The modeling of the Phase-Metric Method of the Geoelectrical Control of Oil Sludge Straits

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Abstract. In the article was provided a simulation of the phasemetric method of geoelectric control of oil sludge straits. Ecological-geochemical and physicochemical properties of oil sludge are considered. The description of the installation used in the work in the form of a model of the fuel and energy complex object is given, the corresponding phase signals are measured for the transverse and longitudinal receiving lines of the electrodes in the presence of simulated oil sludge spills near the soil surface and at a fixed depth relative to it. The necessary illustrative dependencies are given for which characteristic conclusions are made.

1. Introduction

At present, more than 50 million tons of raw materials are lost annually in the global oil industry during the extraction, transportation and processing of petroleum products, what leads to widespread environmental pollution of the environment by oil waste. In Russia, this problem is extremely acute, since the amount of generated waste at oil-producing and oil-refining enterprises of the country is more than 1.3 million tons, of which about 40% are oil sludges, which are complex physicochemical mixtures consisting of oil products, solids and water and generated during production processes, such as oil refining, production and transportation [1].

This type of waste poses a significant environmental hazard, since the constant leakage of raw materials leads to the formation of technogenic deposits due to the infiltration of oil products deep into the earth's surface. At the same time, aquifers play the role of protective shields and most often technogenic deposits are located at a shallow depth (on average, within 10-25 meters). As a result, under almost any object related to the extraction, transportation, and processing of oil products, a zone of soil and groundwater is formed, affected by oil products, and under many large objects of the fuel and energy complex giant oil “lenses” are accumulated [1-2].

In view of the importance of the indicated problems and the features of the formation of oil sludge, various methods are of particular importance, aimed at regular monitoring of the fuel and energy complex with the aim of early warning and detection of leaks of oil products, localization of places of their occurrence and assessment of the dynamics of change. Due to the complexity of the object of research, a special role in the development of these methods is played by full-scale modeling of oil sludge straits on mock-up models of objects of the fuel and energy complex. At the same time, in
order to control the leakage of oil products, it is important to correctly understand the ecological, geochemical, and physicochemical properties of oil sludge [3].

2. Ecological, geochemical and physico-chemical characteristics of oil sludge
As the ecological and geochemical characteristics of the basic composition of various petroleum products, the light fraction, cyclic hydrocarbons, resins and asphaltenes, as well as sulfur compounds are taken into account in them [4].

The main part of the light fraction is methane hydrocarbons (alkanes) with a small number of carbon atoms (from five to eleven), which can adversely affect the ecology of the soil. The main part of the light fraction decomposes and disappears even on the surface of the soil or is washed off by water flows. Oil sludge characteristics such as hydrocarbon composition and the amount of resins and asphaltenes correlate with the light fraction content [5-6].

Methane hydrocarbons with a higher molecular weight (from twelve to seventeen carbon atoms) - cyclic hydrocarbons (cycloalkanes) are toxic to living organisms, but due to high solidification temperatures (from plus 18 degrees Celsius and above), they become solid in the conditions of the earth’s surface, depriving petroleum mobility [7].

Resins and asphaltenes in the composition of petroleum products determine their physical properties and chemical activity. They include carcinogenic polycyclic aromatic structures containing sulfur, oxygen, nitrogen, trace elements. From an environmental point of view, petroleum trace elements are divided into two groups: non-toxic (Si, Fe, Al, Ca, Mg, P and others) and toxic (V, Ni, Co, Pb, Cu, Ag, Hg, Mo, etc.), acting on living organisms as poisons.

For clarity of comparison, Table 1 and Table 2 present the chemical and mineral compositions of oil sludge with an indication of the percentage of various constituent components.

**Table 1.** The chemical composition of oil sludge.

| Components content, % | SiO₂ | CaO | Fe₂O₃ | Al₂O₃ | MgO | Others |
|-----------------------|------|-----|-------|-------|-----|--------|
|                       | 4,65 | 3,24| 1,77  | 2,4   | 1,0 | 3,3    |

**Table 2.** Mineral composition of oil sludge.

| Quantity, mass % | Organic components | Moisture | Sulfur |
|------------------|--------------------|----------|--------|
|                  | 72                 | 10,2     | 1,8    |

It is known that oil sludge pollutants significantly affect the physical properties of soils, changing the density, porosity, heat capacity, electrical conductivity, etc. of the latter.

The density of contaminated soil is determined by the contribution of the densities of its components, so the density of soils containing petroleum contaminants is usually lower than the density of unpolluted soils, since the density of oil products is usually less than one gram per cubic centimeter (the exception is heavy fuel oil and some lubricating oils). Conversely, impurities of heavy pollutants, with a density above one gram per cubic centimeter, increase the density of soils [8-9].

The characteristics of liquid and solid sludge with different contents of water, hydrocarbons and solid particles are presented in Table 3.
Table 3. Characteristics of oil sludge.

| Characteristic                          | Unit of measurement | Source product metrics |
|-----------------------------------------|---------------------|------------------------|
| Type of oil sludge                     |                     |                        |
| Water content in oil sludge             | %, no more          | 50                     |
| Hydrocarbons content in oil sludge      | %, no more          | 95 and more            |
| Particulate matter content in oil sludge| %, no more          | 10                     |
| Size of particulate matter              | mm, %, no more      | 5                      |
| Oil sludge temperature                  | C, no less          | +10                    |
| Oil sludge viscosity                    | C, no more          | 1000                   |

From the point of view of electrical conductivity, the presence of contaminants-electrolytes lowers the electrical resistance of soils, and the more, the more pollutants enter the soil, and inorganic non-electrolyte pollutants (oil products), on the contrary, increase electrical resistance. The dielectric properties of contaminated soils depend on the dielectric constant ($\varepsilon$) of the component of the pollutant and its concentration in the soil (for oil and oil products, the dielectric constant is $\varepsilon = 2–3$) [10-12].

3. Phasometric method of geoelectric control of oil sludge straits

A promising way to detect, track and predict the dynamics of the development of oil sludge straits is to use the phasometric method, which belongs to the class of geoelectric control methods. This control method is implemented using one pair of point emitting grounding electrodes (to which quadrature harmonic signals are supplied), as well as many pairs of receiving grounding electrodes. In general case, the processing of output signals from each pair of receiving electrodes involves the formation of an amplified difference signal, phase detection of this signal relative to the reference signal and low-pass filtering [16]. The indicated stages of processing the input signals of the monitoring system make it possible to distinguish in real time the current phases of the signals between the pairs of receiving grounding electrodes and monitor their dynamics, which in this case is an indicator of the occurrence and development of oil sludge straits at the fuel and energy complex. The advantage of this method in relation to the problems under consideration is that this method of geoelectric control does not require placing the system directly on the objects of the fuel and energy complex, what makes it more flexible and attractive for practical use [17].

To carry out the modeling of the phasometric method of geoelectric control of oil sludge straits, an experimental setup was used in the form of a mock-up model of the fuel and energy complex object, shown in Figure 1.
The experimental setup is a reservoir with soil, on the surface of which a geoelectric control system is located near which channels for simulating oil sludge straits are installed at a certain depth from the soil surface. The arrangement of the emitting and receiving electrodes of the geoelectric control system, as well as the photo of the experimental setup from above, are shown in Figure 2. The following notations are used in the scheme: A and B are the radiating grounding electrodes, M1-M4 and N1-N4 are the receiving grounding electrodes, 1 and 2 are the locations of the modeled straits (near the soil surface in the first case and at a depth of 10 cm in the second). The distance AB between the radiating electrodes is 50 cm, between the receiving M1N1 - 30 cm, between the receiving M2N2 - 10 cm, between the receiving M3N3 - 30 cm and between the receiving M4N4 - 10 cm.

Using the presented experimental setup, the simulation of oil sludge straits at various depths relative to the soil surface were conducted [18-19]. Water with increased salinity (5500 μS / cm) was used as an imitation of oil products.

Figure 3 and Figure 4 show, by way of example, the results of extracting and processing phase signals for the longitudinal M1N1 and transverse M3N3 lines (relative to the emitting line) of the receiving electrodes for points of the strait 1 and 2 (in Figure 2a). In the first case (Figure 3), the time of the introduction of the liquid into the medium is 30 seconds from the moment the data were recorded, and the volume of the injected liquid is 40 ml; in the second case (Figure 4), the moments of...
time the liquid was introduced into the medium are 45 and 300 seconds from the moment the data were recorded, and the volume of liquid injected per cycle is 10 ml.

For the presented dependences, the installation parameters and experimental conditions are identical: soil temperature - plus 24 degrees Celsius; the pH indicator is 6.5, the frequency of the emitted electrical signal is 90 Hz, the sampling frequency of the analog-to-digital converter of the receiving tract of the system is 10 kHz.

**Figure 3.** Phase signals for the longitudinal receiving line M1N1 (a) and the transverse receiving line M3N3 (b) when modeling the strait near the soil surface φ°.

![Figure 3](image)

**Figure 4.** Phase signals for the transverse receiving line M1N1 (a) and the transverse receiving line M3N3 (b) when modeling the strait at a depth of 10 cm from the soil surface.

![Figure 4](image)

From the presented graphical dependencies it is seen that, in the time periods corresponding to the moments of simulation of active spills of oil products, jumps in the phase signals are observed. Moreover, for both cases for the transverse placement of the receiving lines of the electrodes, the indicated phase jumps are more noticeable and characteristic, what is explained by a more "advantageous" placement of these receiving lines relative to the points of the straits [20, 21].

4. Conclusion

The presented results of modeling the phasemetric method of geoelectric control are the basis for the development of phase signal models describing various types of oil sludge straits (flowing at different speeds, the nature of the formation/non-formation of oil sludge emissions on the soil surface, etc.). These models will allow for more accurate and detailed detection of straits, to determine its characteristics, to predict the occurrence or further development. At the same time, in order to draw up the indicated models, it is necessary to take into account the following factors: the characteristics of oil products, the characteristics of the environment under the object of the fuel and energy complex, the influence of possible acting climatic factors, the possibility of oxidation of sludge and contact with atmospheric moisture and precipitation, and some others.
In addition, the presented method allows one to localize the place of occurrence of the strait, outline its shape and evaluate the geometry of the resulting oil sludge lens by the directions of the phases of the detected signals relative to the stationary state of the system (in the absence of spills) by using a network of multiple receiving electrodes.

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