations occurring during the application of EKT depended on the confinement stress and soil initial state (swelling observed for stresses below yielding stress and settlements for stresses above this value). The deformations tended to stabilize after the application of EKT. In addition, secondary consolidation settlements have increased under the application of electrical current stresses, suggesting that electrokinetic flow is associated to microstructural water flow. The double layer repulsion theory was used to analyse the changes in deformation in the soil. This simplified analysis allowed to find interesting conclusions which contribute to understand the electro-hydro-mechanical phenomena occurring in bentonite during EKT.

1 Introduction

Dewatering of soft clayey soils through the application of electrical potential during Electrokinetic Treatment (EKT) is explored in several engineering applications, for example to improve mechanical properties [1,2] or reduce slurry volume for storage [3]. Hydrodynamic consolidation, a hydro-mechanical coupled mechanism, is now a electro-hydro-mechanical one, in which the total flow of fluid extracted is due to the superimposition of hydraulic and electrical gradients.

For electroosmotic consolidation under constant voltage gradient dV/dx, water flow per unit area q can be described by Equation (1) [4].

$$q = -\frac{k_h}{\gamma_w}\frac{\partial u}{\partial x} - k_e\frac{\partial V}{\partial x} \qquad (1)$$

In this equation u is pore water pressure generated by electrical current, γ_w is water volumetric weight, k_h is the saturated permeability measured applying differences in water potential, k_e is the coefficient of electroosmotic permeability measured applying only voltage gradients, and V is voltage.

Changes in pore water pressure correspond to changes on effective stress, and for this reason deformations occur due to the application of electrical current. In this paper volume changes caused by electrical current were investigated on samples of consolidated slurries of bentonite. Oedometer tests were performed in modified cells to study the effects of electrical current on deformations, measured for different constant vertical stresses. Constant electrical potential was applied after more than 90% of settlement had occurred, to distinguish electrical from mechanical effects. The same stress paths were applied in tests performed without electrical potential, for comparison.

2 Materials and methods

2.1 Material properties and sample preparation

The samples tested were prepared with consolidated slurry of bentonite. Sodium bentonite supplied in powder was used, with particle diameters below 1 µm and particle volumetric weight 27.4 kN/m^3. Specific surface area is 800 m^2/g and cation exchange capacity is 76 meq/100 g [5]. The main minerals present are montmorilonite, quartz and microline. The material classifies as highly plastic clay (CH) according with the Unified Soil Classification System (liquid limit 300% and plasticity index 249%).

Slurry samples were prepared with water content equal to 1.5 times the liquid limit [6]. After mixing the powder with distilled water, the material was kept undisturbed for one day in controlled environment to attain homogeneous conditions, and then poured into a

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cylinder tube allowing double drainage for one-dimensional pre-consolidation. Loading was applied in stages up to 18 kPa to consolidate the material, aiming at enhancing its workability. The consolidated slurry soil was then extracted from the tubes for the tests using oedometer rings with 50 mm diameter and 20 mm height. Rings were extracted so that particles bedding caused by consolidation would be horizontal (perpendicular to electrical current). After the sample extraction from the consolidation tubes, the void ratio was around 9.9±0.2.

2.2 Equipment

Oedometer tests were performed in modified cells to investigate the effects of electrical current on secondary deformations. Constant electrical voltage was applied only during the secondary consolidation phase, to isolate its effects from those due to primary consolidation. The experimental setup, shown in Figure 1, comprises a modified oedometer cell and mechanical loading system, and one LVDT for measuring vertical displacements (sensitivity 0.001 mm).

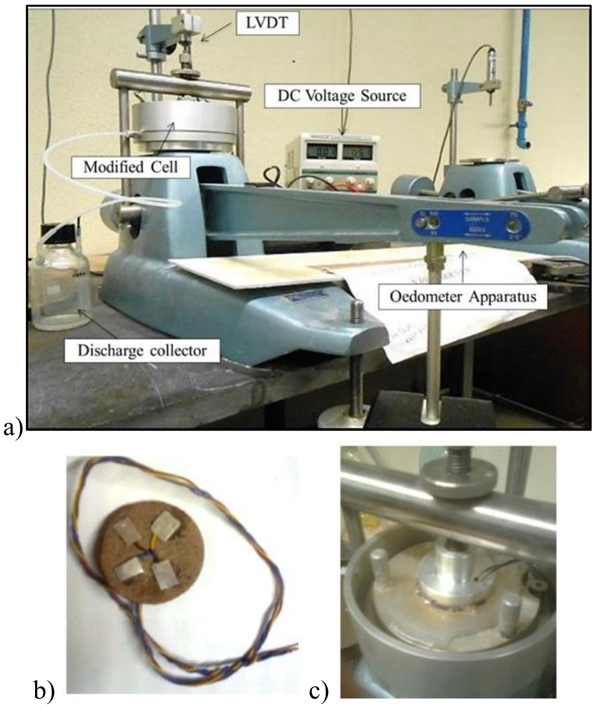

Fig. 1. Electrokinetic test apparatus: a) overall view; b) electrodes; c) adapted cell.

The anode and cathode were at the bottom and top of the sample, respectively. Silver plate electrodes were used (area 0.0004 m^2, Fig 1b) and placed in direct contact with the soil. A DC voltage/current source 280W (0-35 V and 0-4 A) Aim-TTi EX354RD Bench Power Supply, was used. Inlet and outlet of the water was allowed, providing access to the electrical wires for the electrodes (Fig 1c).

2.3 Testing protocols

The tests were performed in identical samples tested with or without electrical current (respectively EK and control tests). Settlements were measured by applying DC Voltage (value depending on the test) at least 24 h after mechanical loading, to avoid overlapping with the primary consolidation phase. At least 90% of settlement had occurred before applying this voltage. The stage where voltage was applied is called EKT in this paper.

Two different studies were performed, as illustrated schematically in Figure 2. The instantaneous response of the soil to electrical current for different vertical stresses was measured in the first study. Loading was applied according to ASTM-D2435. The test was carried for the vertical stresses 25, 50, 100, 200, 400, 800 kPa and then unloaded. 24 hours after mechanical loading, a constant voltage of 5V was applied for 2 h (7200 seconds) (Fig 2a). The compressibility curves of the tests with and without EKT were also determined.

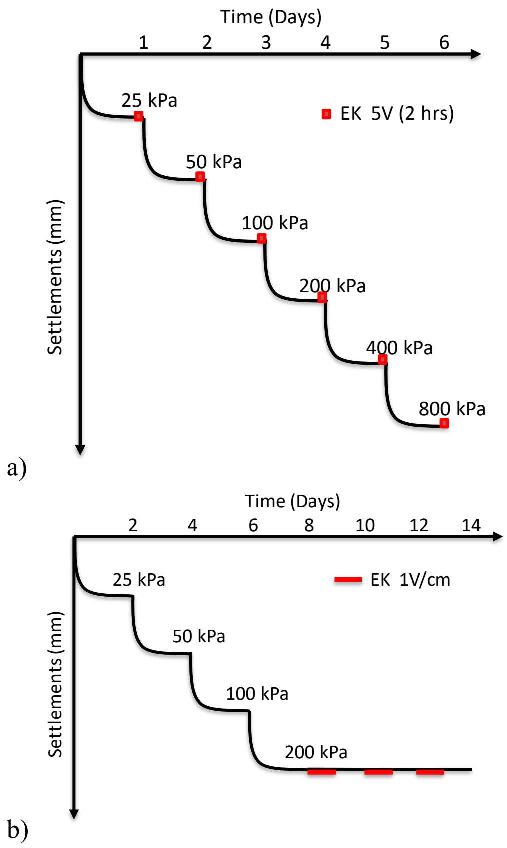

Fig. 2. Loading paths adopted: a) Instantaneous response to electrical current for different vertical stresses; b) Long term response under 3 EKT cycles applied under 200kPa.

Soil response under EKT cycles was quantified in Study 2, in which the cycles were applied in independent samples and for different vertical stresses. The tests were performed for the vertical stresses of 50, 100, 200 and 400 kPa. As illustrated in Figure 2b) for 200 kPa, the samples were loaded as usual until the target vertical stress (each loading stage with 48 h duration). A total time of 48 h was given for the final loading and then 3 EKT cycles were applied, each with 24 h duration. In each cycle the voltage of 2 V was applied in On-Off intermittence (24h on- 24h off- 24h on, 3 days). In total, for each vertical stress, the bentonite was tested for 6 days during the secondary phase, with 3 alternate days of EKT.

3 Results

3.1 Compressibility curves

The compressibility curves for the control and EK tests are presented in Figure 3. Although the curves shapes is not smooth, yielding closer to vertical stress of 25 kPa can be identified in the two tests; this value is closer to the stress applied to consolidate the slurry during sample preparation. The compressibility and swelling indices (C_c and C_s, respectively) are in Table 1. Both C_c and C_s found in the EK test were smaller than those found in the control test. Apparently, irreversible microstructural changes have occurred caused by electrical current because the elastic compressibility measured at unloading for the EK test was different from that of the control test.

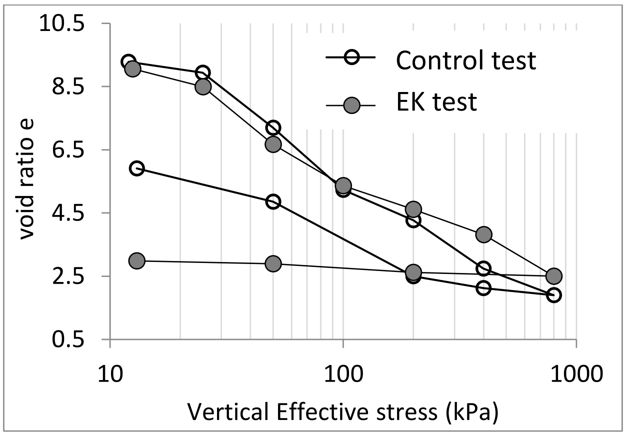

Fig. 3. Compressibility curves.

Table 1. Compressibility indexes.

Test	Cc	Cs
Control sample	4.35	2.52
EK sample	3.29	0.29

3.2 Instantaneous response

The strain and current profiles for each vertical stress are presented in Figure 4. Vertical deformations (named as strains for simplification) were calculated considering the height of the sample during that respective vertical stress. Positive values correspond to compression.

The electroosmotic deformations are related to the current profile because they occur when current is changing. While current was applied, electroosmotic swelling was observed for the lowest stresses (25 kPa and 50 kPa). No relevant swelling or consolidation were observed for the intermediate stresses of 100 kPa and 200 kPa. Electroosmotic consolidation has occurred for the highest stresses of 400 kPa and 800 kPa. Consolidation was observed when the current was turned off, becoming stable at the end of the measurement period. For the lowest stress of 25 kPa, which is closer to the yielding stress measured, the swelling deformations were fully recovered when current was turned off, and no more consolidation occurred after that.

Considering current evolution, for low stresses when the soil undergoes swelling, the current profile is almost linear throughout the period of EKT. For intermediate stress, a non-linear current profile is observed where less or no electroosmotic swelling occurred. Initially the current is high, then within few minutes it starts decreasing, and then it stabilizes to a constant value. For higher stresses, a typical bi-linear current profile is observed, where there is a sudden drop in the current followed by a constant value. Here no swelling was observed. Moreover, the current stabilized around 20 to 30 mA for all vertical stresses. Such value must be related to the cation exchange capacity of the clay, CEC, but this topic is not going to be explored here. Similar current profiles are generally observed in fine grained soil during EKT by others [7-8].

3.3 Long term response under 3 cycles

The vertical deformations observed along time for the control and EK tests are presented in Figure 5 for the vertical stresses of 50 and 400 kPa. The period where the voltage was applied is highlighted and denoted by the term EKT in the plots. Both electroosmotic swelling and consolidation deformations are identified with arrows in this figure.

The settlements observed in the control tests, under all stresses, were those expected in the secondary consolidation phase. For all stresses, this deformation has increased under the effect of electrical current, increasing with the number of cycles of EKT.

For the EK tests under the low stress of 50 kPa, the soil showed electroosmotic swelling in the initial period of the EKT cycle followed by compression at a rate higher than that observed in identical tests performed on the control samples. On the removal of the electrical gradient a small swelling was observed followed by stabilization, suggesting some recover from the electroosmotic consolidation deformations. Although the alternating swelling and consolidation deformations occurring during the period of EKT, irreversible further consolidation settlements were observed when compared with the control test.

For the highest stresses (100, 200, and the presented 400 kPa), the behaviour slightly changed along the three cycles. No initial electroosmotic swelling was observed in the beginning of the first EKT cycle, but always electroosmotic consolidation. Some small electroosmotic swelling was observed at the beginning of the second and third cycles, however. On the removal of the electrical gradient, for all cycles, consolidation has continued at an initial high rate, but soon the rate was almost identical to the one observed in the control test. The electroosmotic consolidation observed reduced over the EKT cycles. As observed for 50 kPa, irreversible final consolidation deformation was observed when compared with the control test.

For all the stresses, the behaviour observed in the first EKT cycle was like that observed when investigating the instantaneous response. The small differences on behaviour observed in the second and third EKT cycles will be discussed next.

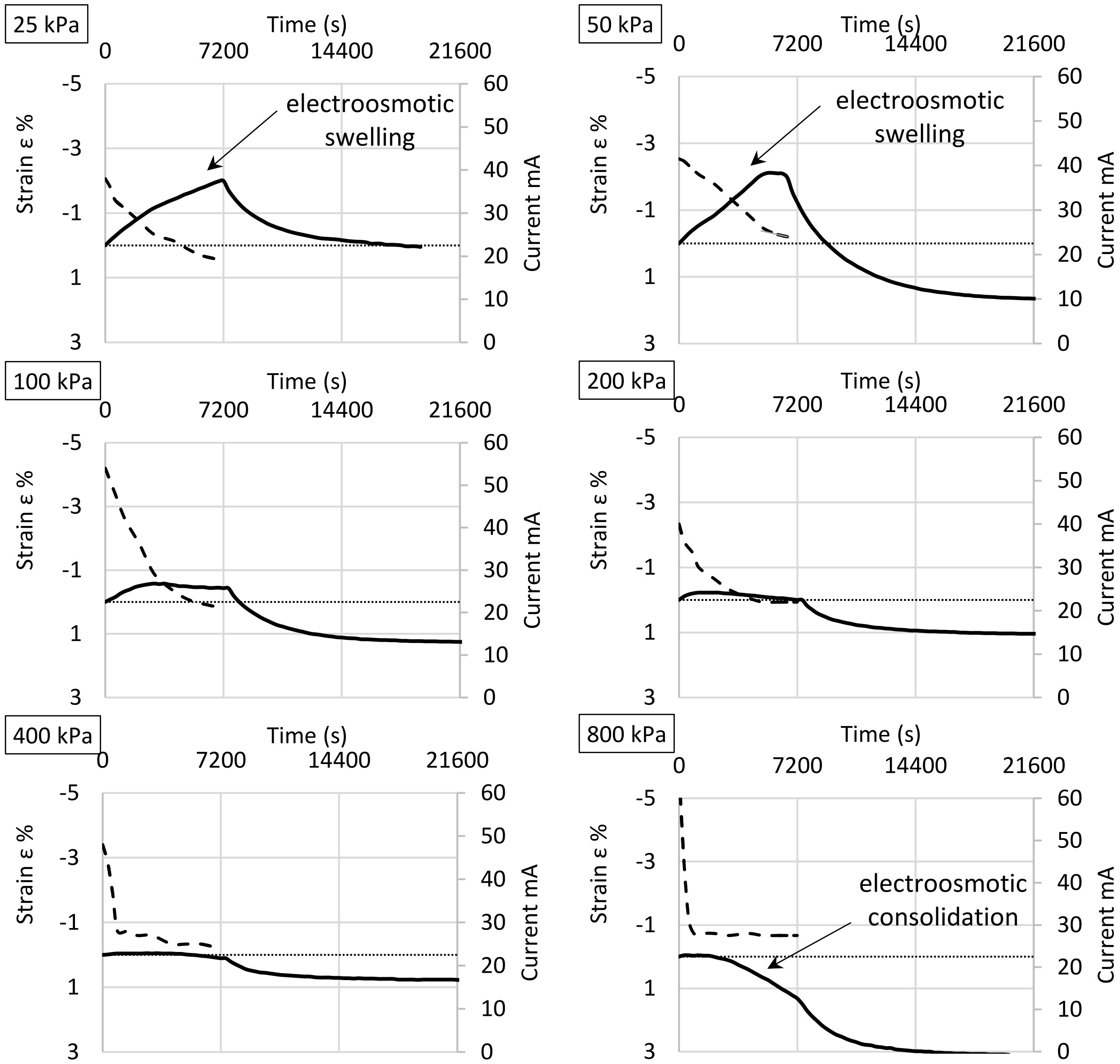

Fig. 4. Vertical deformations (strain) and current measured during EK tests for each vertical stress. Full lines are vertical deformation and dashed lines are electrical current.

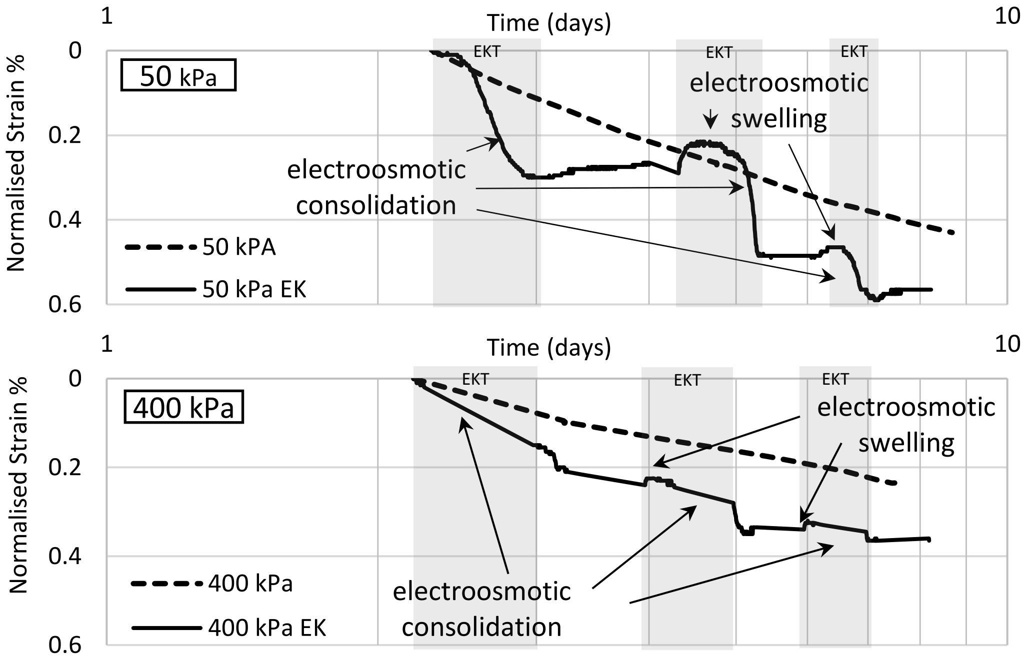

Fig. 5. Strains during the control and EK tests on bentonite.

4 Discussion

Both bulk water and water adsorbed in clay minerals are mobilized by electrical potential. When comparing the hydraulically and the electrically driven water flows, the main difference is that water and ions adsorbed to the clay minerals and in the double layer can be mobilized by electrical current. This can be considered microstructural water.

The exchangeable positively charged ions tend to migrate towards the cathode, thus dragging the adsorbed water from the clay surface along with it (pore water pressure generated given by Eq. 1). The proportion of adsorbed water and ions depends on the specific surface, chemical forces and electrostatic forces on the clay mineral. Bentonite clay was chosen for this study to enhance this effect.

Forces like double layer repulsion and van der Waals attraction hold the clay particles in various fabric formations and electrochemical equilibrium is established for each microstructural configuration. External stress change microstructure through porosity changes, therefore changing the proximity of the clay aggregates and the number of bridges between the clay minerals through which electrical current can flow [9-11]. New particle configuration resulting from these microstructural changes is a new electrochemical equilibrium, and for this reason electroosmotic deformations are stress dependent.

Considering double layer repulsion, electrons flowing increase particles repulsion between themselves and instantaneous electroosmotic swelling occurs. This swelling corresponds to an elastic, recoverable, deformation [9]. Such swelling was observed when EKT was applied under low vertical stress, and in the beginning of each EKT cycle applied under small vertical stress.

Being electrical current applied after primary consolidation, stress effect on soil structure has already occurred. Further particle movements are driven by electrical forces, necessary to reach a new electrochemical equilibrium. These movements are restrained by vertical stress. If the soil is at an over consolidated state (external stress is below yielding stress) microstructural configuration is stable, and therefore electroosmotic deformations are reversible. This is an elastic behaviour and indicates that particles displacements caused by electrical current are small and do not cause microstructural changes.

If the soil is at a normally consolidated state (vertical stress applied in that loading stage has caused plastic deformations), the microstructure is at metastable state and further particle movements driven by electrical forces may cause structural collapse. This corresponds to irreversible electroosmotic consolidation deformations and new electrochemical equilibrium is attained, as well a more stable microstructure. This was observed when EKT was applied under medium-high vertical stresses, and also in the first EKT cycle. Further cycles will mobilize the particles and cause new relative movements between them, creating microstructural configurations with increasing stability (because the become denser or over consolidated).

Finally, because the adsorbed water from the clay surface is mobilized in the deformation process and its moving velocity is extremely low (very small electroosmotic conductivity k_e), further settlement continues when EKT is turned off. This can be seen as a a secondary consolidation mechanism occurring at the microstutural level, as suggested by Navarro and Alonso [12] to explain creep deformations in clayey soils, and by Gingine and Cardoso [13], to explain the increment on secondary deformations in the presence of electrical current. This is equivalent to the dissipation of the excess of the pore pressure generated by electrical potential at the microstructural level, quantified by Eq. 1 previously presented.

5 Conclusions

Instantaneous volume changes caused by electrical current for different constant vertical stresses were investigated on samples of consolidated slurries of bentonite, and during 3 cycles of EKT. In all cases constant electrical potential was applied after more than 90% of settlement had occurred, to distinguish electrical from mechanical effects. The sign of vertical deformations occurring during the application of EKT depended on the confinement stress. Electroosmotic swelling was observed for the lower stresses, below yielding stress, and electroosmotic consolidation for higher stresses, above yielding stress.

Instantaneous electroosmotic swelling was assumed to occur once EKT is applied, considering double layer repulsion caused by electrons flowing in the adsorbed water at particles surface. Thus, particle movements driven by electrical forces were necessary to reach a new electrochemical equilibrium. The effects of these movements on initial particles arrangement, or microstructure, can result in volume increase (electroosmotic swelling) or decrease (electroosmotic consolidation). Swelling corresponds to elastic behavior, occurring for stable microstructural configurations, while consolidation cand be seen as microstructural collapse, occurring for unstable microstructural configurations. A mechanism was proposed to explain the behaviours observed:

- When the soil is overconsolidated (under low confinement stresses, below yielding stress of 50 kPa in this paper) the microstructure is stable. The stable particle arrangement is not affected when particles move due to electrically driven repulsion forces, and electroosmotic swelling deformations are observed. They are reversible once electrical current is turned off.
- When the soil is normally consolidated (confinement stress above yielding stress, for all other stresses investigated in this paper) the microstructure is metastable and particles movements caused by electrically driven repulsion forces cause structural collapse. This corresponds to the electrosmotic consolidation deformations observed. These deformations are irreversible.

Although these are electroosmotic deformations, they continue progressing after turning off the electrical current. This can be interpreted to the dissipation of microstructural pore water pressure generated by the electrical forces, as a hydrodynamic consolidation problem, but now at the level of the microstructure.

This simplified analysis contributes to a better understanding of the electro-hydro-mechanical coupled behaviour of the bentonite or other highly swelling clays during EKT. Further studies are necessary to confirm microstuctural changes caused by EKT.

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