

Assessment of Physical Condition and Identification of Inhomogeneities of the K-25 Earth Dam According to the Self-Potential Method

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Abstract – The increased number of earth dam failures raises the question of the relevance of early determination of the internal condition and causes of erosion of the dam body. The paper deals with the results of using the self-potential method in order to assess the physical condition of the earthen dam of the K-25 reservoir in Kazakhstan. The specificity of this study is that several cycles of measurements were made at different water levels in the reservoir. Based on the results of field data processing, the isoline maps were drawn and their interpretation was carried out. The general regularity in the distribution of self-potential values is their increase to the downstream of dam, which is associated with intensive water seepage, especially in its flanks and central part. The formation of anomalous zones may be due to the complex influence of the inhomogeneity of the dam body and the possible water leakage from the operational pipeline and emergency spillways. Based on the calculated self-potential dispersion, it was established: a) the intensity of seepage and the size of water-saturated zones depend on the hydrodynamic regime of reservoir; b) the change in the intensity of the potential difference and the anomaly sizes depend on the water level in the reservoir. The study results have shown the effectiveness of the self-potential method for determining the erosion zones in the dam body associated with water flows. The method can be used in the geotechnical monitoring in order to ensure the safe operation of earth dams. **Copyright** © 2024 Praise Worthy Prize S.r.l. - All rights reserved.

Keywords: Geophysics, Earth Dam, Self-Potential, Filtration, Monitoring

Nomenclature

A1, A2	Anomalous zone of self-potential
CFD	Computational Fluid Dynamics
EM	Electromagnetic sounding
ERI	Electrical Resistivity Imaging
ERT	Electrical Resistivity Tomography
D1/1... D2	Anomalous zone of SP dispersion
FEM	Finite Element Modeling
GPR	Ground Penetrating Radar
HS	Hydraulic Structures
InSAR	Interferometric Synthetic Aperture Radar
MASW	Multichannel Analysis of Surface Waves
IP	Induced Polarization
SMI	Soil Moisture Index
SP	Self-Potential
SR	Seismic Refraction
U_{SP}	Self-potential difference
VES	Vertical Electrical Sounding
VPF-210	Geophysical Device Model
V_s	Transverse S-wave Velocity
YOLOv5s	You Only Look Once v5s neural network model
σ^2	Dispersion of self-potential

I. Introduction

Throughout human history, the Hydraulic Structures (HS) have played a major role in the life of society. They served primarily to collect and distribute the water for agricultural purposes and other activities. They were mainly dams made of the most available materials, i.e. soil from adjacent territories. The prolonged exploitation, along with the influence of anthropogenic, climatic, and seismic factors, have had a significant impact on the physical condition of these structures over time. These factors under certain conditions lead to the failure. The statistical data indicates that over 67% of all dam failures are attributed to the earthen dams [1]. Moreover, more than half of these failures are due to the geotechnical reasons. One of the reasons for the failure of earth dams is the continuous effect of water filtration on the dam body, which can lead to suffusion or erosion of the soil in the filtration zones. The various failure mechanisms associated with seepage flow and the development of internal erosion are discussed in [2]. In Kazakhstan, the construction of HS was actively conducted during the period of 1960-1980. Over the past decade, there have been more than 10 dam breaches in the country, causing significant economic, social, and environmental damage [3]. Therefore, heightened interest and the utmost

attention are devoted to the technical condition of HS in Kazakhstan. The traditional methods for assessing the condition of these structures include the visual inspection and field observations. Additionally, the water-physical properties of samples from specially drilled wells are studied with the purpose of determining the destructive processes occurring within the dam body. The piezometers are used in order to determine the nature and extent of internal erosion within the dam caused by the increased water pressure (hydraulic fracturing) in the soil.

The processing of the data from piezometers allows for an assessment of the dynamics of internal erosion [1]. The combined analysis of water pressure readings obtained from vibrating wire piezometers and geodetic data on horizontal and vertical displacement of markers on the dam enables the determination of current characteristics of the earth dam [4]. However, these types of studies impose a certain technogenic burden, as earthworks and drilling disrupt the integrity of dam structures and may adversely affect their strength characteristics. In recent decades, the rapid advancements in new technical solutions and modern equipment have provided the foundation for developing new methodologies for diagnosing and monitoring the condition of hydraulic structures. The space industry achievements have become more accessible for the widespread use. The remote sensing data, periodically obtained from Sentinel satellites, allowed for the analysis of Edenville Dam displacement, USA, before its collapse in 2020. Analysis of Soil Moisture Index (SMI) based on Landsat-8 imagery over the four years preceding the collapse has indicated the presence of infiltration zones, which could have led to the dam failure [5]. In [6] the Interferometric Synthetic Aperture Radar (InSAR) technique was used in order to determine the deformations of the Liuduzhai Dam in China before and after the reinforcement with plastic concrete cut-off walls. Analysis of these data has showed that the main cause of the dam deformation before reinforcement was the dynamic seepage. The reinforcement has reduced this seepage quite effectively and now the main cause of dam deformation is the water level fluctuation. As for research directly on dams, non-invasive diagnostic methods and monitoring techniques are increasingly gaining popularity. Geophysical testing methods are widely applied in order to assess the safety condition of HS with the aim of preventing the negative effects. One method that has seen significant development recently is Electrical Resistivity Tomography (ERT), which detects the changes of electrical resistivity, based on the water saturation levels. In study [7] this method was used to map the infiltration zones, which were then compared with results from the geodetic measurements of dam deformation, water level data and pore pressure data collected from various types of piezometers. The analysis has demonstrated the effectiveness of ERT in describing the filtration process through the dam structure. The researchers use specially built test dams to test various research methods. For instance, in Älvärälja, Sweden, various defects were intentionally incorporated into the

test dam structure during the construction of dam [8]. The measurement data using the ERT method was collected daily at a large number of points (up to 14,000). Based on these data, the models of resistivity distribution were built, which additionally have showed the leakage zones not associated with defects. The ERT data inversion and Finite Element Modeling (FEM) based on dam project data was used in order to obtain a more complete picture of seepage, [9]. The modeling has provided insight at the different scenarios of percolation processes depending on the characteristics of the materials used in the dam construction. The mathematical modeling provides the more accurate representation of the behaviour of dam, taking into account the various factors acting on it [10], [11]. The Computational Fluid Dynamics (CFD) methods, which make it possible to simulate and analyse the behaviour of fluids under various conditions, are used in order to solve the complex problems of fluid movement [12]. The Self-Potential (SP) method is widely used in the near-surface geophysics due to its versatility and low cost.

The methodology of practical collection, processing, visualization and interpretation of self-potential data is described in [13]. This methodology is applicable to a wide range of tasks using inexpensive measuring equipment. High values of SP are primarily associated with increased moisture content. Accordingly, they are the signs that determine the location of fluid flow paths through the body of earthen dam [14]-[16]. In [17], an equation characterizing the dependence of SP on water flow and ion diffusion was derived. The constructed three-dimensional models of SP field at different water levels in the reservoir and changes in the hazard level allowed to conclude that the SP values directly depend on the water level difference and the size of leakage channel.

Geophysical methods are indirect, so combinations of different geophysical methods are usually used to increase the information content. For example, a combination of ERT and Induced Polarization (IP) methods was applied in order to determine the hydrodynamic and structural stability of earth dam in Rio de Janeiro, Brazil [18]. The results of IP method complemented the information obtained by the ERT method. In particular, they were able to determine more accurately whether the anomalous ERT readings are due to water-saturated soil or clay. The combined use of ERT and SP methods is quite effective in determining more accurately the location of seepage paths through the earth dam body [19]. Data obtained from geologic boreholes were used to verify the results of electrometric measurements. The researchers had used a combination of ERT, IP and SP methods with the aim of determining the likely pathways of water infiltration through the body of Wolf Creek Dam, Missouri, USA [20]. The results of different methods have complemented each other, which speaks in favour of using such a set of electrometric methods. The effectiveness of using the geophysical complex consisting of different electrometric methods was confirmed by the results of study [21]. The researchers have applied the SP method together with the Vertical Electrical Sounding (VES) method. Two-

dimensional Electrical Resistivity Imaging (ERI) was used to present the results. The results of the combined use of SP, VES, and ERI have showed quite well the anomalous seepage areas in the body of dam as well as at its base. An Electromagnetic sounding (EM) is also used as a first step in order to identify the most weakened areas of dams [22]. Based on the EM results obtained by the GEM2 device, the more detailed assessment of the problem areas of the dam body was then carried out using the ERT and SP methods. All three methods showed the similar characteristics of anomalous zones. One of the modern non-invasive methods of controlling the internal condition of earth dams is the Ground Penetrating Radar (GPR) method, which has been actively used to solve various geotechnical problems. The method is based on the phenomenon of electromagnetic wave reflection from the boundaries of inhomogeneities in the medium under study. In this case, the electrical properties - electrical conductivity or dielectric permittivity - change abruptly.

[23] summarizes the results of the GPR application by examining the state of reservoir dams in Kazakhstan. The studies have shown the decompression zones and voids in the dam body filled with water. Under certain scenarios, they can cause the development of destructive processes that will lead to the dam failure. The quality of the interpretation of GPR measurements largely depends on the experience of geophysicists. The development of neural networks has made it possible by applying their capabilities in order to help the geophysicists. The paper [24] shows an example of the detection of disturbed zones on GPR sections using the You Only Look Once v5s (YOLOv5s) neural network model. The geophysical complex of ERT, GPR and EM methods was applied to determine the internal condition of earthen fishpond dam built in the 15th century in the Czech Republic [25]. As it was old, there was no primary information about its structure and lithologic composition. The applied complex was able to identify the level of the dam crest before previous rehabilitation works, the location of spillways, caverns and water saturation distribution. However, only the ERT method was effective for determining the dam foundation boundary. One of the methods of engineering geophysics, Multichannel Analysis of Surface Waves (MASW), is used to study the upper part of section.

MASW allows obtaining a two-dimensional vertical profile of transverse wave velocities. The method is based on the phenomenon of frequency dispersion of surface waves in layered media. MASW seismic survey is attractive due to relative cheapness and simplicity of field measurements and the possibility of obtaining information about the elastic parameters of layered soil strata.

Therefore, this method has been applied in the assessment of the internal condition of earthen dams. At high water saturation level, the transverse S-wave velocity (V_s) and, accordingly, the shear modulus, which correlates with V_s , decreases. At shallow depths, the method allows us to identify areas with lower velocities associated with wetted or less compacted zones [26]. The MASW method was used in conjunction with the SP and ERT electrical

survey methods for the survey of the Chimney Rock dam, Oklahoma, USA, which had a visually enhancing leakage [27]. This combination of methods provided valuable information about the internal structure of dam, seepage zones, their origin and distribution. The ERT method was combined with Seismic Refraction (SR) and MASW in the investigations described in [28], [29]. The studies have shown that the integration of electrometric and seismic methods improves the characterization of dams and erosion zones. The complexes consisting of electrometric, GPR and seismic methods have also been used for the comprehensive studies of different physical characteristics of the environment [30], [31]. In addition to geophysical methods, the geochemical analysis of water samples is used to determine the source of water whenever possible [32], as well as laboratory analysis of sediment samples from the reservoir bed [33], [34]. The electrical, hydraulic loggings and core analysis from wells, help confirm the lithologic information obtained from the interpretation of electrical geophysical measurements [34]. This approach provides more detailed information on the geology and filtration pathways, as well as their origin. Monitoring observations are carried out to determine the dynamics of changes in the conditions inside the dam body. In [35], observations were carried out for 10 years using the complex of electrical and seismic methods. Based on the results of study, the weakened zones were identified, to which much attention is paid during operation.

This article discusses the results of applying the SP method in order to assess the internal condition and integrity of the K-25 earth dam in the Almaty region of Kazakhstan. In Section II, the selected object of research, as well as the applied methodology for field measurements, their processing and interpretation, is described. Section III shows the results of SP measurements at different water levels in the reservoir, and Section IV discusses the characteristics of the anomalous zones with a plotting the scheme of leakage zones. The conclusions are described in Section V.

II. Materials and Methods

II.1. Study Object

The subject of geophysical investigations was the earthfill clay dam of K-25 reservoir in the Almaty region.

The height of dam is 18 m, with a length of 156 m and a crest width of 4.5 m. There are the operational pipelines and an emergency spillway within the dam body (Fig. 1).

II.2. Instrumentation and Methodology

The electrokinetic permanent natural fields arise from redox, filtration, and diffusion-adsorption processes in rocks. The most common cause of SP anomalies is groundwater. These anomalies are formed because of water passing through the resistive medium or the participation of water in the chemical processes occurring in the rock [36].

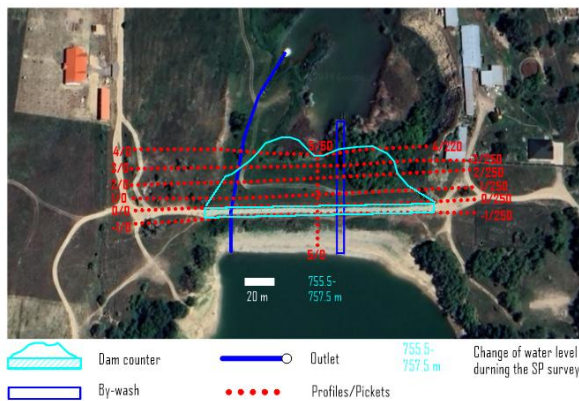


Fig. 1. Scheme of geophysical surveys

Due to the different mobility of cations and anions in the groundwater of different concentrations, an uneven distribution of charges occurs, which leads to the creation of natural electric fields of diffusion nature. The magnitude and sign of diffusion potentials depend on the adsorption properties of minerals, i.e. on the ability of small and colloidal particles to retain ions of a certain sign on their surface. Therefore, the potential differences arising during diffusion in rocks with groundwater of different concentrations are called diffusion-adsorption potentials. The natural potentials are also observed during the groundwater movement (filtration) through the porous rocks. The boundaries and pores in the rock can be considered capillaries, the walls of which can adsorb ions of the same sign (usually negative). The charges of the opposite sign accumulate in the liquid medium. The greater the speed of groundwater movement (or pressure at the ends of capillaries), the greater the potential difference in the natural electric field. The SP sign depends on the direction of groundwater movement: positive potential increases along the direction of water movement.

II.2.1. Field Survey

Self-potentials can be surveyed in two ways: the potential method, and the potential gradient method [37], [38]. The potential method uses one non-moving electrode as the basis for all other measurements. Another electrode is moved between the base point and all observation points along the surveyed profile or area. The potential difference, i.e. SP, is recorded between the points. The survey result is displayed depending on the distance from the base station. The strong negative anomalies indicate the mineralization. The fixed-base method is good at detecting small anomalies and is more accurate than the gradient method. At the potential gradient method, two electrodes located at a constant distance from each other are moved simultaneously along profiles to measure SP.

The advantage of the gradient method is that a 10-meter wire between the two electrodes is sufficient for the survey. However, at the same time, it gets an error at each measurement. Summing all gradient measurements increases the error. As a result, the small anomalies may

not be detected. The potential method was applied for the geoelectric observations at the dam of the K-25 reservoir in the Almaty region. The measurements were carried out along six longitudinal profiles, each approximately 220–250 m in length, and one transverse profile 60 m in length (Fig. 1). Profile 0 was laid along the crest of dam, profiles -1 on the upper berm, and profiles 1–4 along the downstream slope. Three measurement cycles were conducted (from August 26, 2019 to October 27, 2019) during a gradual water release from the reservoir with a one-month interval, resulting in a total water level reduction of 2 meters, with measurements taken every 5 meters. Measurement points were designated as 1/20, where 1 indicates the profile number and 20 indicates the point number. The potential measurements were conducted using the VPF-210 device with the copper-sulfate non-polarizable electrodes. The repeat and control observations were carried out for each profile point.

II.2.2. Processing and Interpretation

The qualitative assessment of the anomalies of self and flow potentials is applied in most studies. At the first stage of EP data processing, the potential graphs are constructed along the profiles, and all values are reduced to one conventionally selected zero. One of the "normal field" points is chosen as a common zero point. After bringing all values to zero, the obtained data are reorganized in the form of graph plan and the plan of potential isolines. With their help it becomes possible to carry out the interpretation at a qualitative level: to determine the size and extent of anomalous zones, to predict the nature of identified anomalous zones, to estimate the depth of occurrence of objects that are the source of anomalies. The outflow of fluid through the dam body creates the negative relative potentials. The fluid inflow leads to the positive potentials. The processing and interpretation of SP data were performed in the following sequence:

- Assessment of survey quality based on the repeat and control observations, with a measurement error not exceeding ± 1.0 mV for the repeat measurements and ± 2.5 – 3.0 mV for the control measurements;
- Calculation of SP dispersion values based on three measurements at the different water levels in the reservoir: 757.5, 756.0, and 755.5 m;
- Interpretation of SP dispersion distribution across the surveyed area;
- Analysis of SP potential variation patterns associated with the filtration processes.

The results of the survey quality assessment based on the repeat observations are presented for longitudinal profile 1 (Fig. 2). As indicated by the data, the average measurement error over all three cycles (August 26, 2019 to October 25, 2019) for this profile did not exceed ± 1.0 mV. Overall, the discrepancies across all 7 profiles within K-25 dam body were approximately ± 0.9 mV. The results of control observations on the longitudinal profile 0 are presented in Fig. 3. The obtained results indicate that the average survey error does not exceed ± 1.6 mV.

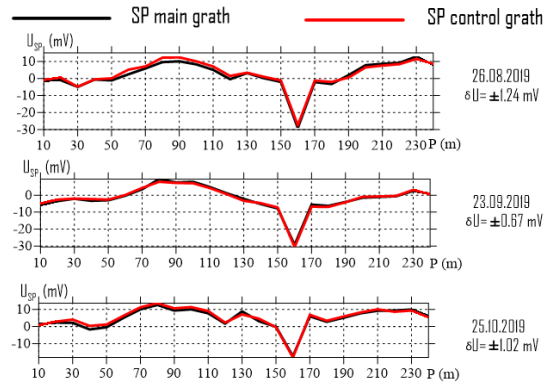


Fig. 2. Assessment of SP survey quality for the profile 1

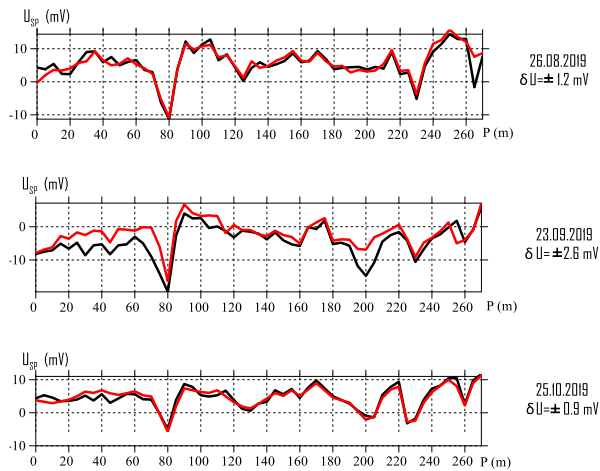


Fig. 3. Results of control observations for the longitudinal profile 0

Overall, the data on SP survey accuracy assessment demonstrate the effectiveness of the equipment and measurement methodology applied.

III. Results

Following the interpretation, the SP contour maps were constructed based on the observed and correlated fields for each measurement cycle. Fig. 4 depicts the observed field during the successive reduction of water levels in the reservoir. A common trend in the distribution of SP values across all measurement cycles is an increase towards the downstream berm. In principle, the elevation could be interpreted as having a filtration nature. However, it should be noted that the most contrasting zones (A1 and A2) were practically only evident along profile 3 line, which, if not correlated, may lead to the erroneous interpretation of data. Regarding the anomalous zone A3, it is worth noting that it is located in the area intersecting with the active spillway and profiles 0, 1, and 2. The dynamics of SP value changes in this anomalous zone are ambiguous. The most significant differences were observed when the water level decreased to 755.5 m, where the intensity and dimensions of area with the elevated SP values substantially decreased against their negative values. The probability of this anomalous zone

formation due to water runoff along the relief is considered. To some extent, the situation with anomalies became clearer after the correlating the potential differences with measurements along the transverse profile 5. The main trend in the distribution of the correlated potential field (Figs. 5b, c, d) is the presence of contrasting zones with the elevated values of this parameter in the northeastern (A1) part of the surveyed area and in the area adjacent to the operational pipeline (A2), where the constant water discharge occurs.

Additionally, a series of zones A3 with anomalously reduced SP values were identified in the areas adjacent to the base of dam. The SP values in zone A4 (Fig. 4) were levelled after the correlation with measurements along the transverse profile 5 and are no longer anomalously reduced (Fig. 5).

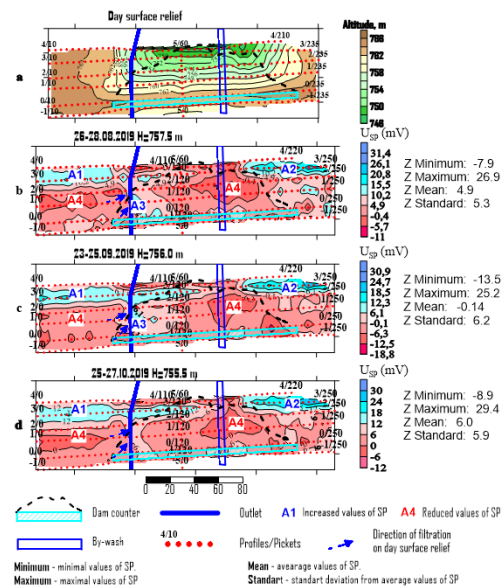


Fig. 4. Observed self-potential field at various water levels in the reservoir

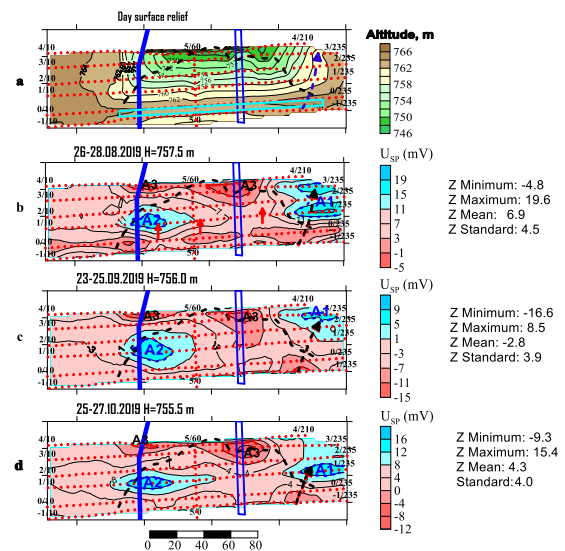


Fig. 5. Correlated (b, c, d) SP field at various water levels in the reservoir (Fig. 4 for the legends)

IV. Discussion

IV.1. Anomalous Zone A1

Most prominently manifested at the maximum water level in the reservoir of 757.5 m (Fig. 5). Considering that there is an increase of potential difference towards this zone from the crest, it is plausible that this circumstance could be caused by the local filtration flow. An indirect confirmation of the presence of such water flow could be seen in the reduced intensity and dimensions of anomalous zone A1 with further reduction of the water level to 756.0 m in the reservoir (Fig. 5). However, a renewed increase of the dimensions of anomalous Zone A1 and an intensification of the potential difference U_{SP} within this zone were observed with a subsequent decrease in the water level by 0.5 m to 755.0 m. The identified fluctuations in the parameters of anomalous zone A2 between the second and third observation periods are correlated with the changes of the volume of water discharge, the increase of the load to the dam body, and, consequently, intensification of water flow filtration.

IV.2. Anomalous Zone A2

Anomalous zone A2 is spatially correlated with the active spillway. Considering that the most significant changes in the configuration and intensity of this anomaly were observed during the third measurement cycle (755.5 m) (Fig. 5), there is a possibility of its filtration nature, associated with the ascending water flows from the leak points of active pipeline. However, the epicenter of this anomaly is located approximately 15 meters away from the pipeline, which is distinctly marked in the observed field by a minimum. In this regard, it is entirely possible that the anomalous zone A2 is formed by the integrated effect of the heterogeneity of the dam body structure, predominantly sandy soils in this part, and the possible leakage from the active pipeline.

IV.3. Group of Zone A3 Anomalies

The maximum intensity of these anomalies is recorded in the area of the existing and emergency spillways, located practically at the daylight surface. Given this circumstance, the oxidative-reductive nature of these anomalies in the zone 3 is most probable. However, one of them, located in the area of the emergency spillway, considering the dynamics of its dimensions, especially between the first and second measurement cycles (Fig. 5), which is similar to anomalous zone A1, may well be due to the drainage effect at the dam base. Overall, as evident from the data presented, the interpretation of SP anomalies in the traditional manner can be considered conditional due to the ambiguity of diagnosing the observed anomalous effects and heterogeneities of the dam body.

The elements of mathematical statistics, particularly dispersion analysis, were applied in order to enhance the reliability of diagnosing U_{SP} effects related to the filtration processes. The dispersion σ^2 was calculated for each point

of triple observation using the formula:

$$\sigma^2 = \frac{\sum (x_i - \bar{x})^2}{n}$$

where x_i is the observed value, $\bar{x}$ is the sample mean value, n is the sample size. Before calculating this parameter, the regional component of U_{SP} was excluded from the observed field along each profile based on its trend. An example of such calculation of the parameter σ^2 is presented in Fig. 6, illustrating the presence of the clear anomalous zone in the interval of points 100-150, which is problematic to detect in the U_{SP} field. Data on the distribution of dispersion $\sigma^2 U_{SP}$ throughout the tablet are presented in Fig. 7, with the contour lines of this parameter accepted to be equal to the standard deviation from the mean – 1.3. As seen in the figure, the most contrasting dispersions of elevated U_{SP} values are established in the space between the water discharge pipelines and in the immediate vicinity of these pipelines. Among them, the anomalous zone D1/1 appears to be the most intense, characterized by its extension along the northwest boundary of the embankment body, up to its base. This zone is interpreted as the area of maximum manifestations of filtration processes in the dam body. Anomalous zones D1/2, D1/3, and D1/4, where maximum U_{SP} dispersion values are recorded, are localized along the profile line -1, laid along the upper berm. Considering the configuration of the contour lines of elevated dispersion values, they can be combined with zone D1/1 into one area of increased filtration. Anomalous zone D2 is detected on the eastern flank of dam in the area adjacent to its crest. The presence of this zone practically confirms the filtration origin of anomaly A1 in the potential difference field and specifies the planned position and direction of local filtration in the embankment part of dam.

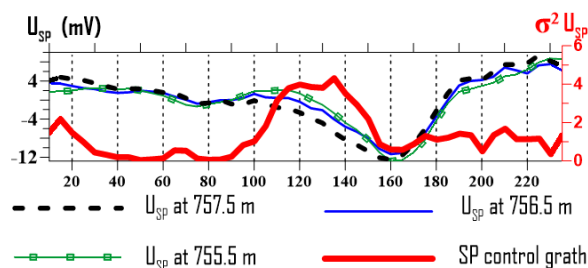


Fig. 6. Results of U_{SP} dispersion calculation for profile 3

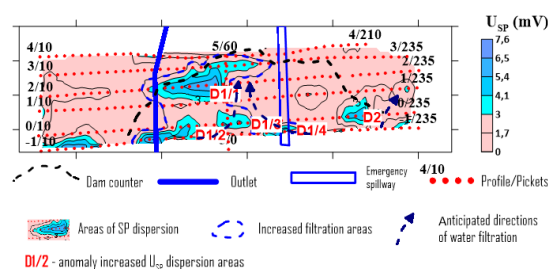


Fig. 7. Map of SP dispersion at the reservoir water level change

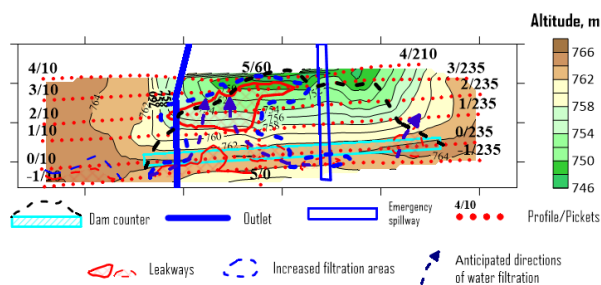


Fig. 8. Scheme of seepage zones in the dam body

The area of probable water filtration in the dam body (Fig. 8), compiled based on the dispersion $\sigma^2 U_{SP}$ parameter, demonstrates the most intensive water seepage in the northwestern and central embankment parts. The peculiarity of zone D2 is its lesser expression in the dispersion parameter. Moreover, the extension of this zone towards the relief depression and practically across the sideboard may contribute to its destruction. Considering that this sideboard is located in the depressed part of daylight relief, additional destructive action of atmospheric precipitation can be expected here. The question of the combined diffusion-adsorption and filtration origin of anomaly D1/1 can be resolved using the seismic survey data.

V. Conclusion

The study was carried out using SP measurements along 7 profiles at different levels of reservoir filling.

During the processing of the obtained data of field measurements by anomalous effects in the self-potential dispersion parameter, the zones presumably related to filtration processes were identified, which require elucidation of their nature and determination of filtration characteristics. Based on the results of qualitative interpretation, the scheme of local areas with increased water filtration in the dam was drawn up. The results have showed the dependence of the infiltration intensity and the size of water-saturated zones on the hydrodynamic regime of the reservoir. The areal electrical survey by the SP method in the variant of regime observations has shown its high efficiency in detecting filtration zones of jet water in the loamy body of dam and mapping them in the plan.

At the same time, the increase of reliability of diagnostics of anomalous effects related to filtration processes was provided by the attraction of the electric potential dispersion parameter. In order to improve the reliability and efficiency of diagnostics of the internal condition of earth dam, the authors plan to expand the range of applied geophysical methods in further studies.

In addition, the seismic, georadar and other electrical methods will be used and their results will be compared with the data of geological and hydraulic engineering surveys. The measured parameters of geophysical fields (potential difference, apparent resistivity, time and velocity of elastic waves propagation, their attenuation) will complement each other. The interpretation of these

fields will make it possible to detect at an early stage the destructive changes in the dam body associated with the process of soil decompaction, primarily with the development of water-saturated seepage zones, and to predict their further behaviour. The methodology applied in this study can be used for the express analysis of the natural state of earth dams during the geotechnical monitoring to ensure the safe operation of similar structures in Kazakhstan. The identification of potential water infiltration locations in the dam body will contribute to the implementation of preventive measures to reduce the probability of structural instability and dam failure.

Acknowledgements

This work has been funded by the Committee of Science of the Ministry of Science and Higher Education of the Republic of Kazakhstan (Grant No. AP14869144).

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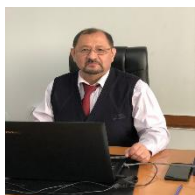
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