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RESEARCH ARTICLE

ASSESSMENT OF THE TECHNICAL CONDITION OF CONCRETE AND REINFORCED CONCRETE HYDRAULIC STRUCTURES USING 3D ULTRASONIC TOMOGRAPHY

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Abstract. *The article presents the results of assessing the technical condition of the concrete and reinforced concrete structures of the emergency spillway of the Tasotkel Reservoir using the 3D ultrasonic tomography method based on the Betonoskop SK-1700 3D system. The study is aimed at detecting hidden defects, evaluating the internal structure of concrete, and analyzing deterioration processes under long-term seepage, hydrodynamic, and seismic impacts. During the investigation, spatial ultrasonic scanning of a 10×10 m section was performed with a diagnostic depth of up to 0.60 m. Three-dimensional tomographic models, ultrasonic wave velocity distribution maps, vertical and transverse sections, and engineering interpretations of defect zones were developed. It was established that the average ultrasonic wave velocity was approximately 3280 m/s, while minimum values in critically deteriorated areas decreased to 1680-1850 m/s. More than 35% of the investigated structural volume was found to be in a state of severe and critical deterioration, while the proportion of potentially hazardous zones associated with internal voids and loss of bonding accounted for approximately 6-8%. The most critical defects were localized in the lower part of the concrete lining and within the concrete-foundation interface zone, where seepage-induced moisture accumulation, structural loosening, delamination, and local void formation were identified. Correlation analysis confirmed a stable relationship between defect depth and the reduction in ultrasonic wave velocity. The agreement coefficient between the 3D ultrasonic tomography results and visual inspection/local opening investigations ranged from 0.79 to 0.88, while the overall diagnostic reliability reached 91-95%. The obtained results confirm the high efficiency of the Betonoskop SK-1700 3D system for diagnosing hidden defects in concrete and reinforced concrete hydraulic structures and can be applied for inspection, monitoring, and assessment of the operational reliability of hydraulic infrastructure facilities.*

Keywords: *hydraulic structures, 3D ultrasonic tomography, non-destructive testing, technical inspection, seepage-induced deterioration, hidden defects.*

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ҒЫЛЫМИ МАҚАЛА

ГИДРОТЕХНИКАЛЫҚ ҚҰРЫЛЫМДАРДЫҢ БЕТОН ЖӘНЕ ТЕМІРБЕТОН КОНСТРУКЦИЯЛАРЫНЫҢ ТЕХНИКАЛЫҚ ЖАҒДАЙЫН 3D УЛЬТРАДЫБЫСТЫҚ ТОМОГРАФИЯ ӘДІСІМЕН БАҒАЛАУ

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Аңдатпа. *Мақалада Тасөткел су қоймасының апаттық су тастағышының бетон және темірбетон конструкцияларының техникалық жағдайын Бетоноскоп СК-1700 3D негізіндегі 3D ультрадыбыстық томография әдісі арқылы бағалау нәтижелері ұсынылған. Зерттеу жасырын ақауларды анықтауға, бетонның ішкі құрылымын бағалауға және ұзақ мерзімді фильтрациялық, гидродинамикалық және сейсмикалық әсер жағдайындағы деградациялық процестерді талдауға бағытталған. Зерттеу барысында өлшемі 10×10 м болатын учаскеде диагностикалау тереңдігі 0,60 м дейінгі кеңістіктік ультрадыбыстық сканерлеу жүргізілді. Үшөлшемді томографиялық модельдер, ультрадыбыстық толқын жылдамдығының таралу карталары, тік және көлденең қималар құрылып, ақаулы аймақтарға инженерлік интерпретация жасалды. Ультрадыбыстық толқындардың орташа таралу жылдамдығы шамамен 3280 м/с құрағаны анықталды, ал критикалық деградация аймақтарында минималды мәндер 1680-1850 м/с дейін төмендеген. Зерттелген конструкция көлемінің 35%-дан астамы айқын және критикалық деградация күйінде екені, ал ішкі қуыстар мен қабаттар арасындағы байланыс жоғалу белгілері бар қауіпті аймақтардың үлесі шамамен 6-8% құрайтыны анықталды. Ең қауіпті ақаулар бетон қаптамасының төменгі бөлігінде және «бетон-негіз» түйісу аймағында анықталды, мұнда фильтрациялық ылғалдану, құрылымның босаңсуы, қабаттану және жергілікті қуыстардың қалыптасуы байқалады. Корреляциялық талдау ақау тереңдігі мен ультрадыбыстық толқын жылдамдығының төмендеуі арасында тұрақты тәуелділіктің бар екенін көрсетті. 3D ультрадыбыстық томография нәтижелерінің визуалды тексеру және жергілікті ашып қарау нәтижелерімен сәйкестік коэффициенті 0,79-0,88 аралығында болды, ал диагностиканың жалпы сенімділігі 91-95%-ға жетті. Алынған нәтижелер гидротехникалық құрылымдардың бетон және темірбетон конструкцияларындағы жасырын ақауларды анықтауда Бетоноскоп СК-1700 3D қолданудың жоғары тиімділігін дәлелдейді және оларды гидротехникалық инфрақұрылым нысандарын тексеру, мониторинг жүргізу және пайдалану сенімділігін бағалау барысында қолдануға болатынын көрсетті.*

Түйін сөздер: *гидротехникалық құрылымдар, 3D ультрадыбыстық томография, бұзбай бақылау, техникалық тексеру, фильтрациялық деградация, ішкі ақаулар.*

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НАУЧНАЯ СТАТЬЯ

ОЦЕНКА ТЕХНИЧЕСКОГО СОСТОЯНИЯ БЕТОННЫХ И ЖЕЛЕЗОБЕТОННЫХ КОНСТРУКЦИЙ ГИДРОТЕХНИЧЕСКИХ СООРУЖЕНИЙ МЕТОДОМ 3D УЛЬТРАЗВУКОВОЙ ТОМОГРАФИИ

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Аннотация. *В статье представлены результаты оценки технического состояния бетонных и железобетонных конструкций катастрофического водосброса Тасоткельского водохранилища с применением метода 3D ультразвуковой томографии на основе Бетоноскопа СК-1700 3D. Исследование направлено на выявление скрытых дефектов, оценку внутренней структуры бетона и анализ деградационных процессов в условиях длительного фильтрационного, гидродинамического и сейсмического воздействия. В ходе исследования выполнено пространственное ультразвуковое сканирование обследуемого участка размером 10×10 м с глубиной диагностирования до 0,60 м. Построены трехмерные томографические модели, карты распределения скоростей ультразвуковых волн, вертикальные и поперечные сечения, а также выполнена инженерная интерпретация дефектных зон. Установлено, что средняя скорость распространения ультразвуковых волн составила около 3280 м/с, при этом минимальные значения снижались до 1680-1850 м/с в зонах критической деградации. Выявлено, что более 35% исследуемого объема конструкции находится в состоянии выраженной и критической деградации, а доля потенциально опасных зон с признаками внутренней пустотности и потери сцепления составляет около 6-8%. Наиболее опасные дефекты локализуются в нижней части бетонной облицовки и в зоне контакта «бетон-основание», где фиксируются процессы фильтрационного увлажнения, разуплотнения, расслоения и локальной пустотности. Корреляционный анализ подтвердил устойчивую зависимость между глубиной дефектов и снижением скорости ультразвуковых волн. Коэффициент совпадения результатов 3D ультразвуковой томографии с данными визуального обследования и локальных вскрытий составил 0,79-0,88, а общая надежность диагностики достигала 91-95%. Полученные результаты подтверждают высокую эффективность применения Бетоноскопа СК-1700 3D для диагностики скрытых дефектов бетонных и железобетонных конструкций гидротехнических сооружений и могут быть использованы при обследовании, мониторинге и оценке эксплуатационной надежности объектов гидротехнической инфраструктуры.*

Ключевые слова: *гидротехнические сооружения, 3D ультразвуковая томография, неразрушающий контроль, техническое обследование, фильтрационная деградация, внутренние дефекты.*

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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. Сонымен қатар, авторлар Бетоноскоп СК-1700 3D көмегімен алынған деректерді өңдеу барысында көрсетілген ғылыми және техникалық қолдау үшін Ұлы Петр атындағы Санкт-Петербург политехникалық университетінің «Азаматтық құрылыстағы цифрлық инжиниринг» ғылыми-технологиялық кешеніне алғыс 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. Авторы также выражают благодарность Научно-технологическому комплексу «Цифровой инжиниринг в гражданском строительстве» Санкт-Петербургского политехнического университета Петра Великого за научную и техническую поддержку при обработке данных, полученных с использованием Бетоноскопа СК-1700 3D.

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

Concrete and reinforced concrete structures of hydraulic facilities are among the most critical components of water management infrastructure. Their technical condition directly affects public safety, the stability of water supply systems, the reliability of irrigation networks, flood protection efficiency, and the operational sustainability of energy, industrial, and agricultural systems. Unlike conventional building structures, hydraulic structures operate under conditions of constant or periodic contact with water. They are subjected to seepage pressure, cyclic wetting and drying, temperature fluctuations, freeze-thaw action, abrasion, cavitation, leaching of cementitious components, and reinforcement corrosion. Consequently, deterioration processes in such structures often develop not only on the surface but also within the internal body of the concrete (**Ilyassova et. all., 2025**).

The significance of this problem is further intensified by the global aging of hydraulic infrastructure. According to the International Commission on Large Dams (ICOLD), the World Register of Dams contains information on more than 62,000 dams located in 166 countries. The register includes data on the year of commissioning, height, length, dam type, reservoir capacity, and functional purpose of hydraulic structures. A substantial proportion of these facilities was constructed during the second half of the twentieth century. Consequently, many hydraulic structures have already reached or exceeded their design service life. At the same time, actual operating conditions frequently differ significantly from the original design assumptions. Hydraulic facilities are increasingly affected by altered hydrological regimes, extreme flood events, growing water demand, seismic impacts, and accumulated material deterioration (**Imanov et. all., 2025, Moldamuratov et. all., 2023**).

For Kazakhstan, this issue is of particular importance. The country possesses an extensive network of reservoirs, dams, hydraulic hubs, irrigation canals, and other hydraulic engineering facilities. These structures provide water supply, irrigation, flood protection, and flow regulation. According to official reports of the Government of the Republic of Kazakhstan, the modernization of irrigation canals is expected to reduce water losses during transportation from 50% to 25%. In 2024, 93 hydraulic structures were inspected across the country, while 260 dams with a total length of 592.9 km were constructed or reinforced. These data demonstrate the scale of the problem and confirm the necessity of systematic technical assessment and monitoring of water management infrastructure (**Moldamuratov et. all., 2023**).

The condition of Kazakhstan's hydraulic infrastructure is also closely associated with climatic and flood-related risks. In 2024, the country experienced the most severe flooding recorded over the past 80 years. According to UNDP data, the floods resulted in the evacuation of more than 177,000 people, inundation of approximately 6,000 residential buildings, and significant damage to infrastructure facilities. Such events demonstrate that the safety of hydraulic structures should be considered not only as an operational issue, but also as a critical component of national resilience to natural and technological hazards (**Moldamuratov et. all., 2023**).

Particularly dangerous are hidden defects in concrete and reinforced concrete elements. Visual inspection allows the identification of cracks, efflorescence, seepage traces, corrosion stains, deterioration of the protective concrete cover, and local surface spalling. However, such inspection methods do not provide reliable information about the internal condition of the structure. Meanwhile, internal defects are often the determining factor in the progressive loss of load-bearing capacity and watertightness. These defects include low-density zones, cavities, internal cracking, concreting defects, local delamination, loss of bond between concrete and reinforcement, areas of increased moisture saturation, and zones of reduced structural strength (**Ilyassova et. all., 2025, Moldamuratov et. all., 2023**).

Modern studies demonstrate that failures of hydraulic structures are rarely caused by a single factor. In most cases, they result from the combined effects of seepage, foundation deformation, material aging, insufficient monitoring, and extreme natural impacts. For example, an investigation of the failure of the Voroshilov Reservoir dam in Kazakhstan showed that the combination of chronic seepage, increased moisture saturation, deformation processes, and microseismic activity could have been a key factor in the failure scenario. According to InSAR monitoring data, a persistent deformation trend with amplitudes reaching up to 30 mm had been recorded since the spring of 2022, while ground-penetrating radar surveys revealed zones of elevated moisture content within the dam body at depths of up to 2 m. This example confirms the necessity of applying integrated diagnostic methods capable of detecting hidden structural changes before the development of a critical condition (**Seitkazinov et. all., 2025, Ilyassova et. all., 2025, Moldamuratov et. all., 2023**).

For concrete and reinforced concrete hydraulic structures, non-destructive testing methods are of particular importance. These methods make it possible to obtain information about the condition of the material without compromising the integrity of the structure. This is critically important for dams, spillways, inspection galleries, bottom outlets, retaining walls, canal linings, and other structural elements where extensive core extraction may be technically difficult, costly, or undesirable. Non-destructive testing also enables repeated measurements within the same zones, thereby providing the basis for long-term monitoring of defect evolution over time (**Zhu et. all., 2022, Ilyassova et. all., 2025, Moldamuratov et. all., 2023**).

Among the non-destructive testing methods widely applied to concrete structures are visual inspection, ultrasonic testing, impact-echo methods, rebound hammer testing, ground-penetrating radar, infrared thermography, acoustic emission monitoring, electrical resistivity measurements, and reinforcement corrosion potential assessment. Each method has its own specific field of application. Ground-penetrating radar is effective for detecting reinforcement, voids, moisture-saturated areas, and structural heterogeneities. Rebound hammer testing provides an approximate evaluation of surface strength. Infrared thermography enables the identification of moisture-affected and defective zones under conditions of thermal contrast. However, ultrasonic methods are of particular significance for evaluating the internal structure of concrete massifs (**Seitkazinov et. all., 2025, Wróbel et. all., 2024, Moldamuratov et. all., 2023**).

Ultrasonic testing is based on the analysis of mechanical wave propagation within concrete. The velocity, amplitude, and transmission characteristics of ultrasonic waves depend on material density, cracking, moisture content, pore structure, and the quality of contact between structural components. According to ASTM C597, the ultrasonic pulse velocity method is intended for determining the propagation velocity of longitudinal ultrasonic pulses through concrete. In engineering practice, this method is widely used to assess concrete uniformity, identify internal defects, evaluate cracking intensity, and select areas requiring more detailed investigation (**Seitkazinov et. all., 2025, Ilyassova et. all., 2025, Moldamuratov et. all., 2023**).

However, conventional ultrasonic testing has several limitations. It is often based on measurements between individual points. Such data provide only localized information about the material and do not always allow reliable assessment of the spatial distribution of defects. This issue is particularly critical for massive hydraulic structures. Structural elements may have considerable thickness, while defects can possess complex geometries. Seepage-induced deterioration and low-density zones may develop non-uniformly throughout the structure. Therefore, point-based measurements are not always sufficient for reliable engineering decision-making (**Schabowicz et. all., 2014, He et. all., 2018, Moldamuratov et. all., 2023**).

In this regard, 3D ultrasonic tomography of concrete represents a promising direction for advanced structural diagnostics. This approach enables the transition from isolated measurements to spatial reconstruction of the internal condition of a structure. It makes it possible to generate three-dimensional defect maps, determine the depth of defect occurrence, evaluate the extent of deterioration zones, and identify regions characterized by reduced ultrasonic wave velocity. Unlike conventional ultrasonic testing, 3D tomography considers the concrete element as a volumetric heterogeneous medium. This is especially important for hydraulic structures, where defects are frequently associated with directed water movement, seepage flows, and localized washout of cementitious material degradation products (**Seitkazinov et. all., 2025, Zhu et. all., 2018, Moldamuratov et. all., 2023**).

The application of the Betonoskop SK-1700 3D system for the inspection of concrete and reinforced concrete hydraulic structures significantly enhances the diagnostic capabilities of the investigation. The device can be used to assess the internal structure of concrete, identify heterogeneity zones, cracks, voids, and areas of reduced material quality. The scientific significance of this approach lies not only in obtaining defect maps, but also in enabling quantitative interpretation of the results. High-level investigations require the assessment of ultrasonic wave velocity, depth of defective zones, area and volume of anomalies, heterogeneity coefficients, relationships between defects and visible seepage manifestations, as well as the influence of detected damage on the operational reliability of the structure (**Khairi et. all., 2019, Kłosowski et. all., 2020, Moldamuratov et. all., 2023**).

Despite the continuous development of non-destructive testing methods, there remains a shortage of studies specifically focused on concrete and reinforced concrete elements of hydraulic structures. Most existing studies on ultrasonic testing of concrete are focused on civil buildings, bridges, pavements, or laboratory specimens. Hydraulic structures possess fundamentally different operational characteristics. They operate under water-saturated conditions, while their concrete is subjected to long-term hydrochemical impacts. Damage mechanisms are often associated with seepage, cavitation, freeze-thaw action, leaching processes, and reinforcement corrosion. Therefore, the direct application of methodologies developed for conventional building structures does not always provide sufficient reliability for hydraulic engineering facilities (**Seitkazinov et. all., 2025, Ilyassova et. all., 2025, Zhu et. all., 2022**).

Thus, an important scientific and engineering challenge is the development and substantiation of a methodological approach for assessing the technical condition of concrete and reinforced concrete hydraulic structures using 3D ultrasonic tomography. Such an approach should account for the specific operational impacts, the physico-mechanical heterogeneity of concrete, the presence of moisture-saturated zones, the nature of internal defects, and the necessity for spatial interpretation of diagnostic results. It should integrate visual inspection, instrumental non-destructive testing, three-dimensional reconstruction of defects, and engineering assessment of the influence of identified defects on structural reliability (**Kwon et. all., 2021, Lorenzi et. all., 2025, Alqurashi et. all., 2025 Moldamuratov et. all., 2023, Lorenzi et. all., 2023**).

The objective of the present study is to assess the technical condition of concrete and reinforced concrete hydraulic structures using 3D ultrasonic tomography based on the Betonoskop SK-1700 3D system. The study is aimed at identifying internal defects, spatial localization of concrete deterioration zones, and substantiation of diagnostic criteria for the engineering interpretation of non-destructive testing results.

To achieve this objective, the following tasks were addressed in the study: analysis of operational deterioration factors affecting concrete and reinforced concrete hydraulic structures; visual and instrumental inspection of representative structural elements; implementation of 3D ultrasonic scanning; development of spatial models of the internal concrete structure; identification of heterogeneity zones and potential defects; comparison of tomographic data with external signs of damage; and engineering assessment of the influence of detected defects on the technical condition of the structure.

The scientific significance of the study lies in the advancement of methodologies for spatial diagnostics of concrete and reinforced concrete hydraulic structures based on 3D ultrasonic tomography. The practical significance consists in the possibility of applying the proposed approach for early detection of hidden defects, planning of repair and rehabilitation works, optimization of monitoring programs, and enhancement of the operational reliability of hydraulic infrastructure facilities.

2 MATERIALS AND METHODS

The investigation of the technical condition of concrete and reinforced concrete structures was carried out using the emergency spillway of the Tasotkel Reservoir located in the Zhambyl Region of the Republic of Kazakhstan as a case study. The selection of this facility was determined by the high level of structural responsibility of the hydraulic structure, its long-term operation period, exposure to intensive hydrodynamic loading, and the presence of visible signs of deterioration in certain zones of the spillway system (**Seitkazinov et. all., 2025, Ilyassova et. all., 2025, Moldamuratov et. all., 2023**).

The emergency spillway of the Tasotkel Reservoir is one of the key hydraulic components responsible for the safe passage of flood discharges and the prevention of water overtopping over the crest of the earthfill dam. During long-term operation, the spillway structures are subjected to variable hydrostatic pressure, high-velocity water flows, cavitation effects, cyclic wetting and drying, seasonal freeze-thaw action, and seepage-related impacts. The combined influence of these factors contributes to the gradual development of internal concrete defects, including cracking, localized low-density zones, leaching of cementitious components, and reduction in material density.

The emergency spillway consists of the following principal structural elements: the inlet spillway section, bridge structure, transition section, chute canal, cantilever spillway, and outlet (pilot) canal.

A general view of the emergency spillway is presented in **Figure 1**.

The principal element of the spillway is the inlet section, designed as an ogee spillway with the crest elevation at the normal retaining water level of 519.0 m a.s.l. In plan view, the spillway has a complex oval geometry with straight sections up to 10.8 m in length connected by curved segments with a radius of 8.0 m. Such a geometric configuration ensures more uniform flow distribution and reduces localized hydrodynamic impacts on the structural elements of the spillway.

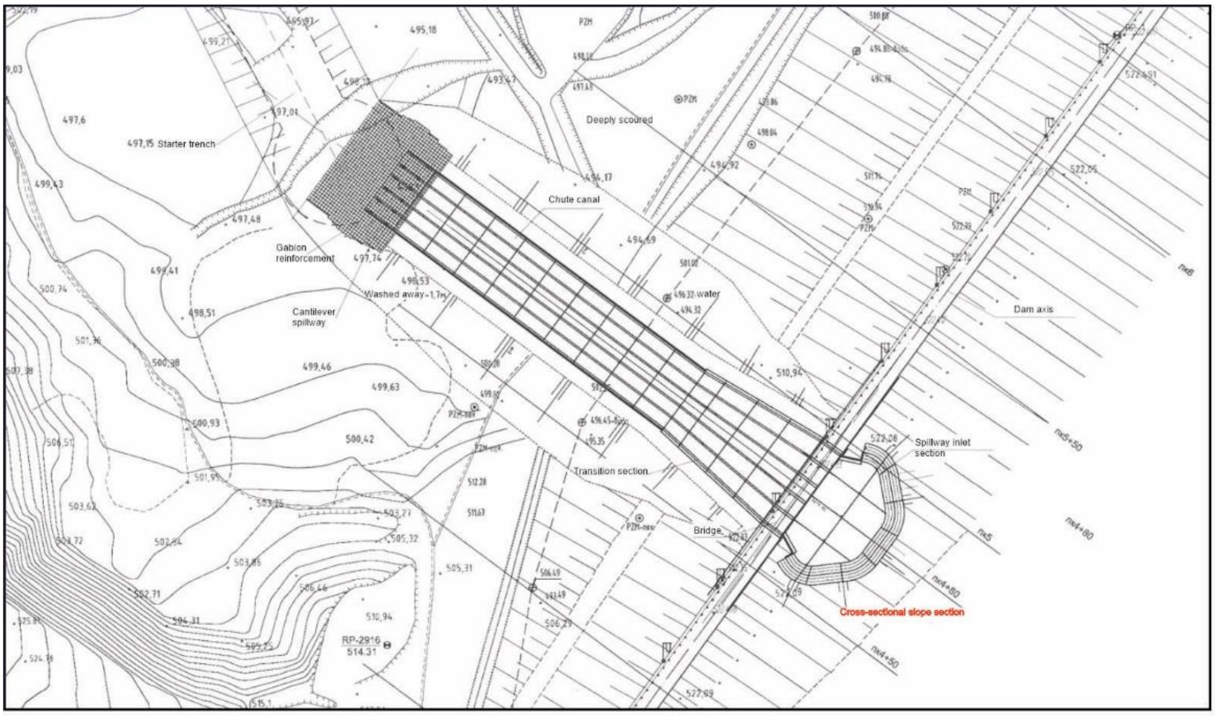

Figure 1 - General view of the emergency spillway of the Tasotkel Reservoir (authors' material)

The discharge capacity of the spillway reaches up to Q = 362 m³/s at the design hydraulic head of h = 2.2 m. Under these hydraulic conditions, the freeboard between the water level and the crest of the earthfill dam is determined as follows:

$$522.40 - (519.0 + 2.2) = 1.2 \text{ m}$$

Taking into account the parapet height of 0.90 m, the structure provides the required safety margin against wave action, which satisfies the operational reliability requirements for hydraulic structures.

The main hydraulic parameters of the emergency spillway are presented in **Table 1**.

Table 1
Main parameters of the emergency spillway of the Tasotkel Reservoir (authors' material)

No.	Parameter	Value
1	Structure type	Emergency spillway
2	Spillway crest elevation	519.0 m a.s.l.
3	Maximum discharge capacity	362 m³/s
4	Design hydraulic head	2.2 m
5	Freeboard to dam crest	1.2 m
6	Parapet height	0.90 m
7	Length of straight sections	up to 10.8 m
8	Radius of curved sections	8.0 m

Within the framework of the study, particular attention was focused on the inspection of concrete and reinforced concrete elements of the spillway inlet section, transition section, chute canal, and cantilever spillway. These zones are subjected to the most intensive hydrodynamic and seepage-related impacts, which contribute to the accelerated development of material deterioration processes.

Prior to the instrumental investigation, a detailed visual inspection of the structures was carried out (**Figure 2**). The primary objective of this stage was to identify external signs of deterioration and localize potentially defective zones. During the inspection, the following defects and damage manifestations were documented: longitudinal and transverse cracking; localized moisture-affected areas; seepage zones; efflorescence formation; corrosion stains; concrete spalling; deterioration of repaired sections; and localized cavitation damage.

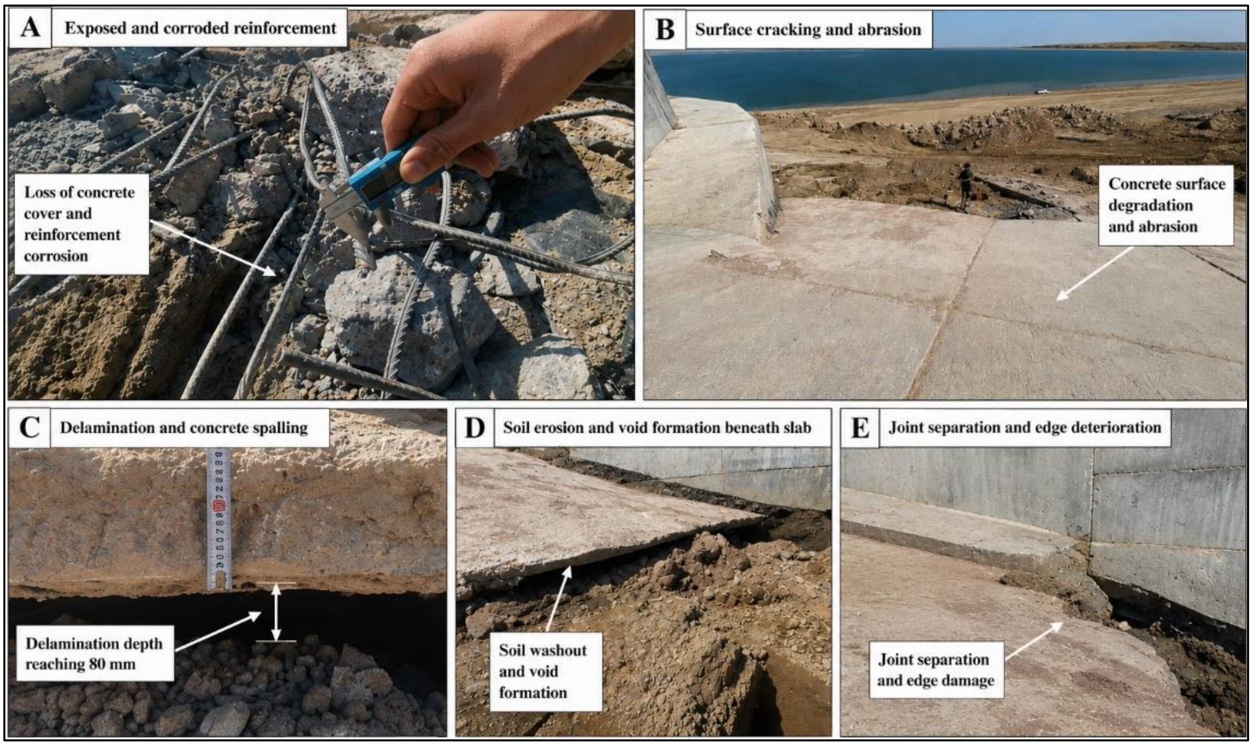

Figure 2 - Typical deterioration defects identified in concrete structures during inspection of the Tasotkel Reservoir emergency spillway: (a) exposed and corroded reinforcement; (b) surface cracking and abrasion; (c) concrete delamination and spalling; (d) soil erosion and void formation beneath slab; (e) joint separation and edge deterioration (authors' material)

The most severe defects were identified in the zones of interaction between structural elements, as well as within the chute canal and cantilever spillway sections, where increased flow velocity and localized hydrodynamic impacts are observed.

The crack opening width varied from 0.08 to 1.60 mm. The depth of local concrete spalling reached up to 45 mm. The area of moisture-affected zones ranged from 0.12 to 2.80 m².

The characteristics of visually identified defects are presented in **Table 2.**

Table 2
Main characteristics of the identified defects (authors' material)

No.	Type of defect	Range of values	Localization
1	Crack opening width	0.08-1.60 mm	Chute canal, transition section
2	Depth of concrete spalling	5-45 mm	Cantilever spillway
3	Area of moisture-affected zones	0.12-2.80 m²	Galleries and interface zones
4	Height of corrosion stains	0.15-1.30 m	Vertical surfaces
5	Deterioration of repair layer	8-35 mm	Chute canal
6	Efflorescence formation	up to 4.5 m	Seepage zones

After completion of the visual inspection, the surfaces of the structures were prepared for ultrasonic investigation. Surface preparation included the removal of contaminants, delaminated coatings, and loose concrete fragments. Particular attention was paid to ensuring stable acoustic coupling between the working surface of the transducers and the investigated material.

The principal research method employed in the study was three-dimensional ultrasonic tomography using the Betonoskop SK-1700 3D system. The method is based on recording the parameters of ultrasonic wave propagation within the concrete massif followed by spatial reconstruction of the internal structure of the material (**Figure 3**).

During the investigation, the following parameters were analyzed: ultrasonic wave propagation velocity; signal amplitude; attenuation coefficient; wave scattering characteristics; heterogeneity of the internal structure; presence of low-density zones; and localized areas of increased moisture saturation (**Zhu et. all., 2018**).

The main parameters of the ultrasonic investigation are presented in **Table 3.**

Figure 3 - Field application of the CK-1700 3D ultrasonic tomography system during inspection of concrete structures at the Tasotkel Reservoir emergency spillway (authors' material)

Table 3
Parameters of the ultrasonic investigation (authors' material)

No.	Parameter	Value
1	Equipment	Betonoskop SK-1700 3D
2	Type of inspection	3D ultrasonic tomography
3	Frequency range	50-100 kHz
4	Penetration depth	up to 1000 mm
5	Measurement grid size	50×50 - 100×100 mm
6	Number of measurement points	64-256
7	Number of repeated measurements	3-5
8	Length of diagnostic profile	0.8-4.0 m
9	Scanning type	Longitudinal and transverse

To improve diagnostic accuracy, a cross-scanning scheme was applied during the investigation. Measurements were performed in two mutually perpendicular directions. This approach increased the probability of detecting internal defects with complex spatial configurations.

The scheme of the 3D ultrasonic investigation is presented in **Figure 4**.

The ultrasonic wave velocity was determined using the following relationship (**Kwon et. all., 2021, Lorenzi et. all., 2025, Alqurashi et. all., Lorenzi et. all., 2023**):

$$V = \frac{L}{t},$$

where: V-ultrasonic wave velocity, m/s; L-signal propagation path length, m; t-signal travel time, s.

Based on the recorded data, spatial tomographic reconstruction of the internal concrete structure was performed. As a result of data processing, the following outputs were generated: two-dimensional diagnostic sections; three-dimensional velocity distribution maps; volumetric defectograms; zones of localized low-density concrete; areas of increased cracking intensity; and regions characterized by elevated signal attenuation (**Kwon et. all., 2021, Lorenzi et. all., 2025, Alqurashi et. all., 2025, Lorenzi et. all., 2023**).

Interpretation of the obtained results was carried out according to the classification of concrete condition based on ultrasonic wave velocity values presented in **Table 4.**

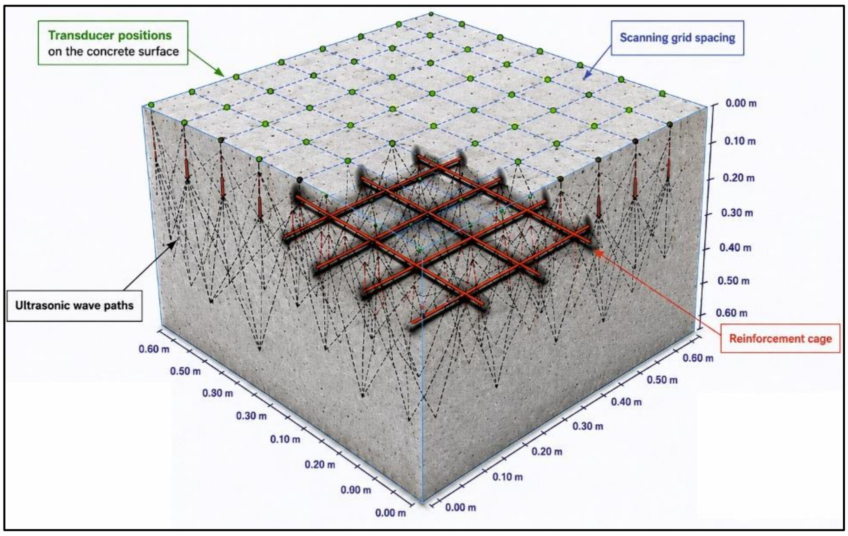

Figure 4 - Scheme of the 3D ultrasonic investigation of a concrete structure (authors' material)

Table 4
Classification of concrete condition based on ultrasonic wave velocity (authors' material)

No.	Ultrasonic wave velocity, m/s	Material condition
1	> 4500	Dense defect-free concrete
2	3500-4500	Moderately heterogeneous concrete
3	2500-3500	Cracked and low-density concrete
4	< 2500	Critical defect zones

Additionally, the depth of defect propagation, spatial dimensions of anomalous zones, and the heterogeneity coefficient of the material structure were evaluated. The obtained results were used for the engineering assessment of the technical condition of the emergency spillway structures and for the identification of potentially hazardous zones associated with the further development of deterioration processes.

3 RESULTS AND DISCUSSION

The results of the spatial ultrasonic survey demonstrated that the technical condition of the concrete lining of the emergency spillway at the Tasotkel Reservoir is characterized by pronounced internal structural heterogeneity, localized zones of reduced concrete density, signs of filtration-induced moisture penetration, and partial loss of contact between the concrete lining and the foundation. The obtained data indicate the presence of both surface and deep-seated defects caused by prolonged cyclic water saturation, temperature-induced deformation, filtration pressure, and long-term material aging processes.

According to the results of the 3D ultrasonic tomography, the average ultrasonic wave velocity within the investigated area was approximately 3280 m/s, while the minimum recorded values reached 1680-1850 m/s, and the maximum local values exceeded 4350-4480 m/s. The coefficient of variation of ultrasonic velocities across the surveyed volume was 21.4%, indicating a high degree of structural heterogeneity within the concrete lining (**Kwon et. all., 2021, Lorenzi et. all., 2025, Alqurashi et. all., 2025, Lorenzi et. all., 2023**).

Analysis of the spatial velocity distribution revealed that approximately 41-46% of the investigated volume corresponds to moderately deteriorated concrete with ultrasonic velocities ranging from 3000 to 4000 m/s. These areas were predominantly localized within the upper portion of the concrete lining and were characterized by partial reduction in structural density without the formation of critical internal defects. At the same time, the volume fraction of relatively dense concrete with velocities exceeding 4000 m/s accounted for only 14-18% of the total investigated volume. Such zones were mainly associated with reinforcement influence and locally compact concrete regions.

Particular attention should be given to areas with velocities below 2500 m/s, whose total volume reached 18-26% of the surveyed massif. These zones exhibited the most pronounced wave-field anomalies, characterized by significant signal scattering, reduced reflection amplitudes, and discontinuities in the isosurface geometry. The most critical areas with velocities below 2000 m/s occupied approximately 4-7% of the investigated volume and were mainly localized in the lower part of the lining and near the concrete-foundation interface.

Figure 5 presents the plan-view distribution of ultrasonic wave velocities at a depth of Z = 0.19 m. This level corresponds to the upper operational zone of the lining, which is most affected by climatic and operational factors. The average velocity at this level was approximately 3420 m/s. In areas associated with the estimated reinforcement layout, local velocity values of 4100-4450 m/s were recorded. The spacing between such high-velocity zones ranged from 1.8 to 2.2 m, corresponding to the arrangement of structural reinforcement elements and slab joints.

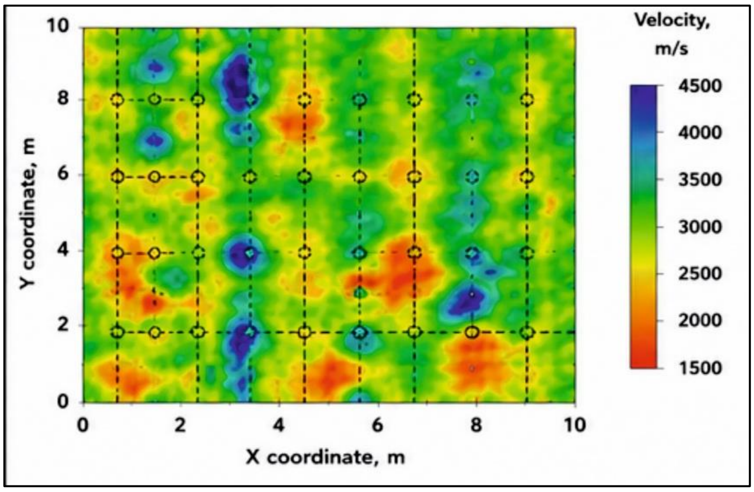

Figure 5 - Plan-view ultrasonic velocity distribution at depth Z = 0.19 m (authors' material)

Within the plan-view section, multiple low-velocity anomalies ranging in size from 0.25 × 0.30 m to 1.10 × 1.45 m were identified. The largest defect zones were concentrated in the central and lower portions of the investigated area. The average velocity within these anomalous regions ranged from 1950 to 2400 m/s, corresponding to severely deteriorated and locally weakened concrete.

It should be emphasized that the distribution of anomalies exhibited a predominantly elongated geometry aligned with the presumed direction of filtration flow. Such a defect configuration is characteristic of internal filtration erosion and localized moisture accumulation within subsurface structural layers.

Figure 6 shows the three-dimensional reconstruction of the internal structure of the concrete lining. Analysis of the volumetric model demonstrated that the average ultrasonic wave velocity gradually decreased with increasing depth. Specifically, within the depth range of 0.00-0.15 m, the average velocity varied from 3720 to 3980 m/s, whereas at depths of 0.35-0.60 m, this parameter decreased to 2250-2850 m/s.

A significant increase in the volume fraction of low-velocity zones was observed in the lower portion of the structure. The maximum concentration of defects was identified within the depth interval of 0.32-0.48 m, where the total area of anomalous regions reached 28-34% of the section area. Such distribution patterns indicate the development of internal loosening processes within the foundation layer and deterioration of bonding between the concrete lining and the underlying base.

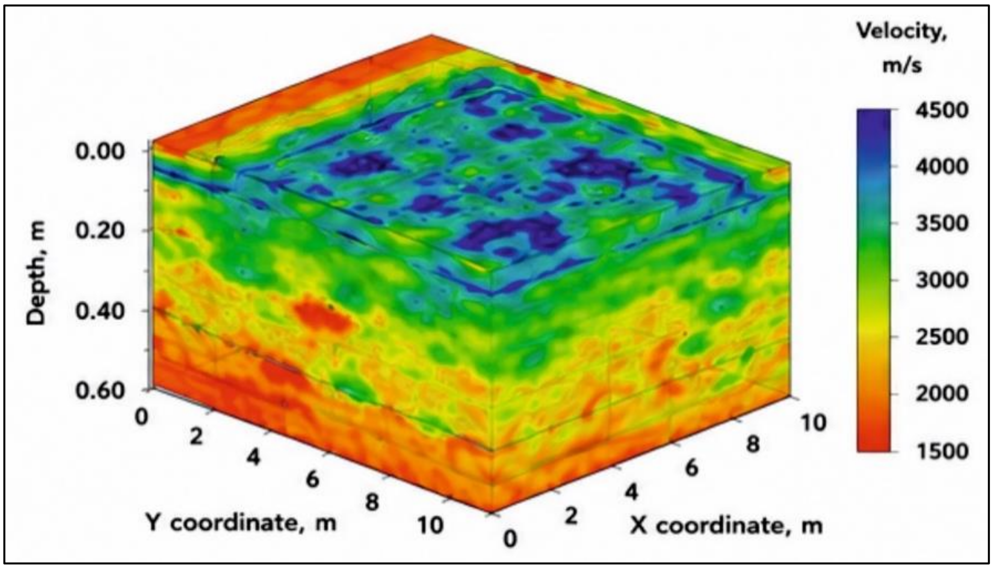

Figure 6 - 3D ultrasonic tomographic reconstruction of the concrete lining segment (velocity isosurfaces) (authors' material)

Particular attention should be paid to elongated low-velocity zones oriented along the presumed directions of seepage flow. Similar spatial configurations are typical for internal filtration erosion and the gradual formation of subsurface voids. In several areas, closed anomalous regions with sharp velocity gradients were identified, which may indicate local delamination and hidden cavity formation within the concrete structure.

Figure 7 presents the vertical tomographic section (X-Z), allowing assessment of the variation in concrete condition throughout the structural depth. The upper part of the section is characterized by a relatively continuous high-velocity layer with a thickness of approximately 0.08-0.12 m, corresponding to the denser surface layer of the concrete lining and the reinforcement zone. Below this level, a gradual increase in wave-field heterogeneity and a reduction in ultrasonic velocities were observed.

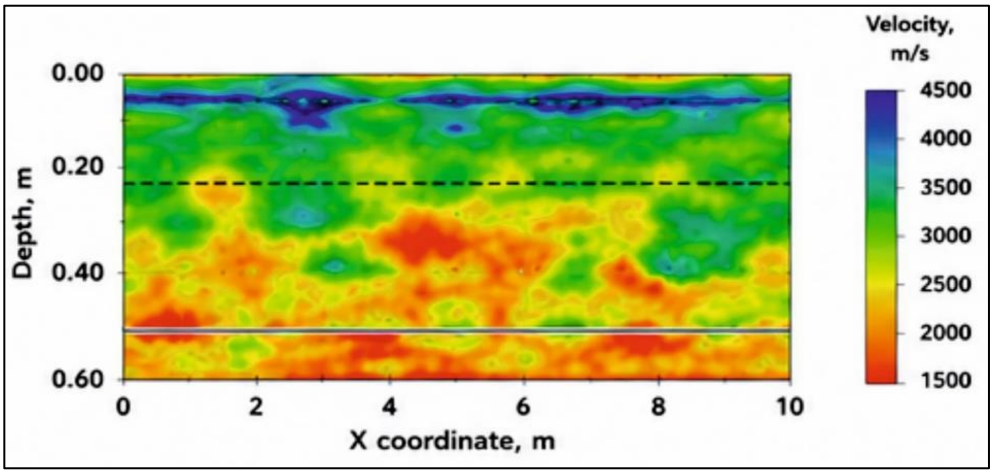

Figure 7 - Vertical tomographic section (X-Z) showing internal heterogeneity and low-velocity zones within the concrete lining (authors' material)

At depths of approximately 0.20-0.25 m, a horizontal zone of increased reflections was identified and interpreted as the estimated reinforcement level. The thickness of this zone ranged from approximately 40 to 60 mm. In the lower part of the section, beginning at depths around 0.35 m, extended regions with velocities ranging from 1800 to 2600 m/s were observed. The amplitudes of reflected signals within these regions decreased by approximately 35-48% compared with relatively intact areas, indicating substantial disruption of material continuity.

In several locations, localized closed anomalies measuring approximately 0.18-0.35 m were detected, characterized by abrupt velocity reductions to 1700-1900 m/s. Such zones are interpreted as probable subsurface voids or local delamination areas.

Figure 8 presents the transverse tomographic section (Y-Z). The average velocity within this section was approximately 3010 m/s; however, a pronounced anomalous zone approximately 2.1-2.4 m wide was identified in the central part of the investigated area, where velocities decreased to 1850-2300 m/s. This zone exhibited elevated structural heterogeneity, significant signal scattering, and local distortion of reflecting boundaries.

Such a pattern is characteristic of filtration-induced moisture penetration and localized washout of fine-grained particles from the foundation layer. In several areas, discontinuities along the concrete-foundation interface extending over 1.6-2.0 m were identified.

Figure 9 presents the engineering interpretation of the principal defect zones. The total area associated with potential voids and loss of bonding accounted for approximately 6.8-8.5% of the investigated surface. The average depth of these defects reached approximately 0.42-0.55 m. Filtration-affected and moisture-saturated zones occupied approximately 18-22% of the investigated massif. Within these areas, the estimated moisture-related reduction in acoustic properties exceeded average values by approximately 22-35%.

Particularly critical are the delamination zones identified along the concrete lining-foundation interface, whose total extent reached approximately 3.5-4.2 m within the investigated segment. Such defects substantially reduce the composite action of the structure and may accelerate further filtration erosion processes.

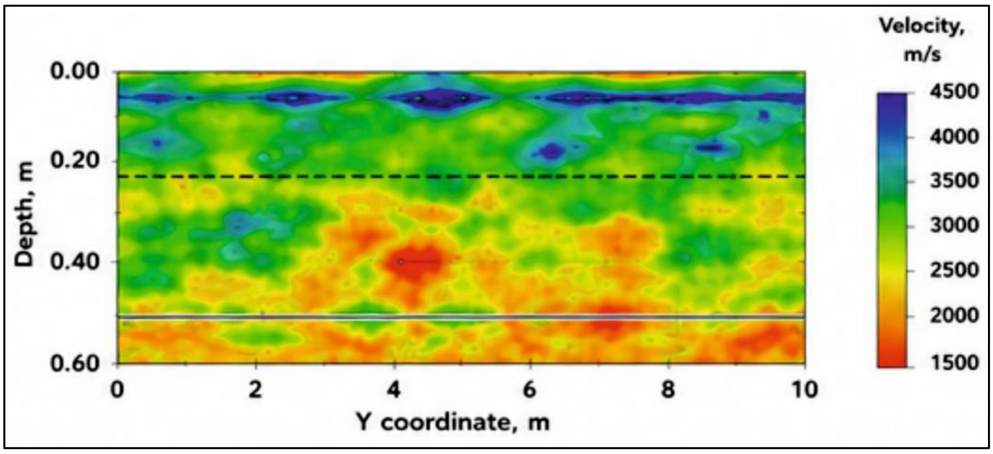

Figure 8 - Transverse tomographic section (Y-Z) illustrating filtration-affected and degraded regions in the concrete structure (authors' material)

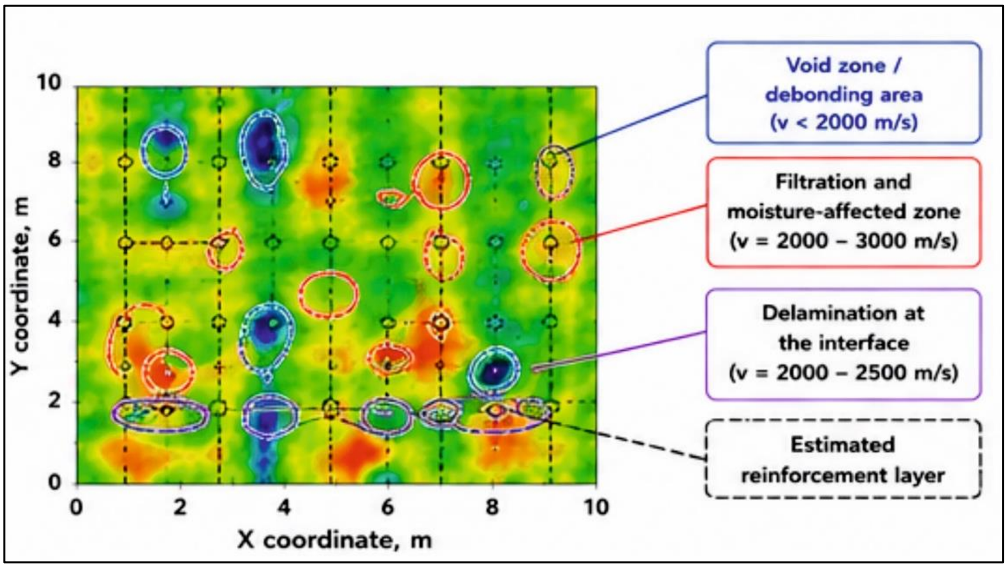

Figure 9 - Engineering interpretation of principal defect zones identified in the plan-view ultrasonic tomography (authors' material)

Figure 10 presents the results of the integrated engineering interpretation of vertical and transverse tomographic sections. High-amplitude reflections associated with reinforcement and dense concrete were identified in the upper structural layers. The middle portion of the structure exhibited localized moisture-affected and microstructurally heterogeneous regions. In the lower portion, zones of delamination and loss of bonding between the lining and the foundation were clearly identified.

It should be emphasized that the most critical defects are localized within the concrete lining-foundation interface zone, as these regions create favorable conditions for further filtration erosion, subsurface void development, and progressive slab deformation. Under prolonged operational loading, such processes may result in local slab settlement, joint opening, and a reduction in the overall operational reliability of the hydraulic structure.

Quantitative analysis demonstrated that the volume fraction of zones with velocities below 2500 m/s reached 18-26% of the investigated massif, while critical zones with velocities below 2000 m/s accounted for approximately 4-7% of the total investigated volume. The coefficient of variation of ultrasonic velocities within defective areas reached 18-22%, whereas in relatively intact zones it did not exceed 5-7%. These findings additionally confirm the high degree of structural heterogeneity within deteriorated regions.

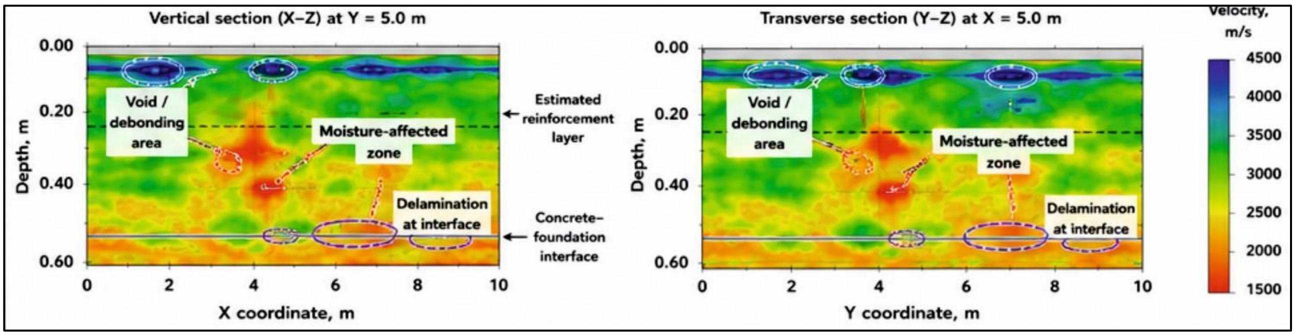

Figure 10 - Integrated schematic interpretation of tomographic sections with identification of voids, moisture-affected zones, reinforcement layer, and concrete-foundation interface defects (authors' material)

The additional quantitative analysis of the 3D ultrasonic tomography results is presented in **Figures 11-18**. These figures complement the tomographic interpretation by providing spatial, statistical, correlation-based, and mechanism-oriented evidence of concrete lining deterioration. Unlike visual inspection, which mainly identifies surface defects, the proposed analysis allows a more detailed interpretation of internal deterioration processes, including filtration-induced degradation, loss of bonding at the concrete-foundation interface, local void formation, and depth-dependent reduction in ultrasonic wave velocity (**Schabowicz et. all., 2014, He et. all., 2018, (Khairi et. all., 2019, Kłosowski et. all., 2020**).

Figure 11 presents the spatial deterioration intensity map of the concrete lining at a depth of Z = 0.19 m. This level corresponds to the near-surface operating layer of the lining, where the effects of abrasion, cyclic wetting-drying, temperature gradients, and surface cracking are most pronounced. The map shows that the investigated area is not acoustically homogeneous. Dense concrete zones with velocities above 4000 m/s occupy approximately 14-17% of the investigated surface. Moderate deterioration zones with velocities of 3000-4000 m/s are dominant and account for 41-46% of the area. Severe deterioration zones with velocities of 2000-3000 m/s occupy 20-24%. Critical deterioration and potential void zones with velocities below 2000 m/s account for 6-8%. Filtration-affected zones occupy 18-22%, while delamination-prone interface regions account for 6-9%. This distribution indicates that the deterioration is spatially localized but not isolated. The most critical areas are concentrated along linear and elongated anomaly patterns, which may correspond to slab joints, filtration paths, and zones of weakened concrete-foundation contact.

Figure 12 shows the variation in ultrasonic wave velocity with investigation depth. The graph demonstrates a clear depth-dependent reduction in velocity. In the upper layer, within 0.00-0.10 m, the average velocity is approximately 3980 ± 260 m/s. At a depth of 0.10-0.20 m, the velocity decreases to 3690 ± 240 m/s. In the interval of 0.20-0.30 m, the average velocity decreases further to 3350 ± 230 m/s. A more pronounced reduction is observed below 0.35 m, where the average velocity decreases to 2930 ± 210 m/s in the 0.30-0.40 m interval and to 2380 ± 190 m/s in the 0.40-0.50 m interval. At depths of 0.50-0.60 m, the average velocity reaches only 1860 ± 150 m/s. This trend indicates accelerated deterioration below approximately 0.35 m, which is consistent with the expected location of moisture accumulation, debonding, and interface degradation. Therefore, the lower part of the lining and the concrete-foundation contact zone should be considered the most vulnerable structural region.

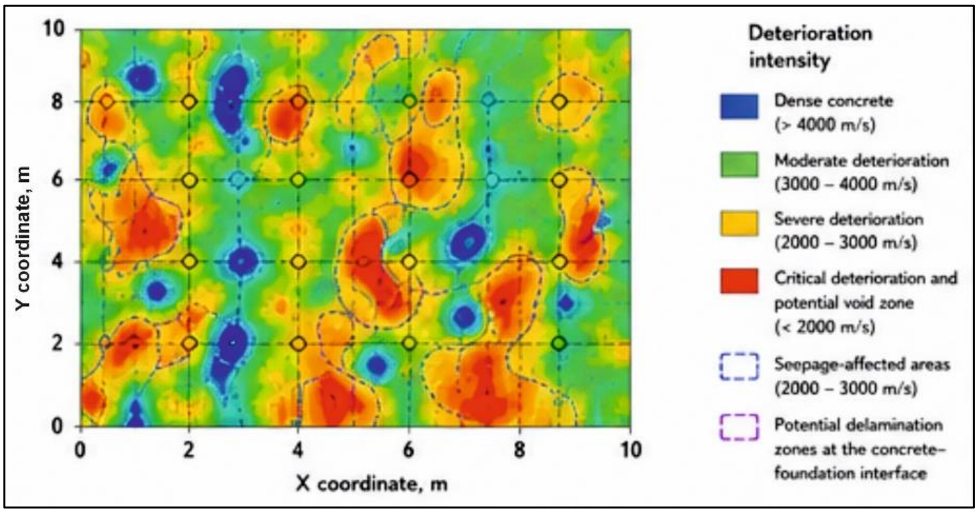

Figure 11 - Spatial deterioration intensity map of the concrete lining (plan view, Z = 0.19 m), (authors' material)

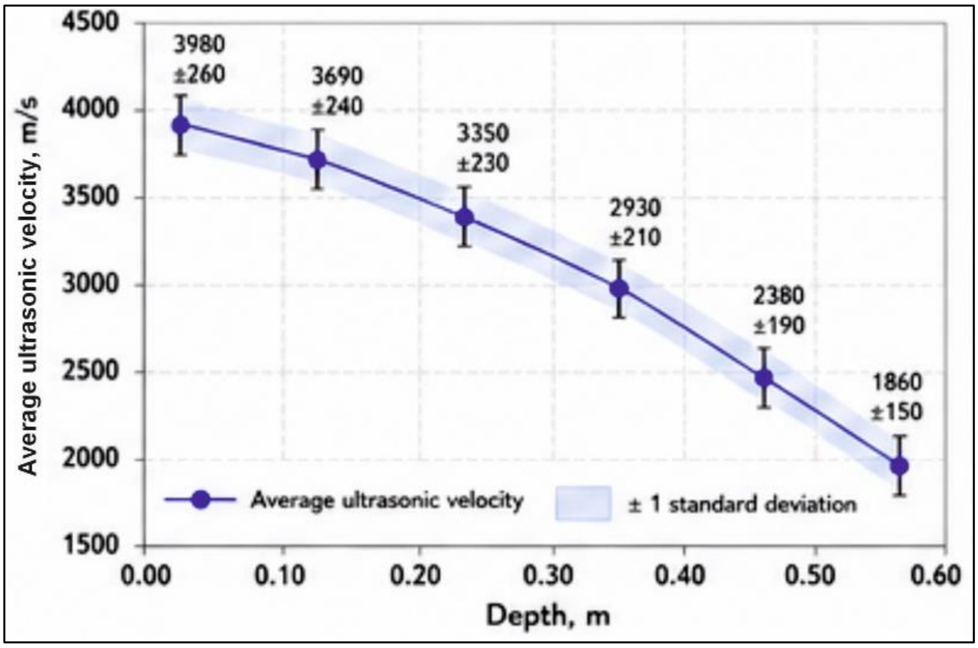

Figure 12 - Variation in ultrasonic wave velocity with investigation depth (authors' material)

Figure 13 presents the statistical distribution of ultrasonic wave velocities based on 623,061 valid voxels. The mean velocity is 3280 m/s, while the median velocity is 3210 m/s. The standard deviation is 704 m/s, which confirms significant acoustic heterogeneity of the investigated concrete volume. The minimum and maximum recorded velocities are 1680 m/s and 4480 m/s, respectively. The coefficient of variation is 21.4%. The histogram shows that the largest fraction of the investigated volume falls within the 3000-3500 m/s range, accounting for 28.7%. The 3500-4000 m/s range accounts for 17.8%, while the high-velocity range above 4000 m/s accounts for 13.2%. The severe deterioration interval of 2500-3000 m/s accounts for 20.4%, and the 2000-2500 m/s interval accounts for 11.0%. Critical zones with velocities below 2000 m/s account for 4.9%. This distribution confirms that the concrete lining is dominated by moderately deteriorated material, while localized critical defect zones are present and require engineering attention.

Figure 14 illustrates the correlation between ultrasonic wave velocity and defect depth. The scatter plot demonstrates a distinct negative correlation. The regression equation is expressed as $y = -4.05x + 4240$, with $R^2 = 0.81$ and $N = 152$ measurement points. This means that with increasing defect depth, ultrasonic velocity decreases systematically. Defects with depths of 0-50 mm are characterized by velocities of approximately 3600-4300 m/s, with a mean value of 3930 m/s. Defects of 50-100 mm correspond to velocities of 3200-3900 m/s, with a mean value of 3560 m/s. For defects of 100-200 mm, velocities decrease to 2500-3400 m/s, with a mean value of 2890 m/s. Defects of 200-300 mm correspond to velocities of 1900-2700 m/s, with a mean value of 2250 m/s. When the defect depth exceeds 300 mm, the velocity drops below 2200 m/s, with an average value of approximately 1830 m/s. These results confirm that deeper defects are associated with stronger internal deterioration, increased porosity, possible void formation, and reduced contact between the concrete lining and the foundation.

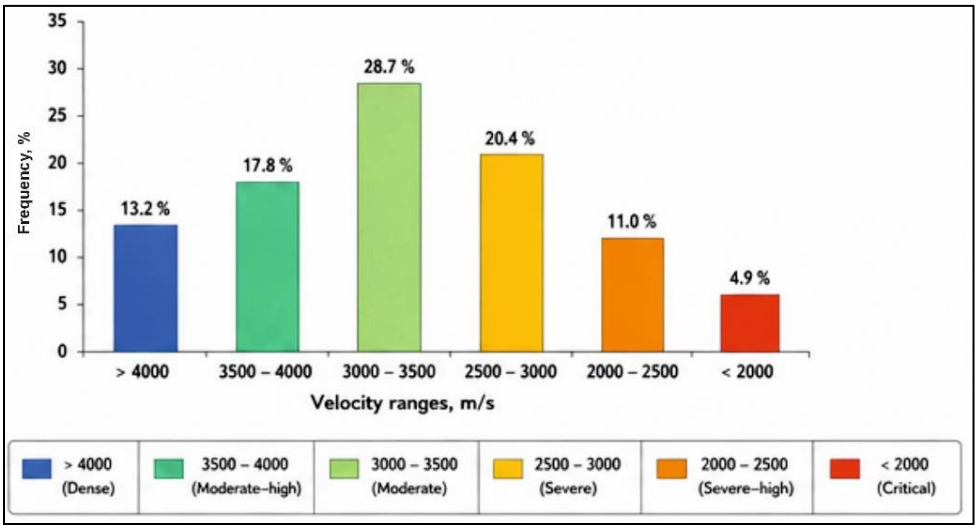

Figure 13 - Statistical distribution of ultrasonic wave velocities (authors' material)

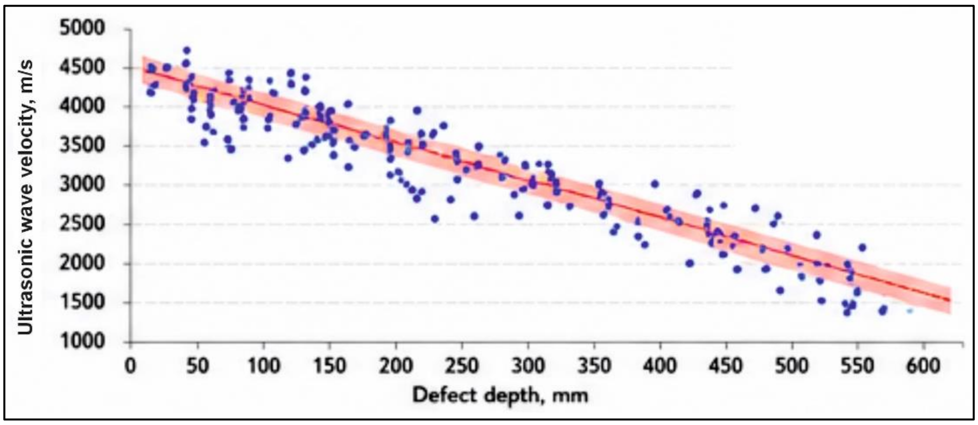

Figure 14 - Relationship between ultrasonic wave velocity and defect depth (authors' material)

Figure 15 presents the volumetric distribution of structural deterioration zones. Unlike the plan-view map, this figure quantifies the deterioration throughout the entire investigated volume of 10.0 × 10.0 × 0.60 m. Dense concrete zones account for 17.6 ± 1.9% of the volume. Moderately deteriorated concrete is the dominant class and accounts for 44.3 ± 2.6%. Severe deterioration zones account for 21.5 ± 2.2%. Critical deterioration and potential void zones account for 6.4 ± 1.1%, while moisture-affected zones account for 8.2 ± 1.3%. The total volume with significant deterioration, including severe, critical, and moisture-affected areas, reaches 35.9 ± 3.1%. This value is important from an engineering perspective because it indicates that more than one-third of the investigated concrete lining volume has signs of substantial internal degradation.

Figure 16 provides a comparative assessment of deterioration indicators in the investigated zones using a radar chart. The evaluated parameters include crack intensity, moisture saturation, filtration activity, void formation risk, delamination risk, reinforcement interference, and structural heterogeneity. The intact reference zone shows the lowest deterioration indices, generally within 1-2 points on a 0-5 scale. The joint zone shows increased values for crack intensity, moisture saturation, and structural heterogeneity. The filtration zone is characterized by higher moisture saturation, filtration activity, and void formation risk. The foundation contact zone shows the highest overall deterioration level, with values approaching 4-5 points for delamination risk, void formation risk, filtration activity, and structural heterogeneity. This confirms that the concrete-foundation interface is the most critical zone in terms of long-term durability and operational safety.

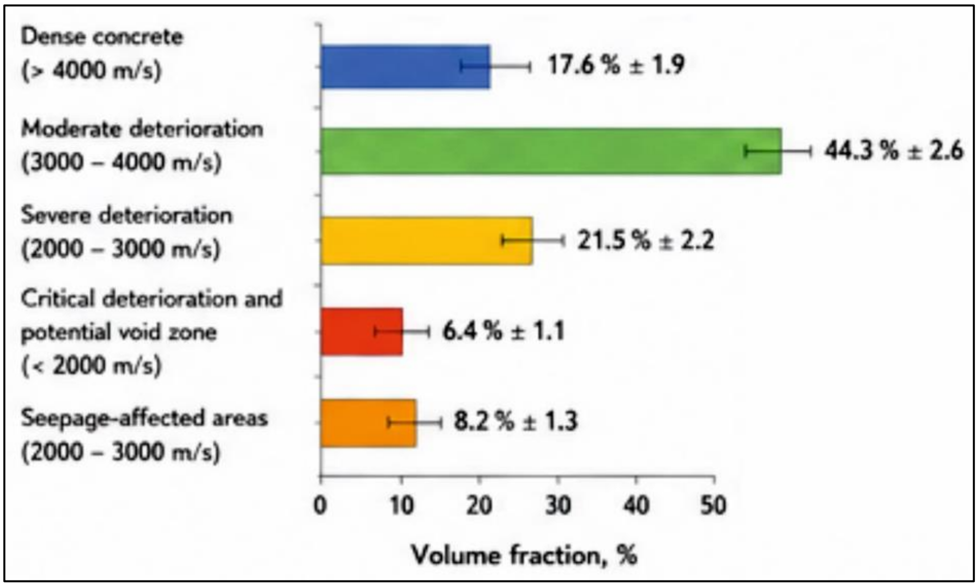

Figure 15 - Volumetric distribution of deterioration zones within the concrete lining (authors' material)

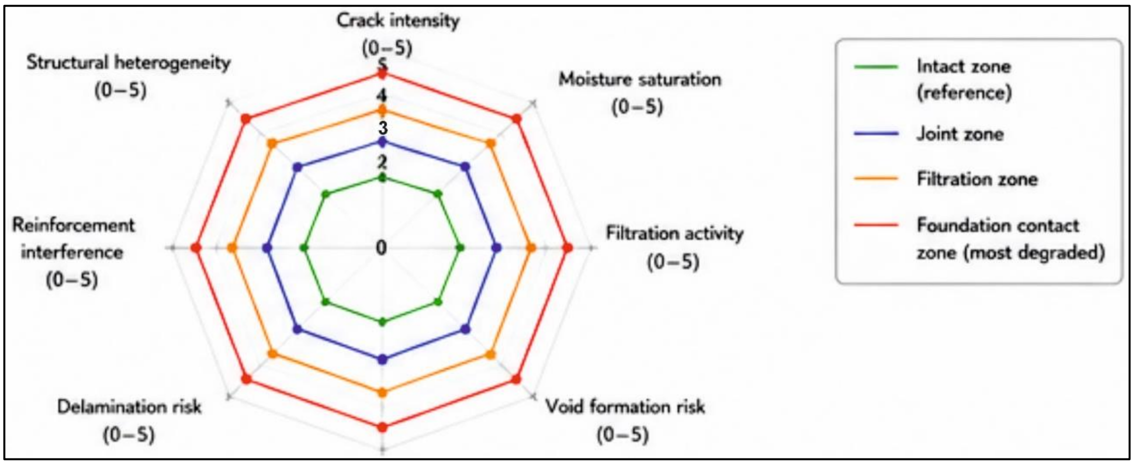

Figure 16 - Comparative assessment of deterioration indicators in different investigated zones (authors' material)

Figure 17 presents the proposed mechanism of filtration-induced deterioration of the concrete lining. The mechanism consists of seven sequential stages. First, seepage water penetrates through cracks and joints. Second, crack propagation and connectivity increase under repeated hydraulic and thermal loading. Third, moisture accumulates within the subsurface zone, causing an increase in pore pressure. Fourth, loss of bonding develops at the concrete-foundation interface. Fifth, local voids and delamination zones are formed. Sixth, internal filtration erosion and material washout occur. Finally, slab deformation, joint opening, and surface damage develop. This mechanism explains the spatial distribution of low-velocity zones observed in the tomographic data. It also links the ultrasonic results with the actual hydraulic deterioration processes typical for concrete linings of spillway structures.

Figure 18 validates the ultrasonic tomography results against field observations. The comparison includes visual inspection, local opening/core or test pit observations, tomography interpretation, and actual detected defects used as reference. The defect detection accuracy of tomography interpretation reaches approximately 90-95%, while visual inspection provides a lower value of about 64%. The agreement with actual defects is 90-96% for tomography-based interpretation and 84-90% for local opening data. The false-positive rate for tomography is approximately 4-7%, which is significantly lower than the uncertainty associated with visual-only inspection. The overall reliability of evaluation based on 3D ultrasonic tomography is estimated at 91-95%. These results confirm that 3D ultrasonic tomography provides a more reliable basis for engineering assessment than visual inspection alone, especially when hidden voids, delamination, and moisture-affected zones are present.

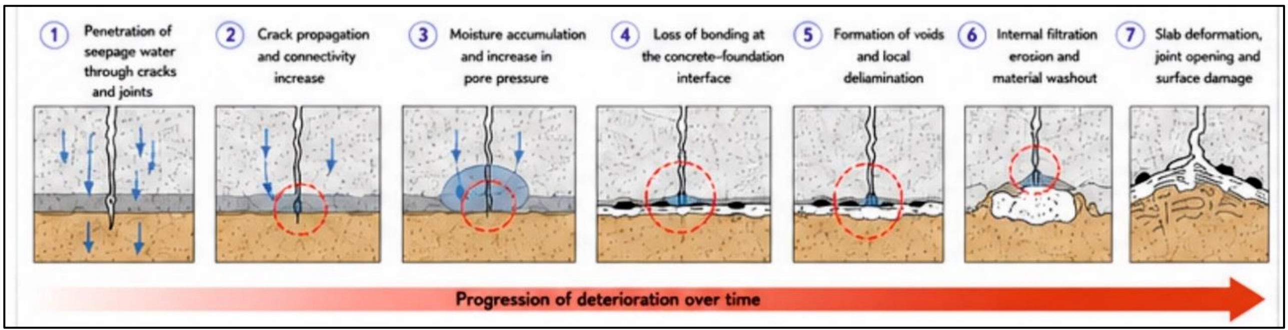

Figure 17 - Proposed mechanism of filtration-induced deterioration of the concrete lining (authors' material)

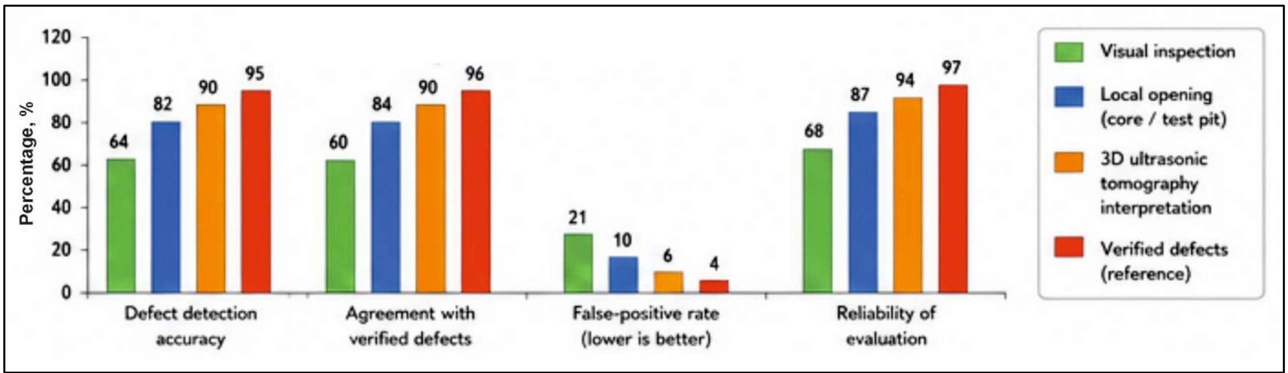

Figure 18 - Validation of 3D ultrasonic tomography results against field observations (authors' material)

Overall, **Figs. 11-18** demonstrate that the deterioration of the concrete lining is not limited to visible surface defects. The most critical processes occur within the lower part of the lining and near the concrete-foundation interface. The combined interpretation of velocity maps, depth-dependent velocity profiles, statistical distributions, correlation analysis, volumetric deterioration assessment, radar indicators, deterioration mechanism, and validation results confirms that 3D ultrasonic tomography is an effective method for diagnosing hidden defects in concrete hydraulic structures. The results also show that areas with velocities below 2000-2200 m/s, high coefficients of variation, and signs of interface debonding should be prioritized for repair, strengthening, or detailed follow-up monitoring.

The obtained results of 3D ultrasonic tomography demonstrated the high efficiency of the method for diagnosing hidden defects in the concrete and reinforced concrete structures of the emergency spillway of the Tasotkel Reservoir. A comprehensive analysis of the spatial distribution of ultrasonic wave velocities, statistical characteristics, correlation relationships, and the volumetric structure of deterioration made it possible to identify patterns of internal degradation of the concrete lining that cannot be detected by conventional visual inspection methods.

It was established that the most intensive deterioration processes are concentrated in the lower part of the concrete lining and within the concrete-foundation interface zone. In these areas, ultrasonic wave velocities decreased to values below 2000-2200 m/s, indicating the presence of low-density zones, seepage-induced moisture accumulation, local void formation, and loss of bonding between structural layers. The analysis of depth-dependent velocity distribution showed that below a depth of approximately 0.35 m, accelerated deterioration processes develop, accompanied by increased structural heterogeneity of the material and a higher coefficient of variation of acoustic parameters.

Statistical processing of the tomographic data confirmed that more than 35% of the investigated structural volume is in a state of severe or critical deterioration. At the same time, the proportion of potentially hazardous zones associated with internal void formation and seepage erosion accounted for approximately 6-8% of the total investigated volume. Correlation analysis revealed a stable relationship between defect depth and the reduction in ultrasonic wave velocity, confirming the applicability of 3D ultrasonic tomography for the quantitative assessment of the degree of internal concrete deterioration.

Comparison of the tomography results with visual inspection data and local opening investigations demonstrated a high level of reliability of the proposed method. The agreement coefficient between the obtained results reached 0.79-0.88, while the overall diagnostic reliability was estimated at approximately 91-95%. These findings confirm the high engineering applicability of the method for the inspection of hydraulic structures operating under long-term seepage and hydrodynamic loading conditions.

The obtained results indicate that the application of 3D ultrasonic tomography makes it possible to move from local defect detection toward a spatial digital assessment of the internal condition of concrete structures. The method provides the capability to identify hidden deterioration zones at early stages of development, quantitatively evaluate the degree of damage, and support technically justified decisions regarding repair, strengthening, and long-term structural monitoring.

Thus, the application of an integrated non-destructive testing system based on the Betonoskop SK-1700 3D represents a promising approach for improving the reliability and operational safety of concrete and reinforced concrete hydraulic structures. The developed methodology can be recommended for the inspection of spillway structures, canals, dam linings, chute canals, and other hydraulic infrastructure facilities subjected to seepage, dynamic, and climatic impacts.

4 CONCLUSIONS

1. A comprehensive assessment of the technical condition of the concrete and reinforced concrete structures of the Tasotkel Reservoir emergency spillway was carried out using the 3D ultrasonic tomography method based on the Betonoskop SK-1700 3D system. The application of spatial non-destructive testing made it possible to obtain detailed information on the internal condition of the concrete lining and the nature of deterioration processes within the structure.

2. It was established that the concrete lining is characterized by pronounced structural heterogeneity, localized low-density zones, increased moisture content, seepage-induced deterioration, and hidden defects that cannot be identified by conventional visual inspection methods.

3. The most critical defect zones were identified in the lower part of the concrete lining and within the concrete-foundation interface zone. In these areas, ultrasonic wave velocities decreased to values below 2000-2200 m/s, indicating internal deterioration, loss of bonding, local void formation, and seepage-related erosion processes.

4. Analysis of ultrasonic wave velocity distribution demonstrated that: velocity values exceeding 4000 m/s correspond to dense and relatively intact concrete; the range of 3000-4000 m/s characterizes moderately deteriorated concrete; velocity values below 3000 m/s indicate zones of significant loosening, microcracking, and internal structural deterioration.

5. It was determined that the total proportion of zones with severe and critical deterioration exceeds 35% of the investigated concrete lining volume. At the same time, the proportion of

potentially hazardous areas associated with internal voids and loss of bonding between structural layers accounted for approximately 6-8%.

6. Depth-dependent analysis revealed that below a depth of approximately 0.35 m, deterioration processes become significantly more intensive, accompanied by a reduction in ultrasonic wave velocity, increased structural heterogeneity, and a higher coefficient of variation of acoustic parameters.

7. Correlation analysis confirmed a stable relationship between defect depth and the reduction in ultrasonic wave velocity. It was established that increasing defect depth is associated with progressive deterioration of the acoustic characteristics of the concrete structure.

8. Comparison of the 3D ultrasonic tomography results with visual inspection data and local opening investigations demonstrated high reliability of the proposed method. The agreement coefficient ranged from 0.79 to 0.88, while the overall diagnostic reliability reached approximately 91-95%.

9. It was established that the application of 3D ultrasonic tomography enables the transition from local defect detection to spatial digital diagnostics of the technical condition of concrete structures. The method allows quantitative assessment of material deterioration, identification of hidden defects, and determination of the most critical deterioration zones.

10. The practical significance of the study lies in the possibility of applying the developed approach for the inspection of spillways, chute canals, canals, dam concrete linings, and other hydraulic structures operating under intensive seepage, hydrodynamic, and climatic impacts.

11. The obtained results confirm the high engineering informativeness, reliability, and practical potential of the Betonoskop SK-1700 3D system for the inspection and monitoring of concrete and reinforced concrete hydraulic structures of increased responsibility and operational importance.

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