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RESEARCH ARTICLE

IMPROVING THE RELIABILITY AND EFFICIENCY OF OPERATION OF HYDRAULIC STRUCTURES OF THE ASTANA RESERVOIR THROUGH RECONSTRUCTION AND MODERNIZATION

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Abstract. *This paper examines ways to improve the reliability and operational efficiency of the Astana Reservoir hydraulic structures through reconstruction and modernization. The reservoir, commissioned in 1970, is a key facility for water supply to Astana and irrigation, and its earth dam has a total length of 1,154 m and a maximum height of 32 m. The study is based on the 2023 dam safety declaration and the 2025 verification report on overall stability and seepage strength. Numerical analyses were performed in PLAXIS 2D using the finite element method, the Mohr–Coulomb model, and a strength-reduction approach for five representative cross-sections. The assessment compared the existing condition with two reconstruction scenarios: installation of an anti-filtration screen, and installation of an anti-filtration screen combined with a cement grout curtain. The results showed that, despite a generally satisfactory visual condition, the existing dam configuration has unsafe seepage behavior and critical local instability in the most unfavorable section. Reconstruction measures significantly increased stability coefficients, reduced seepage gradients and velocities, and ensured filtration strength. The paper concludes that the most effective strategy is an integrated program combining anti-seepage reconstruction, renewal of non-functional monitoring systems, and digitalized water metering and operational control for long-term dam safety and management efficiency.*

Keywords: *Astana Reservoir, hydraulic structures, dam safety, reconstruction and modernization, seepage control, operational efficiency*

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ҒЫЛЫМИ МАҚАЛА

АСТАНА СУ ҚОЙМАСЫНЫҢ ГИДРОТЕХНИКАЛЫҚ ҚҰРЫЛЫСТАРЫН ҚАЙТА ҚҰРУ ЖӘНЕ ЖАҢҒЫРТУ АРҚЫЛЫ ПАЙДАЛАНУДЫҢ СЕНІМДІЛІГІ МЕН ТИІМДІЛІГІН АРТТЫРУ

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Аңдатпа. *Бұл мақалада қайта құру және жаңғырту жолымен Астана су қоймасының гидротехникалық құрылыстарын пайдаланудың сенімділігі мен тиімділігін арттыру жолдары қарастырылады. 1970 жылы пайдалануға берілген су қоймасы Астананы сумен жабдықтау және суару үшін негізгі нысан болып табылып, оның жер бөгетінің жалпы ұзындығы 1154 м және максималды биіктігі 32 м. Зерттеу бөгеттің қауіпсіздігі туралы 2023 жылғы декларацияға және 2025 жылғы жалпы тұрақтылық пен сүзу күшін тексеру туралы есепке негізделген. PLAXIS 2D–де сандық талдау соңғы элементтер әдісін, Мора-Кулон моделін және бес типтік көлденең қиманың беріктігін төмендету әдісін қолдана отырып жүргізілді. Бағалау барысында қазіргі жағдай екі қайта құру сценарийімен салыстырылды: сүзгіге қарсы экранды орнату және сүзгіге қарсы экранды цемент ерітіндісінің пердесімен бірге орнату. Нәтижелер жалпы қанағаттанарлық визуалды күйге қарамастан, бар бөгет конфигурациясы ең қолайсыз учаскедегі қауіпті ағып кету мінез-құлқымен және сыни жергілікті тұрақсыздықпен сипатталатынын көрсетті. Қайта құру шаралары тұрақтылық коэффициенттерін едәуір арттырып, градиенттер мен ағып кету жылдамдығын төмендетіп, сүзу беріктігін қамтамасыз етті. Құжатта ең тиімді стратегия бөгеттің ұзақ мерзімді қауіпсіздігі мен басқару тиімділігін қамтамасыз ету үшін сүзгіге қарсы жүйелерді қайта құруды, функционалды емес бақылау жүйелерін жаңартуды, сондай-ақ суды цифрлық есепке алуды және жедел бақылауды біріктіретін кешенді бағдарлама болып табылады деген қорытынды жасалады.*

Түйін сөздер: *Астана су қоймасы, гидротехникалық құрылыстар, бөгеттердің қауіпсіздігі, реконструкциялау және жаңғырту, сүзуді бақылау, пайдалану тиімділігі*

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НАУЧНАЯ СТАТЬЯ

ПОВЫШЕНИЕ НАДЕЖНОСТИ И ЭФФЕКТИВНОСТИ ЭКСПЛУАТАЦИИ ГИДРОТЕХНИЧЕСКИХ СООРУЖЕНИЙ АСТАНИНСКОГО ВОДОХРАНИЛИЩА ПУТЕМ РЕКОНСТРУКЦИИ И МОДЕРНИЗАЦИИ

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Аннотация. *В данной статье рассматриваются пути повышения надежности и эффективности эксплуатации гидротехнических сооружений Астанинского водохранилища путем реконструкции и модернизации. Водохранилище, введенное в эксплуатацию в 1970 году, является ключевым объектом для водоснабжения Астаны и ирригации, а его земляная плотина имеет общую длину 1154 м и максимальную высоту 32 м. Исследование основано на декларации о безопасности плотины от 2023 года и отчете о проверке общей устойчивости и силы фильтрации от 2025 года. Численный анализ был проведен в PLAXIS 2D с использованием метода конечных элементов, модели Мора–Кулона и метода снижения прочности для пяти типичных поперечных сечений. В ходе оценки существующее состояние было сопоставлено с двумя сценариями реконструкции: установкой противофильтрационного экрана и установкой противофильтрационного экрана в сочетании с завесой из цементного раствора. Результаты показали, что, несмотря на в целом удовлетворительное визуальное состояние, существующая конфигурация плотины характеризуется небезопасным поведением при просачивании и критической локальной нестабильностью на наиболее неблагоприятном участке. Мероприятия по реконструкции значительно повысили коэффициенты устойчивости, снизили градиенты и скорости просачивания и обеспечили прочность фильтрации. В документе делается вывод о том, что наиболее эффективной стратегией является комплексная программа, сочетающая реконструкцию противофильтрационных систем, обновление нефункциональных систем мониторинга, а также цифровой учет воды и оперативный контроль для обеспечения долгосрочной безопасности плотины и эффективности управления.*

Ключевые слова: *Астанинское водохранилище, гидротехнические сооружения, безопасность плотин, реконструкция и модернизация, контроль фильтрации, эксплуатационная эффективность*

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CONFLICT OF INTEREST

The authors state that there is no conflict of interest.

The authors declare that no generative artificial intelligence technologies or AI-based tools were used in the preparation of this article.

АЛҒЫС / ҚАРЖЫЛАНДЫРУ КӨЗІ

Зерттеу жеке қаржыландыру көздерін пайдалана отырып жүргізілді.

МҮДДЕЛЕР ҚАҚТЫҒЫСЫ

Авторлар мүдделер қақтығысы жоқ деп мәлімдейді.

Авторлар мақаланы дайындау барысында генеративті жасанды интеллект технологиялары мен жасанды интеллектке негізделген технологияларды пайдаланбағанын мәлімдейді.

БЛАГОДАРНОСТИ/ИСТОЧНИК ФИНАНСИРОВАНИЯ

Исследование проводилось с использованием частных источников финансирования.

КОНФЛИКТ ИНТЕРЕСОВ

Авторы заявляют, что конфликта интересов нет.

Авторы заявляют о том, что при подготовке статьи не использовались технологии генеративного искусственного интеллекта и технологии, основанные на искусственном интеллекте.

1 INTRODUCTION

The Astana Reservoir is a strategically important hydraulic facility located about 5 km south-east of the village of Arnasai and about 65 km from Astana, in the Arshalyn district of Akmola Region. The reservoir was designed by the Hydroproject Institute in 1967 and commissioned on 19 October 1970. It operates in cascade with the Ishim and Sergeev reservoirs and serves two major functions: water supply for Astana and irrigation. The reservoir is therefore not only an engineering structure, but also a key element of regional water security and socio-economic stability.

The main dam is an earth-fill structure with a total length of 1,154 m, a crest width of 10 m, a maximum height of 32 m, and a maximum head of 25 m. The upstream slope is arranged with two berms and reinforced in the upper part by reinforced-concrete slabs over an area of 1,960 m², while the downstream slope is grassed. According to visual inspection data, the general technical condition of the dam is satisfactory and no obvious emergency deformations have been identified on the crest or slopes. At the same time, the more recent verification calculations show that visual integrity alone is not sufficient to guarantee long-term safety, because seepage behavior and local stability remain critical for the actual reliability of the structure.

Figure 1 – Location of the Astana Reservoir and dam site in Akmola Region, Kazakhstan (author’s materials)

In this context, reconstruction and modernization should be understood not as routine repair, but as a transition from condition-based operation to risk-informed and instrumented management. For the Astana Reservoir, this means combining structural anti-seepage measures with modern monitoring, automatic water metering, and improved operational control of water releases and water distribution. The attached documents show that the current operation still relies heavily on manual observations, while the existing instrumentation network is either absent or nonfunctional.

The classical geotechnical framework for embankment dams was formalized in dam engineering literature by Fell et al., emphasizing that stability, seepage, foundation performance, and seepage-control (anti-filtration) measures should be evaluated as an integrated safety system rather than as separate design components **(Fell et al., 2005).** This systems perspective remains especially relevant for aging reservoirs, where acceptable visual condition may coexist with hidden seepage defects and insufficient instrumentation.

A second major research direction concerns monitoring and interpretation of dam behaviour

(Li et al., 2020) reviewed modern monitoring-data analysis methods and demonstrated the shift from conventional observation toward regression-based, statistical, and intelligent analytical tools that enable earlier detection of abnormal behaviour. **(Fang et al., 2021; Ghafoori et al., 2020)** further showed that distributed optical-fiber temperature sensing can identify concealed seepage paths and leakage zones that are difficult to detect by routine inspection alone. These studies are important because they move the reliability problem from periodic inspection toward continuous diagnosis.

Recent work has also refined the understanding of hydraulic and geotechnical processes in earth dams **(Liu et al., 2024)** demonstrated that downstream-slope safety is strongly influenced by reservoir-level fluctuations and hysteresis in the soil-water characteristic curve. This finding is methodologically important for the present study because seepage and stability cannot be interpreted independently: the position of the depression surface directly affects effective stresses, and hence the safety margin of the downstream slope.

Research published in Vestnik KazGASA provides useful regional context **(Ilyassova et al., 2025)** analyzed degradation mechanisms in concrete hydraulic structures and justified repair technologies for durability extension **(Moldamuratov et al., 2025)** presented a multifactor assessment of hydraulic structures in seismically active zones using the Tasotkel Reservoir as a case study, **(Moldamuratov et al., 2023)** while **(Kirgizbayeva et al., 2025)** emphasized the role of integrated deformation monitoring for engineering structures **(Abdrakhmanova et al., 2025)** demonstrated the practical value of detailed field geotechnical testing in northern Kazakhstan.

Despite these advances, three gaps remain visible in the literature. First, many studies focus either on structural rehabilitation or on monitoring, whereas fewer works address both within one operational modernization program. Second, local publications on hydraulic structures often emphasize concrete deterioration, seismic effects, or canal efficiency, but not seepage-strength verification of an operating earth dam under alternative reconstruction scenarios. Third, operational efficiency is still discussed less often than physical safety, even though nonfunctional instrumentation and manual control can directly reduce the practical value of rehabilitation measures. The Astana Reservoir case is therefore relevant because it links seepage control, slope stability, monitoring renewal, and digitalized operation within one decision framework.

2 MATERIALS AND METHODS

The revised study is based on three information layers: the 2023 dam safety declaration, the 2025 verification report on overall stability and seepage strength, and the published journal article version. The natural setting is characterized by a sharply continental climate, unstable moisture conditions, seasonal freezing depths from 1.86 m to 2.75 m depending on soil type, and flood runoff of the Yesil River formed mainly by snowmelt. Updated hydrological estimates cited in the source materials indicate peak discharges of 2,050 m³/s for a 0.1% exceedance probability and 1,565 m³/s for a 1% exceedance probability

The numerical analysis in **Figure 3** in the 2025 report was performed in PLAXIS 2D using the finite element method. The model employed the Mohr-Coulomb constitutive law and the strength-reduction technique to evaluate slope stability. Five representative cross-sections were selected along the dam. The verification program considered three scenarios: the existing condition without confirmed anti-seepage elements, a reconstructed case with a clay anti-filtration screen, and a reconstructed case with both the anti-filtration screen and a cement grout curtain in the rock foundation. Main source data and modelling framework are presented in **Table 1**.

Figure 2 – Inspection fragments showing cracking and opening of joints in the deteriorated area. (author's materials)

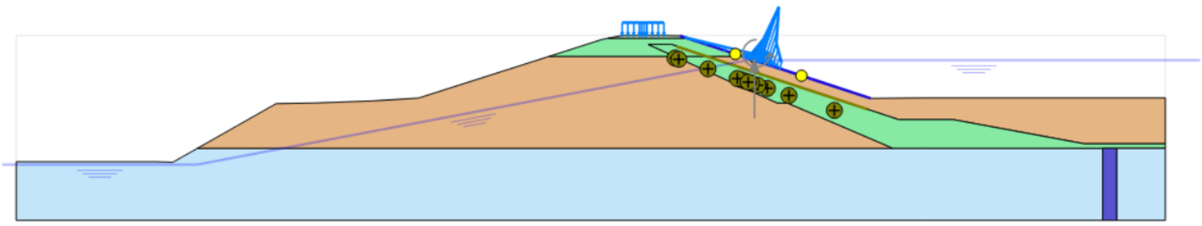

Figure 3 – Schematic design model of the dam and anti-seepage system used for the numerical assessment. (author's materials)

Table 1.
Main source data and modelling framework

Parametres	Value/Discription
Dam type and geometry	Earth-fill dam; length 1,154 m; crest width 10 m; maximum height 32 m; maximum head 25 m.
Protection and visible condition	Upstream slope with two berms and reinforced-concrete slab lining in the upper part; downstream slope grassed; no obvious emergency deformations reported by visual inspection.
Hydrological basis	Design flood estimates of 2,050 m³/s (0.1%) and 1,565 m³/s (1%).
Ground investigation	Six boreholes, total drilling length 83.6 m, plus laboratory tests on physical, shear, compression, and filtration properties.
Material contrast	Low-permeability loam/sandy loam in the dam body; coarse sands, gravelly soils, and alluvium in adjacent zones; filtration coefficients from 0.0001 to 37.2 m/day.
Numerical platform	PLAXIS 2D finite-element analysis with the Mohr–Coulomb constitutive model and strength-reduction procedure.
Assessment sections	Five representative cross-sections along the dam.
Reconstruction scenarios	Scenario 1 – existing condition; Scenario 2 – clay anti-filtration screen; Scenario 3 – clay screen + cement grout curtain in the foundation.
Output indicators	Safety factor, position of the depression surface, hydraulic gradient, seepage velocity, and seepage discharge.

The numerical assessment followed the staged logic of the 2025 verification report. Five representative cross-sections were analysed in plane strain. For each section, the existing configuration was compared with two reconstruction alternatives: (i) restoration of seepage control by means of a clay anti-filtration screen, and (ii) the same screen combined with a cement grout curtain in the foundation. This approach makes it possible to isolate the engineering effect of each anti-seepage measure and to evaluate reconstruction as a measurable change in stability reserve and seepage regime rather than as a generic repair action.

To improve methodological transparency, the revised manuscript explicitly reports the main modelling outputs that controlled the engineering interpretation: the minimum strength-reduction factor, the configuration of the depression curve, hydraulic gradients in the critical zone, seepage velocity, and daily seepage discharge per running meter of structure. The revised text also distinguishes between the normal operating and special design combinations considered in the source calculations, because the most unfavorable section proved sensitive to both seepage and load combination.

A practical limitation of the published source is that not every input parameter from the project calculation file is reproduced in the article itself. For this reason, the revised version reports verified ranges and scenario logic directly supported by the source materials and avoids reproducing undocumented parameters. Nevertheless, the available evidence is sufficient to interpret the relative performance of the three technical solutions and to justify the recommended modernization strategy.

3 RESULTS AND DISCUSSION

The first and most important result is that visual inspection alone gives an incomplete picture of dam safety. Although the general condition of the embankment was described as satisfactory and no emergency deformations were reported visually, the verification calculations identified a serious local problem in cross-section 5, which proved to be the most unfavorable alignment of the entire dam. In the existing condition, the minimum stability coefficient in this section dropped to 0.3166 for the main design case and to 0.1226 for the special case, i.e., far below an acceptable safety reserve. This means that the present condition cannot be characterized as operationally reliable, even if the dam surface does not show dramatic visible distress.

Figure 4 represents Gate 5 turned out to be the most unfavorable of all the design sections considered. For the existing position of the dam at the NPU, the minimum stability coefficients Msf = 0.3166 for the main design case and Msf = 0.1226 for the special case were obtained, which indicates the unsecured stability of the slope in this particular alignment. The summary results of the report also show that gate 5 is the most problematic in terms of stability among all five design sections.

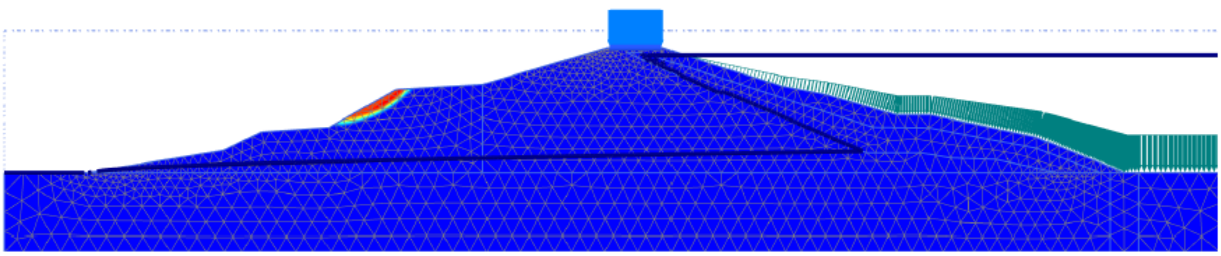

Figure 4 – Gate 5. A general view of the loss of stability during FPU and AK loading.
The coefficient of safety margin Msf =1.667. Stability is assured. (author's materials)

Figure 5 and 6 shows second result is the clear seepage-related mechanism behind this instability. In cross-section 5, the depression surface remains high within the dam body and exits on the downstream slope rather than penetrating deeper into the foundation. Such a configuration indicates intensive water saturation of the embankment and reduced effective stresses in the lower slope zone. The calculated hydraulic gradient in the same section reached 0.8381 in the main case and 0.9591 in the special case, while filtration velocity in section 5 was about 9.50 m/day and the seepage discharge reached 18.49 m³/day per running meter in the main case. Across sections 3 to 5, seepage velocities were approximately 9.5–12.8 m/day and discharge values reached up to 33.94 m³/day per running meter. The report therefore concluded that seepage-strength safety was not ensured in four of the five analysed sections. Summary of key results for the critical cross-section and dam behaviour are presented in **Table 2**.

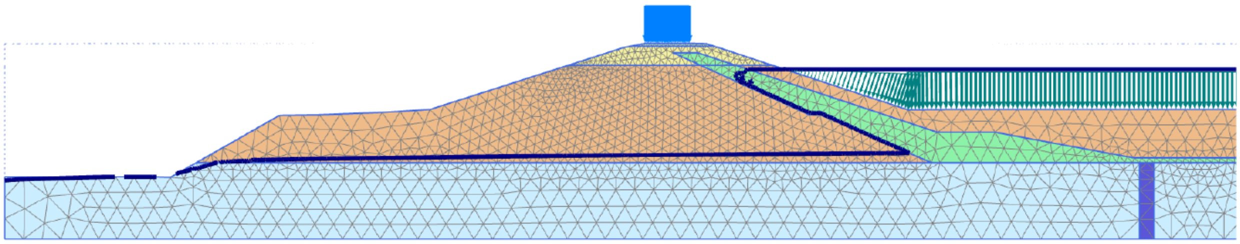

Figure 5 – Critical cross-section 5: calculated depression curve in the existing condition. (author's materials)

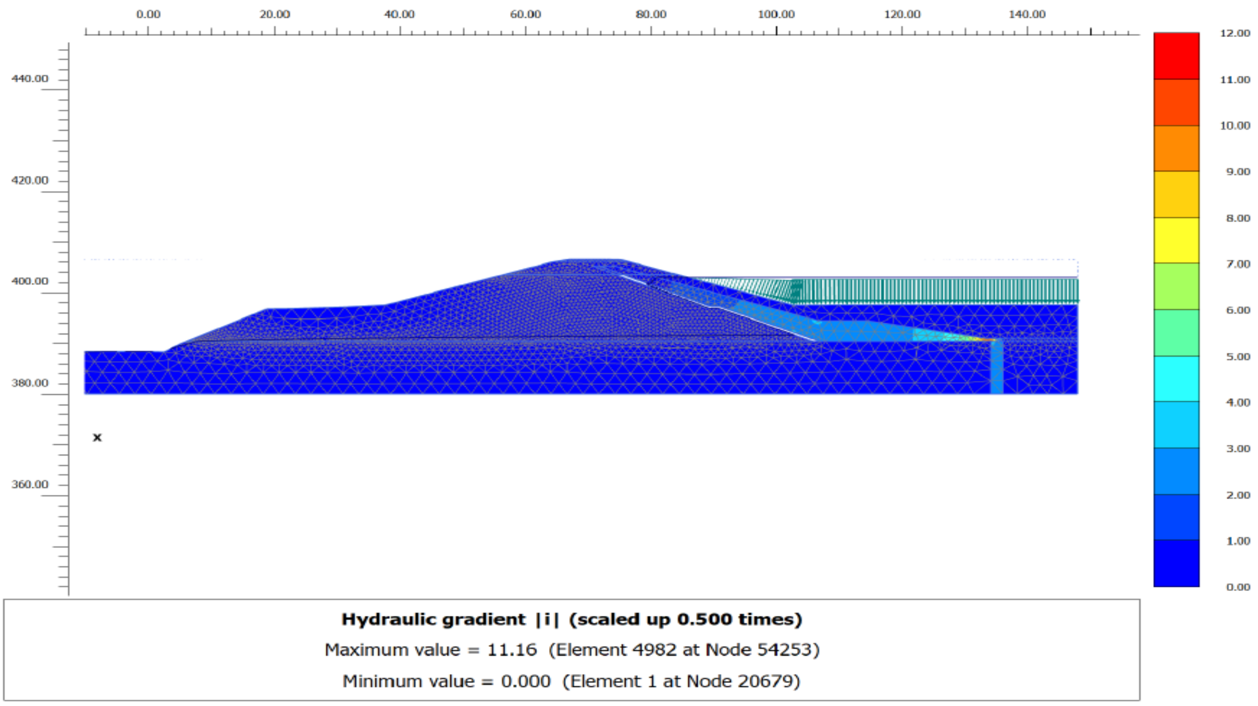

Figure 6 – Hydraulic-gradient field in critical cross-section 5 under the normal operating condition. (author's materials)

Table 2
Summary of key results for the critical cross-section and dam behaviour

Scenario	Minimum safety factor	Hydraulic gradient	Seepage velocity, m/day	Seepage discharge, m³/day per m	Filtration strength
Existing condition	0.3166 / 0.1226	0.8381 / 0.9591	≈9.50 in section 5; ≈9.5–12.8 in sections 3–5	Up to 18.49 in section 5; up to 33.94 in sections 3–5	Not ensured
Clay anti-filtration screen	1.234 in section 5; sections 3–5: 1.680 / 1.669 / 1.234	Reduced below adopted limit	≈0.35–0.60	Strongly reduced	Ensured
Clay screen + cement grout	1.269 in section 5; sections 3–5:	Below critical value in the	≈0.38–0.44	Low	Ensured

The third result is that reconstruction with a clay anti-filtration screen changes the behaviour of the dam fundamentally. For cross-sections 3 to 5, the minimum stability coefficient increased to 1.680, 1.669, and 1.234 in the main design case and remained above the required level in the special case as well. Seepage velocities decreased to approximately 0.35–0.60 m/day, and the verification report explicitly states that seepage-strength safety became ensured. This is the key engineering argument for reconstruction: the screen does not simply reduce leakage, but transforms the dam from a locally unsafe seepage regime to a controlled and acceptable one **(Aniskin et al., 2024; Pianosi et al., 2020).**

The fourth result is that the combined option with both the clay screen and the cement grout curtain also satisfies the safety criteria and provides a slightly higher reserve in the most problematic section. In the main design case, the minimum stability coefficient reached 1.681, 1.664, and 1.269 for sections 3 to 5, while seepage velocities remained low at about 0.38–0.44 m/day. The gradients in the screen remained below the adopted critical level, which confirms the effectiveness of the integrated anti-seepage concept. At the same time, the numerical difference between Scenarios 2 and 3 is moderate rather than radical. From an engineering-economic perspective, this suggests that the clay screen is the principal efficiency measure, whereas the grout curtain acts as an additional safeguard where foundation conditions justify it.

The fifth result concerns the discrepancy between the 2023 safety declaration and the more detailed 2025 verification. The declaration concluded that the dam met safety requirements, whereas the later report showed that the existing state was unsafe with respect to seepage-strength criteria in most analysed sections. This is not merely an inconsistency between documents; it demonstrates the methodological difference between a general safety assessment and a focused seepage-strength verification that explicitly tests the consequences of missing or ineffective anti-filtration elements. The case therefore supports the broader literature finding that dam safety assessments should not rely solely on geometry and overall stability checks, but must include seepage-focused diagnostics and sufficiently detailed modelling **(Lee et al., 2023).**

The final analytical point is that operational efficiency depends not only on embankment reconstruction but also on modernization of the monitoring system. The source materials indicate that hydrometeorological observations and release regulation are already performed, but the measuring and instrumentation system is unsatisfactory: the piezometric network is nonfunctional, and a new monitoring system is recommended, including geodetic marks, piezometric wells, crack meters, and temperature sensors **(Shadkam et al., 2024).** This observation aligns with the reviewed literature on monitoring analytics and local deformation control. A reservoir can only be operated efficiently when seepage, deformations, water levels, and releases are measured continuously and interpreted in time for decision-making. Accordingly, the engineering interpretation of the Astana case is that reconstruction should be implemented together with monitoring renewal and digitalized water accounting **(Alenov et al., 2025; Bessimbayev et al., 2022).**

4 CONCLUSIONS

1. The analysis confirms that the Astana Reservoir remains a strategically important water-supply and irrigation facility. Despite its generally satisfactory visual condition, detailed inspection and verification revealed the presence of unsafe seepage processes and local instability in отдельных участках.

2. Numerical modeling results demonstrate that reconstruction measures—particularly the installation of a clay anti-filtration screen, optionally combined with a cement grout curtain—significantly improve both slope stability and seepage control, bringing the structure to acceptable safety levels.

3. It has been established that the current monitoring system does not ensure reliable long-term operation. A significant portion of instrumentation is either nonfunctional or outdated, which limits the ability to assess the technical condition of the structure in real time.

4. To enhance operational efficiency, it is necessary to implement modernization measures, including the replacement of obsolete instrumentation and the introduction of automated systems for water metering and water-distribution control.

5. Thus, the most effective technical solution is a comprehensive approach that combines anti-seepage reconstruction, renewal of monitoring instrumentation, and the implementation of digitalized operational management systems.

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