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Changes in the properties of clay soil in drained and undrained conditions under the influence of cathodic protection currents

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Abstract. This work examines the influence of cathodic protection currents on the properties of clay soil under drained and undrained conditions. The study was carried out using an experimental setup simulating cathodic protection. At the end of the experiment, soils with an undisturbed structure near the cathode were studied, where changes in the physical properties, particle size distribution and pH of polarized clay soil samples were revealed.

1 Introduction

Today, the corrosion process that occurs in underground metal structures is the main cause of emergency situations. To reduce the rate of corrosion of metal structures in dispersed soil, electrochemical protection is usually used. The most commonly used method is cathodic protection, the essence of which is to suppress corrosion by creating an artificial electrochemical circuit and shifting the potential of a metal structure to the negative side, where the metal structure acts as the cathode, and the anode is the anode ground electrode. Despite the good study of the influence of currents on clay soil [1-4], the organization of active anti-corrosion measures does not take into account the occurrence of electrokinetic and accompanying processes, which inevitably lead to electrical transformation of the soil. In the absence of proper attention to changes in soil properties under the influence of cathodic protection currents, technogenically altered soil is formed in the near-cathode space, the corrosiveness of which may be different from that of the original environment. The most visible changes in soil properties occur due to the electroosmotic process, as a result of which moisture begins to migrate from the anode to the cathode. Depending on engineering and geological conditions, the entire volume of electroosmotic filtrate can either accumulate near the pipeline, or be partially carried out beyond the near-cathode space. Taking this into account, changes in the properties of the same soil under the influence of cathodic protection currents can be different. Thus, the purpose of this study is a comparative analysis of changes in the properties of clayey soil under the influence of

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cathodic protection currents, taking into account their drained and undrained soil conditions.

2 Materials and methods

To carry out the study, a laboratory installation was assembled that simulated the operation of cathodic protection. A monolith of Cambrian clay was used as a space to accommodate the pipeline and anode ground electrode.

The selection of Cambrian clay monoliths of undisturbed composition was carried out on the banks of the river. Tosny. Visually, the consistency of the clay was soft and plastic. The monoliths, in general, had a homogeneous structure. After sampling, the soil was wrapped in stretch film to preserve natural moisture and sent to the soil science laboratory of St. Petersburg State University for further research.

Subsequently, two studies were carried out, during which the operation of cathodic protection was simulated. For this task, experimental installations were assembled, which consisted of the following elements:

- Monolith of clay soil.
- Electrodes.
- DC power supply (laboratory power supply QJ6005E).
- Connecting lines (copper wires).

The cathodic protection station was modeled by a laboratory power supply, the pipeline was one of the electrodes (-); the second electrode was essentially anode grounding (+).

The main difference between the two experiments was that the first study used an open-type setup, and the second one used a closed-type setup. The open-type installation is designed so that moisture migrating towards the cathode as a result of the electroosmotic process is removed from the anode-soil-cathode system (Figure 1). To remove the electroosmotic filtrate, the monolith was installed on a plastic tray with drainage. The size of the monolith for this physical modeling scheme was reduced to a shape close to a parallelepiped (40x25x25 cm).

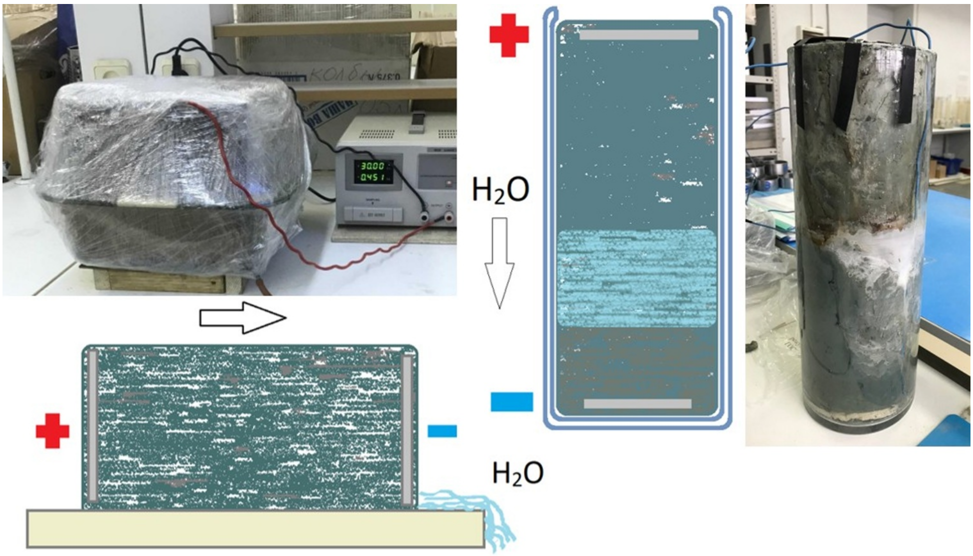

Fig. 1. Installation of open (left) and closed types (right).

In a closed system, using a glass cylinder, conditions were created under which electroosmotic water accumulated in the near-cathode space. The monolith for this part of the study was processed according to the dimensions of the cylinder (diameter 13 cm; height 30 cm).

The duration of the experiments averaged 50 days. The samples were polarized continuously. The output voltage was at 20 V. The current density from the beginning to the end of the experiment varied from 5000 mA/m^2 to 1523 mA/m^2.

Such experimental conditions were necessary due to the laboratory method of work. In conditions of limited laboratory research, it was necessary to select values at which a visible result could be obtained in a short time. In addition, these values were chosen to simulate the “overprotection effect” of the pipeline. It is known that half of the failures due to external corrosion are associated with the “overprotection effect” caused by a strong shift in the potential of the protected structure in the negative direction [5]. When “overprotecting” the pipeline, high current densities are observed, as a result of which it is possible to intensify electrokinetic processes that lead to a transformation of the soil structure.

After the experiments, the physical properties, pH and particle size distribution of the experimental (at the cathode) and initial samples were determined.

3 Results and Discussion

At the end of both the first and second experiments, the formation of macro-layering of the monoliths was revealed (Figure 2). Thus, upon visual examination of a sample from an open-type installation, it was noted that the upper part, located at the anode, became dry and hard, while the lower part had a similar consistency to the natural sample. White streaks were observed throughout the entire area of the near-cathode space (Figure 2).

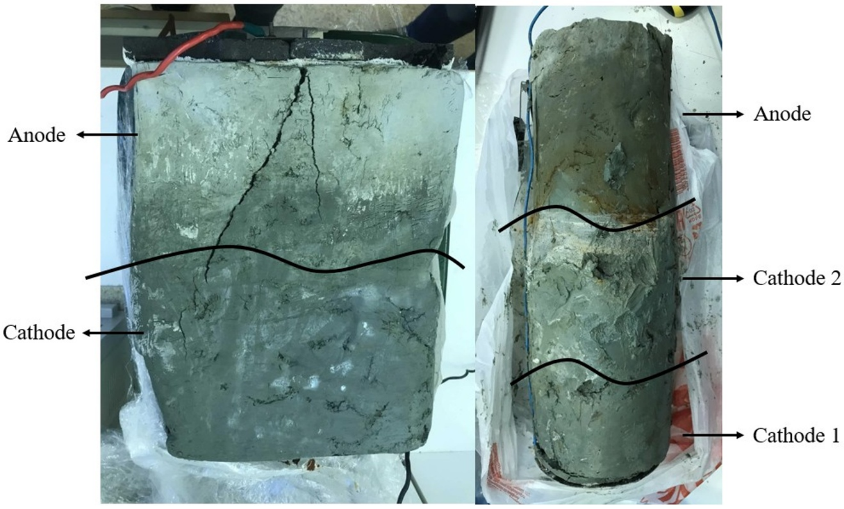

Fig. 2. Monolith of Cambrian clay after polarization. On the left is a sample from an open type installation, on the right - a closed type.

In the sample from a closed-type installation, three layers were distinguished. The first layer was located at the anode and occupied almost ½ of the entire monolith. This part of the sample was dry and had a hard consistency. Cracks and ferrous stains were observed throughout the anode layer. The second layer (cathode 2) was the most wet, sticky and plastic. The third layer (cathode 1), located directly at the cathode, had a loose structure and was less moist than the layer above (Figure 2). An unevenly distributed white deposit was observed on the surface of cathode 1 and cathode 2. In addition, at the contact of the electrode and cathode 1, according to the X-ray phase analysis, a large concentration of precipitated calcium hydroxide and other compounds was detected (Figure 3). Further studies were carried out only for the near-cathode part of the samples.

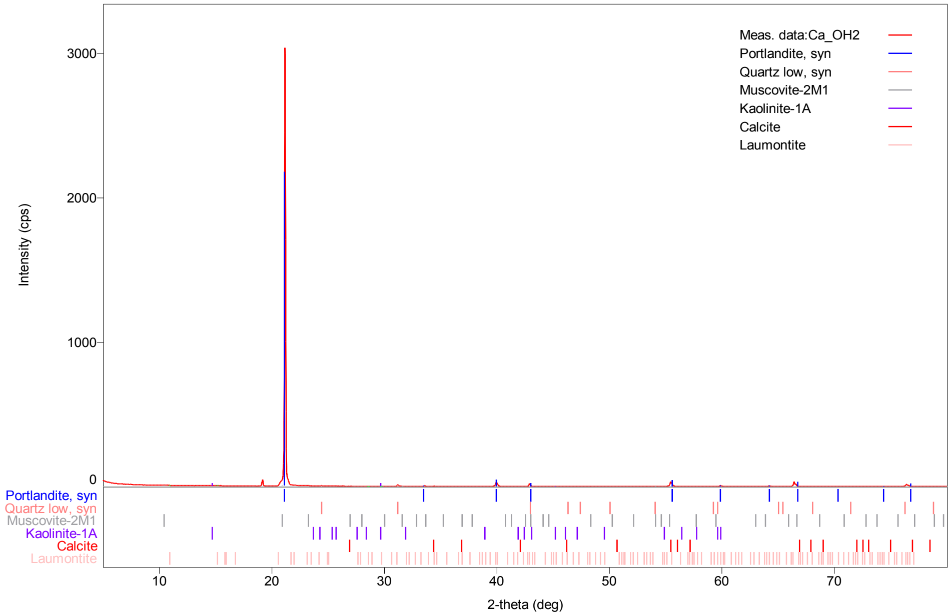

Fig. 3. Results of X-ray phase analysis.

Differences in the formation of layers are primarily associated with the peculiarities of moisture drainage in experimental installations. According to literature data, when a current is applied to the soil under undrained conditions, excess pore pressure occurs in the installation, as a result of which electrokinetic processes occur more intensely [6].

After visual inspection, the soil was divided into layers to determine the particle size distribution, physical properties and pH. Table 1 presents the results of the granulometric composition of the original and experimental samples (Table 1).

Table 1. Granulometric composition.

Sandy				**Dusty**		**Clayey**	**Test soil**	**Type of instalation**
Fraction size, mm								
1-0.5	**0.5-0.25**	**0.25-0.1**	**0.1-0.05**	**0.05-0.01**	**0.01-0.002**	**<0.002**		
Content of fractions in %								
0.6	0.6	0.7	2.9	25.1	26.7	43.4	Original	Open
2.9	3.0	4.4	4.1	28.7	27.7	29.2	At the cathode	
-	-	0.3	4.1	36.3	36.4	22.9	Original	Closed
0.1	0.1	0.6	6.1	27.1	29.6	36.4	Cathode 2 (Overlying Layer)	

Considering the data on the granulometric composition of the sample from the open-type installation, a number of changes can be noted. In the soil near the cathode, the content of the clay fraction decreased by 14.18% (approximately 1.5 times compared to the original sample), while the content of the sandy fraction increased by 9.58%, and the silty fraction by approximately 5%. .

After polarization of the sample in a closed-type setup, changes were also noted. Thus, compared to the original clay, the content of the clay fraction at cathodes 1 and 2 increased by 7.29% and 13.58%, respectively. There is also an increase in the size of particles belonging to the sandy fraction at cathode 1 by 11.41%, at cathode 2 by 2.41%. All observed changes in particle sizes, up or down, occurred due to a decrease in the content of the 0.005-0.002 mm fraction. Presumably, the processes that led to changes in the particle size distribution of the experimental samples are described below.

An increase in the particle size content of more than 0.05 mm in all experimental samples is associated with electrocoagulation processes. According to the literature data on the content of absorbed cations, Cambrian clays belong to Ca-clays, which indicates an insignificant thickness of the electrical double layer (DEL) of mineral particles [7]. During the operation of our experimental installations, a number of electrokinetic and electrochemical processes occurred in the soil. Thus, during the electrolysis process, the hydrogen index shifted towards a highly alkaline medium and the double electrical layer of fine particles was compressed. Thus, in places where the electrical double layer was thinned, phase contacts between particles arose [6, 8-9]. The increase in the clay fraction in samples from a closed-type installation is associated with the process of particle dispersion. These changes are not typical for the sample from the open-type installation due to the experimental conditions. It is known that Ca^{2+} cations, being reduced at the cathode, accumulate in this part and cement the soil, while Na^{2+} remains in dissolved form in the filtrate [6]. As a result of the removal of excess moisture in an open-type installation, dissolved sodium was removed, which was the reason for the absence of the particle dispersion process.

Analysis of the obtained results of the granulometric composition of samples from two experimental installations shows that in the presence of drainage, the dispersion of clay soil in the near-cathode region decreases, while under stagnant conditions it increases.

When determining the physical properties and pH, the values shown in Table 2 were obtained.

Table 2. Physical properties and pH.

Type of instalation	**Open**		**Closed**		
Characteristics	**Source soil**	**At the cathode**	**Source soil**	**Cathode 2 (Overlying Layer)**	**Cathode 1 (Layer at the cathode)**
Density (ρ, g/cm^3)	2.10	1.91	1.96	1.97	1.98
Density of solid particles (ρs, g/cm^3)	2.76	2.77	2.79	2.78	2.79
Density of dry soil (ρd, g/cm^3)	1.72	1.50	1.48	1.43	1.51
Humidity (W, %)	22	27	32	38	31
Porosity (n, %)	37.7	45.8	46.9	48.8	45.9
Lower plastic limit (Wp, %)	26	32	21	28	35
Upper plastic limit (W_L, %)	47	61	47	48	69
Plasticity number (I_p, %.)	21	29	26	20	34
Fluidity index (I_L, units)	-0.19	-0.17	0.42	0.52	-0.10
Hydrogen index (pH, units)	8	10	7	9	10

For a sample from an open-type installation, the density value decreased relative to the value obtained for the original soil, and the porosity increased by 7.1%. These changes are the result of the electrocoagulation process, as well as electroosmotic mass transfer of water, resulting in the formation of open porosity [6]. Despite the presence of drainage, the humidity in the cathode zone increased by 5%, which is also explained by electroosmosis. The original and experimental samples are solid in terms of fluidity. After the experiment, the pH value, due to electrolysis, shifted towards an alkaline environment. The plasticity number increases by 8%, which is associated with an increase in the pH of the environment, and also, possibly, with partial dissolution of the crystal lattice of the mineral particle itself and the new formation of crystalline, amorphous compounds (hydrosilicates, hydroaluminosilicates, limonite, etc.) [10-13]. There is an increase in soil porosity and moisture, which increases corrosive aggressiveness towards metal structures.

A number of changes were also identified for samples from a closed-type installation. Compared to the original sample, the humidity at cathode 2 increased by 6.04%, and at cathode 1 it underwent a slight decrease. The increase in humidity at cathode 2 is associated with water migration caused by electroosmosis. The decrease in humidity at cathode 1, as well as its loosening, may be associated with electrolysis [6]. The increase in porosity at cathode 2 is also explained by electroosmosis. Due to the migration of ground moisture, an increase in open porosity occurred. At cathode 1, the porosity decreased as a result of filling the pores with cementing material [6]. The soil density of the three samples is almost the same. On the one hand, an increase in aggregates should decompact the soil, on the other hand, an increase in dispersion leads to compaction of the samples. Most likely, the superposition of two factors kept the indicators at the level of the original sample. In addition, the density did not change due to the increase in pressure inside the closed installation [6]. Small differences in dry soil density are explained by changes in porosity. The environment of the original soil is neutral, while, like the experimental samples, it is alkaline. The results obtained for the hydrogen index of cathodes 1 and 2 are underestimated, since the determination of the parameter was not carried out immediately after the experiment, and an average sample was taken from each sample. High pH values during polarization are indicated by precipitated substances ($Ca(OH)_2$). According to the fluidity index, the original soil is classified as hard-plastic, cathode 2 - soft-plastic, cathode 1 - hard. The value of the plasticity number for cathode 2 decreased by 6% compared to the original sample, and for cathode 1 it increased by 8%. The main indicator influencing the plasticity number is the specific surface area of the soil [14-15]. The larger the specific surface area of the soil, the more plastic it is, which agrees with our data on the specific surface area for three samples.

Due to the increased pore pressure in a closed installation, the formation of two layers, the properties of which are very different, was noted in the near-cathode space. As a result of this, the formed layers will have different electrical resistivity values, which may affect the cathodic protection parameters of underground metal structures. In addition, an increase in pressure in the system leads to the dissolution of pore gases, as a result of which the concentration of salts in the electrolyte increases [6]. An increase in the concentration of salts in the electrolyte can intensify the occurrence of electrochemical corrosion of the metal.

4 Conclusion

During the study, two experiments were carried out, the installations of which simulated the operation of cathodic protection in drained and undrained conditions.

The results of the study showed that various engineering-geological conditions that promote either the accumulation of electroosmotic filtrate near the cathode-protected pipeline or its removal outside the near-cathode space contribute to the formation of technogenically altered soils characterized by different structures and properties.

After polarization of two clay soil samples, the formation of macro-layering was revealed. Thus, in an open-type installation, two layers were separated (cathode and anode regions); in the open installation there are three layers (anode region and two layers formed in the near-cathode space). This feature is related to the conditions of the experiment. In the experiment with a closed-type installation, electrokinetic phenomena occurred more intensely.

After polarization of the samples in both open and closed installations, changes in the particle size distribution, physical characteristics and pH of the clay soil were detected in the cathode zone. These changes lead to the formation of the engineering-geological element of technogenically altered soils. Thus, due to changed soil properties, the corrosive aggressiveness of the environment may increase, which must be taken into account not only when calculating corrosion protection systems, but also when assessing the engineering and geological conditions of the territory.

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