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The GPR survey method in combination with destructive testing methods for the hydraulic structures technical condition studying

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Abstract. The study examined the technical condition of hydraulic structures (HS) to plan their reconstruction, restoration and development of protective measures. The Sarpinskaya Watering and Irrigation System (SWIS) in the Republic of Kalmykia was the object of study. Promising research and monitoring methods were used: testing of concrete core samples using universal testing machine MIM.4-1000 and ground penetrating radar probing (by the GPR OKO-3) with ground penetrating radar survey of HS. Based on the results obtained, it can be concluded that concrete and reinforced concrete structures on the territory of the SWIS (namely, pumping station No. 1) have low strength, which is explained by their long service life and the lack of major repairs. The studied core samples collapsed under a minimum load of 116...118 kN. This indicates severe wear of the concrete coating of HS, aggravated by the close occurrence of groundwater. Further destruction of the concrete coating is inevitable, and therefore urgent repair and reinforcement of the structures are required. The data obtained will be used as a basis for conducting an examination necessary for operational monitoring of the SWIS and decision-making, when developing protective measures to strengthen the structures.

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1. Introduction

Irrigation canals and hydraulic structures (HS) play a key role in agriculture, providing a constant water supply for irrigation of fields. During the operation of HS, various types of damages occur. The study of the technical condition of HS is important for planning their reconstruction, restoration and development of further protective measures. Under conditions of intensive operation and exposure to natural factors, the following main types of damage occur on HS [1]: corrosion of water-saturated concrete in the zone of variable water level due to alternate freezing and thawing; mechanical damage to concrete masonry (chipping of corners of elements, crushing of concrete in separate zones, etc.); cracks caused by shrinkage or reaction of cement alkalis with aggregates containing active silica, and others.

Such scientists as V.S. Altunin, G.T. Balakay, A.V. Kolganov, B.S. Maslov, V.V. Noskewich, G.M. Nigmetov, I.V. Olgarenko, V.N. Shchedrin and others studied the technical condition of reclamation systems [2–9]. The main direction in the works of these authors was the assessment of the condition of HS under construction and those already built where the main goal was to expand knowledge for further verification of design solutions and the formation of a regulatory and methodological framework.

M.L. Vladov, D.V. Dmitrievtsev, A.D. Zhigalin, O.Kh. Zhukov, S.V. Izumov, K.T. Iskakov, V.V. Kapustin, A.N. Ryzhakov, D.A. Solodovnikov, M.P. Shirobokov and others were engaged in research using ground penetrating radar (GPR) surveys [10–17]. The authors study and consider the issues of complex application of geophysical methods at the stages of design, construction and reconstruction of hydro-reclamation systems, with a description and operation of GPR and the use of the radar sounding method.

The work of D.A. Solodovnikov, N.M. Khavanskaya, N.V. Vishnyakov, A.A. Ivantsova, based on the use of geophysical monitoring, showed that the results of the using GPR monitoring contain more objective information about the depth of the groundwater table. Combining GPR profiling with a hypsometric profile of the terrain allows one to build a model of groundwater dynamics [14].

Such scientists as V.V. Borodychev, E.B. Dedova, A.V. Kolganov, T.N. Mandzhieva, V.A. Suprun, R.M. Shabanov and others conducted their research on the territory of the Sarpinskaya Watering and Irrigation System (SWIS) [18–24]. The research involves environmental monitoring of water bodies in the Republic of Kalmykia, including the SWIS, using methods of studying the biogeocenosis of inland water bodies.

The SWIS was chosen as the object of the present study. It is one of the largest objects of the reclamation complex of the Republic of Kalmykia. The climate of the republic can be characterized as sharply continental, semiarid and arid with cold winters (minimum temperature –37 °C) and hot summers (maximum temperature +44 °C). The SWIS was put into operation in 1968 and was used mainly for irrigation of rice fields. The water source of the system is the Volga River, on the bank of which, near Raygorod (the Volgograd Region), there is a water intake of a machine water lift that supplies irrigation water to the system. Water losses amount to 59 % of the annual volume of water intake (data obtained from the administration of the Oktyabrsky District of the Republic of Kalmykia). Most of the losses are associated with the physical wear of the system, equal to 92 % (data obtained from the administration of the Oktyabrsky District of the Republic of Kalmykia). During the entire period of operation of the system, only routine repairs of pumping stations (NS-2, NS-8, NS-9, etc.) were carried out, as well as repairs of earth dams and emergency repairs of failed system elements.

The republic is one of the most water-deficient regions of Russia. It is not provided with sufficient surface water resources, and the mineralization of the groundwater used for the needs of the population is constantly increasing. In some places, the mineralization index of natural groundwater is close to brines.

Thus, the purpose of this work is to determine the technical condition of the elements of irrigation systems to improve the reliability and environmental safety of their structural elements using non-destructive and destructive testing methods. The objectives of the study are:

- identifying patterns of changes in the physical and mechanical properties of materials of structures and structures during operation and obtaining data on the state of reinforcement and concrete in the studied samples from HS;
- obtaining up-to-date information on the condition, possible deformations and impacts of a natural and anthropogenic nature on structures using GPR;
- assessing the current technical condition of the elements of the SWIS.

To solve the problems associated with the wear and tear of HS and their timely repair, a more accurate assessment and forecast of the service life of HS is required. In accordance with the state assignment, field studies of the technical condition of HS at the SWIS were carried out in 2023. The results of these studies will help to identify defects and problem areas. It is necessary to develop a set of measures to improve the reliability and safety of HS, including more economically viable ways of current repair of structures.

2. Methods and Materials

2.1. SWIS

The SWIS is located in the north-east of the Republic of Kalmykia, in the Oktyabrsky and Maloderbetovsky Districts. The following types of soil are typical for this area: saline light chestnut and brown semi-desert soils combined with salt marshes [2]. The total amount of precipitation is about 300 mm per year [1]. The average daily temperature varies in summer within the range of +23.5 °C...+25.5 °C, in particularly hot years it reaches an absolute maximum of +40 °C...+44 °C. In winter, the average temperatures are negative –12 °C...–7 °C, the minimum temperature in January is –37 °C...–35 °C. Sometimes the temperature drops to –40 °C and below [3].

2.2. Technical Studies of HS

In 2023, georadolocation survey was carried out at certain SWIS sites in the Oktyabrsky District of the Republic of Kalmykia using the GPR OKO-3. Concrete samples were taken from some sections of the concrete lining of the drainage channel for further study in the laboratory (Fig. 1).

Figure 1. Places of concrete cores sampling.

To obtain complete and accurate information about the HS condition, a destructive testing method, “Core sampling and testing” was used, which was carried out on selected sections of HS with the use of a diamond drilling rig (Fig. 2).

Figure 2. Process of cutting the cores using a diamond drilling rig.

The cores were taken from the area of pumping station No. 1 of the SWIS. The sampling site was chosen taking into account the minimum possible damage to HS, at a distance of 600 mm from the joints and edges of the coating, in the area free from reinforcement. The number and location of drilling spots are determined by local conditions.

After cutting, the concrete core samples were sent to the laboratory to determine their strength by measuring the minimum force required for destruction. The number of samples in the series was 6 pieces (Fig. 3).

Figure 3. Concrete samples from the SWIS.

Compression tests of samples were carried out in the laboratory of the Federal Scientific Centre of Agroecology, Complex Melioration and Protective Afforestation of the Russian Academy of Sciences on universal testing machine MIM.4-1000 (Fig. 4). The laboratory analysis consisted of a static load with its constant growth rate, and the subsequent calculation of stresses taking into account the elastic work of the material.

Figure 4. Testing of a core sample using a universal testing machine MIM.4-1000.

The cut-out part of the structure used for the testing was formed and hardened during HS construction under the same conditions and under the same load as the rest of the structure, which means that the results of testes represent the state of HS nearby.

However, after the core was extracted, such a structural characteristic as load-bearing capacity of the structure under study may change. Therefore, it is recommended to extract a concrete sample only with the marks made in advance by the developer, so that the loss of a part of the structure would not affect its strength characteristics in any way. The place, from which the core was removed, was filled with concrete and the surface was leveled.

The GPR survey was performed at the place where the core samples were taken (Fig. 1). The GPR survey of HS was carried out using the GPR OKO-3, manufactured by JSC Geotech (Russia), equipped with a 2-frequency antenna unit 150+400 MHz (Fig. 5).

Figure 5. The GPR survey.

Both antennas of the device are shielded, which prevents electromagnetic radiation from entering the upper half-space of the device, and suppresses reflection from objects of the upper half-space [25]. The 150 MHz antenna probes the soil to a depth of up to 12 m with a resolution (minimum size of detectable objects) of 0.35 m. The 400 MHz antenna provides probing to a depth of 5 m but with a more accurate resolution of 0.15 m. In this work, due to the small capacities of the probed soils, the main instrument was the 400 MHz antenna, the 150 MHz antenna served as a control.

The GPR method is based on the reflection of electromagnetic waves from surfaces, on which electrical properties change. It makes it possible to solve a wide range of applied tasks, in particular: the study of geological sections with determination of capacities layers and types of rocks; determination of the position of the groundwater level; identification of defects in building structures; identification of foreign bodies in the ground, and others [12].

The electromagnetic pulse emitted by the GPR is reflected from any objects or inhomogeneities in it that have electrical permeability or conductivity different from the medium. Such inhomogeneities may include voids, interfaces between layers of different rocks, areas with different humidity, etc. The receiving antenna converts the reflected signal into digital and stores it for further processing. When a GPR scans the surface of the area under study, a radar image or profile appears on the screen, which can be used to determine the location, depth and extent of objects.

3. Results and Discussion

The results of the conducted research show that concrete samples taken from the concrete lining of the drainage channel have low strength, which is natural, given the service life of structures and the lack of major repairs of concrete and reinforced concrete structures. The table shows the data obtained in the laboratory of the Federal Scientific Centre of Agroecology, Complex Melioration and Protective Afforestation of the Russian Academy of Sciences using a universal testing machine (Table 1).

Table 1. Research results obtained using the MIM.4-1000 testing machine.

№	Concrete core sample	Sample diameter, mm	Sample length, mm	Mechanical stress $R(cp)$, MPa	Ultimate compressive strength, kN	Year of HS commissioning
1	1	63.40	110	47.1	150	1968
2	2	63.20	111	34.3	148	1968
3	3	63.10	109	41.2	118	1968
4	4	63.40	110	34.3	116	1968
5	5	63.35	110	38.2	118	1968
6	6	63.37	111	29.1	116	1968

From Table 1, it can be seen that samples No. 3, 4, 5, 6 were destroyed at a minimum load of 116...118 kN. These data indicate a strong wear of the concrete coating of HS, which is complicated by the close occurrence of groundwater, which will cause further damage to the coating.

The graph in Fig. 6 shows fluctuations and a subsequent sharp increase in the load during compression of the core sample on a universal testing machine. This graph is typical for all selected cores, since destruction occurs throughout the area under study.

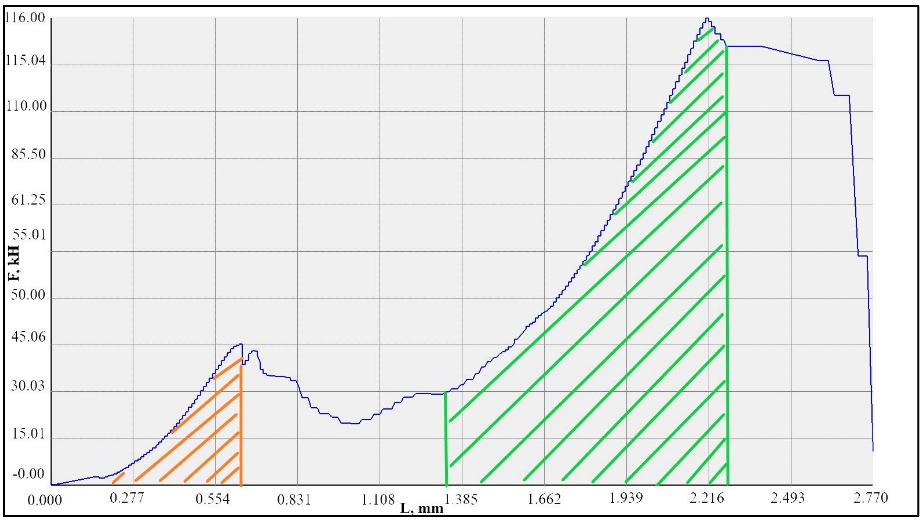

Figure 6. Deformation diagram of the core sample, kN.

When loading the test sample, in the area highlighted in orange in Fig. 6, there is an increase in the deformation curve from 0 to 42 kN. A repeated jump can be observed in the area highlighted in green. In this part, the graph has a stronger amplitude from 30 to 116 kN.

The graph shows that the deformation runs along the layering with an exorbitant characteristic. It follows from this that the site is subject to destruction.

Conducting research using the GPR OKO-3 allowed us to obtain the following results.

1. Graphs of time sections recorded by the variable density method, on which the horizontal axis indicates the distance in meters, and the vertical axis indicates the time of arrival of reflected signals in nanoseconds. In subsequent work in the GeoScan32 program, when processing signals, interference is weakened or removed from the record as much as possible, and useful ones are highlighted [15].
2. The electrical properties of metals are fundamentally different from the properties of any soils, therefore, their detection in the soil by the GPR method does not cause significant difficulties, provided that metal objects are found within the probing depth of the device and linear dimensions exceed the resolution of the device. Concrete structures in the soil also cause changes in the propagation of electromagnetic fields (Fig. 7, 8).

The geoimage (Fig. 7) shows the revealed inhomogeneities of the body: surface local fractures and voids in the reinforced concrete structure of the structure, when scanning with the antenna side of the AB 150/400 MHz, having a width in plan of 0.5...1.5 m and directed across the body of the dam. In this image, we can observe fluctuations through the entire body of the concrete channel bed and up to 12.5 m, which can be formed by voids in the body of the dam [25].

Fig. 8 shows the result of a detailed study of the zone, which was carried out by scanning using the AB 150/400 MHz antenna unit. Some of these zones are visually distinguishable in the lower part of the slope in the form of leaks and filtration passing through the body of the structure. This filtration can be traced from a depth of 0.06–0.40 m to the groundwater level.

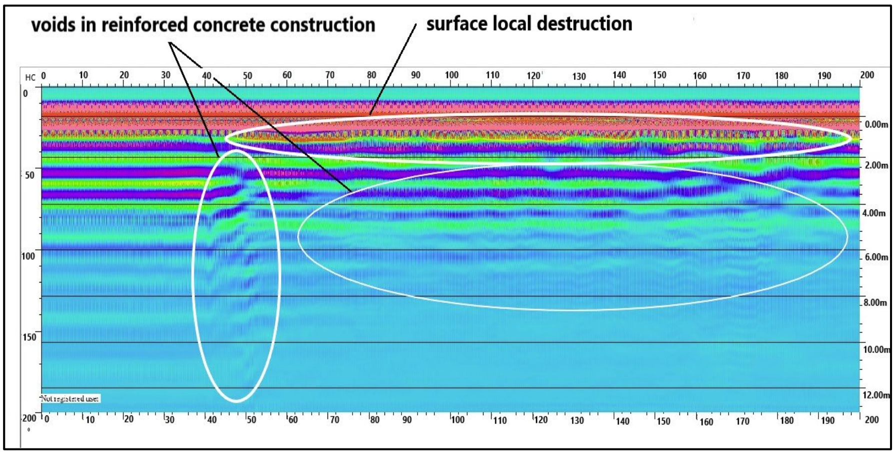

Figure 7. Image from the GPR OKO-3.

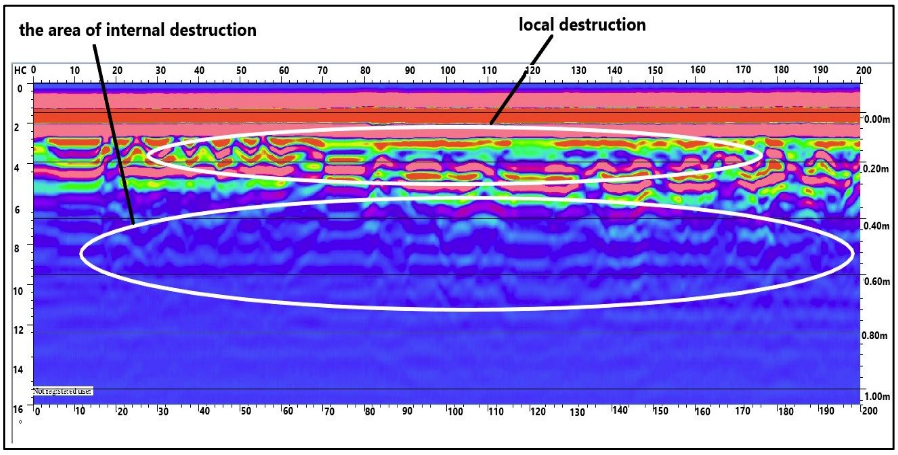

Figure 8. Image from the GPR OKO-3.

4. Conclusions

Based on the results obtained, it can be concluded that:

1. Concrete and reinforced concrete structures on the territory of the SWIS, namely pumping station No. 1, have low strength, which is due to the long service life of the structures and the lack of major repairs. Tests of concrete core samples showed that the samples collapsed at a minimum load of

116...118 kN. This indicates severe wear of the concrete coating of HS, which is aggravated by the close occurrence of groundwater. Further destruction to the concrete coating is inevitable, which requires urgent repair and reinforcement of the structures.

2. The study of the concrete coating using the GPR method on the territory of the SWIS using the GPR OKO-3 with a 2-frequency antenna unit of 150+400 MHz during the diagnosis of the technical condition allowed us to identify the following. Pronounced voids of soil decompression under the concrete base of the body of the dam. Water filtration points through the body of the dam. All of them are characterized by an increase in soil moisture from 3 to 40 %, interpreted through a change in its dielectric constant, which leads to the expansion of the concrete base of a part of HS. Due to the rise of groundwater to the base of the body of the dam, the strength of individual elements of HS is subjected to greater wear, which will lead to the rapid destruction of the concrete coating.

3. The use of non-destructive testing methods, using modern equipment, allows us to carry out a survey of HS with high accuracy and to identify problem areas in time to further ensuring the safety of HS and the rational use of water resources for the development of the agricultural potential of the region.

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