Modern approaches to water drying in the underground transport system

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Abstract. The analysis of the process of electroosmotic water depletion in soils surrounding the track structure of the underground is given. It is established that due to the fact that the structure of soils is disturbed during the construction of the underground, the electroosmotic water loss in them has its own peculiarities, therefore it is necessary to optimize the process by the criterion of specific energy inputs for mass transfer.

1. Introduction
An analysis of the process of electro-osmotic water depression in soils environing the travel structure of the underground is given. In connection with the fact that the structure of soils is disturbed during the construction of the underground, electro-osmotic depression in them has its own peculiarities; therefore it is necessary to optimize the process by the criterion of specific energy costs for mass transfer.

The underground is a popular passenger transportation system all over the world. As of 2017, the passenger turnover of Novosibirsk underground was 88.4 million people, while the average daily traffic was 251.2 thousand passengers. It is because of the high passenger turnover that the underground requires increased security requirements. Increased requirements are imposed not only on power supply systems, rolling stock, the qualifications of maintenance personnel, but also on underground tunnel structures. One of the main requirements for tunnel structures is the lifecycle. The standard lifecycle of the underground tunnel is 100 years, according to the Code of Specification 1230, 13330.

2. Problem definition
The tubing lining applied for tunnel finish could be made of a cast-iron or reinforced concrete. In the case of cast-iron lining, if the technology of construction is observed, a protective layer of concrete is applied behind the lining, which protects the structure from corrosion and from the penetration of groundwater into the tunnel. The thinning of the walls and the reduction in the strength of the structure under the influence of moisture proceed very slowly.

In the case of reinforced concrete tubing, a great deal depends on the initial quality of the concrete components in the manufacture of blocks and the endurance of the product. It is a well-known fact that concrete is gaining strength with time. It is also known that in aggressive environments, reinforced
concrete is rapidly deteriorating. Often a problem in the construction of the underground is the presence of aggressive groundwater contained in the dispersed phase of the soils around the tunnel structures.

In the practice of building hydraulic structures and foundations of buildings, an electrokinetic technology of water depression and electric compaction of soils has developed.

Electrokinetic phenomena reflect the relationship that exists between the relative motion of two phases and the electrical properties of the boundary of their separation. Electrokinetic phenomena arise in those cases when one phase is dispersed in another, i.e. when the system can be characterized as microheterogeneous.

There are four groups of electrokinetic phenomena: electroosmosis, electrophoresis, flow potential and sedimentation potential. Given there is tradition in physics, the flow potential, in our opinion, is called the potential difference, or the osmo-EMF (electromotive force), and the deposition potential is the fore-EMF.

3. Theory

So, according to modern concepts, the process of electrokinetic energy-rivalry is mass transfer in colloidal systems, which occurs when an external electric field is applied or accompanied by the generation of an electric field of a colloidal system. Colloidal systems consist of two phases: the dissipation phase and the dispersion environment, i.e. they are heterogeneous.

| Phenomenon          | The essence of the phenomenon and its features | The cause of the phenomenon | Boundary conditions |
|---------------------|-----------------------------------------------|----------------------------|---------------------|
| Electroosmosis      | Movement of a dispersion environment (liquid, gas) relative to the disperse phase (porous or capillary body). | Movement of a dispersion environment (liquid, gas) relative to the disperse phase (porous or capillary body). | V_{sr}; V_{f}=0; -E; -V_{sr}; V_{f}=0 |
| Electrophoresis     | The motion of particles in the dispersive phase (solid, liquid) dispersed in a dispersion environment (liquid, gas) | The electric field imposed from the outside on the dispersed system | V_{u}=0; E; V_{f} V_{u}=0; -E; -V_{f} |
| Osmo-emf (flow potential) | The appearance of a difference in the electronic potentials between the points located in different sections along the direction of the flow of the dispersion environment (liquid, gas) | The displacement of the dispersion environment relative to the non-movable disperse phase under the action of an external force (hydrodynamic) | -E; V_{u}; V_{f}=0 E; -V_{u}; V_{f}=0 |
| Foro-emf (sedimentation potential) | The appearance of a difference in electrical potentials between the points of a stationary dispersion environment | Displacement of dispersed particles with respect to a stationary dispersion environment under the action of an external force | V_{u}=0; V_{f}; -E V_{u}=0; -V_{f}; E |
in which a flow of dispersed particles takes place (tension, Archimedes, etc.)

The work spent during the fragmentation of the substance to break the bonds between the molecules accumulates in the form of the potential energy of unsaturated bonds at the interface of the phases. With a colossal surface area, this excess surface energy reaches large values. Thus, the substance in a colloidal state has a higher energy and activity than an undigested substance of the same composition [9].

The main cause of the phenomenon of electrokinetic energy and mass transfer is considered to be the existence of a double electric layer (DEL) in an electrically conductive dispersion environment around a dispersed particle of a dielectric material. Adsorption of ions of predominantly a single sign on uncharged surfaces occurs due to dispersive forces that arise as a result of fluctuations in the electron shells of atoms. These forces are called the forces of specific adsorption and they depend on the polarization, i.e. the effect of a given ion on atoms on the surface, and the ability to deform their electronic shells. The polarizing force of the ion depends on the strength of its electric field.

4. Experimental results

According to the classical theory of Gui-Chapman, the model of a double electric layer is based on the idea of the mobility of ions in the outer shell. The electrostatic attraction of them to the surface and the repulsion of ions charged likely with the surface is balanced by the thermal motion of ions, which erodes surface excesses. The steady-state equilibrium distribution forms a "cloud" of electric charges near the interface with a decreasing density, similar to the distribution of the density of gases in the atmosphere. In the electric field, counterions of the diffuse layer of DEL, energetically weakly bound to the surface of the solid phase (membrane), will move to the corresponding electrode and, due to molecular friction, it will entrain the dispersion environment (aqueous electrolyte solution). The greater the electric field strength and the thickness of the diffuse layer, the greater the charge carriers, the faster the fluid is transported in the porous body or the dispersed particle in the conductive dispersion environment. In this case, the volumetric velocity of the liquid during electroosmosis is described by the equation:

\[ V = \frac{I \cdot \varepsilon \cdot e_0 \cdot \xi}{4\pi \cdot \eta \cdot \gamma}, \]

(1)

where \( I \) is the current;
\( \varepsilon \) - the dielectric constant of the liquid;
\( \eta \) - coefficient of internal friction (viscosity);
\( \gamma \) - specific conductivity of the liquid;
\( \xi \) - electrokinetic potential.

Equation (1) is called the Helmholtz-Smoluchowski equation, it is often written relative to the electrokinetic potential \( \xi \):

\[ \xi = \frac{\eta \cdot U_0}{\varepsilon \cdot e_0 \cdot E}, \]

(2)

where \( U_0 \) is the constant linear velocity of the liquid through the membrane;
\( E \) - the electric field strength.

In the case of a homeoporous membrane consisting of capillaries of the same cross section, with an increase in the radius of the capillaries, while maintaining a constant gradient of the potential of the external field on the membrane, it is necessary to achieve such ratio in which a steady flow of liquid in the capillaries could not occur due to large inertia forces.

At the same time, \( V/I \) and \( \xi \) should be turned to "0".
Sometimes a homeoporous membrane takes place during electroosmosis in clays, sandy loam and so on, where the homogeneity of the dispersed fraction is relatively large, i.e. it is more common in construction and chemical industries. However, the real membrane characteristic for the construction of the underground is a heteroporous membrane, i.e. containing capillaries of different radii and it is characterized by a certain curve of the distribution of pore sizes in connection with the disturbance of structures.

An increase in the pore radius of such a membrane should lead to the fact that in the largest capillaries at a given potential gradient, the driving electric force equal to the product of grad $\phi$ by the charge of the surface will not be sufficient to obtain a steady flow, and the electroosmotic transfer in them will cease. At the same time, the motion of ions in an electric field $I$ in such capillaries is preserved and, consequently, the electric current is remained unchanged, if the porosity of the membrane is not changed significantly, so the current also is not decreased. However, the volume of the transferred fluid $V$ will decrease, which should lead to a decrease of $V/I$. The decrease of $V/I$ and $\zeta$ should be proportional to the ratio of the cross-sectional area of large capillaries not participating in electroosmotic transport to the total area of the capillary membrane. Further improvement of the electroosmotic mass transfer equation results in the expression (3) for the steady-state regime \[10\] along the axis parallel to the vector $E$:

$$
\Delta \rho = \frac{8e}{\nu_{a}} \left[ -\zeta \Delta \phi - \frac{8\eta l}{S_{np} \rho_{0}} G \right] - \frac{\sigma S_{np}}{l \Delta \phi} \tag{3}
$$

where $\Delta \rho$ - the electroosmotic pressure;
$\varepsilon$ - dielectric constant of the disperse phase;
$\zeta$ - current potential;
$\Delta \phi$ - the potential difference of the electric field on the membrane;
$\eta$ - viscosity of the dispersion environment;
$l$ – the length of the membrane;
$S_{np}$ – the living section of the membrane;
$\nu_{a}$ - radius of the cylindrical hole (pore) in the septum (membrane);
$G$ – liquid flow through the capillary;
$\sigma$ - electrical conductivity of the liquid.

With electrophoresis, the transfer velocity is also described by the Helmholtz-Smoluchowski equation, transformed with respect to the electric field strength:

$$
U = \frac{e \cdot \xi \cdot E}{4\pi \eta}, \tag{4}
$$

where $E$ is the electric field strength.

Obviously, these dependences describe real processes well in the case of homogeneous dispersions. When working with real heterogeneous systems, there are deviations, which can be taken into account by introducing corrections for the $\zeta$ potential [3].

In agricultural production and processing of agricultural products, dispersed materials subject to electrophoretic processing can be sewage from livestock complexes, vegetable and fruit juices, dusty gas emissions, etc.

The approximate theory of electrokinetic phenomena leads to the following equation for the magnitude of osmol-emf (fore-EMF):

$$
\Delta \varphi = \frac{e \cdot \varepsilon_{0} \cdot P}{4\pi \cdot \eta \cdot \gamma \cdot \zeta}, \tag{5}
$$

with $P$ being the pressure.
where \( \varepsilon_0 \) - the dielectric constant of vacuum;
\( \varepsilon \) - dielectric constant of the dispersion environment;
\( \eta \) - coefficient of internal friction - viscosity of the dispersion environment;
\( \gamma \) - the specific electrical conductivity of the dispersion environment;
\( P \) - the pressure causing the relative movement of the phases along the interface between them, in case of osmo-emf it is, most often, the hydrostatic pressure on the "membrane", in case of the FEF this pressure takes into account the Archimedean force and it is described by the equation:

\[
P = gM \left( 1 - \frac{d_i}{d_s} \right),
\]

where \( g \) is the acceleration due to gravity;
\( M \) - mass of suspended particles passing through the unit cross section of the microheterogeneous system;
\( d_i \) - density of the dispersion environment;
\( d_s \) - density of suspended dispersed particles.

In addition, Eq. (5), after taking into account the dimensions of suspended dispersed particles for the foro-EMF or pores for osmo- EMF, takes the form:

\[
\Delta \phi = \frac{\varepsilon \cdot \varepsilon_0 \cdot P}{4 \pi \cdot \eta} \cdot S \cdot E \cdot \xi,
\]

where \( S \) is the cross section of the suspended particles (or pores);
\( E \) - the intensity of the electric field in a direction parallel to the interface between the dispersed phase and the dispersion environment.

### 5. Discussion of results

The phenomenon of osmo-EMF is observed in some natural phenomena; it can be used in production to generate electricity for the purpose of power supply to low-power consumers. Foro-EMF exists in natural phenomena of electric charging of atmospheric clouds by electricity and can be used in production for gas and water purification.

**Table 2. Types of disperse systems (sols)**

| №  | Dispersed phase | Dispersion medium | Typical examples                       | Possible technological effect          |
|----|-----------------|-------------------|---------------------------------------|----------------------------------------|
| 1  | Hard            | Hard              | Minerals. Ruby glass. Alloys           | Electrets                              |
| 2  | Liquid          | Hard              | Opal. Minerals with liquid inclusions | Electrophoresis. Foro-EMF              |
| 3  | Gas             | Hard              | Pumice. Silica gel. Charcoal           | Electrically-controlled gas filtration |
| 4  | Hard            | Liquid            | Colloidal solutions. Hydrosols. Organosols | Electrophoresis. Electroosmosis. Foro-EMF Osmo-EMF |
| 5  | Liquid          | Liquid            | Emulsions. Milk. Latexes.             | Electrophoresis. Foro-EMF              |
| 6  | Gas             | Liquid            | Gas emulsions. Foam                    | Electrophoresis. Foro-EMF              |
| 7  | Hard            | Gas               | Aerosols. Smokes                      | Electro-gas cleaning                   |
| 8  | Liquid          | Gas               | Fogs                                  | Electrophoresis. Foro-EMF              |
| 9  | Gas             | Gas               | Gas colloids                          | The Rank effect. Electrocoron fans     |
From the analysis of the information given, it is clear that the form of the phenomenon depends on the aggregate state of both the dispersion environment and the dispersed phase. Using previous advances in the classification of disperse systems [4] and the possibility of morphological classification, it is possible to expand the scope of application of the laws of electrokinetics and the list of new technologies (Table 2). The analysis of existing classifications makes it possible to conclude that the modern classification of disperse systems is incomplete, in view of the dialectical incompleteness, there is a unidirectional study towards the micro level.

In addition, the analysis of production of disperse systems made it possible to draw a number of conclusions about the ambiguity of the classical equations of electrokinetics. Due to the fact that in almost all dispersed materials when constructing underground, the soil of a disturbed structure is present as a dispersed phase, and as a dispersive environment water with dissolved salts of natural and technogenic origin, the process of electrokinetic energy and mass transfer in them has its own peculiarities, namely:

a) the heteroporosity of the dispersed phase, i.e. the heterogeneity of the capillary sizes, which depends on the large scatter of the particles in the dispersed phase of the soils, which leads to a surplus of electrical energy for heating the dispersion environment in large capillaries;

b) the multicomponent nature of the electrolyte composition of the dispersion environment; i.e. On the one hand, the presence of indifferent and non-indifferent electrolytes in the solution leads to a decrease in the electrokinetic potential as a result of an increase in the concentration of counterions with an increase in the concentration of indifferent electrolytes and, on the other hand, it leads to the ability of the electrolyte ions to complete the crystal lattice of the dispersed phase resulting finally in decrease of electrokinetic potential;

c) the difference between the hydrogen index of the environment - pH of the neutral - can strongly affect the electrokinetic potential of dispersed particles, since "hydrogen and hydroxyl ions have a high ability to adsorb; the former is due to the small radius. This allows them to approach the surface of the solid phase closely; the latter is because of the large dipole moment." The deviation of the hydrogen index to the acidic or alkaline side for the dispersion environment of underground-construction is integral to it [5];

d) dependence on the concentration of the dispersed phase - when diluting the colloidal system, the electrokinetic potential should be increased, since the thickness of the double electrical layer is increased as a result of a decrease in the concentration of counterions in the solution.

At the same time, when diluting, desorption of the potential-determining ion from the surface of the dispersed phase can be observed, which should lead to a decrease in the electrokinetic potential. The phenomenon is typical for electrophoresis in highly diluted wastewater;

e) temperature dependence of treatment - as the temperature rises, the \( \xi \)-potential \( \xi \) must grow due to an increase in the intensity of the thermal motion of the counterions and the thickness of the double electric layer, but at the same time, the desorption of the potential-determining ions may increase, and the \( \xi \)-potential decreases.

Thus, the main peculiarity of the process of electrokinetic processing of dispersed materials in the construction industry is the relatively high specific energy consumption per process, the dependence of specific energy costs on a large number of uncontrolled and hard-to-control factors due to the inadequacy of the existing theory and technology. The real picture of electrokinetic phenomena should be described by equations for the response functions not in plane coordinates but in the quasisphere (Fig. 1), which has no connection with the real Euclidean space.

The necessity of solving a problem in a spatial coordinates corresponding to real physical space arises when the external force action and the axis of the capillary are mismatched, as well as in harmonic external force action, which is the most adequate to the real world:

\[
E - V_{sr} \begin{cases} 
1 + 3 \text{ quadrants } = \text{electroosmosis} \\
2 + 4 \text{ quadrants } = \text{osmo - EMF} 
\end{cases}
\]
plane of electroosmosis;

\[
E - V_f \begin{cases}
5 + 7 \text{ quadrants} & \text{electrophoresis} \\
6 + 8 \text{ quadrants} & \text{EMF}
\end{cases}
\]

- plane of electrophoresis.

\[V_{sr} - V_f\] - plane of mass transfer under the action of mechanical forces in the absence of a double electrical layer.

Figure 1. The space of the set of phenomena of energy and mass transfer in disperse materials: E is electric field strength; \(V_{sr}\) is the direction and velocity of the dispersion medium; \(V_f\) is the direction and velocity of the dispersed phase; plane of electroosmosis.

For the first time, the analytical dependence on the energetics of the electroosmosis process was proposed by B. F. Reltov. Reltov proposed to consider the coefficient of electroosmosis with respect to the current the criterion of optimization, which is the productivity of \(m^3/A\cdot s\). At the same time, the current electroosmosis coefficient is proportional to the electrokinetic potential of the dispersed phase, the dielectric constant of the dispersion environment, and it is inversely proportional to the specific electrical conductivity and the viscosity coefficient of the liquid phase. Thus, energy costs were taken into account to overcome the forces of electrostatic attraction - electroosmotic, loss of energy for electric heating of the liquid phase and loss of energy to overcome frictional drag.

Later, V.A. Zuev and V.S. Parfenov proposed a refined mechanism of the process, taking into account the forces of electroosmosis, filtration, moisture conductivity, osmosis, thermal conductivity. At the same time, considering the forces of moisture conductivity, osmosis and thermal conductivity are insignificant in comparison with the forces of electroosmosis and piezometric pressure. V.A. Zuev and V.S. Parthenow state that they can be neglected, but in our opinion it does not quite correspond to the physics of the phenomenon. A mention of Prof. G.M. Lomize on postanodic effect [6, 16] indicates the use of the phenomenon of moisture conductivity to increase the energy efficiency of the process. S.S. Vojutskii shows that the concentration of electrolytes in the solution, and consequently the osmosis forces, significantly affect the energy of the process, both positively and negatively, especially in the case of electroosmotic desalinization of solonetzes.

A neglect of thermal conductivity is possible in systems of unlimited volume, where moisture is introduced into the anode region and there is no temperature difference between the anodic and
cathodic regions [7, 11-13]. Practice shows that in the construction industry there are closed volumes of moist materials, and inevitably there is a gradient of the temperature field and, consequently, thermal conductivity [8, 14, 15]. Therefore, when assessing the energy of the process under real production conditions, it is necessary to take into account the influence of associated processes.

In general, the movement of moisture in a dispersed material can be expressed as the sum of a number of components, each of which shows the influence of a factor on electrokinetic energy and mass transfer (in this case, electroosmosis). With the independent effect of these factors on energy costs in electroosmosis:

\[ \Delta H_{mg} - \text{head loss;} \]
\[ a_1 L \Delta B - \text{loss of moisture conductivity;} \]
\[ a_2 L \Delta C - \text{loss of osmosis;} \]
\[ k_e m_e - \text{electrolytic loss of gas;} \]
\[ k_e E^2 S - \text{losses for the polarization of the dielectric of the dispersed phase;} \]
\[ I^2 R \tau - \text{electric heating energy;} \]
\[ a_3 \Delta T - \text{work thermal conductivity (thermo-osmosis);} \]
\[ a_4 E \tau - \text{work of electroosmosis;} \]
\[ a_5 \Delta T \tau - \text{loss of thermal conductivity.} \]

**Figure 2.** Energy diagram of the process of electrokinetic mass transfer (electroosmotic dewatering of wet dispersed materials).

Graphical interpretation of the energy balance is presented on the energy diagram (Fig. 2). The specific energy costs depend on each term of the equation. Of the listed phenomena and processes, only some perform useful work, for example, electroosmosis, thermal conductivity, and others are parasitic.

**6. Conclusion**
Proceeding from the analysis of the physics of parasitic processes, the following working hypothesis is proposed:

a) physical processes: loss of piezometric pressure, moisture conductivity, osmosis affect the energy of dehydration, but it is very difficult to isolate their effects;

b) parasitic electrical processes make a decisive contribution to the total energy losses;
c) to eliminate the influence of parasitic electrical processes on energy consumption, it is sufficient to replace the treatment with a constant electric current for processing by other types of electric energy, i.e. change the parameters of electricity.

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