Geoelectric Monitoring of Earthen Hydraulic Structure State by Resistivity and Induced Polarization Methods: Mine Water Settling Pond Dam Case Study

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Abstract: In earth dams, a permanent filtration of water leads to washing out of sand-clay fraction and to a formation of soil decompression sites, which pose a danger to embankment integrity. Condition monitoring of earth hydraulic structures can be executed by geophysical methods. The article presents the results of geoelectric monitoring conducted on the dam of settling pond of mine water with high metal content. The investigations were carried out by vertical electrical soundings, including electrotomography (ET), and by methods of induced polarization in time and frequency domains. According to the results of the electrical soundings, places of reduced soil resistivity in the dam were identified, associated with infiltration of precipitations and of water from the pond. Geoelectric monitoring showed changes of the soils resistivity in different years, depending on hydrological conditions. Induced polarization methods are sensitive to material composition of soils, such as clayiness and presence of electronically conductive minerals. It is determined that the highest content of clay is in the upper and middle parts of the embankment. In eastern part of the dam, intensive polarizability of the medium was detected. It can be caused by filtration of water, contaminated with metals, through the embankment and sedimentary rocks. Thus, by resistivity measurements, it is possible to identify areas of intensive filtration in the dam body, and induced polarization measurements make it possible to determine clay content in the soil and possible pathways of contamination through the dam, which is of great importance for studying the environmental situation of region.

Keywords: earth dam, electrical soundings, electrotomography, resistivity, frequency effect, chargeability

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Research Article

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1. Introduction

The study of the state of earth dams, enclosing reservoirs and storages of liquid production wastes, is an urgent engineering-geological, as well as geo-environmental, task. Earth dams are constructed of permeable sandy-clay material, therefore they are in condition of permanent filtration of water from the reservoirs. Over time, due to the washing out of clay fraction, areas with weakened soil strength appear, which pose a danger to integrity of the structure. Dams can be monitored by hydrogeological methods, but these methods provide pinpoint information about changes of physical properties of soils. Geophysical methods can be used for operational control of hydraulic structures (HS), allowing us to study the state of soils without interference in structure of a dam [*Fedorova et al.*, 2017; *Hickey et al.*, 2014; *Ulitin et al.*, 2000]. Permanent water filtration through body and base of a dam leads to suffusion processes, an increase of porosity and a formation of cavities. In such places, soils have increased moisture, that is reflected in changes of electrical properties of medium, primarily electrical resistivity. In geophysics, geoelectric methods are most sensitive to rock moisture, respectively they are widely used in the study of dams.

To estimate the state of earth dams, the electrical sounding methods, including electrotomography (ET), are usually used [*Fedorova and Davydov*, 2014; *Loperte et al.*, 2016; *Nthaba et al.*, 2020; *Sentenac et al.*, 2018]. With the help of the soundings, the electrical resistivities of bulk soils and underlying rocks can be determined at different depths. Reduced values of resistivity indicate soil moisture growth associated with increased water filtration. When studying HS, the self-potential method (SP), based on natural electrical polarization of soils due to transfer of ions by fluid filtration in pores, is also used [*Panthulu et al.*, 2001; *Rozycki et al.*, 2006; *Soueid Ahmed et al.*, 2020b]. Some researchers began to use electrical soundings with simultaneous measurement of induced polarization (IP) to diagnose dams [*Loperte et al.*, 2016; *Martínez-Moreno et al.*, 2018]. The IP method is based on the study of secondary electrical potentials that arise in rocks when a direct current passes through them. Alternating current in a medium also causes polarization, which can be studied, for example, by the frequency effect, indicating a change of resistivity with the frequency of the exciting alternating field. Most often, IP can be observed in rocks containing ore conductive minerals, therefore firstly this method was used to find ore deposits [*Gurin et al.*, 2013]. Two types of induced polarization can occur in sedimentary rocks, clays, sandstones, siltstones, and clayey rocks by alternating current: electroosmotic at frequencies of 10^2–10^6 Hz due to the presence of narrow pores and high value of the ζ-potential; membranous at frequencies of 10^{-1}–10^2 Hz due to the difference of the pore cross sections of contacting pores [*Zadorozhnaya*, 2011]. The induced polarization in sedimentary sandy-clayey ion-conducting rocks depends mainly on the porosity, moisture content, and clay content [*Komarov*, 1980].

Electrometric methods were applied to study the state of the earth dam on the Elchovka River (the Middle Urals, Russia). The dam encloses the huge reservoir of neutralized mine waters. Sludges of iron, copper, zinc and manganese metals, etc. are deposited in this pond. The crest of the dam is permanently eroded, which indicates increased moisture content in the bulk material and washing out of clay fraction of the soil during water filtration. After clarification in the pond water goes to another reservoir, which is the main source of drinking water for a big city. Thus, detailed diagnostics of the Elchovka dam is an important engineering and environmental task.

First geophysical surveys on the dam were conducted in 2013. The electrical and elastic properties of bulk soils in the dam body and of rocks in the dam foundation were studied [*Fedorova and Davydov*, 2014]. According to the results of vertical electrical soundings (VES), areas of increased electrical conductivity in the embankment, associated with high soil moisture, were identified. Based on seismic soundings, the elastic properties of bulk soils of the dam and rocks at its base were determined, the boundaries of the dam base and the aeration zone were established. In subsequent years, the dam was monitored by electrical soundings. The results of monitoring showed that in the western and eastern parts of the HS the electrical properties of embankment and rocks change the most depending on the season and the water level in the reservoir.

Over the years, the settling pond has accumulated a large amount of technogenic sludges containing heavy metals. Chemicals can be spreaded with water along the bed of the Elchovka River, along tectonic structures, and also penetrate into the pore space of rocks of the upper aquifer. In this regard, we have included the method of induced polarization on alternating current in the geoelectric monitoring of the dam, because it is sensitive to content of metals in rocks. It should be noted that the IP methods in geophysical practice for the study of environmental pollution have been applied recently [*Aristodemou and Thomas-Betts*, 2000; *Cahyna et al.*, 1990; *Sparrenbom et al.*, 2017]. Also, the method of induced polarization, in addition to electrical soundings, can determine the places where increased water filtration accumulates the clay fraction of soils [*Martínez-Moreno et al.*, 2018]. Firstly the IP was studied by the frequency effect (FE), that is, by the change of electrical resistivity with the frequency of the exciting current [*Davydov et al.*, 2021]. In eastern part of the dam we found an anomalous zone of FE, located above the contacts of sedimentary rocks of different material composition and porosity. In the following years, the study of the electrical resistivity and induced polarization of bulk materials in the dam body and of rocks under the dam base in an anomalous area was continued by a complex of electrometric methods, including: vertical electrical soundings, ET and the IP method in time and frequency domains.

The article presents the results of the geoelectric investigations of the Elchovka earth dam of the settling pond, carried out over several years. The state of the HS and possible places for the spread of chemicals into groundwater from the technogenic reservoir are considered.

2. Site Description

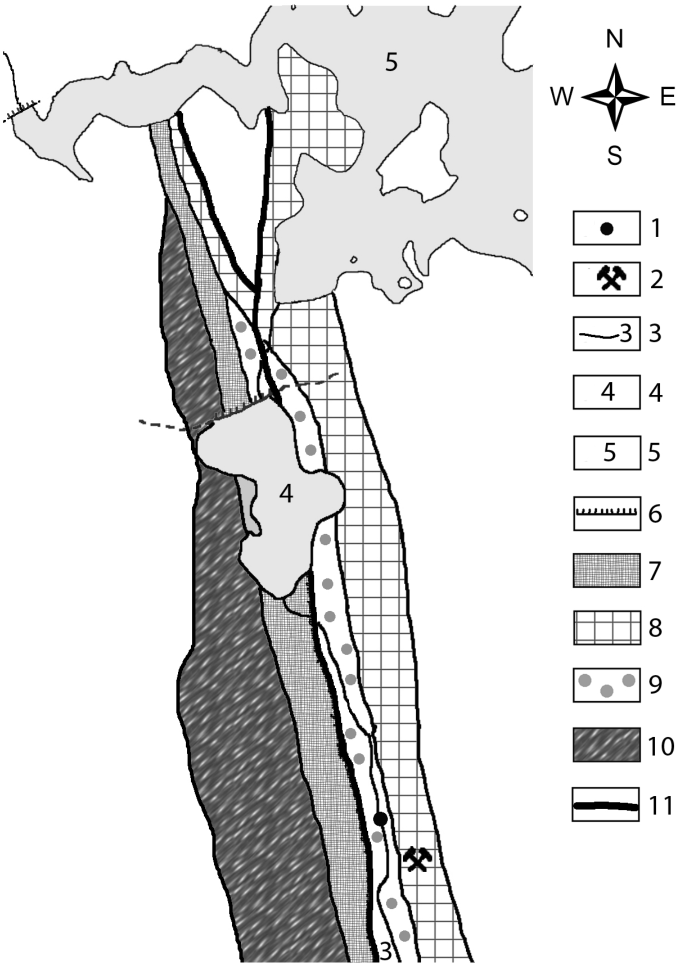

Figure 1. Schematic map. Legend: 1) mine water neutralization station; 2) Degtyarsk copper mine; 3) Elchovka river; 4) Elchovka settling pond; 5) drinking water reservoir; 6) Elchovka dam; 7) Zyuzel suite; 8) Degtyarsk suite; 9) Polevskaya suite; 10) Upper Tagil suite; 11) Serov–Mauk fault.

The Elchovka pond is the reservoir of bottom sediments, which are formed as a result of neutralization of acidic drainage water of the Degtyarsk copper pyrite mine (Figure 1). The total design volume of the pond is 9.34 million m^3. In 1995, the mine was closed, but mine water is poured onto the surface through the mine pit in the amount of more than 5.5 million m^3/year. This water has low pH value (about 2.5) and high content of iron, copper, zinc and manganese [*Elokhina and Ryzhenko*, 2014; *Rybnikova and Rybnikov*, 2016]. Neutralization of mine waters is carried out by slaked lime at the neutralization station to adjust pH to 6.5–8.5. Hydrates, formed after the neutralization of sulfuric acid, and mechanical impurities settle in the pond. In 2011, the volume of bottom sediments amounted to 4.4 million m^3, i.e., currently the settling pond is half full [*Pavlyuk et al.*, 2011]. After clarification, the water from the pond flows to another reservoir, which supplies a large city with drinking water (Figure 1).

The pond dam on the Elchovka River has been built in the fifties of the last century and reconstructed once in 1972. It has length about 650 m, height about 9–13 m and is composed mainly of loam with an admixture of crushed stone. Ungated spillway is constructed in hard rocks to the east of the dam (Figure 2). The dam is located in the zone of the regional Serov–Mauk fault, which separates the volcanogenic-sedimentary rocks of the Tagil trough and the effusive rocks of the East Ural uplift (Figure 1). The dam overlaps the valley of the Elchovka River, which flows along a weakened fault zone. At the west, the base of the dam is composed of the Zyuzel suite (O_3–S_1 zz), which forms a tectonic block in the fault zone. The rocks of this suite are represented by porphyritic basalts and their tuffs; the contacts of the suite with underlying and overlying formations are tectonic. This is followed by the limestone-serpentinite melange horizon of the Polevskaya suite (D_1 pl), which forms the eastern flank of the Tagil megazone. The East Ural uplift is composed of basalts of the Degtyarsk suite (D_2 dg). At the design stage of the dam construction the geological section was studied (Figure 2). It shows contacts of rocks of subvertical bedding with eastern fall of 60–65°. The rocks are very fissured, and contacts of tuffs with porphyrites are complicated by tectonic breaches. In the eastern part of the dam, there is a subvertical zone of fissured, cavernous limestones. Sedimentary formations consist of eluvial and deluvial deposits of the residual soil of bedrocks and alluvium of the Elchovka River valley. The granulometric composition of friable deposits is diverse – from clays, loams and sands to coarse clastic material.

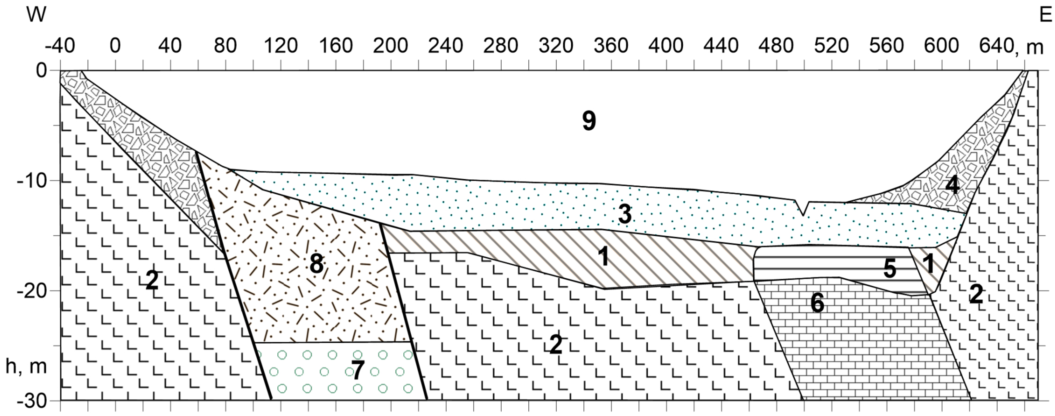

Figure 2. Geological section of the Elchovka dam. Legend: 1) eluvial loams; 2) porphyrites; 3) alluvial deposits; 4) deluvial loams; 5) clay; 6) fissured, cavernous limestones; 7) very fissured tuffs; 8) residual soil of tuffs; 9) dam body.

3. Methods

Geophysical studies were conducted on three profiles: PR 0 – 355 m and PR 1 – 715 m on the crest of the dam; PR 2 – 620 m on the downstream slope of the dam (Figure 3). The profiles were located at a distance from the water: PR 0 – 9 m; PR 1 – 15 m; PR 2 – 25 m. For several years, geoelectric monitoring have been carried out by vertical electrical soundings with frequency effect measurements, as well as by electrical tomography with induced polarization measurement.

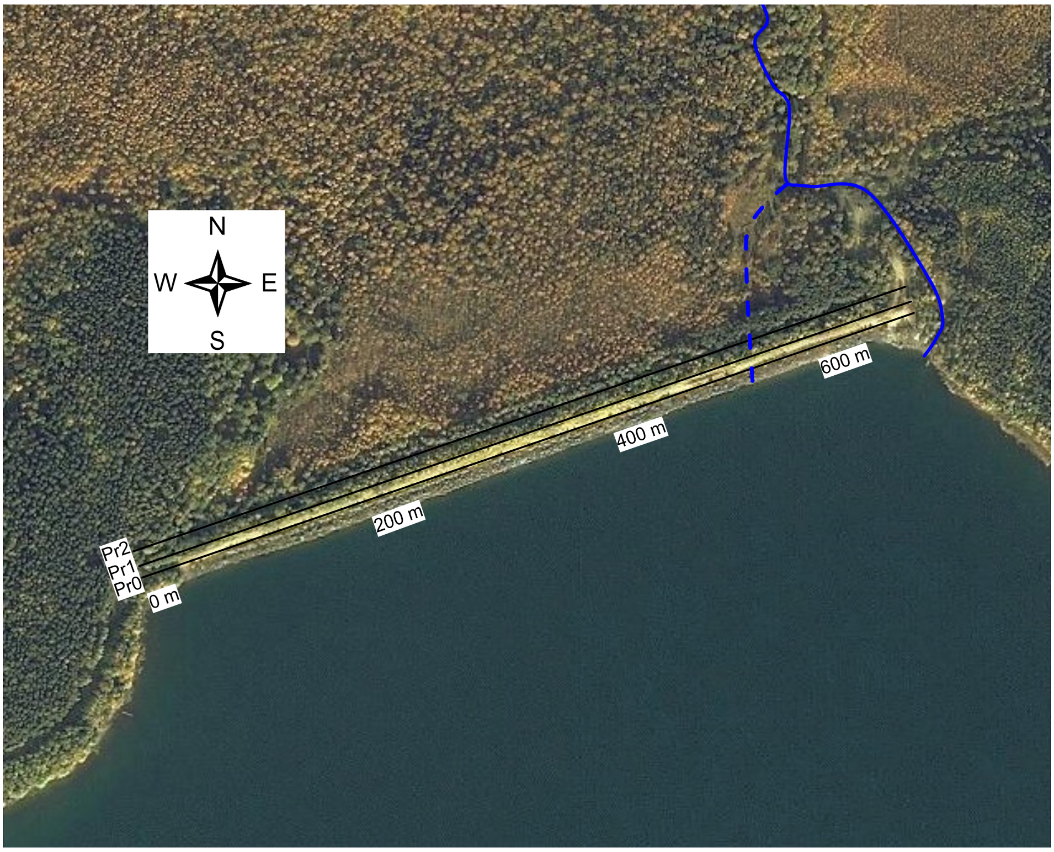

Figure 3. The layout of the research profiles on the satellite image. Thin lines mark the profiles. Thick solid line corresponds to the modern channel of the Elchovka River, thick dashed – to the old river bed.

The base monitoring was carried out on the crest of the dam along profile 1, located on the roadside. The observations network was fixed on the profile, the distance between the pickets was 20 m. The receiving line (MN) of vertical soundings was placed opposite the picket. The supplying electrodes were stretched parallel to the road. When performing electrotomography, the electrical cables were laid out taking into account the fixed pickets. The observation network was also made on profiles 0 and 2, the pickets were located opposite the pickets of profile 1.

3.1. Vertical Electrical Soundings and Frequency Effect

Vertical electrical soundings were performed according to the standard technique. The excitation of the electromagnetic field and the measurement of the potential difference were carried out by the ERA-MAX equipment set (the "ERA" Co., Russia). A four-electrode symmetrical Schlumberger array (AMNB) was used, in which the receiving electrodes (MN) are located in the center between the supply electrodes (AB). Augmentation of the distance between the supply electrodes increases current penetration depth into the medium, which specifies the research depth at the observation point. Spacings (AB distance) varied from 3 to 200 m with a logarithmic step. The distance between the observation points was 20 m. To study the change of resistivity with frequency (frequency effect), at each spacing, the potential difference in the receiving line (MN) was measured at low frequency of 2.44 Hz and at higher frequencies of 19.56; 625; 1250 Hz.

Apparent resistivities ρ_a were calculated at low frequency of 2.44 Hz using the well-known formula:

$$\rho_a = k\Delta U/I,$$

where k is the array coefficient, ΔU is the potential difference measured in the receiving line, I is the current in the supply line.

The induced polarization in frequency domain was considered by the polarization parameter – the frequency effect (f_e) [*Hallof*, 1964; *Slater and Lesmes*, 2002], which can be determined by the expression:

$$f_e = \frac{\rho_a(\omega_1) - \rho_a(\omega_2)}{\rho_a(\omega_2)},$$

where $\rho_a(\omega_1)$ – the apparent resistivity at frequency of 2.44 Hz, $\rho_a(\omega_2)$ – the apparent resistivity at frequency where the lowest value of ρ_a were observed. Since we use apparent resistivities in the formula for calculating the frequency effect, then f_e is an apparent parameter.

The frequency effect can be expressed as a percentage:

$$\mathrm{PFE} = f_e \cdot 100\%.$$

For the obtained apparent resistivity curves, the lateral influence of the reservoir was not taken into account. The profiles are located at a considerable distance from the water, so its influence will be minimal. Apparent resistivity values were interpreted using RES2DINV software (Geotomo Inc.) by means of a standard least-square inversion method [*Loke et al.*, 2003], as a result sections of resistivity (ρ) were obtained. The frequency effect (f_e) sections are plotted taking the effective depth $h_{ef} = AB/4$.

3.2. Electrotomography

In the last year of monitoring the electrical tomography technique was used. The purpose of the research was a more detailed study of the body and foundation of the dam. The measurements were carried out with the "Skala-48" multi-electrode electrical sounding equipment (KB Electrometry, Russia). The equipment set includes 48 electrodes and two electric cables with 24 contacts each. The distance between the electrodes was 5 m. The apparatus automatically measures the current at supply electrodes and the resulting potential difference at receiving electrodes. These values are used to calculate apparent resistivity of medium. Also, the equipment can measure induced polarization. In the IP mode, the duration of the supply pulse is 500 ms. After the current is turned off, "Skala-48" makes a pause of 20 ms, and then records integral value of the IP for a given time T. The induced polarization is expressed by the chargeability parameter (m):

$$m = \frac{1}{U_p(t_1 - t_0)} \int_{t_0}^{t_1} U_s(t)dt,$$

where $U_s(t)$ is the IP decay voltage in the measurement interval from t_0 to t_1, U_p is the measured voltage at some time during application of the current [*Slater and Lesmes*, 2002]. The equipment measures m in units of mV/V. Values of apparent resistivity and chargeability are stored in the internal memory of the device.

The Schlumberger array (AMNB) was chosen for the investigation. The average current supplied into the ground was 40 mA. The induced polarization was measured with given T of 320 ms.

Based on apparent values of resistivity and chargeability, a two-dimensional (2D) interpretation was carried out the same way like for VES data. Inversion procedure generated sections of resistivity (ρ) and chargeability (m). The values of the chargeability are given in dimensionless form to compare the parameters of induced polarization obtained in frequency (f_e) and time (m) domains.

The sections of resistivity, frequency effect, induced polarization and other parameters are built using Surfer (Golden Software, Inc.) for uniformity.

4. Results

The geoelectric monitoring at the Elchovka dam was conducted in different years of the period 2013–2020. In the first years of researches only the vertical soundings method was used. In 2017, in the area of the river bed, experimental work was carried out to study the induced polarization in frequency domain. On a small area, a significant frequency effect was found. The next years, the electrical resistivity and induced polarization of soils were studied on the entire dam or only in the area of the polarization anomaly.

It should be noted that the settling pond is located far from weather stations, so we did not have accurate data on weather conditions in the area of work. The area of the reservoir is 9 million sq. meters, so it rains very often here. The water level was being estimated approximately by the spillway, which is designed for the maximum allowable water level in the pond. If the flow of water through the channel is large, then the water level in the reservoir exceeds the maximum allowable.

4.1. Resistivity Monitoring

The first investigations were carried out in August 2013 on profile 1. The maximum spacing of the supply electrodes AB was 200 m. That year was characterized by large amount of precipitations. The measurements were conducted after a long rainy period. There was an intensive flow of water on the spillway, built to the east of the dam. On the section of electrical resistivity (ρ), the western and eastern conductive areas were distinguished (Figure 4a). The western one is confined to the tectonic zone of the weathering crust of tuffs and fissured porphyrites (interval 10–250 m). Here, the resistivity reached values of 15–25 Ω·m. The eastern area is traced in the former Elchovka River bed above very fractured limestones, which are overlain by a layer of clay. This limestones contact with rocks of different composition and density (interval 460–600 m). Here, decrease of electrical resistivity is observed in bulk soils and reaches limestones. Minimal resistivity values are less than 15 Ω·m. The middle part of the dam has electrical resistivity of 40–70 Ω·m with small local anomalies of 25–30 Ω·m.

This year, the following water parameters were measured: temperature, pH, resistivity and total mineralization in the reservoir near the dam and at the base of the dam from the downstream side, where it was available (Table 1). On the surface of the pond, the water has a ρ of about 9 Ω·m, TDS of about 0.8 g/L, pH of about 8. Such characteristics indicate weakly alkaline water in the uppermost layer of the reservoir. It has a fairly low resistivity. From the downstream side, there is a decrease in water resistivity to 7–8 Ω·m, respectively, TDS increases about 0.9–1 g/L, the medium is neutral. If we take into account that the water temperature here is on average 6 degrees lower than on the surface of the reservoir, then the real resistance may be lower than the measured one, respectively, the mineralization will be higher.

Table 1. Characteristics of water

x coordinate, m	t, °C	pH	ρ, Ω·m	TDS, g/L
		Upstream side		
70	18.6	8.1	8.84	0.789
200	18.5	8.13	8.95	0.778
280	18.3	8.19	8.97	0.777
400	17.9	8.06	8.8	0.793
520	18	8	9.08	0.769
660	18.4	8.14	9.1	0.766
		Downstream side		
70	12.7	7.1	7.63	0.917
110	12.1	7.15	7.53	0.932
140	13.4	6.94	7.95	0.886
200	13.2	6.56	6.98	1.01
250	11.9	6.96	6.54	1.08
320	12.1	6.5	8.6	0.822
380	12.5	6.48	8.65	0.808
430	13.2	6.85	7.37	0.95
480	11.7	6.66	7.84	0.894
520	14.2	6.95	8	0.887
550	11	6.6	7.9	0.886
570	12.5	6.93	7.68	0.913
600	14.5	6.92	7.14	0.99
		Puddle on the crest		
200	17.8	7.8	37	0.178

The soil resistivities obtained from the results of 2-D inversion have minimum values of 6–8 Ω·m in some places (Figure 4a, b, d), which is in good agreement with the ρ of pond water filtered through the dam. Low resistivity values in the upper part of the dam are associated with atmospheric precipitation penetrating into the upper layers of the HS. Moistening of clay material in permeable zones leads to an increase of the mineralization of filtered precipitation and an decrease of the resistivity of the medium.

In 2014, researches were also carried out in August on profile 1 with spacing AB up to 200 m. That year precipitations were significantly less than previous year. The western anomalous area has become less intensive, the average resistivity values are 40–50 Ω·m (Figure 4b). In the eastern anomaly, local resistivity values of <25 Ω·m are observed. In some places closer to the surface, electrical resistivity is 25–30 Ω·m due to infiltration of rainwater into the dam body.

In 2018, investigations were carried out on profile 1 at the end of May, ice on the reservoir had just melted, flood had finished. The maximum spacing of the supply electrodes AB was 100 m. Average values of electrical resistivity both in the anomalous areas and in the central part of the dam practically do not differ and amount to 40–70 Ω·m (Figure 4c).

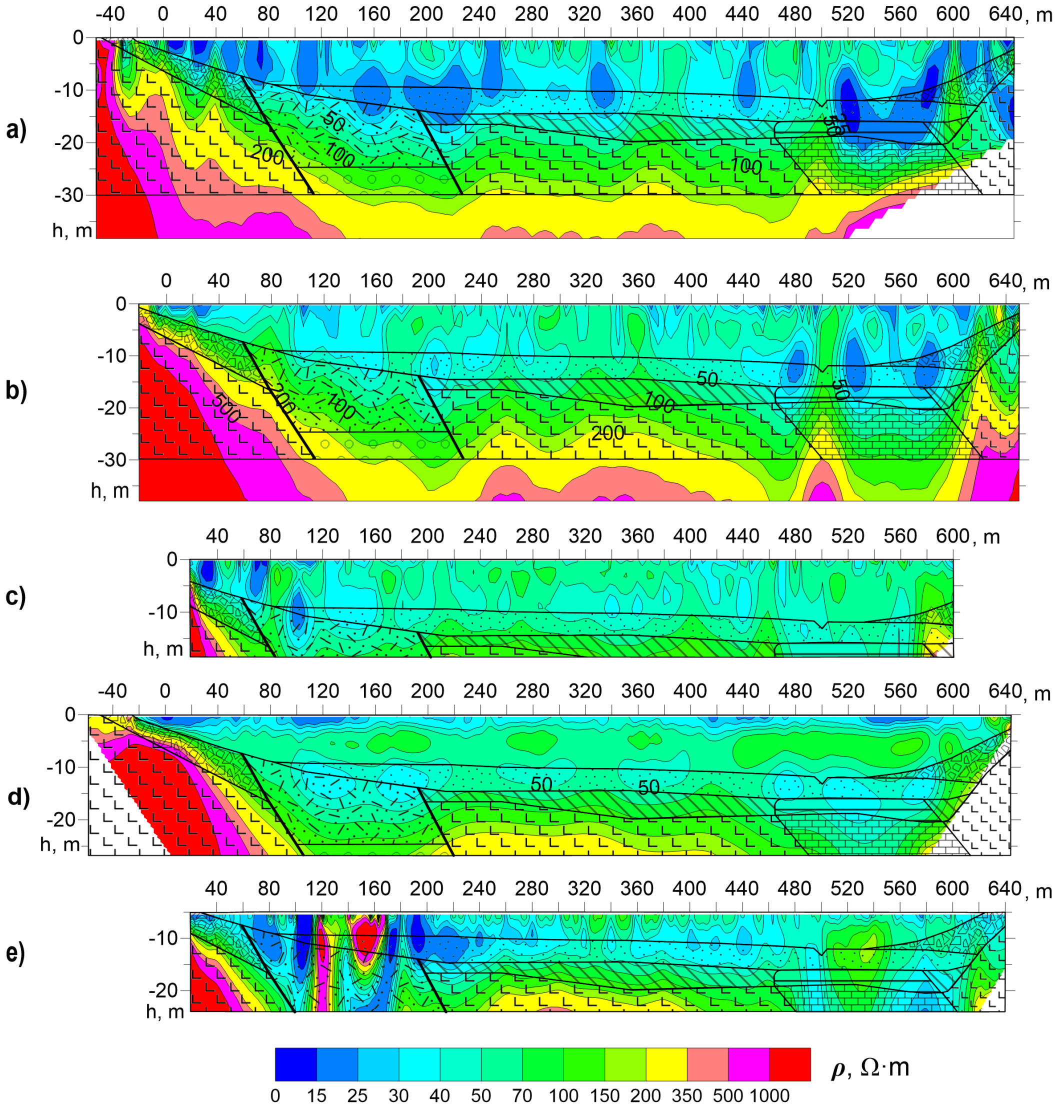

Figure 4. Geoelectric sections along profile 1 on the dam crest for 2013 (a), 2014 (b), 2018 (c), 2020 (d); along profile 2 on the dam slope for 2015 (e).

There are local anomalies with resistivity values of 15–25 Ω·m in the western anomalous area in the range of 30–100 m.

In August 2020, the monitoring was performed using the electrical tomography technique. Two profiles were studied on the dam crest: PR 0 at interval of 295–650 m and whole PR 1 (715 m). And also PR 2 on the dam slope was studied at interval of 295–650 m (Figure 3). In the spring and summer that year, temperature was abnormally high, precipitations were rare, and the water level in the pond was very low. On the resistivity section of profile 1, highest (50–100 Ω·m) average resistivity values are observed in central part of the dam for the entire monitoring period (Figure 4d). At the dam base, the resistivity decreases to 40–50 Ω·m. There are resistivity values less than 40 Ω·m in anomalous zones. Figure 5 presents sections on profiles 0 and 2 and also a part of profile 1 sections in the range 295–650 m, full profile 1 resistivity section is presented at Figure 4d. In the range of 460–600 m of PR 0, resistivity values drops to 15–25 Ω·m (Figure 5a). Increased resistivity values are observed in this interval on PR 2.

In 2015, vertical electrical soundings were carried out on the entire dam slope (PR 2, interval 20–650 m), located 5 m below the crest (Figure 4e). In the western anomalous zone, an area of high resistivity (5–1000 Ω·m) in the embankment was revealed. This can be explained by purposeful strengthening of the slope. But there are zones of increased

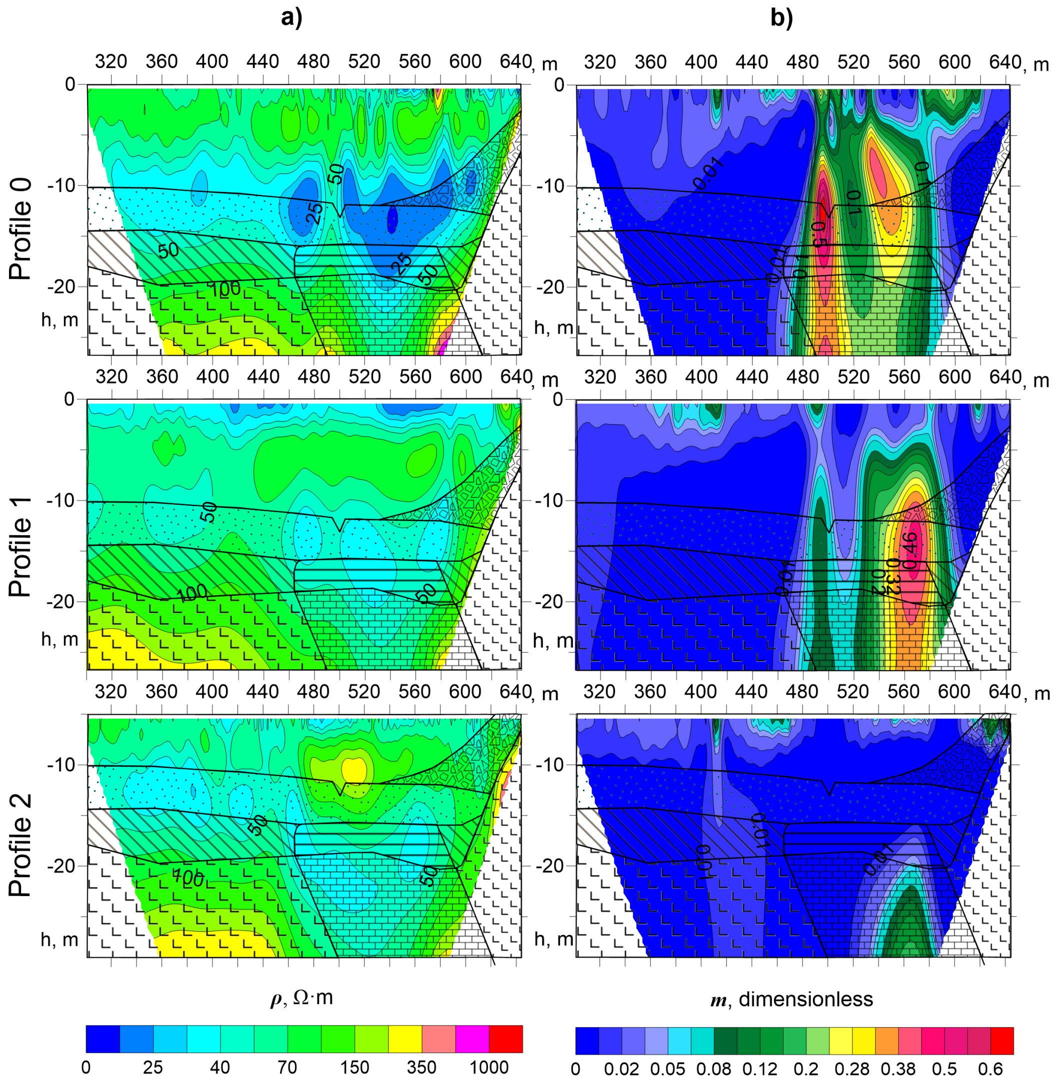

Figure 5. Results of electrotomography for 2020 on three profiles. Geoelectric sections (a), chargeability sections (b).

moisture around this watertight area from the surface to the base of the dam, where resistivity values are less than 15–25 Ω·m. In the range of 500–560 m in the body of the embankment and under its base, resistivity have increased values (80–200 Ω·m).

Thus, geoelectric monitoring shows the dependence of resistivity of soils of body of the dam and rocks under its foundation on hydrological conditions in the spring-summer season. Reduced resistivity values in local areas indicate increased soil moisture in a certain period of measurements.

4.2. Induced Polarization Monitoring

In 2018–2019, induced polarization in frequency domain was studied on profile 1. Measurements were carried out mainly at three frequencies: 2.44, 19.56 and 625 Hz, sometimes at a frequency of 1250 Hz. The frequency effect was studied at each spacing. For example, Figure 6a shows the curves of apparent resistivities at the sounding points of 540 and 560 m, obtained in 2018. Decrease of resistivity at increasing frequency appears at $AB/2 = 5-10$ m. The values of ρ_a at three high frequencies are almost the same up to the spacing $AB/2 = 20$ m. In this case to calculate f_e resistivity $\rho_a(\omega_2)$ was selected at a frequency of 19.56 or 625 Hz. Induction begins to affect at frequency 625 Hz at spacing above 20 m, therefore, to calculate the frequency effect $\rho_a(\omega_2)$ at a frequency of 19.56 Hz was chosen.

On the section of apparent parameter f_e for 2018, an intensive anomaly is observed in the eastern conductive area (Figure 6b). Maximal f_e values of 0.3–0.4 are confined to the eastern side of the dam and to the right steeply dipping contact of fissured limestones with porphyrites. Two more minor anomalies were found: one with $f_e = 0.3$ in a tectonic fault (interval 200–220), the other with $f_e = 0.1$ near that fault (220–240). In the upper (aeration zone) and in middle parts of the dam, anomalous areas with values of $f_e = 0.04$–0.05 are noted. In 2019, studies were carried out only in the eastern anomalous area in the range of 460–600 m (Figure 6c). The dimensions of the anomalous area remained practically the same. But intensity of the frequency effect in the range of 550–580 m increased greatly and amounted to 0.6–0.7.

In 2020, monitoring was performed using the electrotomography technique. This year, like 2019, is characterized by a dry spring and summer seasons. On the chargeability section (Figure 6d) the IP anomaly with maximum intensity of 0.4–0.5 manifests itself as a narrow local zone in the area of the river bed (500 m) and, like in previous years, in the range of 520–580 m. In the area of tectonic structures in the western part of the dam, low intensity anomalies are distinguished. In local areas of the aeration zone, the chargeability reaches values of 0.08–0.15.

To determine contours of the eastern IP anomaly, additional measurements were made along profiles 0 (dam crest) and profile 2 (dam slope) (Figure 5b). At the closest to water profile 0, the chargeability anomaly in the area of the natural river bed has value of 0.6, at profile 1 the anomaly decreases and it is no longer observed on the slope of the dam (profile 2). On the profile 1 in the interval of 520–580 m maximal chargeability values are manifested under the base of the dam down to the limestones. On the profile 2, IP has small values in limestones at depths of 20–30 m.

Three-year monitoring of induced polarization on alternating and direct currents confirms existence of intensive IP anomaly (f_e up to 0.6–0.7 and m up to 0.6) in the eastern permeable part of hydraulic structure and of rocks under its base. The anomaly is observed under the crest of the embankment, on the slope it manifests itself slightly.

5. Discussion

The main task of the geophysical researches was to survey the earth dam on the Elchovka River, which encloses the reservoir of liquid chemicals, which come with mine waters. Bulk material of the dam body consists of natural soils. The crest of the structure is not waterproofed, therefore atmospheric precipitations infiltrate into the upper part of the embankment. This leads to formation of places of soil washing, which are periodically reinforced with crushed stone. The dam is under constant hydraulic pressure, and water from the reservoir percolates through the embankment. All these factors lead to movement of sandy-clay fraction by water inside the dam and under its base, to decompression of bulk material, and to formation of places of increased filtration. Filtration and suffusion can lead to weakening of the strength of the soil structure.

According to the geoelectric sections of the Elchovka dam, places of increased water permeability were found in the upper part and at the base of the hydraulic structure (Figure 4). An important role was played by long-term monitoring of changes of resistivity, which depends on hydrological conditions in different years of the researches. In the first year of the researches, large amount of precipitations fell during the spring–summer period. The body of the dam was subjected to intensive infiltration by atmospheric water and water from the reservoir. This made it possible to identify the western and eastern anomalous areas of electrical resistivity, which are confined to subvertical contacts, to increased thickness of weathering crust and to tectonic faults in rocks. During the rainy season, electrical resistivity of soils in some places decreases to less than 15–25 Ω·m (Figure 4a). This indicates high water content in the medium. Subsequent years have been characterized by less precipitations, especially 2020. On geoelectric sections, an increase of resistivity in anomalous zones was observed. In general, according to the results of monitoring the resistivity at the PR 1, two areas are identified where increased water infiltration can

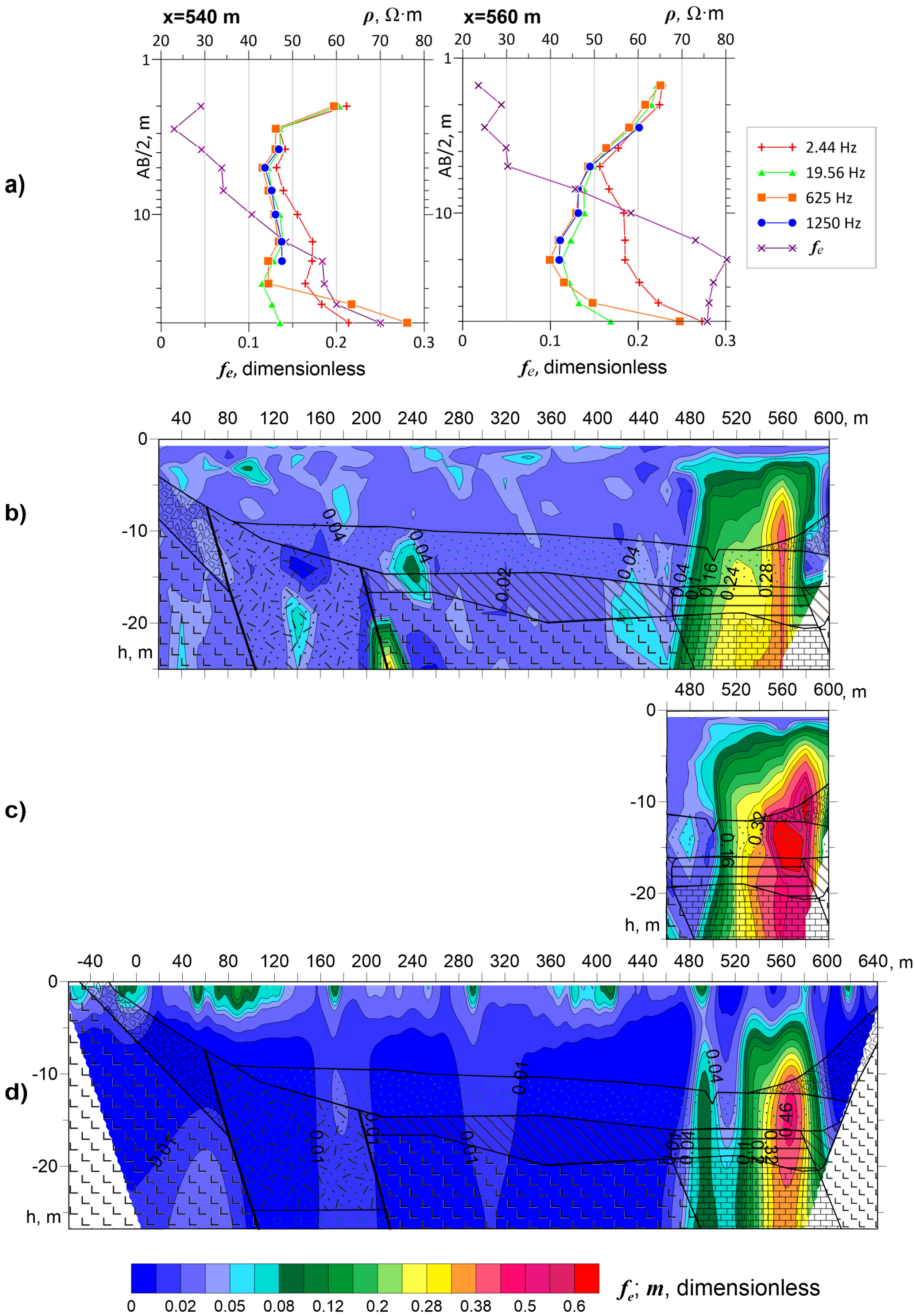

Figure 6. Sounding curves at different frequencies and f_e at pickets 540 and 560 m for 2018 (a), frequency effect sections along profile 1 on the dam crest for 2018 (b); 2019 (c), chargeability section for 2020 (d).

occur: intervals 10–260 m and 480–600 m. Moreover, atmospheric precipitations most often infiltrate into the dam body in same places where increased filtration of water from the pond is observed.

We calculated change of resistivity in rainiest 2013 compared to dry 2020, when highest resistivity values were observed:

$$\Delta\rho = \frac{\rho_2 - \rho_1}{\rho_2} \cdot 100\%,$$

where ρ_1 – 2013 resistivity; ρ_2 – 2020 resistivity.

The section of $\Delta\rho$ shows that in the body of the embankment the main changes occur in the western and eastern anomalous zones (Figure 7). Here, resistivity can vary up to 60–80%. Below the embankment, zones of increased $\Delta\rho$ are traced near the tectonic fault (interval 200–240 m), in the area of increased thickness of eluvial loams (interval 320–340 m). Anomalous local areas of increased values of $\Delta\rho$ are extended towards the surface. In these places, soil subsidence may occur.

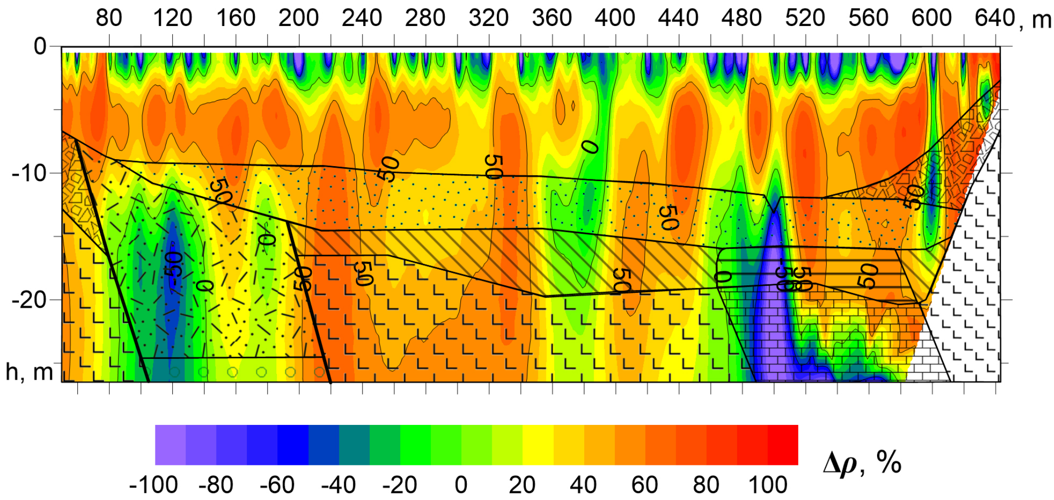

Figure 7. Section of changes of resistivity in 2013 compared to 2020 along profile 1.

An important task is to detect leakages under the HS foundation. On the resistivity section of profile 2, several local anomalies with low resistivity values in the western part of the dam were detected, there are also zones with reduced resistivity in central part of base of the embankment (Figure 4e). Here, increased filtration of water from the reservoir is possible. At the downstream foot of the dam, the outflow of water to the surface is observed in the natural Elchovka River valley in interval of 460–580 m. Therefore, in 2020, electrotomography studies were carried out in this place on three profiles. Reduced resistivity values are observed on the profile 0, closest to the water (Figure 5a). On the PR 1, soil resistivity increases. On the slope (PR 2) it becomes much higher. In all likelihood, the downstream slope of the dam is blocked by a weakly permeable material in the former river bed area.

It is well visible on the horizontal slices, how resistivity changes along the profiles at different depths (Figure 8a). In the river valley, the landform is lower, height of the embankment increases from 10 to 13 m. On the slice $h = -13$ m under the embankment, reduced electrical resistivity values are detected only in the ranges 460–480 and 560–580 m. With a high probability, water comes to the surface in these places and, due to the lowering of the relief, flows into the present riverbed. The chargeability slices at different depths show that higher polarizability of the medium spreads deep down the same way like lower resistivity (Figure 8b). In this part of the dam, increased vertical water filtration occurs, caused firstly by the reinforcement of the slope with low-permeable material, secondly by presence of porous and fractured rocks at the base of the embankment. This is confirmed by the self-potential investigations, performed earlier [*Davydov et al.*, 2021].

When interpreting the field IP parameters, it is proposed to consider the normalized chargeability parameters.

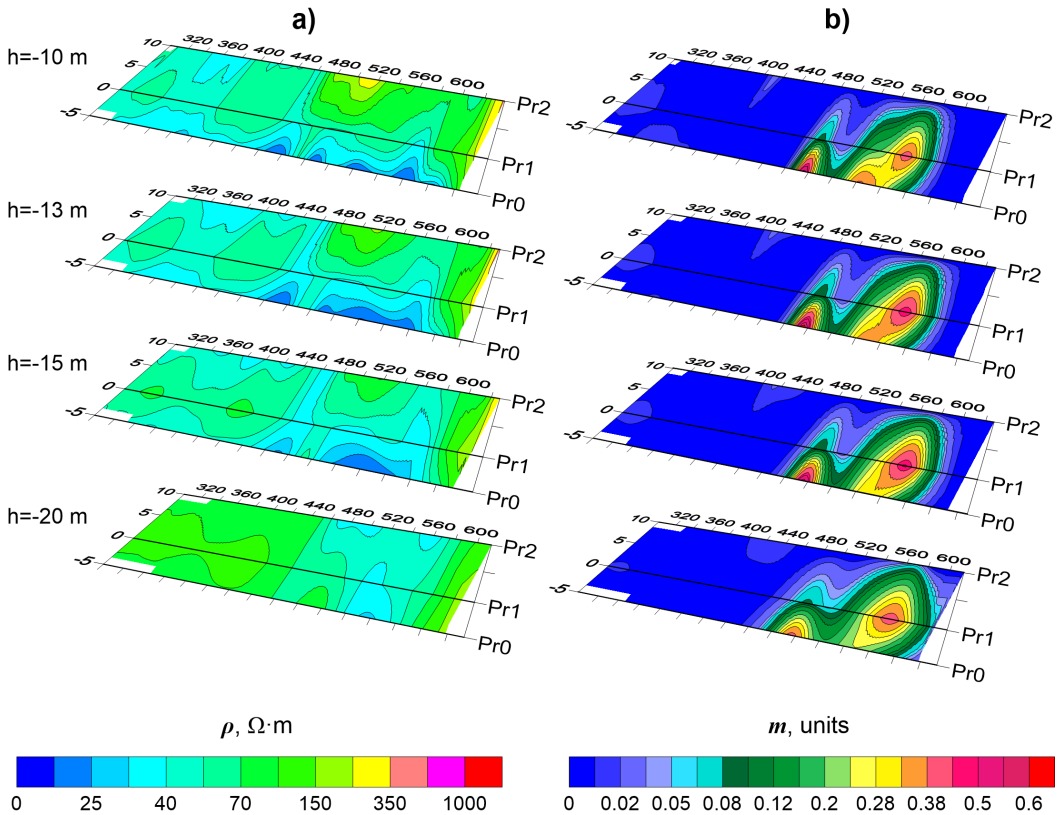

Figure 8. Horizontal slices of resistivity (a) and chargeability (b) for three profiles at different depths in 2020.

The time domain normalized chargeability is given by

$$m_n = m/\rho,$$

where m – chargeability, ρ – resistivity. The metal factor (MF), as defined by *Marshall and Madden* [1959], is given by

$$\mathrm{MF} = 2\pi 10^5 f_e/\rho_a(\omega_1).$$

It is shown [*Slater and Lesmes*, 2002; *Soueid Ahmed et al.*, 2020a] that frequency effect and chargeability of porous rocks depend on volume and surface conductivities of matter, on conductivity of pore fluid, on cation exchange capacity, and also on content of clay in pores of that rocks. Based on laboratory studies, a direct dependence of the normalized chargeability on clay content in the rock is shown, confirmed by experimental examples.

The normalized parameter MF is mainly used to study the medium with the inclusion of ore minerals and in the searches for ore deposits [*Edwards*, 1977; *Hallof*, 1964]. *Al-Oufi et al.* [2012] applied the metal factor in studying cavities filled with clay and other sedimentary rocks.

In our case, the research was carried out on an artificial sandy-clay structure through which water is filtered. Increased values of the m_n (1–4 mS/m) are observed in the upper part of the dam in the aeration zone (Figure 9a). The soil here consists mainly of clay. In the area of the tectonic deformations and in the center of the dam, slight values of m_n (0.2–0.5 mS/m) indicate movement of the clayey fraction deep down with water filtration. The background values of the m_n of the embankment are less than 0.15 mS/m. Intensive anomaly of normalized chargeability over limestones has very high values of 10–14 mS/m, which may indicate not only an increased clay content in medium, but also presence of chemicals with metal content. The background values of the metal factor of bulk soils are 250–400 S/m, elevated values are 500–1000 S/m (Figure 9b). Abnormal

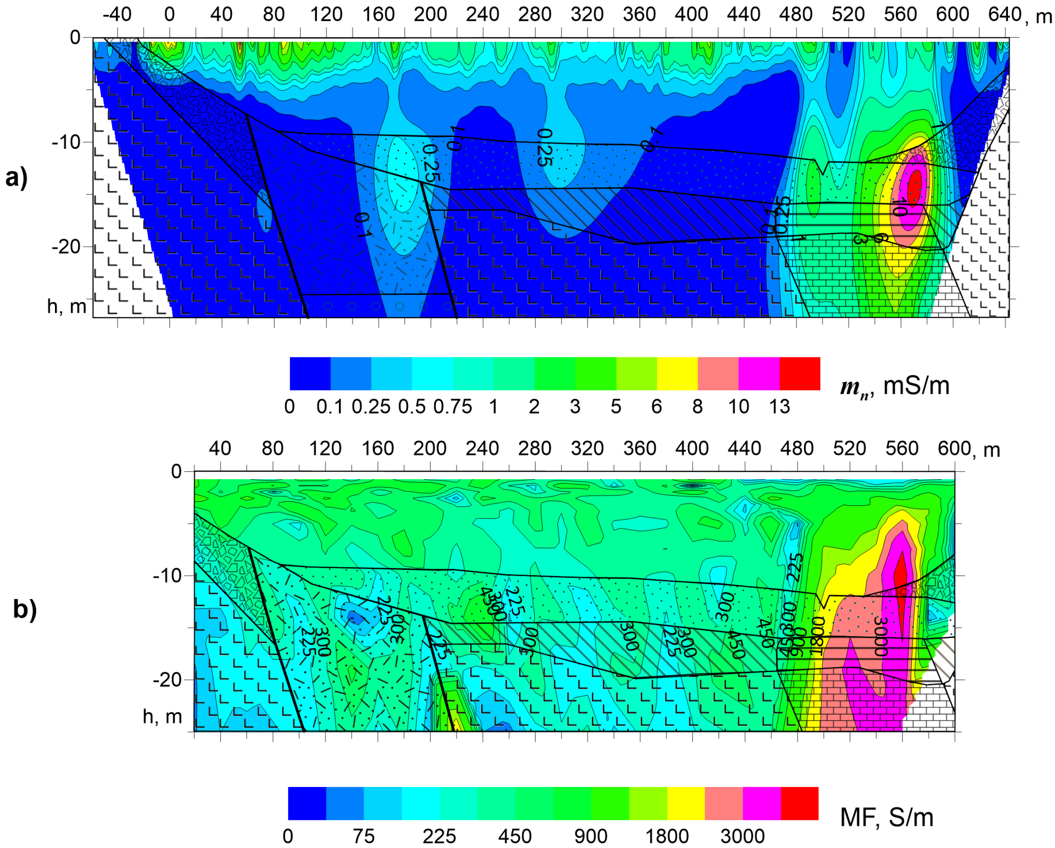

Figure 9. Sections on profile 1 of: a) normalized chargability (m_n) for 2020; b) metal factor for 2018.

values of MF (3000–4000 S/m) in the eastern part of the dam stand out near the base of the structure, extend to a depth of more than 20 meters and may also be associated with the metal content in the medium. Rocks under base of other parts of the dam have values of normalized chargeability and metal factor lower than the average values of m_n and MF of bulk soils, with the exception of some areas.

The IP anomaly in the eastern part of the dam is currently difficult to explain without hydrogeological drilling. As is known, the polarizability of the medium 40–60% can occur over disseminated ore minerals [*Gurin et al.*, 2013; *Komarov*, 1980]. Sandy-clayey soil was extracted from a quarry located near the dam. The hydraulic structure and that quarry are in area of the regional Serov–Mauk fault, to which copper-pyrite deposits are confined (Figure 1). Therefore, bulk soils of hydraulic structure and rocks under its base can contain minerals with iron, copper and other metals. Detailed core samples analysis was not carried out during project drilling. In the interval 460–600, clays and limestones lie under the dam. It is shown [*Kulikov et al.*, 2018] that chargeability of clays can be more than 25% due to presence of microscopic minerals such as pyrrhotite, magnetite, greigite, and other sulfides. However, significant polarizability of sedimentary rocks has not been observed in practice.

Another explanation of detected high polarizability may be in technogenical pollution of settling pond water. According to the data for 2004 at the outflow from the Degtyarsk mine, water can contain 18 g of sulfate anions and 4.7 g of Fe cations, and total mineralization can reach 25 g/L [*Elokhina and Ryzhenko*, 2014; *Rybnikova and Rybnikov*, 2016]. There is also high content of ions of other metals, such as Cu, Pd, Zn, Mn, Cd, etc. After neutralization by liming, the mine water flows to the settling pond. Solid and suspended particles of various chemicals of mine water settle to pond bottom in the form of technogenic sludges. By watercourse, chemicals are moved basically over riverbed and to ungated spillway, constructed to the east of the dam. Sludges can contain a large amount of iron oxides and hydroxides, which have good sorption properties [*Benjamin and Leckie*, 1981; *Lukashevich and Usova*, 2018] and are able to adsorb heavy metal ions from water. It is shown [*Pavlyuk et al.*, 2011] that technogenic silts are deposited primarily in the center of Elchovka pond (silt thickness is about 5–6 m). Near the dam, the silt thickness is not more than 1 m. It is known that clay also adsorbs heavy metal ions [*Zhao*, 2011]. In the eastern anomalous zone of the embankment, an increase of clay content is observed. Under this zone is located highly porous clay, which can adsorb metal cations from water during filtration. Metallized silts can seep through large filtration channels and deposit in cracks and cavities of the rocks of the dam base and below. All these factors increase polarizability of the medium.

Thus, the integrated approach to the study of electrophysical properties of the Elchovka earth dam made it possible to solve some engineering-geological tasks. It should be noted that the regional Serov–Mauk fault runs under the eastern edge of the settling pond (Figure 1). Water, containing metals and bottom sediments, can move through fractured rocks of the fault for significant distances. To determine places of possible dissemination of chemicals into groundwater is of great importance for ascertaining of ecological situation in the region and requires additional research.

6. Conclusion

For several years, geoelectric monitoring of the state of the Elchovka earth dam, which encloses the mine water settling pond, has been carried out. We used vertical electrical soundings technique with study of frequency effect and electrotomography with measurement of chargeability. According to geoelectric monitoring, distribution of electrical resistivity in the body of the dam and under its foundation in different years was determined. As a result, places, subjected to greatest changes of electrical characteristics depending on hydrological conditions, were found. During the dry period, the average resistivities of soils have increased values, which indicates the safe condition of the dam. In the rainy season, resistivities drops significantly mainly in western and eastern anomalous parts of the embankment, which indicates increased infiltration of precipitation water and water from the reservoir. This can lead to decompression of soils and unstable condition of the dam.

By studying the polarizability of the medium in time and frequency domains, the background values of the normalized chargeability (m_n) and the metal factor for the bulk soils of the dam and rocks at its base are determined. Local anomalies of m_n and MF, which are associated with increased clay content in the medium, were detected in the aeration zone, in the middle and in the lower parts of the embankment. The intensive IP anomaly was found in the eastern part of the dam. The anomaly may have a technogenic nature associated with the adsorption of chemicals in the body of the dam and in sedimentary rocks during filtration of polluted water. Chemicals can spread beyond the settling pond through groundwater, through tectonic structures, and through a regional fault towards the large drinking water reservoir.

Thus, monitoring of earth hydraulic structures by resistivity and induced polarization methods, carried out under various hydrological conditions, makes it possible to identify unstable areas in the structure and to give more reliable assessment of its condition.

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