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RESEARCH ARTICLE

NON-DESTRUCTIVE GROUND PENETRATING RADAR INSPECTION OF HYDRAULIC STRUCTURES USING THE OKO-3 GEORADAR FOR DETECTION OF HIDDEN DEFECTS AND ASSESSMENT OF TECHNICAL CONDITION

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Abstract. *This paper presents the results of a Ground Penetrating Radar (GPR) survey of the earth-fill dam of the Tasotkel Reservoir located in the Zhambyl Region of the Republic of Kazakhstan. The relevance of the study is associated with the need to improve the reliability and safety of hydraulic structures operating under long-term service conditions and seismic activity. The aim of the study is to evaluate the effectiveness of the GPR method for detecting hidden defects, moisture-rich zones, and local heterogeneities within the dam body and foundation. The investigations were carried out using the OKO-3 Ground Penetrating Radar system equipped with 250, 400, and 900 MHz antennas. A comprehensive inspection algorithm was developed and validated, including collection of initial data, field measurements along longitudinal and transverse survey profiles, digital signal processing, and engineering interpretation of radargrams. Data processing involved dewow filtering, band-pass filtering, signal gain correction, time-zero correction, and migration of reflected signals. The obtained results showed that the dam body is generally characterized by a stable and relatively homogeneous layered structure. Continuous reflecting horizons were identified on most profiles without indications of critical disturbances. Local loosening zones were detected at depths of 0.5-1.5 m, while areas of increased moisture content were identified at depths of 1.0-3.0 m, manifested by signal attenuation and scattered reflection patterns. Hyperbolic anomalies associated with local heterogeneities of the soil mass were recorded on several profiles. The probable contact boundary between the dam body and the foundation was traced at depths of approximately 3.5-4.5 m and exhibited a relatively stable character. It was established that the actual piezometric levels are 3.1-7.2 m lower than the design values, indicating satisfactory seepage conditions and high drainage capacity of the foundation soils.*

Keywords: *hydraulic structures, Ground Penetrating Radar, earth-fill dam, non-destructive testing, seepage, loosening, moisture content.*

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ҒЫЛЫМИ МАҚАЛА

ЖАСЫРЫН АҚАУЛАРДЫ АНЫҚТАУ ЖӘНЕ ТЕХНИКАЛЫҚ ЖАҒДАЙЫН БАҒАЛАУ ҮШІН ОКО-3 ГЕОРАДАРЫН ҚОЛДАНА ОТЫРЫП ГИДРОТЕХНИКАЛЫҚ ҚҰРЫЛЫМДАРДЫ БҰЗБАЙ ГЕОРАДИОЛОКАЦИЯЛЫҚ ЗЕРТТЕУ

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Аңдатпа. Мақалада Қазақстан Республикасының Жамбыл облысында орналасқан Тасөткел су қоймасының топырақты бөгетіне жүргізілген георадиолокациялық зерттеу нәтижелері ұсынылған. Зерттеудің өзектілігі ұзақ мерзім пайдаланылып келе жатқан және сейсмикалық белсенді аймақтарда орналасқан гидротехникалық құрылымдардың сенімділігі мен қауіпсіздігін арттыру қажеттілігімен байланысты. Жұмыстың мақсаты - бөгет денесі мен негізіндегі жасырын ақауларды, ылғалдылығы жоғары аймақтарды және жергілікті біртектіліктерді анықтау үшін георадиолокациялық әдістің тиімділігін бағалау. Зерттеулер 250, 400 және 900 МГц жиілікті антенналармен жабдықталған ОКО-3 георадары арқылы орындалды. Бастанқы мәліметтерді жинау, бойлық және көлденең профильдер бойынша далалық өлшеулер жүргізу, сигналдарды цифрлық өңдеу және радарограммаларды инженерлік интерпретациялау кезеңдерін қамтитын кешенді зерттеу алгоритмі әзірленіп, тәжірибеде сыналды. Мәліметтерді өңдеу барысында төмен жиілікті дрейфті жою, жолақтық сүзгілеу, сигналды күшейту, нөлдік уақытты түзету және шағылған сигналдарды миграциялау процедуралары қолданылды. Зерттеу нәтижелері бөгет денесінің жалпы алғанда тұрақты және салыстырмалы түрде біртекті қабатты құрылыммен сипатталатынын көрсетті. Профильдердің басым бөлігінде күрделі бұзылулардың белгілерінсіз үздіксіз шағылысу горизонттары анықталды. Тереңдігі 0,5-1,5 м аралығында жергілікті тығыздығы төмен аймақтар, ал 1,0-3,0 м тереңдікте сигнал амплитудасының әлсіреуі мен шағылысулардың шашыраңқы сипатымен ерекшеленетін ылғалдылығы жоғары аймақтар анықталды. Жекелеген профильдерде топырақ массивінің жергілікті біртектіліктерімен байланысты гиперболалық аномалиялар тіркелді. Бөгет денесі мен негіз арасындағы ықтимал шекара шамамен 3,5-4,5 м тереңдікте анықталып, салыстырмалы түрде тұрақты сипат көрсетті. Нақты пьезометриялық деңгейлердің жобалық мәндерден 3,1-7,2 м төмен екендігі анықталды, бұл бөгеттің фильтрациялық жағдайының қанағаттанарлық деңгейде екенін және негіз топырақтарының жоғары дренаждық қабілетін көрсетеді.

Түйін сөздер: гидротехникалық құрылымдар, георадиолокация, топырақты бөгет, бұзбай бақылау, фильтрация, тығыздығы төмен аймақтар, ылғалдылық.

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НАУЧНАЯ СТАТЬЯ

НЕРАЗРУШАЮЩЕЕ ГЕОРАДИОЛОКАЦИОННОЕ ОБСЛЕДОВАНИЕ ГИДРОТЕХНИЧЕСКИХ СООРУЖЕНИЙ С ПРИМЕНЕНИЕМ ГЕОРАДАРА ОКО-3 ДЛЯ ВЫЯВЛЕНИЯ СКРЫТЫХ ДЕФЕКТОВ И ОЦЕНКИ ТЕХНИЧЕСКОГО СОСТОЯНИЯ

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Аннотация. В статье представлены результаты георадиолокационного обследования грунтовой плотины Тасоткельского водохранилища, расположенного в Жамбылской области Республики Казахстан. Актуальность исследования обусловлена необходимостью повышения надежности и безопасности гидротехнических сооружений, эксплуатируемых в условиях длительного срока службы и сейсмической активности. Целью работы является оценка эффективности георадиолокационного метода для выявления скрытых дефектов, зон повышенного влагосодержания и локальных неоднородностей в теле плотины и основании. Исследования выполнены с использованием георадара ОКО-3 с антеннами частотой 250, 400 и 900 МГц. Разработан и апробирован комплексный алгоритм обследования, включающий сбор исходных данных, полевые измерения по системе продольных и поперечных профилей, цифровую обработку сигналов и инженерную интерпретацию радарограмм. Обработка данных выполнялась с применением процедур удаления низкочастотного дрейфа, полосовой фильтрации, усиления сигнала, коррекции нулевого времени и миграции отражений. По результатам исследований установлено, что тело плотины в целом характеризуется устойчивой и относительно однородной слоистой структурой. На большинстве профилей прослеживаются непрерывные отражающие горизонты без признаков критических нарушений. Выявлены локальные зоны разуплотнения на глубине 0,5-1,5 м, а также участки повышенного влагосодержания на глубине 1,0-3,0 м, проявляющиеся снижением амплитуды сигнала и рассеянным характером отражений. На отдельных профилях зафиксированы гиперболические аномалии, связанные с локальными неоднородностями грунтового массива. Вероятная граница контакта тела плотины с основанием прослеживается на глубине около 3,5-4,5 м и имеет относительно устойчивый характер. Установлено, что фактические пьезометрические уровни находятся ниже проектных значений на 3,1-7,2 м, что свидетельствует об удовлетворительном фильтрационном состоянии сооружения и высокой дренирующей способности основания.

Ключевые слова: гидротехнические сооружения, георадиолокация, грунтовая плотина, неразрушающий контроль, фильтрация, разуплотнение, влагосодержание.

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CONFLICT OF INTEREST

The authors state that there is no conflict of interest.

During the preparation of this manuscript, the authors used artificial intelligence tools solely for editorial assistance, such as improving phrasing and checking grammar, spelling, and punctuation. All ideas, interpretations, and conclusions are the responsibility of the authors, who take full accountability for the content of the article.

АЛҒЫС/ҚАРЖЫЛАНДЫРУ КӨЗІ

Зерттеу Қазақстан Республикасы Ғылым және жоғары білім министрлігі Ғылым комитетінің № AP23487624 ғылыми жобасы аясындағы қаржылық қолдауымен орындалды.

Авторлар зерттеулерді нысанда жүргізуге мүмкіндік жасап, көрсеткен қолдауы мен көмегі үшін Жамбыл облысындағы «Қазсушар» РМК Тасөткел су қоймасының басшылығы мен мамандарына шынайы алғыстарын білдіреді.

МҮДДЕЛЕР ҚАҚТЫҒЫСЫ

Авторлар мүдделер қақтығысы жоқ деп мәлімдейді.

Мақаланы дайындау барысында авторлар жасанды интеллект құралдарын тек редакциялық көмек мақсатында пайдаланды: тұжырымдарды жетілдіру, грамматикалық, орфографиялық және тыныс белгілеріндегі қателерді тексеру үшін. Барлық идеялар, интерпретациялар мен қорытындылар авторларға тиесілі және олар мақаланың мазмұнына толық жауапты.

БЛАГОДАРНОСТИ/ИСТОЧНИК ФИНАНСИРОВАНИЯ

Исследование выполнено при финансовой поддержке Комитета науки Министерства науки и высшего образования Республики Казахстан в рамках научного проекта № AP23487624.

Авторы выражают искреннюю благодарность руководству и специалистам Тасоткельского водохранилища РГП «Казводхоз» Жамбылской области за содействие, оказанную помощь и предоставленную возможность проведения натурных исследований на объекте.

КОНФЛИКТ ИНТЕРЕСОВ

Авторы заявляют, что конфликта интересов нет.

При подготовке рукописи авторы использовали инструменты искусственного интеллекта исключительно для редакторской поддержки: корректировки формулировок, проверки грамматических, орфографических и пунктуационных ошибок. Все идеи, интерпретации и выводы принадлежат авторам, которые несут полную ответственность за содержание статьи.

1 INTRODUCTION

Hydraulic structures (HSs) are classified as high-responsibility engineering facilities. Their failure can result in significant economic, environmental, and social consequences. A considerable proportion of existing hydraulic structures have been in operation for more than 30-50 years. Under such conditions, the probability of accumulation of hidden defects significantly increases. According to inspection data, the proportion of internal damage reaches 40-60% of the total number of detected defects. The most critical defects are those localized within the body of the structure and in the contact zone with the foundation (Ilyassova et. al., 2025, Moldamuratov et. al., 2025).

The operation of hydraulic structures occurs under a complex combination of loads. These include hydrostatic pressure, seepage flows, and temperature-induced deformations. In seismically active regions, additional dynamic loads are imposed on the structure. Repeated loading cycles contribute to the development of microcracks with widths below 0.05-0.30 mm. Over time, these defects evolve into macrodefects, voids, and zones of loosening. Seepage channels may subsequently form within the structure, significantly reducing its operational reliability and safety (Moldamuratov et. al., 2025).

The problem of structural diagnostics is particularly relevant in the Republic of Kazakhstan. More than 1,800 hydraulic structures of various purposes are currently in operation in the country. A substantial number of these facilities were constructed between the 1960s and 1980s. The design service life of many structures has already been exceeded. The level of physical deterioration reaches 60% or more. According to various assessments, more than 400-500 hydraulic structures are currently in unsatisfactory or near-emergency condition (Ilyassova et. al., 2025, Moldamuratov et. al., 2025). The main types of defects and their characteristics are presented in Table 1.

Table 1
Main Defects of Hydraulic Structures (author's materials)

No.	Defect Type	Characteristics	Depth of Distribution	Impact on Structural Safety
1	Cracks	Micro- and macrocracks	0.01-1.0 m	High
2	Voids	Delamination, cavities	0.05-2.0 m	Very high
3	Foundation loosening	Reduction in soil density	up to 3.0-5.0 m	Critical
4	Seepage zones	Moisture accumulation, particle washout	0.1-3.0 m	Critical

As shown in Table 1, hidden defects represent the greatest hazard for hydraulic structures. Such defects cannot be identified through conventional visual inspection. Their progressive development may lead to gradual structural degradation and loss of operational reliability (Bandurin et. al., 2023).

An additional risk factor is the location of a significant number of hydraulic structures within seismically active regions. The southern and southeastern regions of Kazakhstan are characterized by seismic intensities of 7-9 points according to the MSK-64 scale. Under these conditions, structures are subjected to dynamic impacts causing stress redistribution within structural elements and foundation soils. During seismic events, additional stresses may exceed design values by 20-50%, accelerating the development of hidden defects and weakening zones (Ilyassova et. al., 2025, Moldamuratov et. al., 2025).

The mechanism of damage formation under seismic loading conditions is presented in Figure 1.

As shown in Figure 1, dynamic loading contributes to the formation of cracks, loosening zones, and seepage channels within hydraulic structures. In water-saturated soils, liquefaction processes may occur under seismic воздействия. This results in a reduction of the bearing capacity of the foundation by 20-40%. In addition, the coefficient of permeability may increase by 1.5-3 times. Consequently, hidden defects develop within the structure and foundation, remaining undetected by conventional inspection methods (Bandurin et. al., 2023).

The analysis of failure cases indicates that the primary causes of structural deterioration include material aging, the presence of hidden defects, and the absence of effective monitoring systems. A significant proportion of defects develop within near-surface and internal structural layers. Their timely detection is critically important for ensuring the operational safety and long-term reliability of hydraulic structures (Khaptanov et. all., 2022).

Traditional inspection methods have limited diagnostic capability. Visual inspection allows identification of only surface damage. Destructive testing methods provide high accuracy; however, they cover no more than 1-3% of the structural surface. Ultrasonic testing is generally effective at depths up to 0.5-1.0 m. Infrared thermography can detect defects at depths of approximately 0.05-0.10 m. Seismic methods provide greater investigation depth but are characterized by relatively low spatial resolution (Ryazantsev, 2020, Tulokhonov et. all., 2018, Ostapchuk, 2025). A comparison of the main inspection methods is presented in Table 2.

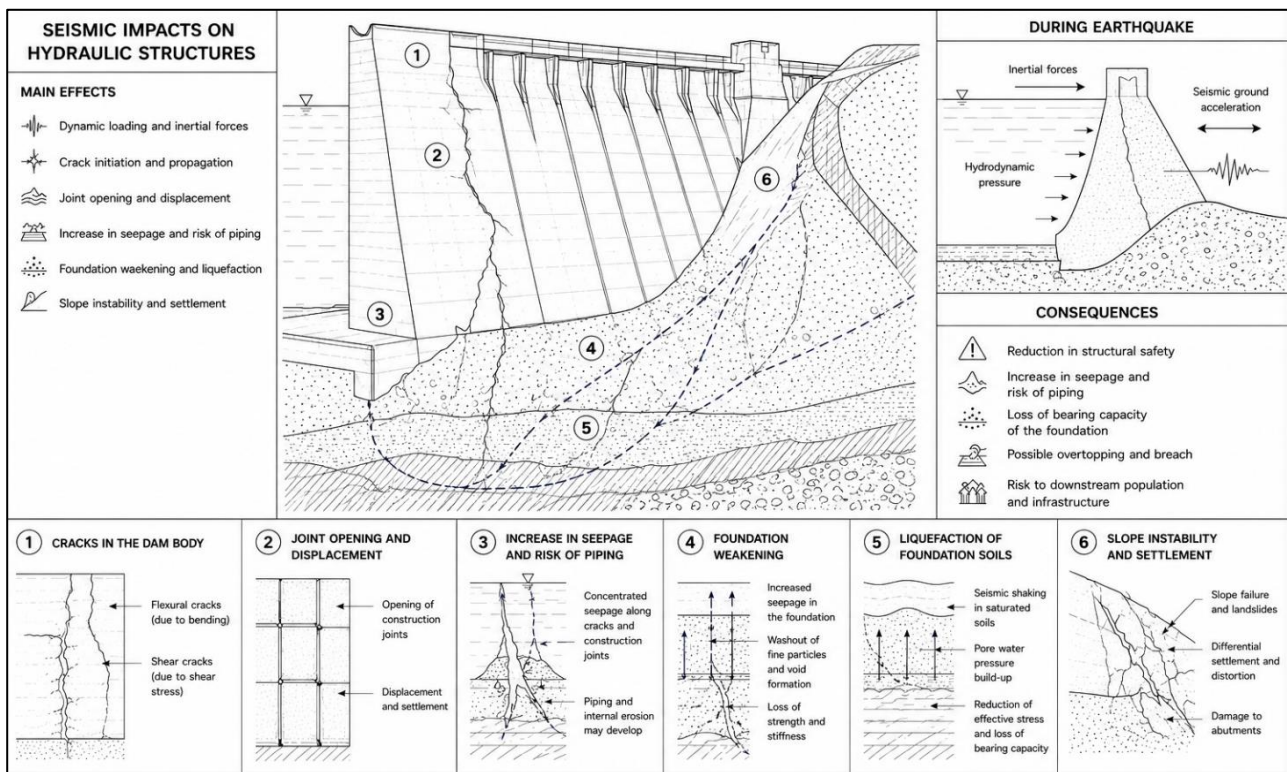


Figure 1 - Formation of Defects in Hydraulic Structures under Seismic Loading Conditions (author’s materials)

Table 2
Comparison of Inspection Methods for Hydraulic Structures (author’s materials)

No.	Method	Investigation Depth, m	Resolution, m	Productivity	Limitations
1	Visual inspection	up to 0.01	low	high	surface defects only
2	Ultrasonic testing	up to 1.0	0.01-0.05	low	contact-based method
3	Infrared thermography	up to 0.1	0.01	medium	limited to near-surface layer
4	Seismic method	up to 10-50	0.3-0.5	low	low spatial resolution
5	Ground Penetrating Radar (GPR)	up to 5.0	0.02-0.10	high	dependent on moisture conditions

As follows from Table 2, the GPR method provides an optimal combination of investigation depth and spatial resolution.

The GPR method is based on the registration of electromagnetic waves reflected from interfaces between materials with different dielectric properties. The operating principle of the method is illustrated in **Figure 2**.

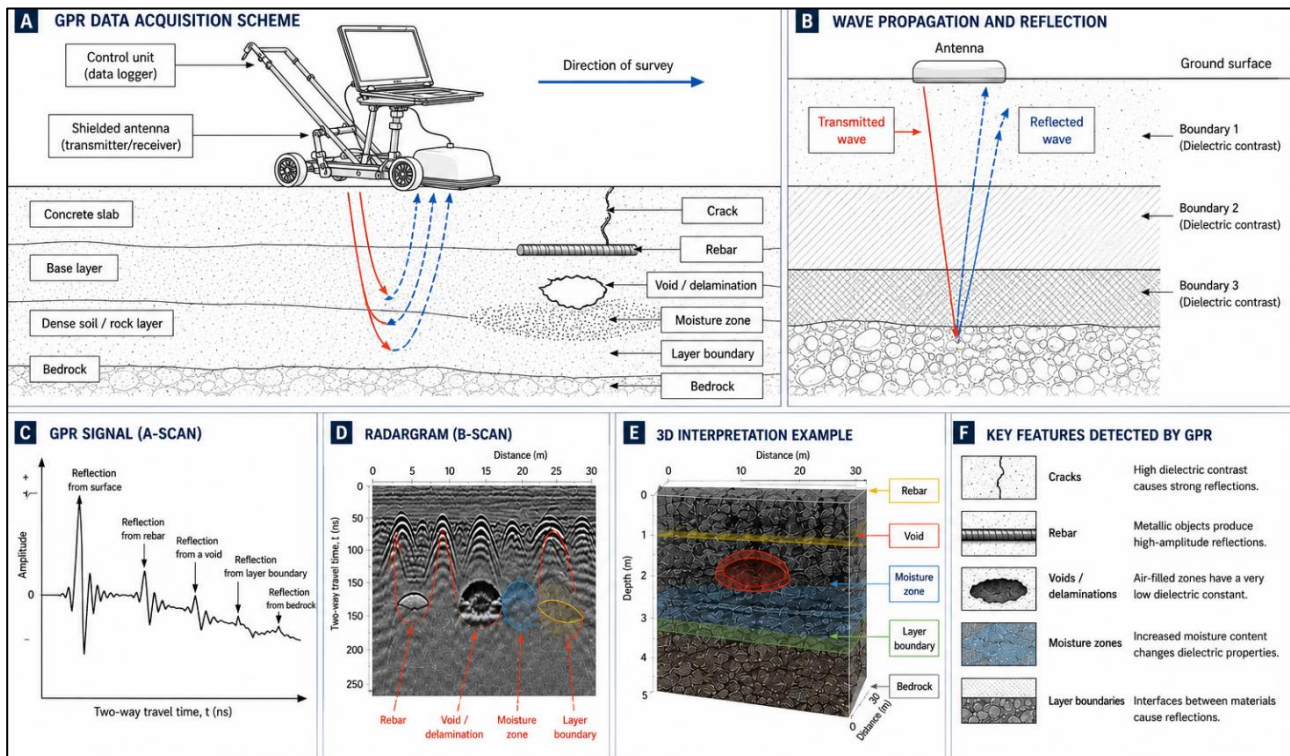


Figure 2 - Principle of the GPR Method for Detection of Internal Defects and Subsurface Heterogeneities in Hydraulic Structures (author’s materials)

As shown in **Figure 2**, reflected signals are generated at the interfaces between materials with different electromagnetic properties. This makes it possible to detect voids, cracks, moisture zones, and other subsurface heterogeneities within hydraulic structures.

The main parameters of the GPR method are presented in **Table 3**.

Table 3
Main Parameters of the GPR Method (author’s materials)

No.	Parameter	Value
1	Frequency range	50-2000 MHz
2	Investigation depth	0.5-5.0 m
3	Spatial resolution	0.02-0.10 m
4	Electromagnetic wave velocity in concrete	0.06-0.12 m/ns
5	Productivity	500-1500 m ² per shift

Modern studies confirm the high efficiency of the GPR method. The probability of defect detection reaches 85-95%, while the accuracy of depth determination is within 5-10%. The method is particularly sensitive to changes in moisture content. An increase in moisture by 5-10% may lead to a 1.5-2-fold change in dielectric properties (**Ludeno et. all., 2018**).

In engineering practice, GPR is widely used for the inspection of dams, canals, galleries, and other hydraulic structures. The method enables detection of voids with dimensions ranging from 0.05 to 0.5 m. Moisture zones can be identified at depths up to 10-12 m. In addition, areas of foundation loosening and internal heterogeneity can be effectively detected. The productivity of GPR surveys reaches 500-1500 m² per working shift (**Skibbe et. all., 2021, Xu et. all., 2020, Gallardo et. all., 2003**).

The method demonstrates particularly high efficiency in seismically active regions. It allows identification of structural changes after dynamic impacts, including zones of microcracking, contact disturbances, and seepage channels. When integrated with complementary geophysical methods, the reliability of diagnostics increases to 90-98% (Skibbe et. all., 2021, Xu et. all., 2020, Gallardo et. all., 2003).

The application of the OKO-3 Ground Penetrating Radar system provides high flexibility and adaptability of investigations. Antennas with frequencies ranging from 150 to 900 MHz can be used depending on the required investigation depth and spatial resolution. The achievable investigation depth reaches 3-5 m. The system also enables rapid data processing and three-dimensional visualization of subsurface structures (Skibbe et. all., 2021, Xu et. all., 2020, Gallardo et. all., 2003).

Conventional inspection methods do not provide sufficient diagnostic capability for detecting hidden defects within hydraulic structures. In contrast, the GPR method allows continuous non-destructive investigation of structural elements and enables early-stage detection of hidden defects. This significantly improves the operational reliability of hydraulic structures and increases the validity of engineering decisions.

The Tasotkel Reservoir, located in the Zhambyl Region of the Republic of Kazakhstan, was selected as the research object (Figure 3). The reservoir was commissioned in 1974 and represents an important component of the regional water management system. Its operation is carried out in accordance with current regulatory documents, particularly the Reservoir Operation Rules developed in 2001 by the Kazyuzhgirovodkhoz Design and Survey Institute (Moldamuratov et. all., 2025).



Figure 3 - Field conditions of the Tasotkel dam and the GPR survey environment: (a) general view of the reservoir and dam crest; (b-c) survey movement and profile layout along the crest; (d) piezometer (observation well); (e-f) downstream slope and surface condition of the embankment (author’s materials)

During the operational period of the reservoir, including the stage following the reconstruction of the dam outlet works in 2005-2006, no emergency situations or accidents affecting the stability and operational performance of the hydraulic structures were recorded. The hydraulic complex has been operated under normal conditions in compliance with established regulatory requirements. The reconstruction of the outlet system was carried out within the framework of the project “Reconstruction of the Hydraulic Complex of the Tasotkel Reservoir, Zhambyl Region,” developed by the Kazgiprovodkhoz Institute (2003), which significantly improved the operational reliability of the structure (Moldamuratov et. all., 2025).

In 2018, comprehensive engineering investigations were conducted, including topographic-geodetic surveys, engineering-geological investigations, and instrumental inspection of the dam. According to the inspection results, the dam and associated hydraulic structures were generally found to be in satisfactory technical condition. However, several operational features and local defects typical of long-term operated hydraulic structures were identified (**Moldamuratov et. all., 2025**).

The earth-fill dam does not exhibit pronounced settlements, sinkholes, or erosion damage. The crest elevation is 522.40 m. During the operational period after reconstruction, minor deformations of the dam crest associated with traffic loading were recorded. The magnitude of these deformations ranges from 0.1 to 0.2 m. These changes do not critically affect the structural stability of the dam; however, they require continuous monitoring and restoration of the operational surface layer.

The dam parapet is constructed of reinforced concrete blocks with a height of 0.9 m. The design elevation of the parapet crest is 523.30 m. During operation, local settlements ranging from 0.05 to 0.10 m were identified. These defects are minor in nature but require restoration of the design parameters (**Moldamuratov et. all., 2025**).

The dam drainage system is functioning in satisfactory condition. No visible damage was identified. At the same time, preventive maintenance measures are planned, including flushing of drainage elements and repair of inspection wells. Spillway and drainage channels are partially deformed. Processes of siltation, vegetation overgrowth, and local slope sliding have been observed, resulting in reduced hydraulic capacity.

The upstream slope of the dam is protected by reinforced concrete slabs. No damage to the protective lining was detected, and the condition of the slabs is assessed as satisfactory. The downstream slope is covered with vegetation. In several areas, erosion gullies with depths of 0.10-0.15 m were identified. These defects are local and do not significantly affect structural stability; however, they require repair and preventive maintenance (**Moldamuratov et. all., 2025**).

Additional infrastructure elements also exhibit signs of deterioration. The dam lighting system remains operational, although its efficiency has decreased due to equipment wear. The access road to the reservoir has a total length of 6.3 km and belongs to Category IV roads. The carriageway width is 4.5 m. During long-term operation, local pavement damage with a total area of approximately 1400 m² has developed.

The engineering structures of the hydraulic complex, including the tower structure, remain in operational condition. Gate control is performed under normal operating conditions. However, insufficient heating efficiency is observed during the winter period, requiring modernization of the engineering systems.

The analysis of the Tasotkel Reservoir condition indicates that despite the generally satisfactory state of the hydraulic structures, the dam body and associated infrastructure contain local defects and zones of potential risk. Most of these defects belong to the category of hidden or weakly expressed damage. Such defects may progressively develop under operational and environmental impacts, including seismic loading.

Under these conditions, the application of conventional inspection methods is insufficiently effective, as they do not provide reliable detection of internal defects and seepage zones. This justifies the necessity of applying advanced non-destructive testing methods (**Moldamuratov et. all., 2025**).

The GPR method makes it possible to obtain continuous information about the internal structure of hydraulic facilities. Its application at the Tasotkel Reservoir enables detection of hidden defects, localization of moisture zones, and assessment of foundation conditions. This makes GPR an effective diagnostic tool for hydraulic structures operating under long-term service conditions and seismic activity (**Moldamuratov et. all., 2025**).

2 MATERIALS AND METHODS

2.1 General Concept and Inspection Algorithm

In this study, a reproducible methodology for non-destructive inspection of hydraulic structures using the GPR method and the OKO-3 georadar system was implemented. The proposed algorithm

includes the following sequential stages: (1) collection and analysis of initial data on the structure; (2) selection of survey parameters considering engineering-geological conditions; (3) field measurements along a predefined grid of survey profiles; (4) digital signal processing; (5) interpretation of radargrams and verification of the obtained results (Liu et. all., 2022, Lombardi et. all., 2022, Di Prinzio et. all., 2010).

The general workflow of the inspection algorithm is presented in Figure 4.

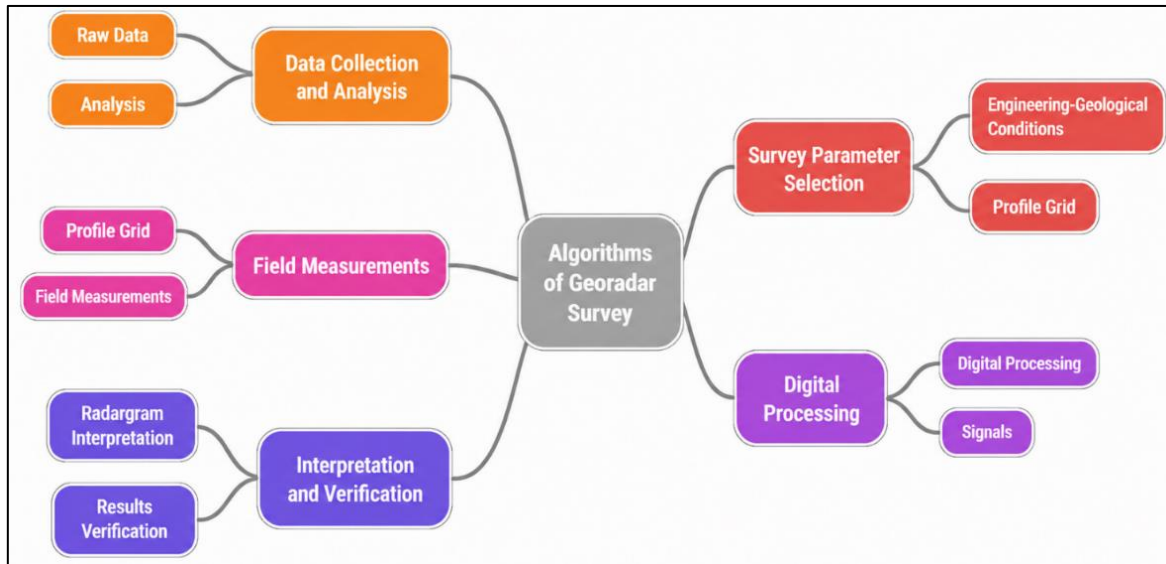


Figure 4 - Algorithm of GPR Inspection of a Hydraulic Structure (author’s materials)

As shown in Figure 4, the proposed methodology provides a transition from initial geological and engineering data to the quantitative assessment of defect parameters.

2.2 Research Object and Engineering-Geological Conditions

The research object is the Tasotkel Reservoir. The dam is an earth-fill hydraulic structure composed predominantly of cohesive soils (Figure 5). The foundation consists of alluvial deposits with predominance of sand-gravel soils having a total thickness exceeding 40 m.

The upper part of the foundation is overlain by loamy and sandy-loam soils with thicknesses ranging from 1-2 to 5-8 m. The foundation materials include sands of various grain sizes, as well as gravelly soils containing pebble inclusions of approximately 5-15%. Lens-shaped interlayers of cohesive soils with thicknesses ranging from 0.1 to 1.0 m are also identified within the geological profile (Moldamuratov et. all., 2025).

The soils are predominantly in a compacted condition. The dry unit weight of the soil skeleton exceeds 1.66 g/cm³. Medium-compacted zones are mainly localized in the upper part of the dam body at depths up to 5 m.

The main physical and mechanical properties of the soils are presented in Table 4.

The analysis of Table 4 indicates that:

- the soil density varies from 1.91 to 2.50 g/cm³;
- the deformation modulus ranges from 20,000 to 40,000 kN/m²;
- the coefficient of permeability reaches 35-75 m/day for the foundation soils;
- the internal friction angle varies between 18° and 40°;
- the cohesion reaches 24-31 kPa.

The high permeability coefficients indicate increased water conductivity of the foundation soils, which is critically important for the analysis of seepage processes.

2.3 Seepage Conditions and Phreatic Surface

The seepage regime was evaluated based on the position of the phreatic surface. Measurements were carried out along cross-sections PK 5+5, PK 9+10, and PK 13+00 (Moldamuratov et. all., 2025).

The actual piezometric levels were found to be 3.1-7.2 m lower than the design values. For example: PK 5+5: 497.49 m compared to the design elevation of 505.80 m; PK 9+10: approximately 498.8 m.

The relatively gentle shape of the phreatic surface indicates a high drainage capacity of the foundation soils. This confirms the absence of excessive water saturation within the dam body and foundation.

The seepage regime scheme is presented in Figure 6.

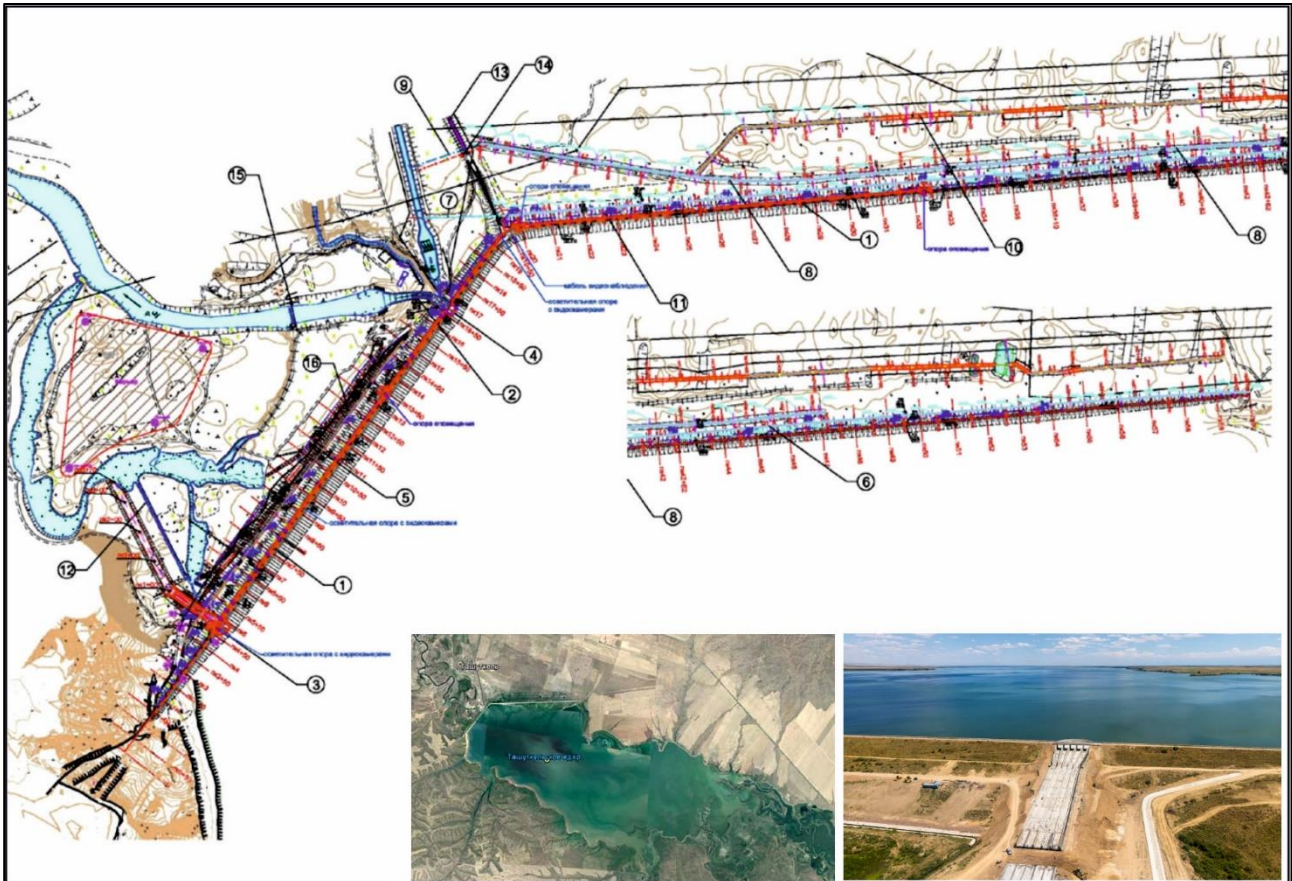


Figure 5 - Schematic layout of the main hydraulic structures and components of the reservoir (author’s materials)

Table 4
Physical and Mechanical Properties of Soils (author’s materials)

No.	Parameter	Symbol	Unit	Dam Body Soils	Counterweight Prism (Gravelly Soil)	Sand-Gravel Foundation Soil	Gravel
1	2	3	4	5	6	7	8
1	Natural moisture unit weight	γ	g/cm ³	2.03	1.91	1.91	2.30
2	Saturated unit weight	γ_{sat}	g/cm ³	2.06	2.00	2.00	2.50
3	Deformation modulus (natural moisture condition)	E	kN/m ²	39,000	40,000	40,000	-
4	Deformation modulus (water-saturated condition)	E	kN/m ²	20,000	30,000	30,000	40,000

Table 4 (continued)

1	2	3	4	5	6	7	8
5	Coefficient of permeability	k_f	m/day	0.41	32	35	75
6	Poisson's ratio	ν	-	0.35	0.27	0.27	0.27
7	Cohesion (natural moisture condition)	C	kPa	31	1	-	-
8	Cohesion (water-saturated condition)	C	kPa	24	-	2	1
9	Internal friction angle (natural moisture condition)	φ	$^\circ$	25	31	-	-
10	Internal friction angle (water-saturated condition)	φ	$^\circ$	18	-	33	40

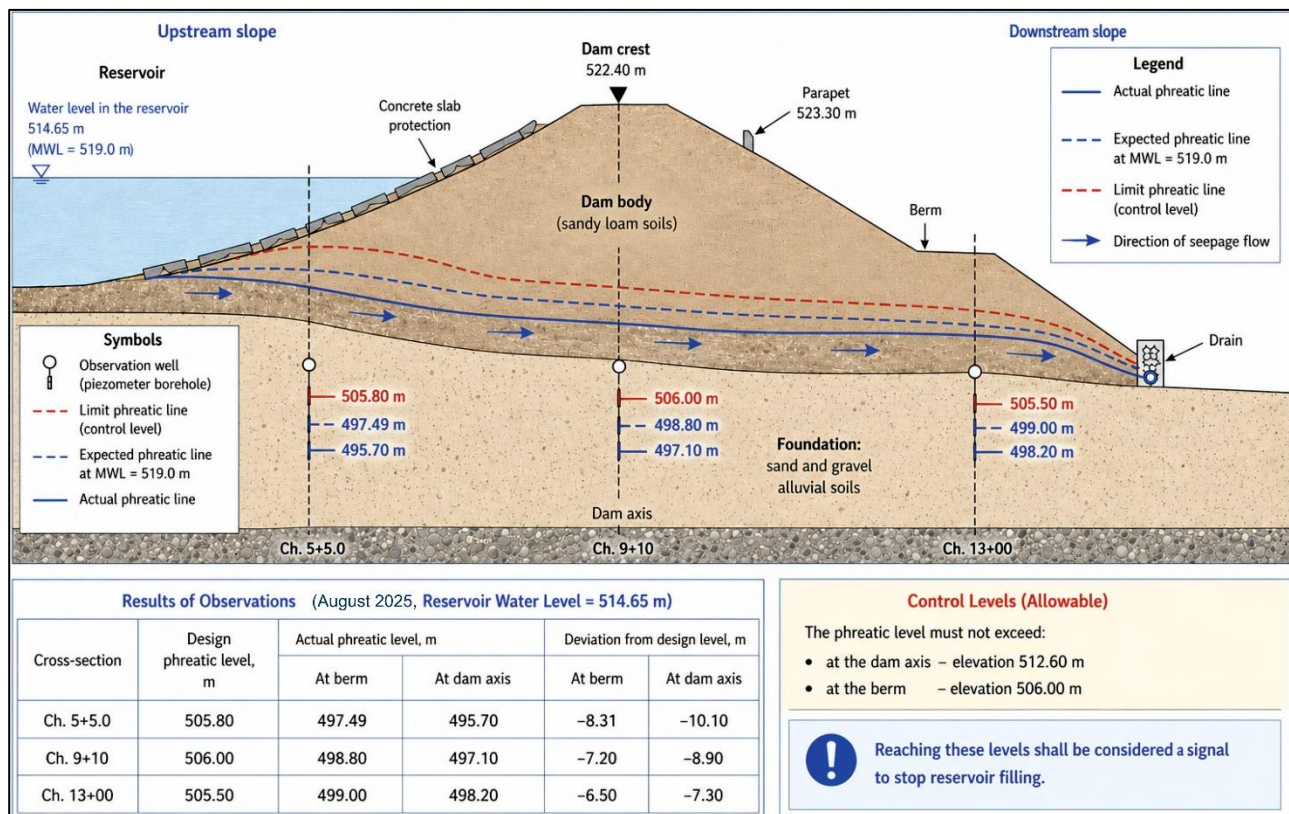


Figure 6 - Scheme of the Phreatic Surface and Seepage Flow within the Dam Body (author's materials)

2.4 Equipment and Parameters of the Ground Penetrating Radar Survey

The investigations were performed using the OKO-3 GPR system designed for engineering-geophysical inspection of structural elements and soil foundations. The equipment complex provides registration of reflected electromagnetic signals over a wide frequency range with subsequent digital processing and interpretation of the acquired data (Liu et. all., 2022, Alcalá et. all., 2021).

The GPR system was equipped with shielded antennas operating at frequencies of: 250 MHz - for deep sounding and investigation of the dam foundation to depths of 4-5 m; 400 MHz - as the primary survey mode providing an optimal balance between penetration depth (up to 3 m) and spatial resolution; 900 MHz - for detailed investigation of near-surface zones (up to 1-1.5 m) with high spatial resolution of approximately 0.02-0.05 m.

The selection of antenna frequencies was performed considering the engineering-geological conditions of the site, particularly the high permeability of the sand-gravel foundation soils and the presence of layered structures within the dam body.

The main GPR survey parameters included: signal recording time window: 50-150 ns depending on the required investigation depth; sampling frequency: up to 5 GHz (equivalent time sampling); antenna movement speed: 0.3-1.0 m/s; survey mode: continuous contact mode; number of signal stacks: 8-32 to improve the signal-to-noise ratio; trace interval along the profile: 0.02-0.05 m; profile spacing: 0.1-0.5 m.

The survey was carried out under conditions of continuous antenna contact with the surface, minimizing signal loss and ensuring stable signal acquisition. When necessary, the antenna position was adjusted considering surface irregularities and local defects of the protective covering.

The electromagnetic wave velocity in the investigated media was assumed within the range of 0.06-0.12 m/ns and refined using calibration measurements performed on reference sections with known geometry. This approach ensured accurate conversion of signal travel time into the depth of reflecting interfaces.

The spatial resolution of the method depended on the antenna frequency and was approximately: 0.02-0.05 m for the 900 MHz antenna; 0.05-0.10 m for the 400 MHz antenna; up to 0.10-0.20 m for the 250 MHz antenna.

The investigation depth varied depending on soil composition and moisture conditions and reached: up to 5 m within sand-gravel foundation soils; up to 2-3 m within the dam body; up to 1-1.5 m within saturated or clay-rich layers.

The selected equipment configuration and survey parameters ensured acquisition of reliable information about the internal structure of the hydraulic facility, including zones of loosening, seepage, and potential defects under actual engineering-geological conditions of the investigated object. The main survey parameters are summarized in **Table 5**.

Table 5
Technical Parameters of the Ground Penetrating Radar System (author's materials)

No.	Parameter	Value
1	Antenna frequency range	150-900 MHz
2	Investigation depth	up to 5.0 m
3	Spatial resolution	0.02-0.10 m
4	Time window	50-150 ns
5	Sampling frequency	up to 1-5 GHz
6	Survey speed	0.3-1.0 m/s

2.5 Field Measurements

Field GPR measurements were carried out along a regular grid of survey profiles, ensuring spatial representativeness and enabling subsequent three-dimensional interpretation of the acquired data (**Figure 7**). The profiles were arranged in two mutually perpendicular directions: along the longitudinal axis of the dam (longitudinal profiles) and across the dam body (transverse profiles). Such a survey configuration made it possible to obtain both extended structural sections and detailed transverse cross-sections of the hydraulic structure (**Pan et. all., 2019, Ludeno et. all., 2018, Bandurin et. all., 2023**).



Figure 7 - Field GPR Measurements (author's materials)

The main profiling parameters included: spacing between longitudinal and transverse profiles: 0.1-0.5 m; trace interval along the profile: 0.02-0.05 m; length of individual profiles: up to 100 m; number of signal stacks: 8-32 depending on the noise level and survey conditions.

The profiles were referenced to the chainage system (Ch.) of the hydraulic structure, ensuring accurate spatial identification of anomalies and their correlation with engineering-geological data and field observations.

The survey was performed in continuous contact mode while maintaining close antenna coupling with the surface. The antenna movement speed was maintained within the range of 0.3-1.0 m/s, ensuring uniform data sampling and stable signal acquisition. When surveying areas with uneven surfaces or local surface defects, the antenna trajectory was adjusted to prevent contact loss and signal distortion (Pan et. all., 2019, Ludeno et. all., 2018, Bandurin et. all., 2023).

During field measurements, the following quality indicators were continuously monitored: signal amplitude stability; absence of trace discontinuities; uniformity of time scanning; noise and interference levels.

When necessary, repeated surveys were carried out in sections characterized by elevated noise levels or anomalous signal responses.

The layout of the survey profiles, including longitudinal and transverse scanning lines, as well as their relation to key structural elements of the dam (crest, berms, and slopes), is presented in Figure 8.

As shown in Figure 8, the longitudinal profiles were oriented along the axis of the dam and were intended for the analysis of extended heterogeneities and seepage zones. The transverse profiles were arranged perpendicular to the dam axis and were used for constructing cross-sectional geometry and identifying local defects within the dam body and foundation (Pan et. all., 2019, Ludeno et. all., 2018, Bandurin et. all., 2023).

Such an organization of field measurements ensures high data density, spatial consistency of the acquired information, and the possibility of constructing reliable two-dimensional and three-dimensional models of the internal structure of the hydraulic facility.

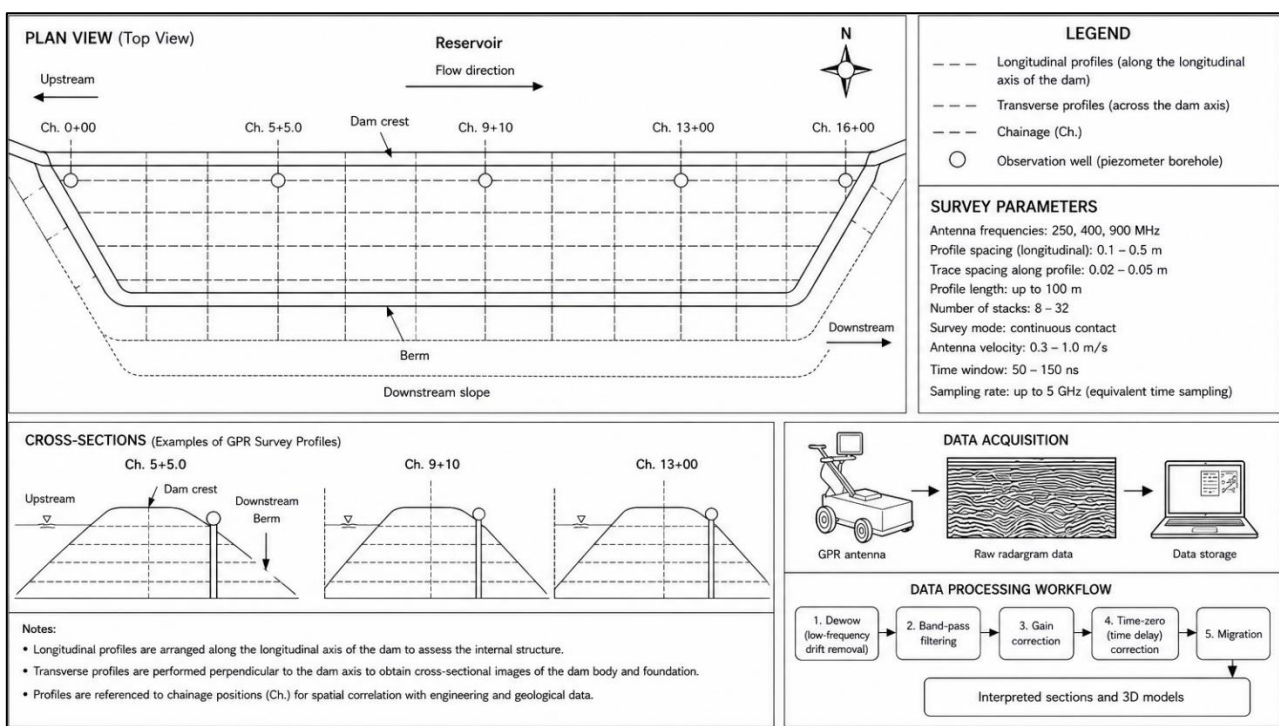


Figure 8 - Layout Scheme of GPR Survey Profiles (author's materials)

2.6 Data Processing

The processing of GPR data was performed using specialized software in a strictly defined sequence, ensuring accurate transformation of raw signals into interpretable subsurface sections (Tulokhonov et. all., 2018). The data processing workflow is presented in Figure 9.

The data processing workflow included the following stages:

1. Dewow filtering. Removal of low-frequency signal drift and baseline correction.
2. Band-pass filtering. Application of a filter within the frequency range of 50-500 MHz to suppress noise outside the operating spectrum of the antennas.
3. Gain correction. Compensation for signal attenuation with depth using SEC and AGC gain functions.
4. Time-zero correction. Alignment of the signal origin with the surface and elimination of temporal offset.
5. Migration. Geometrical correction of reflected signals and transformation of hyperbolic responses into the actual positions of subsurface objects.

The applied processing sequence ensured: improvement of the signal-to-noise ratio; accurate depth referencing; increased accuracy in localization of reflecting interfaces and defects.

All processing operations were performed within a unified coordinate system while preserving the spatial referencing of the survey profiles.

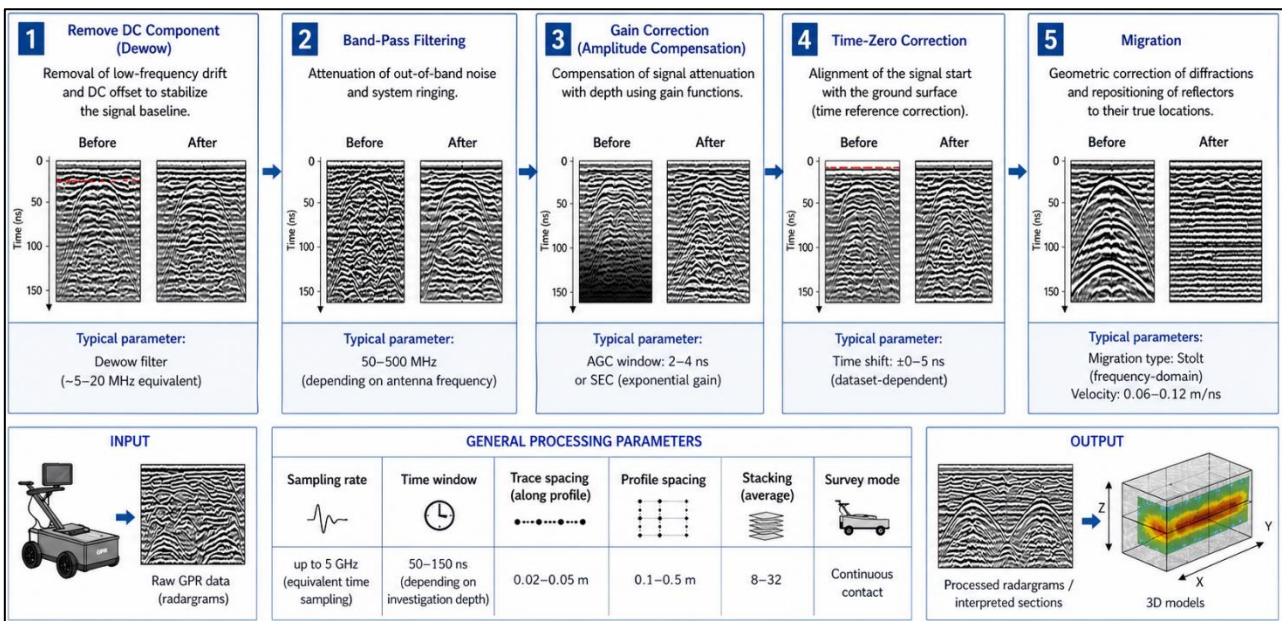


Figure 9 - Stages of GPR Data Processing (author’s materials)

2.7 Calculation of Parameters

The depth of detected defects was determined based on the travel time of the reflected signal using the standard relationship:

$$h = \frac{v \cdot t}{2},$$

where: h - depth of the reflecting interface, m; v - electromagnetic wave velocity in the medium, m/ns; t - two-way travel time of the signal, ns.

The wave propagation velocity was assumed within the range of 0.06-0.12 m/ns depending on soil type and moisture conditions and was refined using calibration measurements performed on reference sections.

The error in depth determination ranged from 5% to 10%, which is associated with variations in dielectric properties of the medium and heterogeneity of the soil mass.

2.8 Interpretation Criteria

The interpretation of GPR data was performed based on a comprehensive analysis of the amplitude, temporal, and morphological characteristics of reflected signals. Particular attention was given to the shape of reflections, their continuity, signal amplitude, attenuation behavior, and the spatial relationships between identified anomalies (Ryazantsev et al., 2020).

The main diagnostic indicators included: presence of hyperbolic reflections; changes in signal amplitude; disruption of reflecting horizon continuity; local signal attenuation or scattering; variations in the phase structure of the signal.

To improve the reliability of interpretation, the engineering-geological conditions of the site were taken into account, including soil type, moisture conditions, and seepage properties. The interpretation was performed through comparative analysis of longitudinal and transverse profiles, which made it possible to minimize false anomalies and improve the reliability of defect identification (Pan et al., 2019, Ludeno et al., 2018, Bandurin et al., 2023).

The classification of defect indicators identified from GPR data is presented in Table 6.

As follows from Table 6, each type of defect is characterized by a specific set of diagnostic features, which makes it possible to differentiate between various subsurface anomalies. Hyperbolic reflections are considered the most informative indicators, as they typically correspond to localized heterogeneities such as voids or inclusions.

In addition, the following quantitative signal parameters were taken into account: reflection amplitude; signal arrival time; degree of signal attenuation; spatial extent of the anomaly.

Table 6
Interpretation Criteria of Defects Based on GPR Data (author’s materials)

No.	Defect Type	Radargram Signature	Physical Nature
1	Voids and cavities	High-amplitude hyperbolic reflections	Sharp contrast in dielectric properties (air-soil/concrete interface)
2	Cracks	Linear or discontinuous reflections	Disruption of material continuity
3	Moisture zones	Signal attenuation and reduced amplitude	Increase in dielectric permittivity
4	Loosened zones	Blurred reflections and reduced boundary clarity	Reduced density and structural heterogeneity
5	Layer boundaries	Distinct continuous reflections	Contrast in material properties between layers

A comprehensive analysis of these characteristics ensured reliable identification and localization of defects within the dam body and foundation.

3 RESULTS AND DISCUSSION

The GPR survey of the Tasotkel dam made it possible to obtain a series of longitudinal and transverse profiles reflecting the internal structure of the dam body and the condition of near-surface zones. Data processing included dewow filtering, band-pass filtering, signal gain correction, time-zero correction, background noise removal, and migration. These procedures significantly improved the contrast of reflecting horizons and enabled localization of zones with changes in the structure of the soil mass.

The overall interpretation was performed using the processed radargrams considering the engineering-geological conditions of the site, physical and mechanical properties of the soils, and the position of the phreatic surface. The interpretation depth was assumed to be up to 5.0 m using a calculated electromagnetic wave velocity of 0.10 m/ns. The main diagnostic indicators included reflecting horizons, zones of reduced signal amplitude, areas of scattered reflections, hyperbolic anomalies, and the probable contact boundary between the dam body and the underlying deposits.

Figure 10 presents the general view of the processed radargram obtained along the longitudinal profile located on the dam crest. Three stable reflecting horizons are identified at depths of approximately 0.4-0.8 m, 1.2-1.6 m, and 2.0-2.5 m. The presence of extended and relatively continuous reflections indicates a pronounced layered structure of the dam body soils. In several sections, local disruptions in signal continuity and zones of reduced amplitude were detected. These features may be associated with heterogeneity of soil compaction, variations in moisture conditions, or local structural irregularities within the soil mass.

Figure 11 shows a section of the dam crest containing a local loosening zone. This zone is observed at a depth of approximately 0.5-1.5 m. The main diagnostic features include reduced signal amplitude, disruption of reflection regularity, and a scattered signal pattern. Such characteristics are typical of areas with reduced density or heterogeneous soil structure.

From an engineering perspective, such zones require continuous monitoring, since during long-term operation they may be associated with non-uniform compaction, local weathering, internal erosion processes, or operational deformations of the dam crest.

Figure 12 illustrates a section characterized by signs of increased moisture content within the dam body. The moisture-rich zone is identified at depths ranging from approximately 1.0 to 3.0 m. It is characterized by reduced signal amplitude, attenuation of deep reflections, and a chaotic reflection pattern. Physically, this behavior is explained by the increase in dielectric permittivity of water-saturated soils. Increased moisture content results in greater absorption of electromagnetic energy and a reduction in the effective investigation depth.

Such a zone may indicate local moisture accumulation, areas of insufficient drainage, or potential seepage pathways within the dam body.

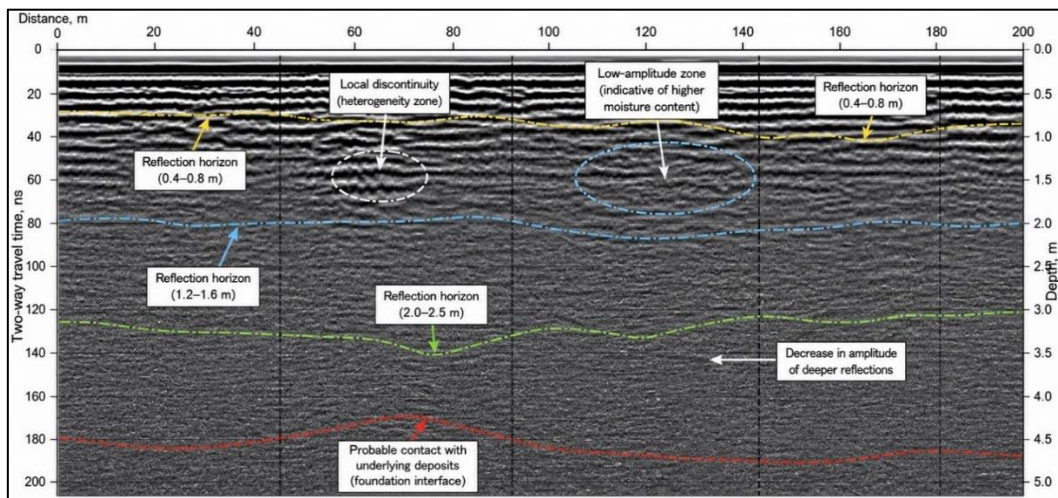


Figure 10 - Processed GPR Radargram of the Longitudinal Profile along the Dam Crest with Identified Reflecting Horizons and Local Anomalies (author’s materials)

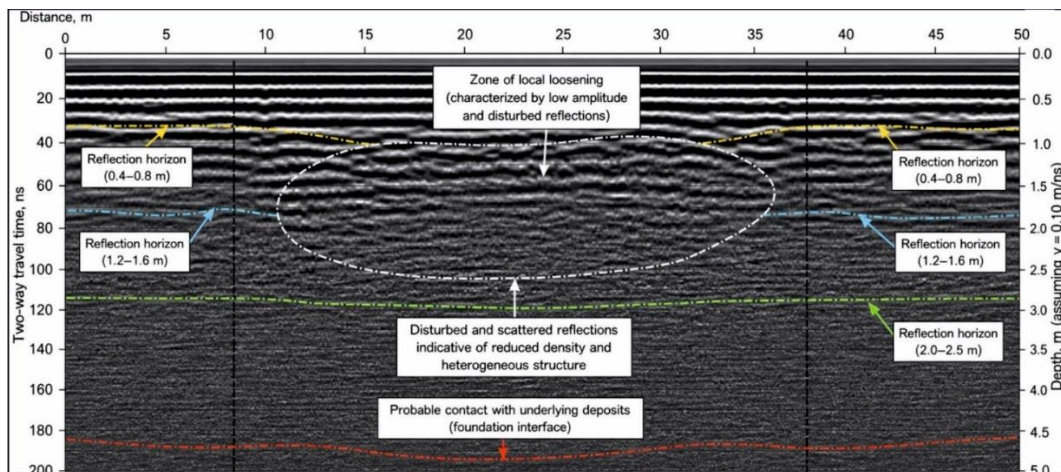


Figure 11 - Processed GPR Radargram of the Dam Crest Section with a Local Loosening Zone at a Depth of 0.5-1.5 m (author’s materials)

Figure 13 presents hyperbolic reflections associated with local subsurface anomalies. Such signals are typical of point reflectors and may correspond to boulders, gravel inclusions, dense localized inclusions, small voids, or zones of disturbed material. In the presented radargram, the hyperbolic reflections are localized and do not form an extended disturbed zone.

This observation is important for engineering assessment, since isolated hyperbolic responses do not necessarily indicate hazardous defects. Their interpretation should be performed in conjunction with adjacent profiles and the engineering-geological conditions of the investigated area.

Figure 14 summarizes the interpretation results obtained for one of the representative survey profiles. The radargram simultaneously identifies a local loosening zone, an area of increased moisture content, hyperbolic reflections, and the probable contact boundary with the underlying deposits.

This integrated interpretation demonstrates that the detected anomalies are distributed non-uniformly within the investigated section. The most significant changes are observed in the upper and middle parts of the profile at depths up to approximately 3.0 m. The probable contact boundary with

the foundation is traced at depths of about 3.5-4.5 m and exhibits a relatively stable and continuous character.

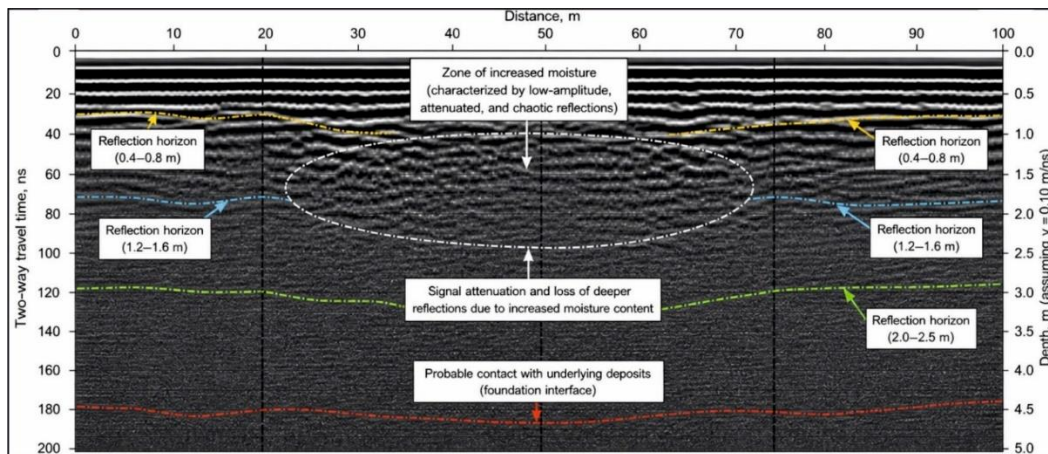


Figure 12 - Processed GPR Radargram with a Zone of Increased Moisture Content within the Dam Body at a Depth of 1.0-3.0 m (author's materials)

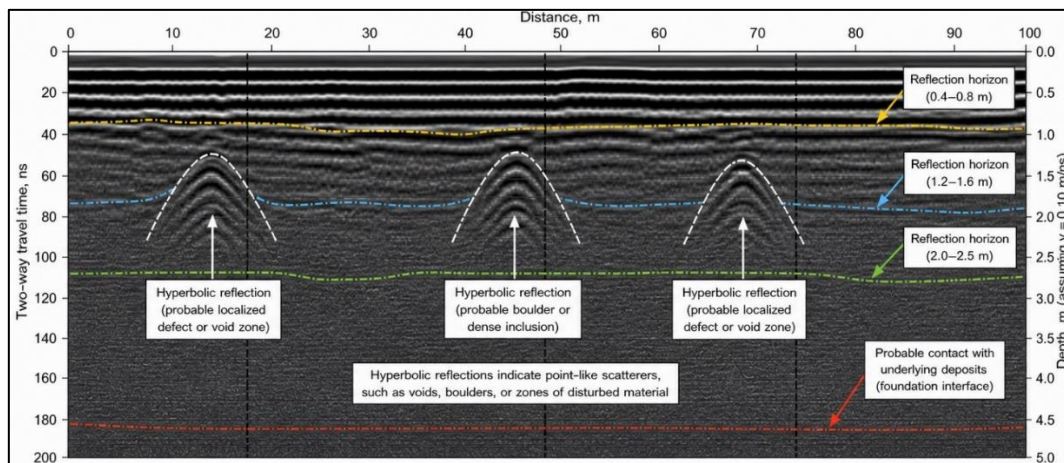


Figure 13 - Processed GPR Radargram with Hyperbolic Reflections Associated with Local Subsurface Anomalies (author's materials)

Figure 15 presents a conceptual subsurface model developed based on the interpretation of GPR data. The model illustrates the main engineering-geophysical zones, including the compacted embankment body, a local loosening zone, an area of increased moisture content, point anomalies, and the probable contact with the underlying deposits.

This scheme enables the transition from individual radargrams to an engineering-oriented model of the dam condition. Such an approach is important for practical assessment, since the results are presented not only as signal responses but also as a spatially interpretable structural model.

Figure 16 presents a summary of the GPR survey results and their engineering interpretation. Four key diagnostic indicators were identified: a local loosening zone, an area of increased moisture content, hyperbolic anomalies, and the contact boundary with the underlying deposits.

For each identified zone, possible engineering implications and recommended actions were determined. Loosening zones require density control and, if necessary, local compaction measures. Areas with increased moisture content require analysis of drainage conditions and monitoring of the seepage regime. Hyperbolic anomalies require verification using complementary methods or additional control surveys. In contrast, the contact with the foundation is characterized as relatively continuous and stable.

As shown in **Figure 17**, the relative signal amplitude consistently decreases with increasing depth for all investigated engineering-geological zones. The lowest signal attenuation is observed within the stable zone composed of compacted soils. At a depth of 3.0 m, the normalized signal amplitude remains at approximately 0.28, while at a depth of 5.0 m it decreases to about 0.06. This behavior indicates relatively low absorption of electromagnetic energy and a comparatively homogeneous soil structure.

In the high moisture content zone, a significantly more intensive decrease in signal amplitude is observed. At a depth of 3.0 m, the normalized amplitude decreases to approximately 0.06, and at a depth of 5.0 m it reaches about 0.006. This effect is associated with an increase in dielectric permittivity and electrical conductivity of water-saturated soils, resulting in stronger attenuation of electromagnetic waves.

The highest signal attenuation is recorded within the loosening zone. At depths of 1.5-2.0 m, the amplitude decreases to approximately 0.11-0.055, while at a depth of 5.0 m it reaches a minimum value of 0.0006. Such signal behavior is related to the heterogeneous soil structure, scattering of electromagnetic energy, and discontinuity of the medium.

The obtained relationships confirm the high sensitivity of the Ground Penetrating Radar method to variations in moisture conditions and soil compaction. As illustrated in **Figure 17**, analysis of amplitude characteristics can be used as a quantitative diagnostic criterion for identifying zones of increased moisture content and local loosening within earth-fill hydraulic structures.

Overall, the results indicate that the dam body is characterized by a predominantly stable layered structure. Extended reflecting horizons are traced throughout most of the survey profiles. This indicates the absence of major discontinuities or pronounced disturbed zones within the investigated depth range. At the same time, several local areas with signs of loosening and increased moisture content were identified. These zones do not form a single continuous weakened region; however, they require periodic monitoring.

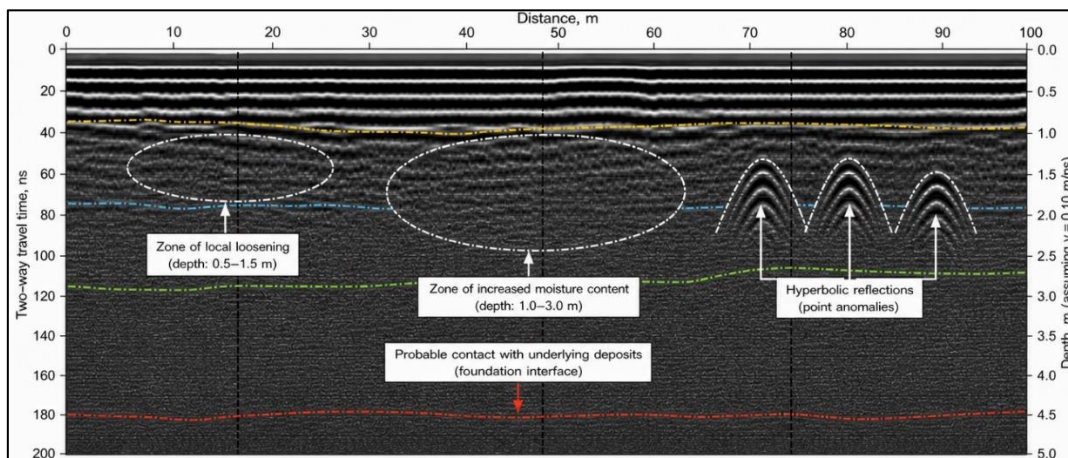


Figure 14 - Processed GPR Radargram with Interpreted Stratigraphy and Identified Subsurface Anomalies (author's materials)

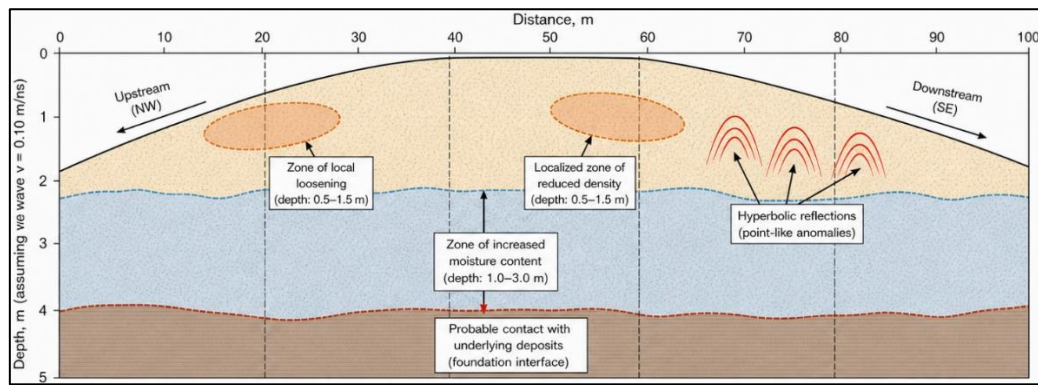


Figure 15 - Conceptual Subsurface Model Based on GPR Data with Identification of Local Loosening Zones, Increased Moisture Content, Point Anomalies, and the Probable Contact with the Foundation (author’s materials)

Particular importance is associated with the moisture-rich zone identified at depths of 1.0-3.0 m. For hydraulic structures, such areas are critically important from the viewpoint of seepage safety. However, according to the available data on the phreatic surface, the actual piezometric levels remain below the design values. This indicates that the detected moisture zones do not necessarily correspond to critical seepage conditions. More likely, they reflect local variations in moisture content, drainage conditions, or soil properties.

The local loosening zones identified at depths of 0.5-1.5 m may be associated with operational loading on the dam crest. Previously recorded crest deformations within the range of 0.1-0.2 m additionally confirm the necessity of monitoring the upper part of the structure. At the same time, the GPR data do not indicate deep propagation of these zones toward the foundation contact. Therefore, they can be considered localized areas requiring scheduled monitoring and possible restoration of the surface layer or additional compaction.

The detected hyperbolic reflections are interpreted as local point anomalies. Their occurrence is consistent with the engineering-geological structure of the dam body and foundation, where sand-gravel deposits, gravel soils, and pebble inclusions are present. Therefore, such signals should not automatically be interpreted as voids. Verification using adjacent profiles or complementary investigation methods is required to confirm their nature.

The probable contact with the underlying deposits is traced at depths of approximately 3.5-4.5 m and exhibits a relatively continuous character. This indicates the absence of abrupt disturbances in the transition zone between the dam body and the foundation within the investigated profiles. This result is consistent with the engineering-geological data indicating the presence of alluvial sand-gravel foundation soils.

The obtained results confirm the high informativeness of the Ground Penetrating Radar method for inspection of earth-fill hydraulic structures. The method enables identification of hidden heterogeneity zones without disturbing the integrity of the dam. Particularly important is the fact that GPR provides continuous profiling in contrast to localized point-based inspection methods. This makes it possible to evaluate not only isolated sections but also the spatial variability of the structural condition.

From an engineering perspective, the investigation results allow classification of the detected zones into three condition levels. The first level corresponds to stable zones characterized by continuous reflecting horizons. The second level includes monitoring zones containing local areas of loosening and increased moisture content. The third level includes areas requiring additional verification, where pronounced hyperbolic anomalies or abrupt changes in signal structure are observed.

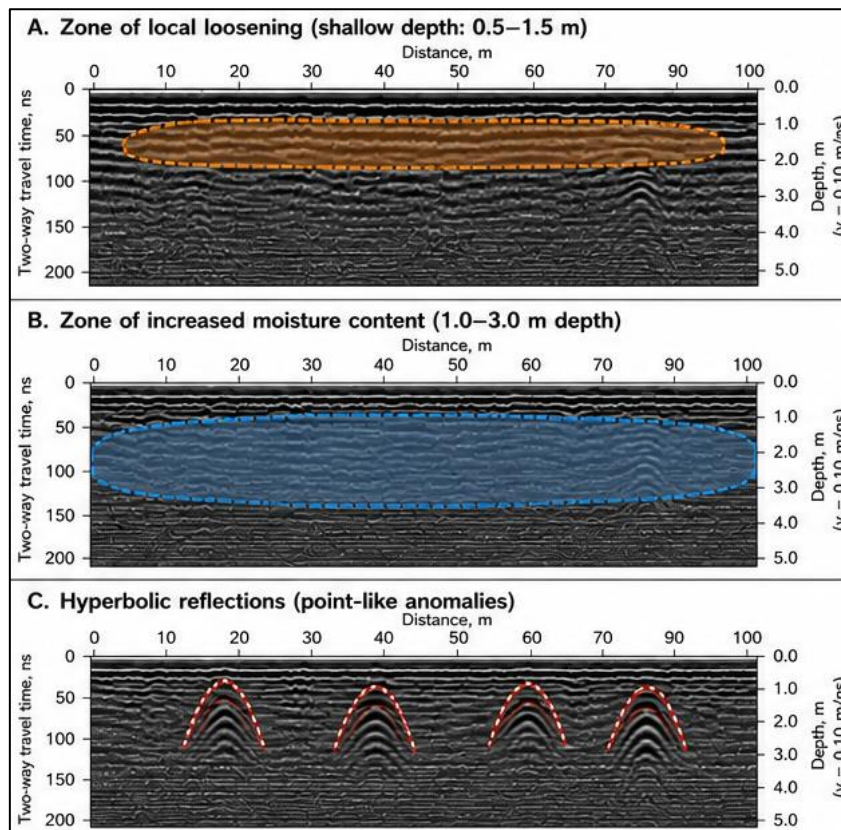


Figure 16 - Summary of GPR Survey Results (author’s materials)

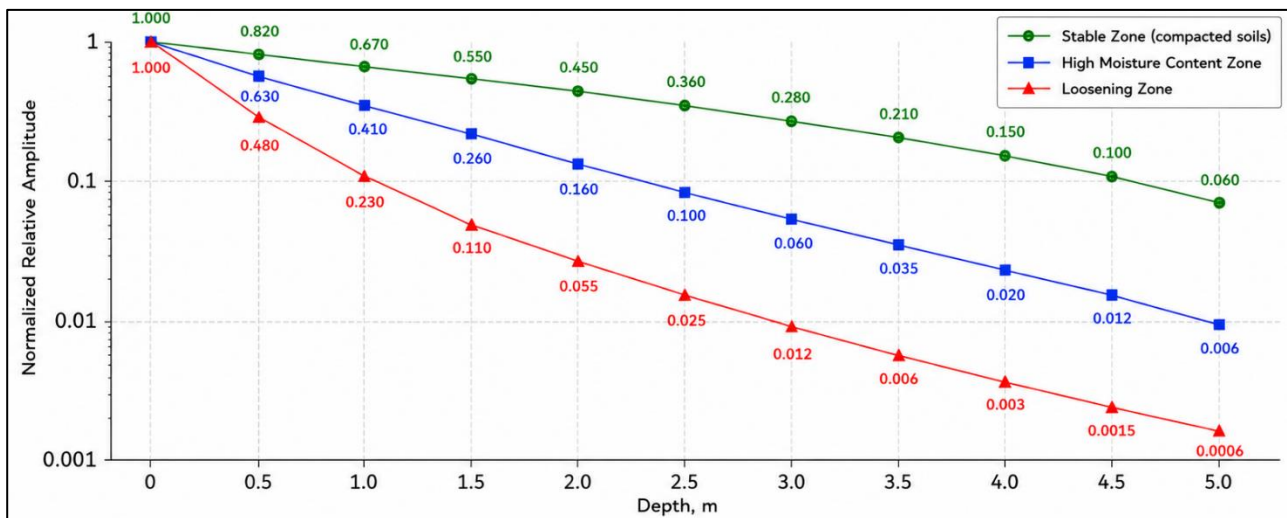


Figure 17 – Variation in Relative Signal Amplitude with Depth for Different Engineering-Geological Zones Based on GPR Data (400 MHz Antenna) (author’s materials)

Thus, the GPR survey results indicate that within the investigated depth range no signs of critical extended defects, large voids, or developed seepage channels were identified. The main detected features are local in nature. These features should be considered during planning of monitoring activities, preventive maintenance, and future inspections of the dam. In this case, the Ground Penetrating Radar method confirmed its effectiveness as a tool for early detection of hidden changes within the dam body and foundation.

4 CONCLUSIONS

Based on the results of the performed investigations, the following conclusions can be drawn:

1. A comprehensive GPR survey of the earth-fill dam of the Tasotkel Reservoir was carried out using the OKO-3 georadar system equipped with 250, 400, and 900 MHz antennas, providing an investigation depth of up to 5.0 m and high-resolution imaging of near-surface zones.
2. A reproducible algorithm for GPR inspection of hydraulic structures was developed and validated, including field measurements, digital signal processing, radargram interpretation, and engineering verification of the obtained results.
3. It was established that the dam body is generally characterized by a stable and relatively homogeneous layered structure. Most survey profiles exhibit continuous reflecting horizons without signs of major discontinuities, developed seepage channels, or critical defects.
4. Local loosening zones at depths of 0.5-1.5 m were identified during the survey. These zones are associated with heterogeneous soil compaction, operational loading, and local deformations of the dam crest.
5. Areas of increased moisture content were detected at depths of 1.0-3.0 m, characterized by signal attenuation and changes in reflection structure. The identified zones are local in nature and do not form extended weakened regions.
6. Hyperbolic reflections recorded on individual profiles were interpreted as local subsurface anomalies associated with gravel inclusions, soil heterogeneity, or isolated structural defects.
7. Analysis of the phreatic surface demonstrated that the actual piezometric levels are 3.1-7.2 m lower than the design values, indicating high drainage capacity of the foundation soils and satisfactory seepage conditions of the dam.
8. The study confirmed that the Ground Penetrating Radar method possesses high informativeness and efficiency for the inspection of earth-fill hydraulic structures, providing continuous non-destructive monitoring of the internal structure of the dam.
9. The obtained results can be used for development of technical condition monitoring systems for hydraulic structures, localization of potentially hazardous zones, planning of repair and rehabilitation measures, and improvement of the operational reliability of hydraulic facilities.

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