



INTEGRATED SEISMIC ASSESSMENT AND SAFETY IMPROVEMENT OF THE KAPCHAGAY HPP DAM, KAZAKHSTAN

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ABSTRACT: The Kapchagay Hydropower Plant (HPP), one of the largest hydraulic structures in Kazakhstan, is located in a seismically active region. This study was conducted in 2000 after an abnormal drop in the water level in the Kapchagay Reservoir was discovered during its operation. A comprehensive investigation was conducted to identify the causes of water losses and assess the operational and seismic safety of the facility. The program included seismic hazard assessment, synthetic accelerogram generation, seismic risk modeling, vertical electrical sounding (VES), underwater inspections, and stability analyses of the riverbed and saddle dams. Based on geological, geophysical, and seismotectonic data, the characteristics of potentially hazardous seismogenic zones were refined and design seismic loading scenarios were developed. The results showed that the Zailiysky seismogenic zone represents the most critical seismic source for the site, producing a peak ground acceleration of 205 cm/s², corresponding to an intensity of 8 points on the MSK-64 scale. Stability analyses confirmed that both dams satisfy the safety requirements for Class II hydraulic structures at the recommended normal retaining water level of 479 m. VES investigations identified seepage-related anomalies, which were subsequently confirmed through underwater inspections. Pressure grouting of the weakened zone eliminated abnormal water losses and improved the reliability of the hydraulic structures. The study demonstrates the effectiveness of integrating seismic hazard assessment, risk analysis, geophysical diagnostics, underwater inspections, and engineering remediation within a unified framework for hydraulic structure safety management.

Keywords: *Seismic risk, Hydraulic structure, Synthetic accelerograms, GIS-based system "Extremum", Vertical electrical sounding, Injection cementing.*

1. INTRODUCTION

Hydropower remains one of the most accessible renewable energy sources. Hydroelectric power plants provide not only electricity generation but also water resource regulation, support for irrigation systems, and environmental protection functions [1,2]. Therefore, ensuring the safety of hydraulic structures remains a key engineering challenge, particularly in regions exposed to elevated seismic risk. Studies of the consequences of potential dam failures indicate that, in addition to ensuring operational reliability, it is necessary to consider the risk to the population and infrastructure within potential flood zones [3]. For example, the Kyzylagash disaster in the Almaty Region, which occurred on the night of March 11–12, 2010, as a result of overtopping and dam failure, claimed the lives of 45 people and destroyed approximately 300

houses in the settlement of Kyzylagash.

Numerous factors, including the condition of the soil mass, seepage regime, hydrogeological conditions, reservoir operating conditions, and environmental influences, determine the reliability of earth dams. Hidden seepage processes developing within the dam body pose a particular hazard. Such processes may evolve over long periods without visible signs, gradually reducing the dam's stability margin and increasing the probability of damage during strong seismic events [4,5]. Analyses of failures and damage to hydraulic structures show that the most severe consequences are usually associated with a combination of several adverse factors, among which seepage, internal soil erosion, and seismic loading play significant roles [6]. Among dams constructed from local materials, particularly rockfill dams, those designed and built in accordance with seismic-resistant engineering requirements

have proven to be among the safest under seismic conditions [7,8].

Recent studies demonstrate the high effectiveness of modern diagnostic and engineering protection methods for hydraulic structures. Case studies of several dams in Vietnam have shown that the timely identification of zones with increased seepage can prevent the development of slope deformations and the loss of structural stability [9,10]. Technologies such as grouting, pressure-injection treatment of soils, and other seepage-control measures have been successfully applied to localize these processes [11–13]. At the same time, the use of geophysical investigation methods is expanding, enabling the detection of hidden defects without disrupting the normal operation of hydraulic structures.

A separate area of research is focused on assessing the behavior of earth dams under seismic loading. Experimental and numerical studies have shown that the presence of loosened zones and areas with increased water saturation can significantly affect the seismic stability of dams during strong earthquakes [14–16]. In recent years, machine learning methods have been increasingly applied to the analysis of such phenomena, enabling the identification of factors controlling the development of seismically induced deformations in soil masses [17]. Consequently, integrated assessment approaches that combine seismic hazard analysis, field investigations, and engineering calculations are becoming increasingly important.

Despite the large number of studies devoted to the seismic stability of dams, seepage processes, and soil reinforcement technologies, practical case studies in which structural inspection, seismic hazard assessment, risk analysis, geophysical diagnostics, and subsequent engineering measures are considered as a unified process remain relatively limited in the literature [18].

The Kapchagay HPP, located on the Ili River approximately 70 km north of Almaty, is one of the largest hydropower facilities in Kazakhstan. The hydropower complex is situated within the influence zone of the active seismogenic structures of the Northern Tien Shan, where several destructive earthquakes with magnitudes exceeding 8.0 have occurred over the past 150 years [19,20]. According to long-term observations and recent studies, this region is considered one of the most seismically hazardous areas in Central Asia [21].

In early 2000, an anomalous decrease in the water level of the Kapchagay Reservoir was detected during its operation. It could not be explained by the hydropower complex's operating regime or hydrological conditions. To determine the causes of

water losses and assess the technical condition of the hydropower complex, a comprehensive investigation program was conducted. It included an analysis of the region's seismotectonic setting, a seismic hazard assessment, the development of design seismic loading scenarios, an evaluation of individual seismic risk, geophysical surveys using the vertical electrical sounding (VES) method, and underwater inspections of the dams. The results obtained were subsequently used to develop and implement engineering measures to eliminate the identified defects.

This study aims to analyze the results of investigations and engineering measures conducted at the Kapchagay HPP to identify the causes of the anomalous decrease in the reservoir water level, assess operational and seismic safety, and improve the reliability of the hydraulic structure. Unlike most previously published studies that focus on individual aspects of dam safety, the present work adopts an integrated approach that combines seismic hazard assessment, individual seismic risk modeling, geophysical diagnostics, underwater inspection of hydraulic structures, stability analyses, and engineering measures to eliminate identified defects within a unified framework for engineering decision-making.

2. RESEARCH SIGNIFICANCE

The scientific significance of this study lies in the development and validation of an integrated methodology for evaluating the seismic safety and technical condition of hydraulic structures located in seismically active regions. The novelty of the proposed approach is the combined application of seismic hazard assessment, synthetic ground-motion modeling, individual seismic risk analysis, geophysical investigations, and underwater inspection to solve a single engineering problem. The consistency of these independent methods enabled reliable identification and verification of a hidden seepage zone and supported the selection of effective remediation measures. The proposed methodology can be applied to improve the safety assessment and management of earth dams and other hydraulic structures in seismic regions.

3. MATERIALS AND METHODS

3.1. Study Area and Characteristics of Kapchagay HPP

The Kapchagay HPP is one of Kazakhstan's strategic infrastructure facilities, enabling the effective utilization of the Ili River's water resources

(Fig. 1). Although it was commissioned in the early 1970s, it remains an important hydraulic structure. It plays a key role in supplying electricity to the region, including part of the city of Almaty.



Fig. 1. a) aerial view of the Kapchagay Hydroelectric Power Plant; b) view from the downstream side showing the turbine penstocks and operational spillways.

The Kapchagay HPP is a dam-type hydropower facility with a powerhouse located on the riverbank. The main structures of the hydropower complex include the riverbed and saddle earth dams, intake structure, four turbine penstocks, operational spillway, powerhouse, and tailrace canal (Table 1). Water impoundment is provided by the Kapchagay Reservoir, which has a surface area of approximately 1,847 km² and a storage capacity of about 28 km³, making it one of the largest reservoirs in Kazakhstan. The average annual electricity generation ranges from 972 to 1,163 million kWh, depending on the hydrological conditions of the Ili River basin.

3.2. Monitoring System and Initial Data

To monitor the dynamic behavior of the Kapchagay HPP structures, an engineering seismometric station was established in 1975. The station consists of three recording points located on the crest of the earth dam, on the bedrock foundation, and on the structural frame of the powerhouse building. Observations have been

conducted continuously throughout the entire operational period of the hydropower complex. During its operation, the station recorded several significant regional earthquakes, including the 1978 Zhalanash-Tyup earthquake ($M = 6.6$) and the 1979 Bakanas earthquake ($M = 5.9$) [22]. Instrumental records of ground motions with intensities of up to 4–5 points on the MSK-64 scale were obtained. In subsequent years, the station recorded numerous weak local earthquakes. The engineering seismometric station remains operational today, providing valuable information on the dynamic response of the structures to natural seismic loading [23].

Table 1. Main Geometric Characteristics of the Kapchagay Hydroelectric Power Plant Structures

Structure	Geometric Parameter	Value, m
Riverbed Dam	Length	470.0
	Height	50.0
	Base width	450.0
Saddle Dam	Length	370.0
	Height	56.0
	Base width	270.0
Intake Structure	Length	102.0
	Height	33.0
Turbine Penstocks	Diameter	8.0
	Length of tunnel section	92.08
	Length of open section	10.2
	Length of each tunnel	150.3

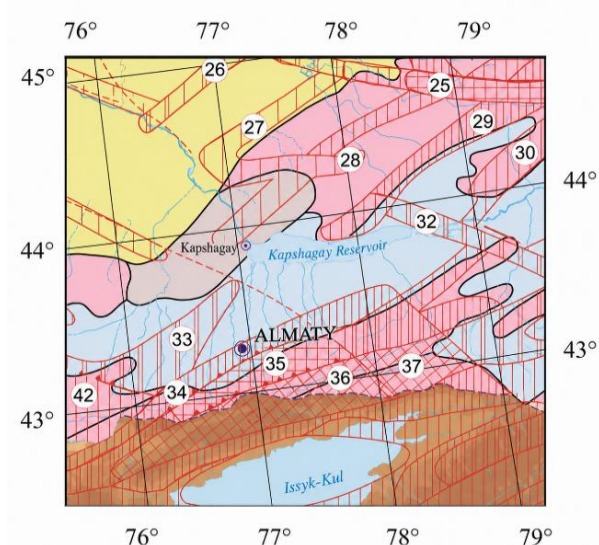


Figure 2. Fragment of the map of seismogenic zones of Kazakhstan.

The Kapchagay HPP is located within the influence zone of the active seismogenic structures of the Northern Tien Shan. According to seismological studies, the nearest seismogenic zones can generate earthquakes that may produce seismic intensities of 7–8 points at the structure's site [24]. The most significant seismic sources affecting the region are the Almaty, Zailiysky, Kungey, Malaisary, and Degeres seismogenic zones (Fig. 2). The parameters of these zones were used in the seismic hazard assessment and in generating design synthetic accelerograms.

3.3. Research Methodology

In early 2000, an anomalous decrease in the water level of the Kapchagay Reservoir was detected that could not be explained by hydrological conditions or the operating regime. Analysis of the water balance revealed a discrepancy between the volume of water entering the reservoir via the Ili River and the discharge from the hydropower plant's hydraulic structures. In the event of a failure, settlements located downstream, including Bakanas, Bakbakhty, Akshi, and others, could have been exposed to significant risk.

In response to the identified anomalous water losses, specialists of the Institute of Seismology (currently the National Scientific Center for Seismological Observations and Research of the Ministry of Emergency Situations of the Republic of Kazakhstan) were tasked with determining their causes, assessing their potential impact on the reliability of the hydraulic structures, and developing measures to ensure the continued safe operation of the hydropower complex.

To address this problem, a comprehensive investigation program was implemented (Figure 3), including visual inspection of the structures and analysis of design and technical documentation, seismotectonic analysis of the study area, seismic hazard assessment and modeling of design seismic loading scenarios, individual seismic risk assessment, determination of the dynamic properties of soils, stability analyses of the riverbed and saddle dams under seismic loading, geophysical investigations using the vertical electrical sounding (VES) method, underwater inspection of the most critical hydraulic structures, as well as the development and implementation of engineering measures to eliminate the identified defects.

The geophysical investigations were carried out using the vertical electrical sounding (VES) method based on the Schlumberger array configuration. Observation points were spaced at 5 m intervals along the survey profile, and the depth of

investigation reached approximately 25 m within the soil mass. The measurement error did not exceed $\pm 5\%$.

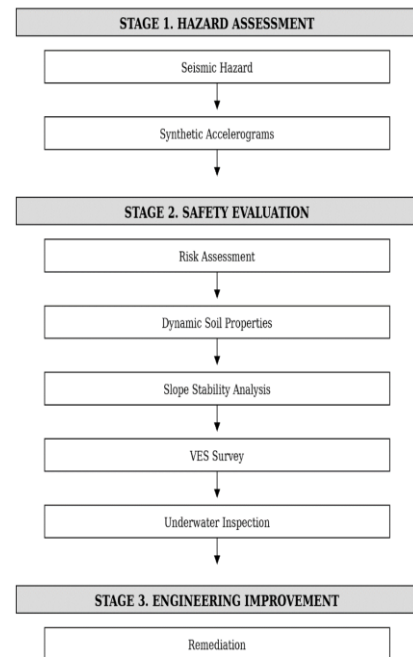


Fig. 3. Workflow of the integrated investigation, seismic risk assessment, and engineering remediation program implemented at the Kapchagay Hydroelectric Power Station.

The integrated application of these methods enabled the systematic identification of the cause of the anomalous water losses, the assessment of the associated operational and seismic risks, and the development and implementation of effective measures to enhance the reliability and safety of the Kapchagay HPP.

4. RESULTS AND DISCUSSION.

4.1. Seismic Hazard Assessment

Analysis of seismological, geological, and seismotectonic data showed that several active seismogenic structures of the Northern Tien Shan influence the Kapchagay HPP. The regional earthquake catalog revealed periods of increased seismic activity in the area of the hydropower complex and its immediate vicinity in 1964, 1989, and 1993. Although the Kapchagay HPP is not located directly within an active seismogenic zone, the possibility of strong seismic impacts from nearby sources in northeastern Dzungaria and southeastern Kazakhstan cannot be ruled out. The parameters of potential earthquake sources were estimated using

the seismotectonic model and the seismic source zone map of Kazakhstan [25].

Therefore, five seismogenic zones with the greatest potential impact on the Kapchagay HPP were selected for further analysis: Kungey, Zailiysky, Almaty, Malaisary, and Degeres. These zones are characterized by expected maximum earthquake magnitudes ranging from $M_{\max} = 6.0$ to $M_{\max} = 8.3$ and by varying distances from the hydraulic complex. Table 2 presents the main parameters of the selected potential earthquake sources, including the maximum magnitude, focal depth, and minimum epicentral distance to the Kapchagay hydropower complex.

Table 2. Main parameters of the potential earthquake sources (PESs)

Seismogenic zone	Maximum magnitude, $M_{\max}$	Epicentral distance $R_{\min}$ (km)	Depth of PES, (km)	Coordinates of the PES
Kungey	8.3	104	25	43°06' N-78°09' E
Zailiysky	8.0	72	25	43°23' N-77°47' E
Almaty	7.0	63	15	43°28' N-77°09' E
Malaisary	6.5	41	15	44°12' N-77°24' E
Degeres	6.0	23	10	43°59' N-76°53' E

Figure 4 shows the locations of the potential earthquake sources within the selected seismogenic zones.

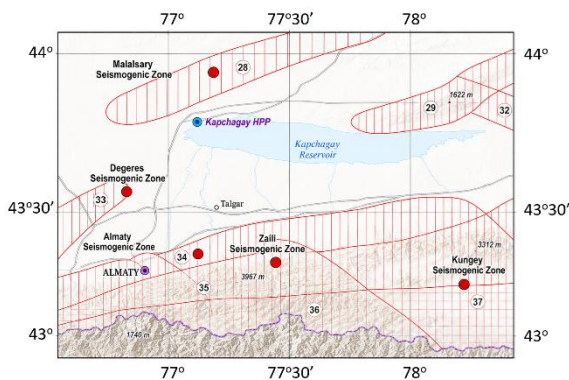


Fig. 4. Map of the potential earthquake sources (PESs) within the selected seismogenic zones.

Based on the parameters of the identified potential earthquake sources, the characteristics of the expected seismic loading were determined for each seismogenic zone. The resulting values of peak ground acceleration, predominant vibration periods, and pulse durations were used to generate

ensembles of synthetic accelerograms and response spectra required for the subsequent assessment of the seismic stability of the Kapchagay HPP structures.

4.2. Synthetic Accelerogram Generation

To assess the seismic stability of the Kapchagay HPP structures, design seismic loading parameters were determined for each identified potential earthquake source. The primary objective was to generate ensembles of synthetic accelerograms and corresponding response spectra representing the most probable characteristics of strong earthquakes that could affect the facility. In developing the design seismic loading scenarios, the principal ground-motion parameters required to generate accelerograms in both the time and spectral domains were determined, including peak ground acceleration (PGA), predominant period (T), and effective pulse duration (Δt). These parameters were subsequently used to generate ensembles of synthetic accelerograms and construct the corresponding response spectra. The main characteristics of the expected strong earthquakes are presented in Table 3.

Due to the absence of instrumental records of strong earthquakes in the vicinity of the Kapchagay HPP, the spectral characteristics of the design seismic loading were determined from analyses of international strong-motion databases and contemporary approaches to synthetic accelerogram modeling [26,27].

Table 3. Main characteristics of the expected strong earthquakes

Seismogenic zone	PGA (cm/s^2)	T (s)	Δt (s)
Kungey	171	0.8	27.0
Zailiysky	205	0.66	19.0
Almaty	127	0.45	12.0
Malaisary	102	0.25	7.4
Degeres	142	0.26	4.5

The selection of the most critical potential earthquake source (PES) for the Kapchagay HPP was based on an analysis of several factors, including the potential earthquake magnitude, the distance to the hydropower site, the expected ground-acceleration level, and the characteristics of the ground-motion spectral content.

Despite its slightly lower maximum magnitude ($M_{\max} = 8.0$), the Zailiysky seismogenic zone is located significantly closer to the Kapchagay

hydropower complex. The minimum distance from the Zailiysky zone to the site is approximately 72 km, whereas the minimum distance from the Kungey zone to the site exceeds 100 km. The calculations showed that the peak ground acceleration (PGA) for the Zailiysky zone reaches 205 cm/s², corresponding to a seismic intensity of 8 points on the MSK-64 scale. In contrast, the calculated PGA for the Kungey zone is 171 cm/s², despite the higher potential earthquake magnitude. These results indicate that, in this case, the distance from the seismic source to the site has a greater influence on the expected seismic loading than the difference in earthquake magnitude.

Thus, the calculations showed that the Zailiysky seismogenic zone causes the most intense seismic loading on the Kapchagay HPP structures. Consequently, this scenario was adopted as the controlling case for the seismic stability analysis of the hydropower complex. Figure 5 presents the synthetic accelerogram for the potential earthquake source (PES) within the Zailiysky seismogenic zone and the corresponding response spectra.

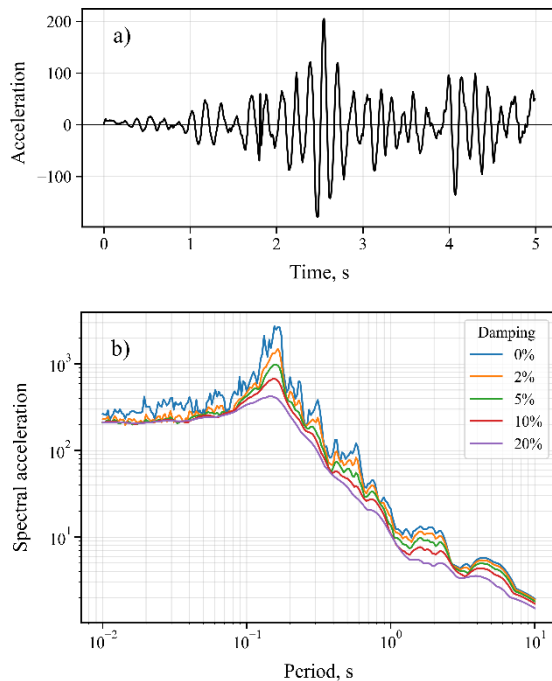


Fig. 5. (a) Synthetic accelerogram corresponding to the most hazardous seismic loading level with $M_{max} = 8.0$; (b) corresponding response spectra for damping ratios of 0, 2, 5, 10, and 20% for the potential earthquake source within the Zailiysky seismogenic zone.

4.3. Seismic Risk Modeling

A probabilistic approach is commonly used to assess the consequences of strong earthquakes

because both seismic loading parameters and structural response are inherently uncertain. At the stage of predictive calculations, it is impossible to determine the exact ground-shaking intensity for each structure. Even under identical seismic loading, the degree of damage to similar structures may vary considerably depending on their design characteristics and technical condition. Therefore, the extent of structural damage and the potential loss of life result from the interaction between two factors: earthquake intensity and the seismic resistance of the affected structures [28].

To assess the potential consequences of a strong earthquake associated with the Zailiysky seismogenic zone, an individual seismic risk assessment was conducted for the Kapchagay HPP area over a 10-year forecast period. The calculations were performed using the GIS-based system "Extremum," which is designed to model the consequences of natural hazards and estimate potential losses to population and infrastructure [29].

The individual risk of people being present in damaged buildings within the considered seismically hazardous area was determined using the following equation:

$$Re_i = P_z \times \sum_{i=1}^n \frac{m_i}{N_i \cdot T} \quad (1),$$

where P_z – probability of occurrence of the considered seismic event;

m_i – expected human losses within the i -th territorial unit;

N_i – population exposed to hazardous seismic impact within the considered territorial unit;

T – assessment time period.

The probability of occurrence of the considered seismic event, considering the combined set of registered earthquake precursors, was determined using the following relationship:

$$P_z = 1 - \prod_{i=1}^n (1 - P_i) \quad (2),$$

where P_z – integrated probability of occurrence of the considered seismic event, taking into account the combined set of registered earthquake precursors;

P_i – probability of earthquake occurrence associated with the manifestation of the i -th precursor.

The expected population losses were estimated using the GIS-based system "Extremum." For the design earthquake scenario associated with the Zailiysky seismogenic zone, the probability of

occurrence within the 10-year forecast period was assumed to be 0.7. According to the simulation results, the expected population losses for the considered earthquake scenario amounted to 521,653 people. Given a total population of 11,536,018 within the potential impact zone, the individual seismic risk was calculated as follows:

$$R_{ei} = 0,7 \times \frac{(521653)}{(10 \times 11536018)} = 3.16 \times 10^{-3} \text{ year}^{-1} \quad (3)$$

It should be noted that the population figure of 11,536,018 corresponds to the total population within the computational domain covered by the GIS-based system “Extremum,” rather than only the population of settlements located within the potential flood zone downstream of the Kapchagay HPP. The obtained value corresponds to the design scenario for the maximum expected earthquake and was used to compare the hazard associated with different potential earthquake sources. The modeling results for the earthquake scenario originating from the Zailiysky seismogenic zone are presented in Figure 6. The calculations showed that this scenario has the most severe expected consequences among all considered potential earthquake sources and was therefore adopted as the controlling design scenario for the safety assessment of the Kapchagay HPP.

The risk map indicates that the greatest expected losses are concentrated in settlements located downstream along the Ili River. The resulting population value corresponds to the entire calculation zone used in the Extremum GIS system and was used solely for comparative assessment of seismic scenarios, not for assessing direct losses associated with the potential failure of the Kapchagay Hydroelectric Power Plant.

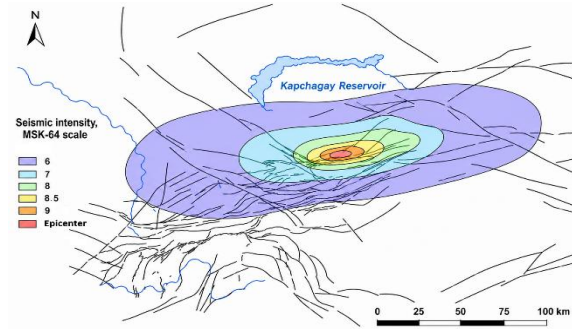


Fig. 6. Results of the calculations for the potential earthquake source (PES) within the Zailiysky zone.

4.4. Seismic Stability Analysis of the Dams

Visual inspection and analysis of the design documentation showed that the HPP dams are founded against competent rock formations. The dams were constructed on bedrock and consist of three soil layers: a gravelly-crushed stone layer, overlain by sandy loam and sand, with a final leveling and compaction layer composed of aeolian sand (Table 4).

The study used experimental data on the dynamic characteristics of the dams, previously obtained using the impact excitation method and a JDK-24 digital seismic station manufactured by the Swiss company Geosys [30]. The dynamic characteristics of the riverbed and saddle dams are presented in Table 5.

Analysis of the natural vibration characteristics showed that the saddle dam has higher natural frequencies (2.56–8.26 Hz) than the riverbed dam (1.78–6.31 Hz), indicating greater structural stiffness. The most significant differences are observed in the first vibration mode: the natural period of the riverbed dam is 0.56 s, whereas that of the saddle dam is 0.39 s. This indicates a higher dynamic flexibility of the riverbed dam under seismic loading.

Table 4. Design Properties of Soils in the Dam Body and Foundation of the Riverbed and Saddle Dams of the Kapchagay HPP

No.	Soil Type	$\rho_d, \text{t/m}^3$	$\rho, \text{t/m}^3$	$\Phi (^{\circ})$	$C \cdot 10^3, \text{kg/cm}^2$	$\rho_s, \text{t/m}^3$	ν
1	Riverbed Earthfill Dam Aeolian hydraulic-fill sand, central dam zone	1.50	1.94	26.6	0.0	2.67	0.30
2	Aeolian hydraulic-fill sand, side shells	1.54	1.96	27.5	0.0	2.67	0.28
3	Aeolian hydraulic-fill sand, downstream wedge	1.65	2.03	28.8	0.0	2.67	0.27
4	Gravelly-crushed stone soil	1.70	2.06	32.2	0.0	2.65	0.25
5	Sandy-gravel soil, transition layer in the downstream wedge	1.65	2.03	31.8	0.0	2.66	0.27
6	Alluvial gravel-sand deposits in the dam foundation	1.80	2.10	31.5	0.0	2.62	0.28

Table 4 Continue

7	Rockfill mass, downstream rock berm	2.06	2.28	33.4	0.0	2.65	0.22
8	Foundation bedrock (fractured quartz porphyry)	2.58	2.61	31.0	0.2	2.65	0.25
9	Saddle Earthfill Dam						
9	Gravelly-crushed stone soils, upstream wedge	1.80	2.13	32.6	0.0	2.70	0.25
10	Aeolian sands, downstream embankment	1.65	2.03	28.8	0.0	2.67	0.27
11	Sandy-loam soil, internal dam core	1.70	2.06	27.9	0.0	2.67	0.32
12	Rockfill mass, supporting prisms, and upstream slope protection	2.06	2.28	33.4	0.0	2.65	0.22
13	Sandy-gravel deposits in the foundation	1.70	2.06	29.7	0.0	2.65	0.28

Note: ρ_d — dry soil density; ρ — density of fully saturated soil; ρ_s — density of soil particles; ν — Poisson's ratio; ϕ — internal friction angle; C — cohesion.

The soil properties were adopted from the design documentation and engineering investigations of the Kapchagay HPP [30–32].

Table 5. Dynamic Characteristics of the Riverbed and Saddle Dams

Parameter	Riverbed Dam	Saddle Dam
First natural frequency, Hz	1.78	2.56
First natural period, s	0.56	0.39
Maximum frequency, Hz	6.31	8.26
Minimum period, s	0.16	0.12
Frequency range, Hz	1.78 – 6.31	2.56 – 8.26
Period range, s	0.16 – 0.56	0.12–0.39

Slope stability analysis was performed using the computer program “Otkos” (Moscow, Hydroproject) [31]. Four upstream water level conditions corresponding to different normal retaining water levels (NRWL) were considered:

1. Elevation 485 m – maximum design water level;
2. Elevation 475.9 m – water level according to the survey conducted by KazHydro LLP [32];
3. Elevation 479 m – maximum permitted operating water level;

4. Elevation 475 m.

The stability analyses were performed in accordance with the requirements of Building Codes, Standards, and Regulations (SNiP), SNiP 2.06.05-84 and SNiP II-7-81, Section 5, “Hydraulic Structures”. Currently, similar analyses in Kazakhstan are carried out in accordance with the Code of Practice of the Republic of Kazakhstan (SP RK) 3.04-01-2013 and SP RK 3.04-105-2014. For Class II hydraulic structures, the design reliability factor associated with the structure's importance is set at $\gamma_n = 1.20$. With an operating conditions factor of $\gamma_c = 1.05$, the minimum allowable factor of safety is $K_s, \min = \gamma_n/\gamma_c = 1.14$.

The analyses showed that, at a normal retaining water level (NRWL) of 479 m, the required stability level of both the riverbed and saddle dams is maintained under a design earthquake of 8 points on the MSK-64 scale, corresponding to a peak ground acceleration of 205 cm/s². Table 6 presents the calculated slope stability safety factors (K_s) for the riverbed and saddle dams at different NRWL elevations for potential earthquakes with intensities of 8 and 9 points on the MSK-64 macroseismic scale.

Table 6. Calculated Slope Stability Safety Factors of the Riverbed and Saddle Dams at Different Normal Retaining Water Levels (NRWLs)

Seismic Intensity (MSK-64), points	Upstream Water Level Elevation, m	Riverbed Dam		Saddle Dam	
		Upstream Slope K_s	Downstream Slope K_s	Upstream Slope K_s	Downstream Slope K_s
8	485.0	1.00	1.47	1.15	1.25
8	479.0	1.14	1.47	1.50	1.25
9	485.0	0.689	1.076	0.785	0.917
9	475.9	0.944*	1.076	1.11*	0.917
9	475.0	0.91	1.076	1.11	0.917

*The safety factors of 0.944 and 1.11 were calculated using the phreatic surface (depression curve) determined from field observations reported by KazHydro LLP [32].

Analysis of the calculation results showed that the stability of the dams of the Kapchagay HPP depends significantly on both the reservoir water level and the intensity of seismic loading. Under the design earthquake scenario with an intensity of 8 points on the MSK-64 scale ($PGA = 205 \text{ cm/s}^2$), both the riverbed and saddle dams satisfy the stability requirements established for Class II hydraulic structures.

The most favorable operating condition corresponds to a normal retaining water level (NRWL) of 479.0 m. Under this condition, the calculated safety factors varied from 1.14 to 1.50 for upstream slopes and from 1.25 to 1.47 for downstream slopes, exceeding the minimum allowable regulatory value of 1.14. These results indicate that both dams maintain the required margin of stability under the design seismic loading conditions.

For the 9-point earthquake scenario, the calculated safety factors decrease significantly. In several cases, the stability factors of the upstream slopes fall below the regulatory threshold, indicating the potential for substantial deformations and loss of stability in individual sections of the structures. The riverbed dam was found to be the most sensitive to increased seismic loading, consistent with its lower natural frequencies and greater dynamic flexibility relative to the saddle dam.

Based on the analysis results, a reservoir water level of 479.0 m was recommended as the optimal operating level from a seismic safety standpoint. This level provides a rational balance between operational requirements and the stability margin required to ensure the safe performance of the structures during strong earthquakes.

4.5. Identification of High-Seepage Zones within the Dam Body Using Vertical Electrical Sounding and Underwater Inspection

Visual inspection of the exposed portions of the riverbed and saddle dams revealed no signs of deformation, damage, or other defects that could explain the observed decline in the reservoir water level. Therefore, geophysical investigations using the vertical electrical sounding (VES) method were conducted to identify possible seepage pathways within the submerged sections of the structures. The survey was carried out along a section of the saddle dam located between the abutment against the rock outcrop and the service spillway. Observation points were positioned along the dam crest at 5 m intervals (Fig.7).

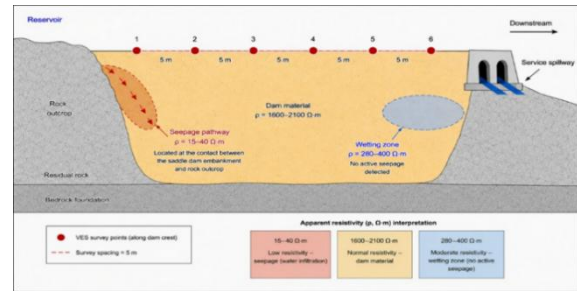


Fig. 7. Layout of the Vertical Electrical Sounding (VES) Survey Area

The primary objective was to identify zones of reduced electrical resistivity, which could indicate increased soil saturation and seepage.

Measurements were carried out using a four-electrode Schlumberger array (Figure 8). By progressively increasing the spacing between the current electrodes, the depth of investigation was increased, allowing information to be obtained on the condition of the soil mass at different depths. The maximum investigation depth was approximately 25 m.

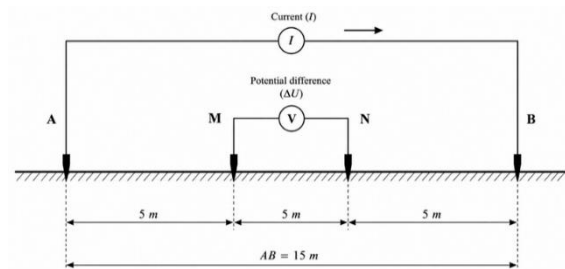


Fig. 8. Schlumberger electrode configuration used for vertical electrical sounding (VES).

A, B – current electrodes used for injecting electrical current into the ground;

M, N – potential electrodes used for measuring the electrical potential difference;

I – electric current supplied through the current electrodes A and B;

V (ΔU) – measured potential difference between the potential electrodes M and N;

AB – distance between the current electrodes;

MN – distance between the potential electrodes.

The VES results showed that throughout most of the dam body, the apparent electrical resistivity ranged from 1600 to 2100 $\Omega \cdot m$, which is typical of relatively dry, well-compacted soils. However, a pronounced anomaly was identified in the zone where the saddle dam adjoins the rock outcrop, where resistivity values decreased to 15–40 $\Omega \cdot m$. Such a significant reduction in electrical resistivity indicates a highly water-saturated zone and suggests

a seepage pathway along the contact between the dam fill material and the bedrock foundation. In addition, an area with intermediate resistivity values of 280–400 $\Omega \cdot m$ was detected near the service spillway. These data indicate localized soil moistening without the development of an intensive seepage flow, which may be associated with the partial spread of moisture from the main seepage zone.

To verify the geophysical investigation results and determine the exact location of the leakage, an underwater inspection of the upstream face of the hydropower complex was conducted. The survey was carried out by a specialized diving contractor using pontoon-based equipment. Attention was given to areas where the VES survey had indicated signs of increased seepage, as well as to the contact zones between the hydraulic structures and the bedrock foundation. During the inspection, the submerged sections of the intake structure, the service spillway, and the areas where the structures adjoin the adjacent rock masses were examined.

In the area of the right-bank junction of the intake structure, at a depth of approximately 14 m below the upstream water level, a zone of intensive seepage was identified. A partially open crack was detected at this location, measuring approximately 1.5 m in height, up to 0.15 m in width, and about 0.8 m in depth. The inspection revealed that the seepage flow was occurring not only through the crack itself but also along the contact between the structure and the bedrock foundation. The results of the underwater survey provided independent confirmation of the seepage anomaly identified by the VES investigation. The agreement between these two independent investigation methods made it possible to accurately localize the leakage zone and determine the mechanism responsible for the development of the seepage process. The results provided the basis for developing a set of engineering measures to eliminate the identified defect and improve the reliability of the pressure-retaining structures of the Kapchagay HPP.

The combined application of the VES method and underwater inspection proved highly effective for diagnosing hidden defects in hydraulic structures. The geophysical investigations enabled rapid localization of a potentially hazardous zone without disrupting facility operations, while the underwater inspection provided direct confirmation of the nature and geometric characteristics of the identified defect. The use of these two complementary methods significantly increased diagnostic reliability and reduced uncertainty in selecting subsequent engineering measures.

4.6. Engineering Measures for Seepage Mitigation

Following the identification of the intensive seepage zone, a series of engineering measures was developed and implemented to eliminate the detected defect and improve the reliability of the pressure-retaining structures of the Kapchagay HPP. The work was carried out by the specialized company JSC “Hydrospetsstroy,” which has extensive experience in repairing and reinforcing hydraulic structures. Grout injection into the soil mass was selected as the primary method for mitigating seepage because it effectively seals seepage pathways without interrupting facility operations.

The work was carried out by injecting a cement–sand grout through a system of specially drilled boreholes located within the identified leakage zone. As the voids and weakened soil sections were filled, a seepage-control barrier formed, preventing further water movement along the embankment–bedrock interface. The grouting operations were performed in stages under controlled pressure. Technological pauses of 4 to 24 hours were maintained between individual injection cycles to allow adequate grout setting and improve the effectiveness of subsequent injections. During each cycle, approximately 2.5–5.0 m^3 of grout was injected into the soil mass.

The layout of the repair areas is shown in Fig. 9. A mixture of M300 hydraulic Portland cement and coarse-grained sand was used as the grouting material, with a cement-to-sand ratio ranging from 1:1 to 1:3 depending on the conditions of the treated section. In total, 215 m^3 of cement–sand grout and 65 m^3 of crushed stone were used for the preparation and compaction of working areas during the repair works.

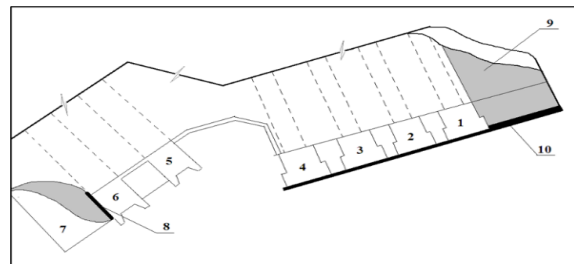


Fig.9. Layout of the repair work areas at the Kapchagay Hydroelectric Power Station: 1, 2, 3, 4 – water intake structures; 5, 6 – operational spillways; 7 – saddle dam; 8 – filling grouting of the rock outcrop lining; 9 – reinforcement grouting of the right-bank junction of the hydropower station water intake structure; 10 – filling grouting of the gate-storage platform area of the hydropower station water intake structure.

Approximately 95% of the materials were allocated to reinforcing the most critical section at the contact between the earthfill dam and the bedrock foundation, where underwater inspection had confirmed intense seepage. The remaining materials were used to provide additional reinforcement to selected elements of the service spillway.

The implemented measures successfully eliminated the identified seepage pathway and restored the reliability of the most vulnerable component of the hydraulic structure. This was particularly important for ensuring seismic safety, as prolonged seepage can lead to soil loosening, degradation of strength properties, and an increased likelihood of deformation during strong earthquakes. The subsequent operation of the Kapchagay HPP has confirmed the effectiveness of the repair work. Following the completion of the rehabilitation measures, no signs of abnormal water losses were observed, and the hydropower complex has operated for many years without incidents related to seepage processes. Recent studies on the operational performance of the Kapchagay HPP also confirm that the main structures of the hydropower complex continue to meet the required reliability standards [33].

4.7. Comparison of Results with Previous Studies

The results obtained are in good agreement with findings from previous studies on the seismic safety of earthfill dams, seepage processes, and methods for improving the reliability of hydraulic structures. Earlier research has shown that zones of increased water saturation and seepage reduce soil strength and increase the likelihood of deformation during strong earthquakes (Han et al. [7]). A similar situation was identified at the Kapchagay HPP, where a seepage zone was detected at the contact between the earthfill dam and the bedrock foundation.

Post-earthquake investigations of dams following the 2010 Maule earthquake in Chile demonstrated that properly designed earthfill and rockfill dams can maintain their functionality even under intense seismic loading (Verdugo et al. [8]). The analyses performed in this study showed that the riverbed and saddle dams of the Kapchagay HPP also possess an adequate margin of stability under the design earthquake with an intensity of 8 points on the MSK-64 scale.

According to Tran et al. [9], one of the main causes of damage to earthfill dams is the long-term development of uncontrolled seepage. In the present case, the combined application of the VES

method and underwater inspection enabled localization of a hidden seepage pathway that had not been detected during the visual inspection of the structures.

The effectiveness of soil grouting in reducing seepage and improving the reliability of hydraulic structures has been confirmed by several studies, including Do et al. [10]. A similar outcome was achieved at the Kapchagay HPP, where the implemented grouting works successfully eliminated the identified seepage pathway and restored the reliability of the most vulnerable section of the pressure-retaining structures.

Thus, the results of this study are consistent with the international experience of operating earthfill dams in seismically active regions. The distinctive feature of the present work is the integrated application of seismic hazard assessment, design ground-motion modeling, risk analysis, geophysical diagnostics, underwater inspection, and engineering reinforcement measures within a single framework to solve a specific practical problem.

4.8. Limitations and Uncertainties

As with any engineering investigation, the results presented in this study are subject to several sources of uncertainty.

The seismic hazard assessment and the generated synthetic accelerograms are based on the adopted parameters of potential seismic sources. Therefore, the calculated seismic impacts should be regarded as plausible design scenarios rather than exact predictions of future earthquakes. The actual characteristics of a seismic event, including its magnitude, focal depth, and peak ground acceleration, may differ from the assumed scenario parameters.

The interpretation of the vertical electrical sounding (VES) data is inherently non-unique, as variations in electrical resistivity may be influenced by multiple factors, including lithological differences, moisture conditions, and geological heterogeneity. The precise location of the seepage pathway was subsequently confirmed through underwater inspections. It should be noted that the underwater surveys focused not only on the areas identified as most critical in terms of seepage losses. A diving survey was conducted at two dams — riverbed and saddle dams. However, the existence of smaller seepage paths that were not detected during the survey cannot be completely ruled out.

The effectiveness of the remediation measures was evaluated primarily through operational observations, including the absence of recurring abnormal water losses and the stable performance

of the hydraulic structures during subsequent operation. Although systematic quantitative post-remediation monitoring data were not available, the consistency of the results obtained from seismic analyses, geophysical investigations, underwater inspections, and engineering observations indicates that the identified seepage mechanism and the implemented mitigation measures adequately reflect the actual condition of the Kapchagay Hydropower Plant.

5. CONCLUSIONS

The investigations conducted demonstrated that ensuring the safety of hydraulic structures in seismically active regions requires an integrated approach that combines seismic hazard assessment, risk analysis, engineering calculations, geophysical surveys, and field inspections.

It was established that the Zailiysky seismic source zone poses the greatest potential hazard to the Kapchagay HPP. The calculated peak ground acceleration for this scenario was 205 cm/s^2 , corresponding to a seismic intensity of 8 points on the MSK-64 scale. Based on the parameters of the identified potential earthquake sources, an ensemble of synthetic accelerograms was generated and subsequently used to assess the seismic stability of the hydropower complex structures.

The stability analyses showed that, at a normal retaining water level of 479 m, both the riverbed and saddle dams maintain the required margin of stability under the design seismic loading conditions. The calculated safety factors satisfy the regulatory requirements established for Class II hydraulic structures. However, under more intense seismic loading scenarios, a reduction in the stability of certain structural elements is observed, highlighting the need for careful control of the reservoir operating regime.

Geophysical investigations using the vertical electrical sounding (VES) method identified a localized zone of low electrical resistivity at the contact between the earthfill dam and the bedrock foundation. Subsequent underwater inspection confirmed the presence of a seepage pathway and enabled precise localization of the defective section through which water was leaking.

To eliminate the identified defect, soil grouting works were carried out. The implemented engineering measures effectively reduced seepage and eliminated the abnormal water losses from the reservoir observed prior to the grouting work.

The results confirm the effectiveness of the integrated application of seismic hazard assessment, design ground-motion modeling, risk analysis,

geophysical diagnostics, and structural reinforcement methods. The proposed approach can be applied to the inspection and safety enhancement of earthfill dams and other hydraulic structures operating in seismically active regions.

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7. REFERENCES

- [1] Siri R., Mondal S.R., and Das S., Hydropower: A Renewable Energy Resource for Sustainability in Terms of Climate Change and Environmental Protection, in *Alternative Energy Resources: The Way to a Sustainable Modern Society*, Springer International Publishing, Cham, Switzerland, 2020, pp. 93–113. DOI: 10.1007/978-93-8001-635-0_635.
- [2] Shah J., Hu J., Edelenbosch O.Y., and van Vliet M.T.H., Global Dataset Combining Open-Source Hydropower Plant and Reservoir Data, *Scientific Data*, Vol. 12, 2025, Article 646. DOI: 10.1038/s41597-025-04975-0.
- [3] Nguyen K.T., Pham L.T., Nguyen D.D., and Tran G.H.T., Downstream Inundation Analysis of Small Hydropower Plants Dam Break: A Case Study in Lang Son Province, Vietnam, *International Journal of GEOMATE*, Vol. 21, No. 83, 2021, pp. 101–112. DOI: 10.21660/2021.83.6210.
- [4] Hameed I.H., Al-Shukur A.H.K., and Jafer H.M., Experimental and Numerical Investigation of Seepage and Seismic Dynamic Behavior of Zoned Earth Dams with Subsurface Cavities, *GeoHazards*, Vol. 6, No. 3, 2025, Article 37. DOI: 10.3390/geohazards6030037.
- [5] Zhang J., Chen X., Li J., and Xu S., Seismic Response of Earth-Rock Dams Considering Microscopic Fluid–Solid Coupling Effects, *Sustainability*, Vol. 15, No. 17, 2023, Article 12749. DOI: 10.3390/su151712749.
- [6] United States Society on Dams (USSD), *Observed Performance of Dams During Earthquakes*, Vol. II, Denver, USA, 2000, 492 p.
- [7] Han C., Wang J., Song E., and Xu G., Hydrodynamic Effects and Hydromechanical Coupling in the Seismic Response of Dams, *Computers and Geotechnics*, Vol. 76, 2016, pp. 12–24. DOI: 10.1016/j.compgeo.2016.02.006.
- [8] Verdugo R., Sitar N., Frost J.D., Bray J.D., Candia G., Eldridge T., Hashash Y., Olson S.M., and Urzua

- A., Seismic Performance of Earth Structures During the February 2010 Maule, Chile Earthquake: Dams, Levees, Tailings Dams, and Retaining Walls, *Earthquake Spectra*, Vol. 28, Issue S1, 2012, pp. S75–S96. DOI: 10.1193/1.4000043.
- [9] Tran T.V., Vu B.T., Pham M.V., Nguyen D.Q., and Phan D.C., Understanding Downstream Slope Failure in Earth Dams: Causes and Remedies – A Case Study of Trieu Thuong No. 2 Dam, Quang Tri, Vietnam, *International Journal of GEOMATE*, Vol. 25, No. 108, 2023, pp. 163–171. DOI: 10.21660/2023.108.3798.
- [10] Do M.N., Nguyen T.N., Bui T.S., Hoang N.D.C., and Nguyen H.D., Evaluation of Anti-Seepage Quality for the Pac Ma Hydropower Dam Foundation Using Grouting Method, *International Journal of GEOMATE*, Vol. 30, No. 142, 2026, pp. 50–59. DOI: 10.21660/2026.142.5418.
- [11] Liu H., Shi Z., Li Z., and Wang Y., Experimental Investigation on Reinforcement Application of Newly Permeable Polymers in Dam Engineering with Fine Sand Layers, *Water*, Vol. 15, No. 21, 2023, Article 3761. DOI: 10.3390/w15213761.
- [12] Wang S., Zhang X., Zhang P., and Chen Z., Strength Performance and Stabilization Mechanism of Fine Sandy Soils Stabilized with Cement and Metakaolin, *Sustainability*, Vol. 15, No. 4, 2023, Article 3431. DOI: 10.3390/su15043431.
- [13] Pratter P., Boley C., and Forouzandeh Y., Innovative Ground Improvement with Chemical Grouts: Potential and Limits of Partial Saturation with Polymers, *Geotechnical and Geological Engineering*, Vol. 41, No. 1, 2023, pp. 477–489. DOI: 10.1007/s10706-022-02301-8.
- [14] Huang H., Zhu J., Wu Z., Chen J., and Tian J., System Reliability Analysis of Slope Stability of Earth-Rock Dams Based on Finite Element Strength Reduction Method, *Applied Sciences*, Vol. 15, No. 9, 2025, Article 4672. DOI: 10.3390/app15094672.
- [15] Qiu W., Li Y., Zhao W., Zhang Q., Wen L., Zhang Y., and Wang T., Mathematical Model and Application of Overtopping Breach of Cascade Earth-Rock Dams Considering Flood Peak Enhancement Effect, *Water Resources Management*, Vol. 39, No. 3, 2025, pp. 1403–1433. DOI: 10.1007/s11269-024-04022-4.
- [16] Belazouz L., Bouzelha K., Hammoum H., Amiri O., and Khelil N., Reliability Analysis of the Slope Stability of Homogeneous Earth Dam under Seismic Loading, *Periodica Polytechnica Civil Engineering*, Vol. 68, No. 1, 2024, pp. 107–121. DOI: 10.3311/PPci.22537.
- [17] Torres E.S., and Dungca J.R., Understanding the Mechanisms of Liquefaction-Induced Soil Ejecta Using Interpretable Machine Learning, *International Journal of GEOMATE*, Vol. 30, No. 142, 2026, pp. 118–125. DOI: 10.21660/2026.142g15157.
- [18] Lee P.H., Nishimura S., Nishiyama T., Fang C., and Nguyen T.C., Seismic Deformation of Earth Dams: A State-of-the-Art Review, *Reviews in Agricultural Science*, Vol. 10, 2022, pp. 138–154. DOI: 10.7831/ras.10.0_138.
- [19] Abdrakhmatov K.E., Walker R.T., Campbell G.E., Carr A.S., Elliott A., Hillemann C., Hollingsworth J., Landgraf A., Mackenzie D., Mukambayev A., and Rizza M., Multisegment Rupture in the 11 July 1889 Chilik Earthquake (Mw 8.0–8.3), *Kazakh Tien Shan, Interpreted from Remote Sensing, Field Survey, and Paleoseismic Trenching, Journal of Geophysical Research: Solid Earth*, Vol. 121, No. 6, 2016, pp. 4615–4640. DOI: 10.1002/2015JB012763.
- [20] Kulikova G., and Krüger F., Source Process of the 1911 M8.0 Chon-Kemin Earthquake: Investigation Results by Analog Seismic Records, *Geophysical Journal International*, Vol. 201, No. 3, 2015, pp. 1891–1911. DOI: 10.1093/gji/ggv091.
- [21] Miramont C., Rizza M., Guibal F., Brisset E., Brousset L., Guiter F., Millagou P., Sarzhanov S., Adilkhan B., Akkemik Ü., and Mazarzhanova K., Tree Rings Reveal the Correlation Between the Kaindy Lake Submerged Forest and the Historical 1889 M8.2 Chilik Earthquake (Kazakhstan), *Natural Hazards*, Vol. 121, No. 9, 2025, pp. 11221–11241. DOI: 10.1007/s11069-024-06927-0.
- [22] Mikhaylova N.N., and Poleshko N.N., About Unusual Bakanas Earthquake in 1979 in Kazakhstan (Mw=5.7), *NNC RK Bulletin*, No. 2, 2013, pp. 154–160 (in Russian).
- [23] Lapin V., Aldakhov Y., Makish N., Aldachov S., and Ali A., Dynamic and Spectral Characteristics of the Kapchagay HPP Dam, *Smart Geotechnics for Smart Societies*, 2023, pp. 2160–2165. DOI: 10.1201/9781003299127-353.
- [24] Silacheva N.V., Kulbayeva U.K., and Kravchenko N.A., On the Realization of Seismic Microzonation of Almaty (Kazakhstan) in Ground Accelerations Based on the Continual Approach, *Engineering*

- and Mining Geophysics 2018 Conference Proceedings, 2018. DOI: 10.3997/2214-4609.201800492.
- [25] Abakanov T., Kusainov A.A., Teplykh A.V., and Bondarev D.E., *Seismology and Seismic Resistance of Structures*, SKAD SOFT Publishing House and ASV Publishing House, Moscow, Russia, 2024, pp. 381–382 (in Russian).
- [26] Rathje E.M., Faraj F., Russell S., and Bray J.D., *Empirical Relationships for Frequency Content Parameters of Earthquake Ground Motions, Earthquake Spectra*, Vol. 20, No. 1, 2004, pp. 119–144. DOI: 10.1193/1.1643356.
- [27] Fu L., Chen K., and Li X., *Strong Ground-Motion Spectral Statistical Properties of the East Anatolian Fault Region, Türkiye: Heterogeneous Attenuation, Stress Drop, and Site Variations*, *Bulletin of Earthquake Engineering*, Vol. 23, No. 8, 2025, pp. 3239–3267. DOI: 10.1007/s10518-025-02175-0.
- [28] Shakhramanyan M.A., Larionov V.I., Nigmatov G.M., Sushchev S.P., Ugarov A.N., Nikolaev A.V., and Frolova N.I., *Methodology for Earthquake Consequence Prediction*, VNI GOChS, Moscow, Russia, 2000, 25 p. (in Russian).
- [29] Nigmatov G., Savinov A., and Nigmatov T., *Monitoring of Individual Seismic Risk at All Stages of Development of a Possible Earthquake Source, Reliability: Theory & Applications*, Vol. 18, SI 5(75), 2023, pp. 489–499. DOI: 10.24412/1932-2321-2023-575-489-499.
- [30] Hydroproject Institute, *Report on Seismic Investigation of the Condition and Seismic Resistance of the Pressure Front Structures of the Kapchagay Hydraulic Complex on the Ili River*, Moscow, Russia, 1992 (in Russian).
- [31] Institute of Seismology, *Report on Determination of Seismic Actions on the Kapchagay HPP Facilities*, Almaty, Kazakhstan, 2000 (in Russian).
- [32] KazHydro LLP, *Report on the Analysis of Monitoring Results of the Pressure Structures of the Kapchagay Hydraulic Complex for the Period 1991–1995*, Almaty, Kazakhstan, 1998 (in Russian).
- [33] Abdykadyrov A., Tuleshov A., Bekbayev A., Sarsenbayev Y., Nurgaliyeva R., Smailov N., Dosbayev Z., and Marxuly S., *Integrated Reliability Modeling and Maintenance Optimization for Performance Enhancement of Hydropower Equipment: A Case Study of the Kapshagay HPP, Sustainability*, Vol. 18, No. 6, 2026, Article 2946. DOI: 10.3390/su18062946.

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