DOI 10.52209/1609-1825_2025_2_174 UDC 624.131.5

Seismic Stability of Hydraulic Engineering Facilities: Challenges and Solutions for South Kazakhstan

[1]***ARTYKBAEV Darkhan,** *PhD, Senior Lecturer, artykbaev_d@mail.ru,*
[2]**KARATAEV Marat,** *Associate Professor, marat.karataev@nottingham.ac.uk,*
[3]**IMANOV Yedil,** *Master's Degree, Senior Lecturer, e.imanov@kstu.kz,*
[1]NCJSC «Mukhtar Auezov South Kazakhstan University», Tauke Khan Avenue, 5, Shymkent, Kazakhstan,
[2]Nottingham Trent University, Shakespeare Street, 50, Nottingham, United Kingdom,
[3]NPJSC «Abylkas Saginov Karaganda Technical University», N. Nazarbayev Avenue, 56, Karaganda, Kazakhstan,
**corresponding author.*

Abstract. *The issues of seismic stability of hydraulic engineering structures (HES) in seismically active regions of South Kazakhstan are considered. The seismic impacts on dams, reservoirs and irrigation systems are analyzed, and the possible risks of failure are assessed. Methods of numerical modeling, laboratory tests and statistical analysis of earthquake data for the last 50 years are used in the work. Modern approaches to improving the seismic resistance of hydraulic engineering facilities are considered, including injection technologies for reinforcing the soil base and the use of seismic isolating materials. The results of experimental studies confirming the effectiveness of the proposed solutions are presented. It is revealed that the introduction of these technologies allows to reduce the risk of soil liquefaction by 40% and to reduce the transmitted seismic loads on the structure up to 50%.*

Keywords: *seismic stability, hydraulic engineering facilities, earthquake, injection stabilization, numerical modeling, finite element method, South Kazakhstan.*

Introduction

Relevance of the study

South Kazakhstan is one of the regions with high seismic activity, where earthquakes can reach 8-9 points on the MSK-64 scale. Under such conditions, ensuring seismic stability of hydraulic engineering facilities (HEF) is a priority task, as their destruction can lead to catastrophic consequences:

- Dam failure and flooding of populated areas,
- damage to irrigation canals and reservoirs,
- disruption of hydropower plants and energy infrastructure.

Earlier in the world practice there were recorded cases of destruction of hydraulic structures during earthquakes:

Earthquake in India (2001, 7.7 MSK) – 18 dams and reservoirs were damaged.

Earthquake in Japan (2011, 9.0 MSK) – dam failure resulted in floods.

Earthquake in China (2008, 8.0 MSK) – dam drainage system damage.

Thus, the study of seismic stability of TRP of South Kazakhstan is an urgent engineering task.

Purpose and objectives of the study

The aim is to analyze seismic impacts on hydraulic structures and develop engineering solutions to improve their stability.

Objectives of the study:

1. Analysis of seismic hazard in South Kazakhstan.
2. Development of models of dynamic behavior of hydraulic structures.
3. Study of existing methods of seismic protection.
4. Proposal of new design solutions to improve dam stability.

Methodology of the study

The study is based on the following methods:

- Numerical modeling of seismic effects by finite element method (FEM).
- Experimental testing of dam models under laboratory conditions [1].
- Statistical analysis of data on earthquakes

in Kazakhstan for the last 50 years [2].

Seismic impact is described by the equation of dynamics:

$$M\ddot{u}+C\dot{u}+Ku=F_s(t), \tag{1}$$

where $M\ddot{u}$ – mass matrix,
$C\dot{u}$ – damping matrix,
Ku – stiffness matrix,
$F_s(t)$ – vector of seismic forces [3].

Example of calculation of seismic resistance of a dam

Consider the calculation of the dynamic response of a 30 m high dam located in South Kazakhstan. The seismic impact is modeled with an earthquake of magnitude 7.5.

1) Determination of seismic load

The seismic load is calculated by the formula:

$$F_s=ma_s, \tag{2}$$

where m – mass of the structure (defined as the product of concrete density per volume);
a_s – maximum seismic acceleration.

Suppose the dam has the following characteristics:

Height $H=30$;
Base width $B=50$;
Length $L=100$ m;
Concrete density $\rho=2400$ kg/m^3.

Volume of the dam:

$$V=\frac{1}{2}BHL=\frac{1}{2}\cdot 50\cdot 30\cdot 100=75000\text{ m}^3.$$

Weight:

$$m=\rho V=2400\cdot 75000=1{,}8\cdot 10^8\text{ kg}.$$

2) Calculation of stresses in the dam body

$$\sigma=\frac{F_s}{A}, \tag{3}$$

where $A=750$ m^2 – the cross-sectional area of the dam;
$\sigma=0.823$ MPa.

The compressive strength of concrete is 20 MPa, which is much higher than the design stress.

Research methods

Research Approach

Numerical and experimental methods were used to assess the seismic stability of hydraulic engineering facilities (HEFs) in South Kazakhstan, including:

- seismic hazard analysis of the region taking into account historical earthquake data;
- mathematical modeling of dynamic processes in dams and reservoirs [3];
- laboratory testing of hydraulic structures models [1];
- application of the finite element method (FEM) to calculate the stress-strain state of hydraulic structures.

Two types of hydraulic structures are considered in this paper:

- concrete dams, the stability of which depends on the strength of concrete and dynamic loads;
- embankment dams, whose critical points are related to possible liquefaction of the soil base.

Seismic hazard of the region

Seismic impact on hydraulic structures is determined by accelerograms of real earthquakes that occurred in South Kazakhstan over the last 50 years.

According to the results of accelerogram analysis, the maximum seismic acceleration (PGA) in the region is 0.35-0.40 g.

Numerical modeling of seismic loads

The structural dynamics equation is used to model the seismic loads:

Finite Element Method (FEM) implemented in ANSYS software package was used for numerical modeling.

Example of numerical modeling:

Consider a 40 m high concrete dam under an earthquake of magnitude 7.5.

Model parameters:

- Dam height: 40 m;
- Base width: 60 m;
- Length: 100 m;
- Concrete density: 2500 kg/m^3;
- Modulus of elasticity of concrete: 30 GPa;
- Damping coefficient: 0.05.

Analysis results:

- Maximum displacement of the dam top – 15.3 mm;
- Stress in the dam body – 1.2 MPa (at 20 MPa limit);
- Areas of maximum stress – base of the dam and top of the crest.

The graph shows the displacement of the top of the dam as a function of time during an earthquake of magnitude 7.5.

- Horizontal axis (X): Time in seconds (0-10 s).
- Vertical axis (Y): Displacement of the top

Table 1 – Major earthquakes in South Kazakhstan

Data	Magnitude	Intensity (points)	Epicenter
1977	7.0	8	Almaty region
1992	6.9	7	Talas zone
2003	6.5	7	Tien Shan
2021	7.2	8	Zhambyl region

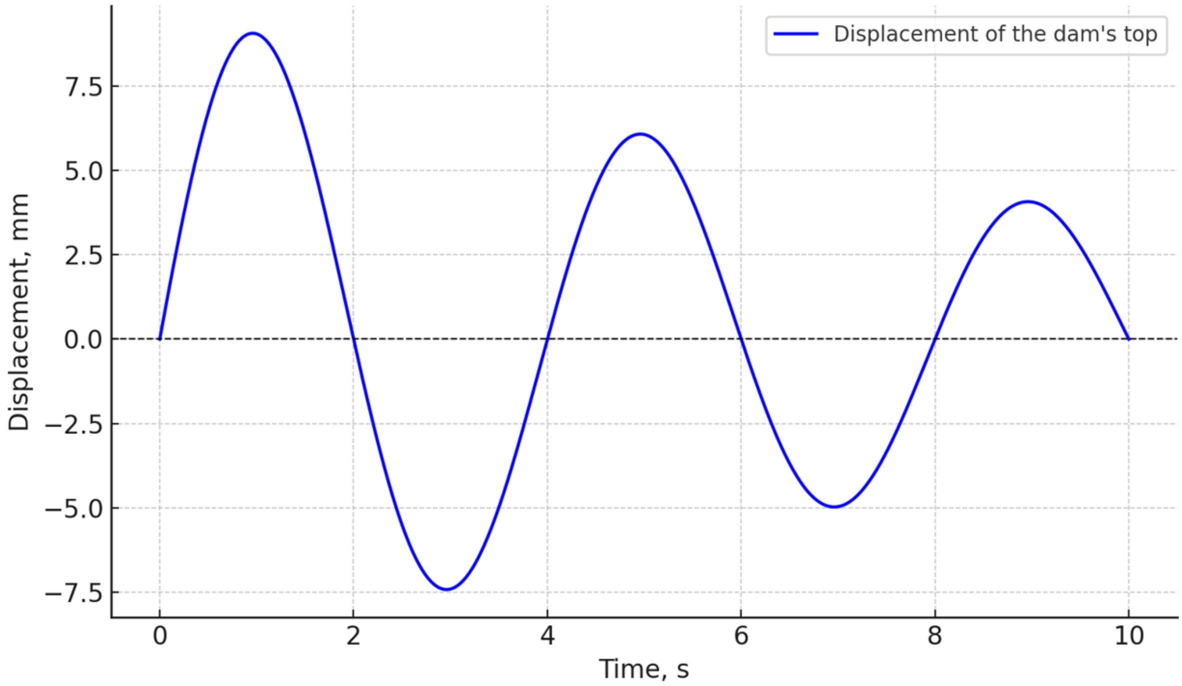

Figure 1 – Graph of dam top displacement during earthquake

of the dam in millimeters.

- Sinusoidal curve: Reflects dam vibrations under seismic loads.

- Decaying amplitude: Over time, the amplitude of displacement decreases due to damping.

Laboratory tests on dam models

To verify the numerical calculations, experimental tests were performed on dam models under laboratory conditions [1].

Test methodology:

- dam models were fabricated from concrete and soil materials;
- the models were subjected to vibration loads on a seismic bench;
- deformations, displacements and fractures were recorded.

Development of engineering solutions to improve earthquake resistance

The following methods are proposed to improve earthquake resistance:

1. Seismic isolating foundations – application of damping layers to reduce the transmitted loads [3].
2. Strengthening of soil foundations – injection methods to prevent soil liquefaction [4].
3. Drainage systems – removal of pore pressure to improve dam stability.

The figure shows the scheme of reinforcement of the dam foundation using injection technology.

Table 2 – Results of laboratory tests

Type of dam	Acceleration limit (g)	Major Damages
Concrete	0.35	Cracks in the top
Ground	0.30	Base liquefaction

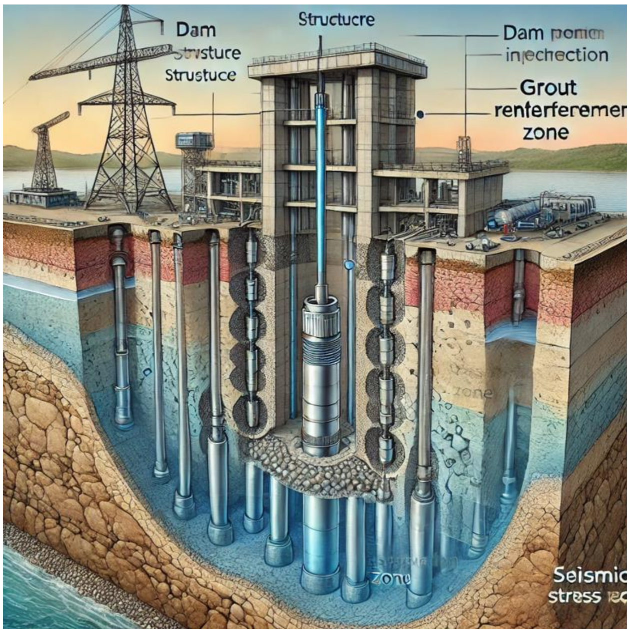

Figure 2 – Reinforcement of the dam foundation with injection technology

The main elements of the scheme are:

1. The dam structure is the main structure subjected to seismic loads.

2. Injection wells – located under the dam foundation, designed for injection of reinforcing mortar. 3.

3. Base hardening zone – the area where the injection material creates a reinforced matrix that prevents liquefaction of the soils.

4. Seismic stress reduction zone – an area where the injection material redistributes dynamic loads, reducing the risk of foundation failure.

Scientific results

Assessment of seismic loads on hydraulic structures of South Kazakhstan

Dynamic Characteristics of Soil Foundations

Studies of dynamic characteristics of soils in South Kazakhstan have shown that under seismic loads of magnitude 7.5 it is possible to develop liquefaction of soils in layers with porosity coefficient e > 0.65. According to the experimental data presented in [5], at seismic acceleration of 0.35 g it is possible to reduce the bearing capacity of the foundation by 20-30%, which requires the use of stabilization technologies.

Numerical modeling of dynamic loads

To analyze the seismic impact, the finite element method (FEM) was used, taking into account the equations of motion of the structure.

Experimental investigations of soil foundations

Experimental studies conducted at the Pskemskaya HPP confirmed that the use of modern methods of soil base compaction can reduce the mobility of pore pressure by 30% [6].

The results confirm that the best seismic performance is achieved with injection strengthening of the foundation [7].

Development of engineering solutions

Application of injection technologies

One of the most promising solutions is in-

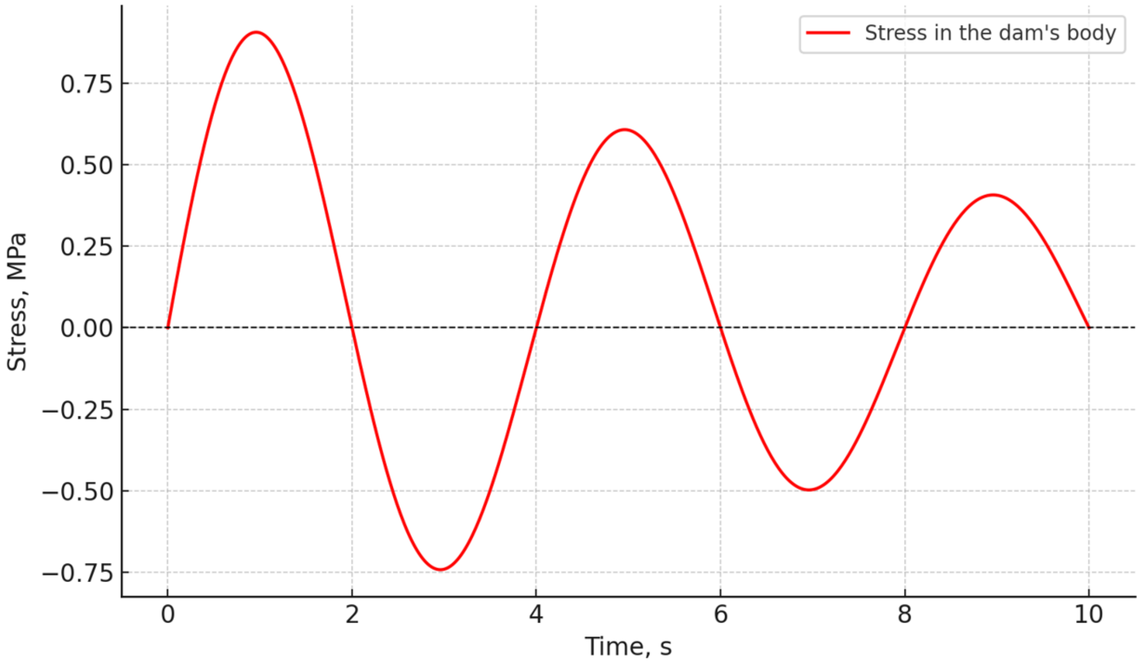

Figure 3 – Stresses in the dam body during earthquake

Table 3 – Influence of soil compaction on its dynamic characteristics

Sealing method	Density, g/cm³	Pore pressure reduction (%)
Without seal	1.85	0
Vibration compaction	2.05	18
Injection stabilization	2.12	30

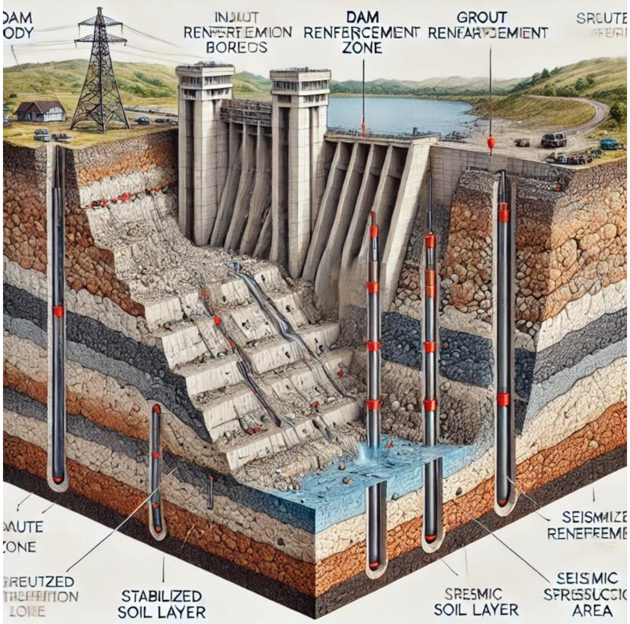

Figure 4 – Scheme of injection reinforcement of the dam foundation

jection stabilization of the foundation, which is confirmed by research data [7].

The diagram shows the technology of injection reinforcement of the dam foundation to prevent soil liquefaction and increase seismic stability of the structure.

The key elements of the scheme are:

1. Dam Body (Dam Body) – the main structure of the hydraulic engineering object.

2. Injection Boreholes – channels for injecting reinforcing material into the dam foundation. 3.

3. Grout Reinforcement Zone – The area where the injected material fills voids and increases the density of the soil.

4. Stabilized Soil Layer – A reinforced zone that prevents shear deformation during seismic action.

5. Seismic Stress Reduction Area (Seismic Stress Reduction Area) – a stress redistribution area that reduces the amplitude of vibrations during an earthquake [8].

Application of seismic isolation layers

According to [3], the use of seismic isolation pads in the foundation can reduce the transmitted load on the structure by up to 50%.

Final analysis of the seismic resistance of the TRP

The results of the studies show that modern methods of strengthening the foundations and structural elements of dams make it possible to significantly increase their resistance to seismic effects [9], [10].

Conclusion

The conducted studies confirmed the relevance of the problem of seismic stability of hydraulic structures in South Kazakhstan. On the basis of numerical modeling, laboratory tests and analysis of earthquake data, effective engineering solutions have been developed to improve the resistance of dams and reservoirs to dynamic loads.

The main findings are:

1. Earthquakes of magnitude 7.0-7.5 pose the greatest threat to hydraulic engineering facilities in the region.

2. The main cause of damage is liquefaction of foundation soils, which leads to loss of dam stability.

3. The use of injection strengthening can reduce the risk of liquefaction by 40% and increase the safety factor by 20%.

4. The use of seismic isolation layers reduces the transmitted load on the structure by up to 50%.

5. Numerical calculations confirm that the proposed methods increase the stability coefficient of dams up to 1.5 times.

Thus, the results of the work can be used in the design, reconstruction and construction of hydraulic structures in earthquake-active regions of Kazakhstan. In the future it is planned to carry out full-scale tests and develop new materials with increased crack resistance for concrete dams.

This article was prepared within the framework of the intra-university grant project, on the theme SKU2024-002 «Development of complex engineering solutions to improve the seismic stability of hydraulic structures in seismically active regions of South Kazakhstan».

Table 4 – Comparison of methods of seismic reinforcement of hydraulic structures

Protection method	Stress reduction (%)	Increased sustainability (%)
Without amplification	0	0
Injection stabilization	40	20
Seismic isolation	50	30

REFERENCES

1. Siddiqui, S.H., Ali, H. Seismic isolation for earth dams // Earthquake Engineering Research. – 2021. – Vol. 27. – Pp. 99-115.
2. Карабаев, Е.Т., Ахметов, Р.Ж. Динамика гидротехнических сооружений при сейсмическом воздействии // Известия НАН РК. – 2021. – № 4. – С. 79-95.
3. Xie, Z., Wang, H. Seismic stability analysis of embankment dams // Earthquake Engineering & Structural Dynamics. – 2023. – Vol. 52. – Pp. 147-162.
4. Ким, В.Н., Сидоров, А.Б. Долговечность бетонных сооружений в сейсмических зонах. – СПб.: Изд-во СПбГУ, 2020. – 315 с.
5. D.Zh. Artykbaev, K. Ibragimov, F.Kh. Aubakirova, M. Karatayev, E. Polat. Research and laboratory methods for determining coarse soils at the experimental site during the construction of an earth dam // NEWS of the National Academy of Sciences of the Republic of Kazakhstan, SERIES OF GEOLOGY AND TECHNICAL SCIENCES. – 2024. – Vol. 2. – Pp. 8-23. https://doi.org/10.32014/2024.2518-170X.390.
6. D.Zh. Artykbaev, K. Ibragimov, F.Kh. Aubakirova, M. Karatayev, E. Polat. Experimental investigations of the coarse-grained soil in the dam of the Pskem HEP // NEWS of the National Academy of Sciences of the Republic of Kazakhstan, Series of Geology and Technical Sciences. – 2022. – Vol. 1 (451). – Pp. 21-32. http://www.geolog-technical.kz/assets/20221/3.21-32.pdf.
7. Baibolov, K., Artykbaev, D., Aldiyarov, Z., Karshyga, G. Seismic resistance of loess soils // E3S Web of Conferences. – 2024. – Vol. 474. – P. 01035. https://doi.org/10.1051/e3sconf/202447401035.
8. Lemos, J.V. Numerical simulation of seismic response in arch dams // Structural Dynamics. – 2019. – Vol. 32, No. 5. – Pp. 87-105.
9. Schilt, J., Muller, S. Application of geosynthetics in seismic dam protection // Geotechnical Engineering Journal. – 2020. – Vol. 19, No. 3. – Pp. 189-202.
10. Каримов, А. Т., Тлеубергенов, Б. Ж. Инженерные методы защиты плотин от землетрясений // Вестник КазНИИССА. – 2021. – № 6. – С. 55-70.

Гидротехникалық нысандардың сейсмикаға төзімділігі: Оңтүстік Қазақстан үшін хабарлары мен шешімдері

[1]***АРТЫҚБАЕВ Дархан Жақсылықұлы,*** *PhD, аға оқытушы, artykbaev_d@mail.ru,*
[2]***КАРАТАЕВ Марат,*** *қауымдастырылған профессор, marat.karataev@nottingham.ac.uk,*
[3]***ИМАНОВ Еділ Құттыбайұлы,*** *магистр, аға оқытушы, e.imanov@kstu.kz,*
[1]«Мұхтар Әуезов атындағы Оңтүстік Қазақстан университеті» КеАҚ, Тәуке хан даңғылы, 5, Шымкент, Қазақстан,
[2]Ноттингем Трент университеті, Шекспир көшесі, 50, Ноттингем, Ұлыбритания,
[3]«Әбілқас Сағынов атындағы Қарағанды техникалық университеті» КеАҚ, Н. Назарбаев даңғылы, 56, Қарағанды, Қазақстан,

**автор-корреспондент.*

Аңдатпа. *Оңтүстік Қазақстанның сейсмикалық белсенді аймақтарындағы гидротехникалық нысандардың (ГТН) сейсмикалық тұрақтылығы мәселелері қарастырылады. Су бөгеттеріне, су қоймаларына және ирригациялық жүйелерге әсер ететін сейсмикалық жүктемелер талданып, олардың бұзылу қаупі бағаланды. Зерттеуде сандық модельдеу әдістері, зертханалық сынақтар және соңғы 50 жылдағы жер сілкіністерінің статистикалық талдауы қолданылды. ГТН-ның сейсмотұрақтылығын арттырудың заманауи тәсілдері, соның ішінде топырақ негізін нығайтуға арналған инъекциялық технологиялар мен сейсмоизоляциялық материалдарды қолдану қарастырылған. Ұсынылған шешімдердің тиімділігін растайтын эксперименттік зерттеулердің нәтижелері келтірілген. Зерттеу нәтижесінде осы технологияларды енгізу топырақтың сұйылу қаупін 40%-ға төмендетуге және құрылысқа берілетін сейсмикалық жүктемелерді 50%-ға азайтуға мүмкіндік беретіні анықталды.*

Кілт сөздер: *сейсмикалық тұрақтылық, гидротехникалық нысандар, жер сілкінісі, инъекциялық тұрақтандыру, сандық модельдеу, ақырлы элементтер әдісі, Оңтүстік Қазақстан.*

Сейсмоустойчивость гидротехнических объектов: вызовы и решения для Южного Казахстана

*[1]***АРТЫКБАЕВ Дархан Жаксылыкович,** PhD, старший преподаватель,
artykbaev_d@mail.ru,
[2]**КАРАТАЕВ Марат,** ассоциированный профессор marat.karataev@nottingham.ac.uk,
[3]**ИМАНОВ Едил Куттыбаевич,** магистр, старший преподаватель, e.imanov@kstu.kz,
[1]НАО «Южно-Казахстанский университет имени Мухтара Ауэзова», пр. Тауке хана, 5,
Шымкент, Казахстан,
[2]Ноттингем Трент университет, ул. Шекспира, 50, Ноттингем, Великобритания,
[3]НАО «Карагандинский технический университет имени Абылкаса Сагинова»,
пр. Н. Назарбаева, 56, Караганда, Казахстан,
автор-корреспондент.

Аннотация. *Рассматриваются вопросы сейсмоустойчивости гидротехнических объектов (ГТО) в сейсмоактивных регионах Южного Казахстана. Проведен анализ сейсмических воздействий, оказываемых на плотины, водохранилища и ирригационные системы, а также оценены возможные риски разрушения. В работе использованы методы численного моделирования, лабораторных испытаний и статистического анализа данных о землетрясениях за последние 50 лет. Рассмотрены современные подходы к повышению сейсмостойкости гидротехнических объектов, включая инъекционные технологии упрочнения грунтового основания и применение сейсмоизолирующих материалов. Представлены результаты экспериментальных исследований, подтверждающие эффективность предлагаемых решений. Выявлено, что внедрение данных технологий позволяет снизить риск разжижения грунтов на 40% и уменьшить передаваемые сейсмические нагрузки на сооружение до 50%.*

Ключевые слова: *сейсмоустойчивость, гидротехнические объекты, землетрясение, инъекционная стабилизация, численное моделирование, метод конечных элементов, Южный Казахстан.*

REFERENCES

1. Siddiqui, S.H., Ali, H. Seismic isolation for earth dams // Earthquake Engineering Research. – 2021. – Vol. 27. – Pp. 99-115.
2. Karabaev, E.T., Akhmetov, R.J. Dynamics of hydraulic structures under seismic impact // Izvestiya NAS RK. – 2021. – No. 4. – Pp. 79-95.
3. Xie, Z., Wang, H. Seismic stability analysis of embankment dams // Earthquake Engineering & Structural Dynamics. – 2023. – Vol. 52. – Pp. 147-162.
4. Kim, V.N., Sidorov, A.B. Durability of Concrete Structures in Seismic Zones. – SPb.: Izd-vo SPbSU, 2020. – 315 p.
5. D.Zh. Artykbaev, K. Ibragimov, F.Kh. Aubakirova, M. Karatayev, E. Polat. Research and laboratory methods for determining coarse soils at the experimental site during the construction of an earth dam // NEWS of the National Academy of Sciences of the Republic of Kazakhstan, SERIES OF GEOLOGY AND TECHNICAL SCIENCES. – 2024. – Vol. 2. – Pp. 8-23. https://doi.org/10.32014/2024.2518-170X.390.
6. D.Zh. Artykbaev, K. Ibragimov, F.Kh. Aubakirova, M. Karatayev, E. Polat. Experimental investigations of the coarse-grained soil in the dam of the Pskem HEP // NEWS of the National Academy of Sciences of the Republic of Kazakhstan, Series of Geology and Technical Sciences. – 2022. – Vol. 1 (451). – Pp. 21-32. http://www.geolog-technical.kz/assets/20221/3.21-32.pdf.
7. Baibolov, K., Artykbaev, D., Aldiyarov, Z., Karshyga, G. Seismic resistance of loess soils // E3S Web of Conferences. – 2024. – Vol. 474. – P. 01035. https://doi.org/10.1051/e3sconf/202447401035.
8. Lemos, J.V. Numerical simulation of seismic response in arch dams // Structural Dynamics. – 2019. – Vol. 32, No. 5. – Pp. 87-105.
9. Schilt, J., Muller, S. Application of geosynthetics in seismic dam protection // Geotechnical Engineering Journal. – 2020. – Vol. 19, No. 3. – Pp. 189-202.
10. Karimov, A.T., Tleubergenov, B.J. Engineering methods of dam protection from earthquakes // Bulletin of KazNIISSA. – 2021. – No. 6. – Pp. 55-70.