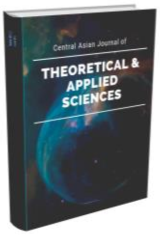

CENTRAL ASIAN JOURNAL OF THEORETICAL AND APPLIED SCIENCE

CENTRAL ASIAN STUDIES

https://cajotas.centralasianstudies.org/index.php/CAJOTAS
Volume: 06 Issue: 04 | October 2025 ISSN: 2660-5317

Article

Operational Reliability of the Pumping Station of the Karshi Main Canal

Rustam Xujakulov [1*], Feruz Tursunov [2], Ilhom Islomov[3], Gavhar Samandarova [4] ,Xo'jayorov Shaxzodbek [5]

[1,2,5]Karshi State Technical Institute, st. Mustakillik 225,180100, Karshi, Republic of Uzbekistan
[3]Research Institute of Irrigation and Water Problems, Kara-su 4, 100187, Tashkent, Republic of Uzbekistan
[4]Bukhara State Technical Institute , st. K. Murtazoyev 15, 200100, Bukhara, Republic of Uzbekistan
* Correspondence: rustam868793@mail.ru

Abstract: The main goal of increasing the reliability of cascades of pumping stations of mechanical water lifting systems includes calculating the reliability of main facilities. Identification of the main problems of reliability and safety of operation of cascades is based on the stated theoretical premises. Effective measures to combat sediment and driftwood during water intake from the river into supply canals are considered. Using a full-scale survey of water intakes, digital modeling of the developed mathematical models of the supply channel of the main Karshi and Kuyumazar pumping stations was carried out with algorithms for calculating their operating modes. clarification of the physical nature of failures, especially emergency shutdowns. Studies taking into account non-stationary pressure pulsations in pumps, especially the interaction of mating units and working parts of the pump, have established a connection between pressure pulsations and flow structure, as well as a decrease in reliability when parameters change. The applied parametric diagnostics made it possible to estimate the spectrum of vibration acceleration amplitude on the pump impeller chamber. Mathematical models have been created for pressure pipelines of large-diameter pumping stations. Dependencies for calculating the total longitudinal and transverse vibrations of the pipeline with their interaction are proposed. Increasing reliability during the rehabilitation of cascades will significantly increase the service life of structures and pumping equipment, ensuring a guaranteed water supply.

Keywords: reliability, safety, operation, pumping units, pipelines, parametric diagnostics, vibration strength

Citation: R. Xujakulov, Tursunov F., Islomov I., Samandarova G., Xo'jayorov Sh. Operational Reliability of the Pumping Station of the Karshi Main Canal. Central Asian Journal of Theoretical and Applied Science 2025, 6(4), 639-647.

Received: 10th May 2025
Revised: 11th Jun 2025
Accepted: 24th Jul 2025
Published: 08th Aug 2025

1. Introduction

The world has recognized the urgent tasks of increasing the reliability and safety of large cascades of irrigation pumping stations (PS). The creation of reliable systems, structures, and equipment is the subject of consideration of reliability theory. This theory is common to all technical devices. However, when forecasting and developing measures to improve the reliability of critical hydraulic structures, their features must be taken into account. Reliability theory makes it possible to solve problems of the stability of structures in conjunction with modern achievements in the use of artificial intelligence, which is associated with a similar problem of using computers in the SCADA system, diagnostics, control of the systems under study, which consist of many elements [1]. The methodology for designing various structures without assessing reliability does not make it possible to take into account the benefits of clarifying operating conditions, estimate the service life in advance, and clarify the degree of safety guarantee [2].

At present, methodological approaches and relevant regulatory documentation for assessing, determining and regulating the safety and operational reliability of PS have not been fully developed. Safety is defined as the property of an object during manufacture and operation and, in the event of a malfunction, not to create a threat to the life and health of people, as well as to the environment, and reliability as the property of an object to maintain over time within the established limits the values of all parameters characterizing the ability to perform the required functions in specified modes [3].

Existing cascades of PS machine water lifting systems are often approaching the stage of wear-out failures due to their age. This period of operation is characterized by an increase in the intensity of failures and accidents, an increase in the volume of work on the reconstruction and modernization of buildings, structures and equipment and, accordingly, an increase in the costs and consumption of electrical energy per unit volume of pumped water [4].

In 2024, the 50th anniversary of the launch of the first unit of the Karshi Main Canal (KMC) was celebrated. The Karshi cascade, being a vitally important facility, serves a population of over 1.5 million, supplying water to an irrigation system that provides water to 400,000 hectares in the south of Uzbekistan and a number of regions in Turkmenistan [5][6]. The cascades of the Amubukhar PS (ABMC), Amuzang and other machine canals play the same leading role in the irrigation of Uzbekistan. The increase in operational reliability is confirmed by the operating experience of Chinese and American scientists [7][8].

To meet the growing demand for energy savings in many areas, the stability and long-term performance of pumps is very important. This is also important for power plants supplying electricity to PS cascades, where, for example, nuclear reactor and technical water supply pumps must operate safely for 60 years without any repairs to the main hydraulic components [9][10].

2. Methods

In the process of research, methods of algorithmization of systems with distributed parameters according to the principles of system analysis and statistical processing of experimental results of field studies based on the laws of fluid mechanics were used. The results of studies at the largest cascades and generally accepted standard methods for measuring the parameters of units were used for their further use and application [11][12].

Methods for recording non-stationary changes in pressure in pumps and pipelines have established a connection between pressure pulsation and flow structure, as well as a decrease in safety and reliability when parameters change and vibrations of pump pipelines. The numerical modeling method was used to predict the characteristics of pressure pulsations using the RANS (Reynolds Averaged Navier Stokes) method [13]. Due to the shortcomings of the RANS model, the DDES method with modeling of individual vortices was used to capture the exact flow structures in pumps [14]. The RANS method cannot predict flow patterns and pressure pulsations for pumps under off-design operating conditions. In recent years, a more advanced numerical method has been adopted. The main goal of pressure pulsation research is to establish effective control of reducing the energy of pressure pulsations and pump vibration. To achieve this goal, the authors study the impact of new pump designs.

3. Results

Experience in operating PS cascades shows that the reliability and technical condition of such units as damless water intake, various discharges, structures at the intersection of canals with partitioning structures significantly affect the performance of the entire complex. Therefore, the reliability of cascades primarily depends on the water supply structures of the head part (Fig. 1).

Fig. 1. Damless water intake of KMC and water intake of PS ABMC

The main objectives of a comprehensive analysis of the work during operation of the head part of the pumping station are to identify changes in the processes of hydrodynamics of the working parts of the pump with changing water parameters in the flow part of hydraulic units. The complete picture of hydraulic phenomena during pump operation was determined experimentally [15][16].

Studies of the condition of the supply channel of the largest PS cascades have shown that the geometry of the channels undergoes significant changes due to erosion, sedimentation, and artificial cleaning.

Studying the distribution of sediment deposits along the length of the channel is important to ensure a guaranteed flow of water to the head PS-1 of the KMC. As a result of a decrease in flow velocity, a sharper decrease in depth is observed in the initial sections of the channel, depending on the number of operating pumping units. An increase in turbidity requires a revision of the standard value of the slope of the channel bottom, which is determined based on all possible volumes of removal of this turbidity from the channel.

Data on sediment pumped through the pump and deposited in the PS-1 channel of the KMC has been increasing in recent years: in 2019. – 3512.0 thousand m^3 (4390106 tons), in 2020 – 8268.5 thousand m^3 (10335614 tons), in 2021 – 9204.0 thousand m^3 (11505251 tons), in 2022 11399.0 thousand m3 (14,248,927 tons) and deposited in the canal in 2019. – 9442.0 thousand m^3 (11802684 tons), in 2020 – 10742.2 thousand m^3 (13428540 tons), in 2021 – 15743.7 thousand m^3 (19679684 tons), in 2022 30402.4 thousand m^3 (38,003,016 tons).

An increase in sediment supply to the channel causes a decrease in the depth of flow of water moving in the channel and an increase in the width of the channel. This situation, in turn, leads to the emergence of a dynamic equilibrium. Expansion of the channel width leads to an increase in the width of the sediment transport front. When modernizing structures, the function of a settling tank arises.

Siltation and sedimentation are observed in the forechamber. When the outermost pumps operate in the front chamber near the receiving chambers, the formation of funnels on the water surface is noted at the entrance to the suction pipe (Fig. 2).

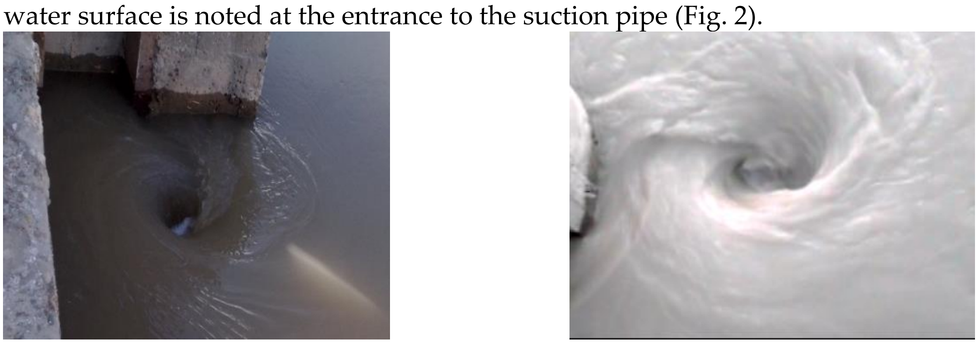

Fig. 2. Formation of craters on the water surface of the water intake

This phenomenon, associated with periodic air leaks in front of the impeller, affects a sharp increase in cavitation and vibration of the pump unit.

The resulting frequency acting on the pump impeller housing is:

$f = n \cdot Z_r \cdot q$, (1)

where Z_r is impeller blade number;

n is rotation speed;

q is the number of harmonics.

In a conventional vane pump, the blade passing frequency will dominate the pressure spectrum. A numerical simulation method can be used to predict the amplitude; however, this requires special acoustic studies to predict the corresponding amplitude [17]. The model parameters were corrected by experimental data. However, the pressure distribution at the periphery of the impeller chamber was assumed to be uniform, which was not accurate.

The above theoretical analysis can be useful in pump design. For a vane diffuser pump, using formula (1), it is easy to obtain the dominant frequency for a typical impeller type without matching blade numbers. An unintended number of coincidences resulted in high pressure pulsation and even abnormal vibration. The effect of the number of coincidences on pressure pulsation must be clarified experimentally.

When several pumping units are operating, the water level rise limit is determined by the sum of water flow rates at the boundaries of areas where the water rise height is constant. The flow, gauge pressure and efficiency of each operating pump are characterized by the values of the rotation angles of the impeller blades $(z_{нб}, z_{вб}, \varphi)$.

Consequently, the flow rate and efficiency of the i-th pumping unit are determined as the point of intersection of the operational characteristics with the pressure characteristics of the pipeline

$$\Omega^i_p\left(Q^i_p, H^i_p, \varphi^p_i\right) = \Omega^i_T \cap \Omega_{H,Q,\varphi},$$
$$\Omega^i_p\left(Q^i_p, \eta^i_p, \varphi^p_i\right) = \Omega^i_T \cap \Omega_{H,Q,\eta}, \quad (1)$$
$$\varphi_i = \varphi^p_i, \qquad \Omega_{H,Q,\varphi} \subset \Omega^i_э, \quad \Omega^i_{H,\eta,\varphi} \subset \Omega^i_э$$

Flow and power consumption for the PS as a whole are defined as the algebraic sums of the flows and powers of the operating unit.

Digital modeling was carried out taking into account the developed mathematical models of the supply channel of the Kuyumazar PS and algorithms for calculating their operating modes [18]. In Figure 3 presents the results of numerical experiments to determine the level and flow of water over time.

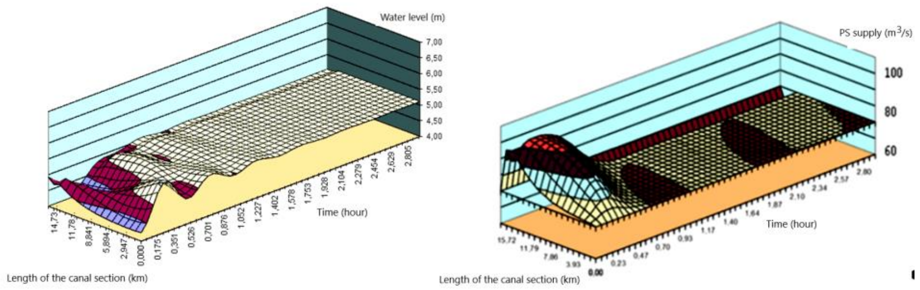

Fig. 3. Changes in water level and ABMC supply over time and length

If the set supply value is greater than the head PS, there is a certain supply reserve that cannot be realized due to insufficient channel capacity.

The supply value obtained for the KMC has a certain supply margin, which cannot be realized by the PS-1. (Table 1).

Table 1 – Operating modes of PS-1

Water mark in the Amudarya (conditional)	Maximum channel capacity, m3/s	Number of pump jobs/things	Maximum pump flow m3/s	Total station flow, m3/s	Pump head, m	Impeller blade installation angle	Impeller depth∇TWL, m
43,0	145,0	5	29	145,0	19,74	-6,50	
	145,0	4	32	128,0	19,35	-50	
43,4	172,0	5	32	160,0	19,74	-4,50	-3,5
43,6	201,0	5	32	160,0	19,18	-50	
44,0	236,0	5	32	160,0	18,45	-60	
43,0	114,0	4	28,5	114,0	18,88	-7,50	
	114,0	3	35,0	105,0	18,88	-40	
43,4	145,0	5	29,0	145,0	19,22	-70	-4,0
	145,0	4	34,6	138,4	19,22	-40	
43,6	176,0	5	34,0	170,0	19,51	-40	
44,0	215,0	5	35,0	165,0	18,67	-40	
42,0	68,5	2	34,25	68,5	18,13	-50	
43,4	110,0	4	27,5	110,0	18,31	-90	
	110,0	3	36,6	110,0	18,60	-3,50	
43,6	147,0	5	29,4	147,0	18,75	-70	-4,5
	147,0	4	36,75	147,0	18,995	-30	
44,0	190,0	5	37,0	185,0	19,29	-2,50	

The results of calculations of the maximum supply of PS-1 for various situations are given in the process of reconstructing the water intake, supply canal and water outlet [19][20].

All existing theories and criteria for the reliability of machine water lift system are adequate and are based on the determination of qualitative characteristics [21][22]. Reliability management during pump operation is achieved by identifying and preventing failures. At the same time, operating failures with a complete loss of performance become prevalent due to three main reasons: the emergency condition of the body parts and working parts of the unit, the cessation of the possibility of supplying or draining water, a sharp increase in cavitation and vibration phenomena that threaten the integrity of the unit.

According to the research program, tests were carried out on three PS-1 units. Based on the actual operating mode of the PS (three units of different supply when the water levels of the lower and upper pools change), a new unit of type 300VO-37/26Ts (pumping unit № 3) and two units of type OPV11-260 (pumping unit № 2, 6), the parameters of which are presented in table. 2.

Table 2 - Basic nominal parameters of pump tests

PS-1 KMC	Pumping unit №3	Pumping unit №2, 6
Pump brand	300 MO-37/26C	OPV 11-260 EG
Supply, m3/s	39,0	40,5
Total head, m	21,5	19,3
power, kWt	9500	8700
Efficiency,	87	86
Allowable cavitation reserve, m	13,0	11,0

To measure the general level of vibration velocity in the frequency band 2...1000 Hz and spectral analysis, an SD-12M vibration analyzer was used, which has the main technical characteristics: frequency range with maximum unevenness of the frequency response

+0.5 dB 0.5...25600 Hz; vibration parameters: vibration displacement, vibration velocity, vibration acceleration.

From the point of view of vibration strength in units, the most dangerous are periodic vibrations, which are the result of mechanical, electromagnetic and hydraulic processes with clearly defined discrete components. Such dangerous vibrations are generally strong diagnostic signals and stand out well against the background of vibration noise. Such a defect as a consequence of a change in the profile of the blades during wear was recorded when measuring vibration on pumping unit № 3 (21 μm) PS-1 and pumping unit № 5 (42 μm) when measuring vibration on impellers 24 and 50 μm (Fig. 4).

Radial direction Vertical direction

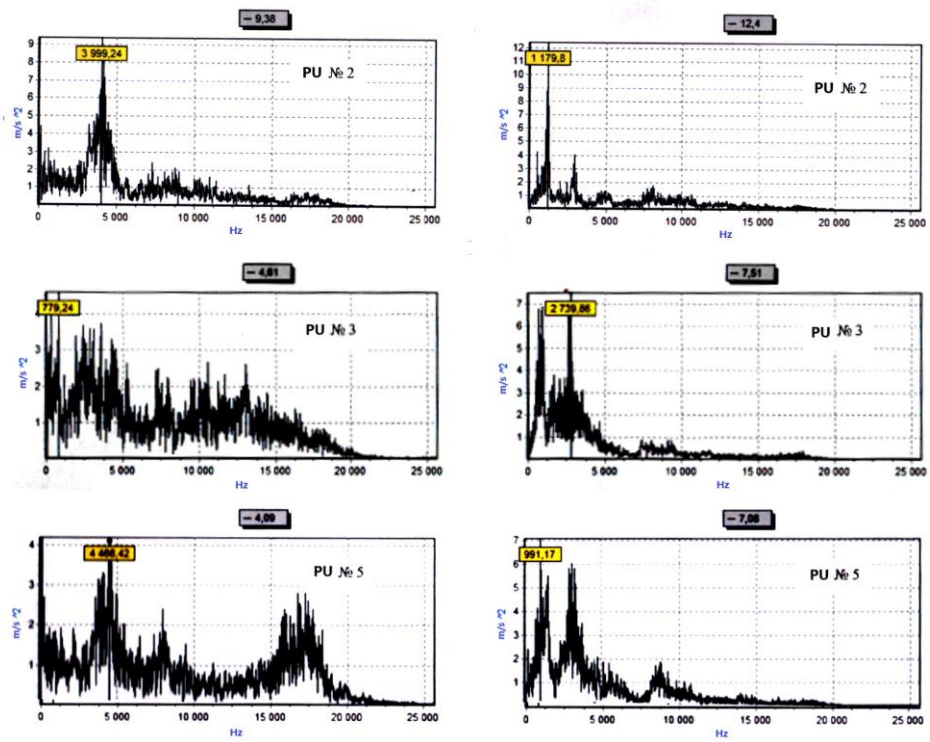

Fig.4. Spectrum of vibration acceleration amplitude on the impeller chamber of PS-1 pumps, m/s^2

If vibration diagnostics, first of all, solves the problem of increasing equipment reliability, then parametric diagnostics of a pumping unit helps to achieve more economical operating parameters. Parametric diagnostics are also based on assessments of the pressure, power and efficiency of the pump and the unit as a whole, identifying the reasons causing the deterioration of these parameters, developing and implementing measures to improve or restore the pressure and energy characteristics of the pump, determining the trend of their change as it operates [23][24][25].

Structures deserve special attention in terms of their strength and reliability, all elements of which have increased dimensions and elements for various purposes [26]. In theoretical terms, it is necessary to create various mathematical models for large diameter PS pressure pipelines. At the PS of the Jizzakh cascade the diameter is 4.2 m, at the PS of the Karshi and Amubukhara cascades it is 3.6 m (Fig. 5).

Fig.5. Pressure pipelines of PS ABMC

The equation for longitudinal vibrations of the main pipelines B_x caused by pressure along the x axis will be written in the form

$$B_x \frac{\partial^2 u_x}{\partial x^2} - \left(\tau_{xz} d_y + \tau_{xy} d_z\right) = 0 \qquad (2)$$

The differential equation of longitudinal vibrations u_x along x in relative displacements d_y and d_z has the form

$$B_x \frac{\partial^2 u_x}{\partial x^2} - k_x u = -m \frac{\partial^2 u_0}{\partial t^2} + B_x \frac{\partial^2 u_0}{\partial x^2} \qquad (3)$$

where k_x denotes the value of the parameters relative to d_y and d_z in formula (2).

Additionally, the total longitudinal and transverse vibrations u of the straight final section of the pipeline are considered with a variable longitudinal interaction coefficient.

$$\rho \frac{\partial^2 u}{\partial t^2} = E \frac{\partial^2 u}{\partial x^2} - \frac{2R}{(R^2 - r^2)} k_x (u - u_0) \qquad (4)$$

$$\rho F \frac{\partial^2 \psi}{\partial t^2} + EI \frac{\partial^4 \psi}{\partial x^4} + 2\pi R k_x (\psi - u_0) = 0 \qquad (5)$$

where ϱ is the density of the support material; F – cross-sectional area of the pipe; E – elastic modulus; η – viscosity coefficient; $k_x(x)$ - coefficient of transverse interaction of the pipeline with the support; R,r – outer and inner radii of the pipeline; ψ – transverse displacement with pipeline deflection, u_0 – displacement relative to the support; EI – bending stiffness.

The problem of significant bending of pipelines under longitudinal loading is solved

$$EJ \frac{\partial^4 (W_1 - W_0)}{\partial x^4} + m_p \frac{\partial^2 W_1}{\partial t^2} + (W_1 - W_0) + P(t) \frac{2R}{(R^2 - r^2)} \frac{\partial^2 W_1}{\partial t^2} \qquad (6)$$

where $W_1(x,t)$, $W_0(x)$ – initial and total pipe deflections; u(0,t) and u(l,t) – longitudinal movement of the ends of the pipeline; E modulus of elasticity of the pipe material; J – axial moment of inertia of the pipe section; m_p – linear mass of the pipeline; P(t) – external force of water flow [27].

The problems of ensuring the reliability of pipeline operation were solved in both linear and geometrically nonlinear formulations. Solutions were obtained by analytical and numerical methods [28]. It was revealed that the stability of the pipeline is mainly influenced by the values of the longitudinal force, the initial deflection, the geometric dimensions of the pipe, and the coefficient of elastic interaction of the pipeline with the supports. The results obtained make it possible to establish in each specific case the value of the critical values of time and force at which the pipeline finds itself in a state of dynamic instability

4. Conclusion

1. The main goal of increasing the reliability of the operation of cascades of PS systems of machine water lifting is to calculate the certain reliability of the main objects. This is a

multifaceted problem that reflects the various stages of their existence, including the creation of effective measures to control sediment and driftwood during water intake from the river into the inlet canals of the head pump stations and further into the irrigation canals.
2. For the period 2020-2022. A full-scale inspection of the KMC and ABMC water intakes was carried out for the operating mode of the main equipment. Digital modeling was carried out taking into account the developed mathematical models of the supply channel of the Kuyumazar PS and algorithms for calculating their operating modes. The results of numerical experiments to determine the level and flow of water over time are presented graphically.
3. Research into the reliability of PS operation is developing in two independent directions: clarifying the physical essence of failures and eliminating their consequences, especially emergency shutdowns. The need to limit the service life of PS equipment and pipelines is determined by their physical and moral wear and tear, determined by diagnostic results, with a decrease in the required reliability.
4. Parametric diagnostics are based on assessments of the main parameters of the pump and the unit as a whole, identification of the reasons causing the deterioration of these parameters, development and implementation of measures to improve the pressure and energy characteristics of the pump, their changes as the operating time progresses. Modernization of pumps will ensure the speedy completion of the cascade rehabilitation program, will significantly increase the service life of pumping equipment and guaranteed water supply to the regions.

REFERENCES

[1] B. Mrugalska and E. Tytyk, "Quality control methods for product reliability and safety," *Procedia Manufacturing*, vol. 3, pp. 3373–3380, 2015. doi: 10.1016/j.promfg.2015.07.683

[2] N. Leveson, N. Dulac, et al., *Engineering Resilience into Safety-Critical Systems*, 2006. [Online]. Available: https://www.taylorfrancis.com

[3] JCSS (Joint Committee on Structural Safety), *Probabilistic Assessment of Existing Structures*, RILEM Publications, 2001.

[4] B. Kühn, "Assessment of existing steel structures - Recommendations for estimation of the remaining fatigue life," *Procedia Engineering*, vol. 66, pp. 3–12, 2013. doi: 10.1016/j.proeng.2013.12.057

[5] K. Dzhuraev, A. Nasrulin, F. Shadibekova, and S. Kurbonov, "Geoinformation systems at the selection of engineering infrastructure of pumped storage hydropower for the Tuyamuyun complex," *IOP Conf. Ser.: Mater. Sci. Eng.*, vol. 869, p. 042004, 2020. doi: 10.1088/1757-899X/869/4/042004

[6] O. Glovatskiy et al., "Practice of permanent presence and equipment of the Karshi main canal," *E3S Web Conf.*, vol. 401, 2023. doi: 10.1051/e3sconf/202340101022

[7] Y. Fu et al., "Numerical and experimental analysis of flow phenomena in a centrifugal pump operating under low flow rates," *ASME J. Fluids Eng.*, vol. 137, no. 1, p. 011102, 2015.

[8] NEESR Annual Report, Cornell Univ., Rensselaer Polytech. Inst., Sciencenter Discovery Center, USA, 2006.

[9] Y.G. Lu et al., "Research on the structure design of the LBE reactor coolant pump in the lead base heap," *Nucl. Eng. Technol.*, vol. 51, pp. 546–555, 2019.

[10] C.G. Rodriguez, B. Mateos-Prieto, and E. Egusquiza, "Monitoring of rotor-stator interaction in a pump-turbine using vibration measured with onboard sensors rotating with shaft," *Shock Vib.*, vol. 2014, p. 276796, 2014.

[11] M. Sinha, A. Pinarbashi, and J. Katz, "The flow structure during onset and developed states of rotating stall within a vaned diffuser of a centrifugal pump," *ASME J. Fluids Eng.*, vol. 123, pp. 490–499, 2001.

[12] N. Krause, K. Zähringer, and E. Pap, "Time-resolved particle imaging velocimetry for the investigation of rotating stall in a radial pump," *Exp. Fluids*, vol. 39, pp. 192–201, 2005.

[13] Q.R. Si et al., “Numerical investigation of pressure fluctuation in centrifugal pump volute based on SAS model and experimental validation,” *Adv. Mech. Eng.*, vol. 6, p. 972081, 2014.

[14] A. Posa, A. Lippolis, and E. Balaras, “Investigation of separation phenomena in a radial pump at reduced flow rate by large eddy simulation,” *ASME J. Fluids Eng.*, vol. 138, p. 121101, 2016.

[15] N. Nasyrova, O. Glovatskiy, F. Artykbekova, and S. Sultanov, “Operation of the cascade of pumping stations of the Karshi Main Canal,” in *Water Resources Engineering*, Springer, 2021, pp. 287–296. doi: 10.1007/978-3-030-72404-7_23

[16] E. Kan, M. Mukhammadiev, and N. Ikramov, “Methods of regulating the work of units at irrigation pumping stations,” *IOP Conf. Ser.: Mater. Sci. Eng.*, vol. 869, p. 042009, 2020. doi: 10.1088/1757-899X/869/4/042009

[17] J.L. Parrondo, J. González, and J. Fernández, “The effect of the operating point on the pressure fluctuations at the blade passage frequency in the volute of a centrifugal pump,” *ASME J. Fluids Eng.*, vol. 124, pp. 784–790, 2002.

[18] A.J. Seytov et al., “Mathematical models and optimal control algorithms for channels of irrigation systems,” *Acad. Res. Educ. Sci.*, vol. 2, no. 5, 2021.

[19] O. Glovatsky et al., “Improvement of water intake in large machine water lifting systems (On the example of the Karshi main canal),” *AIP Conf. Proc.*, vol. 2612, p. 020031, 2023. doi: 10.1063/5.0113298

[20] N. Ismoilov et al., “Technology of water supply to water inlets of pumping stations,” *IOP Conf. Ser.: Mater. Sci. Eng.*, vol. 1030, no. 1, p. 012156, 2021. doi: 10.1088/1757-899X/1030/1/012156

[21] T. Mirskhou1ava, “Scour in River Basin in its Bed Mechanism Forecast,” in *Int. Symp. River Mechanism*, Hong Kong, Thailand, 2003.

[22] N. Nasyrova et al., “Use of combined floating structures at water inlets of pumping stations,” in *Proc. of EECE 2020*, vol. 150, Springer, Cham, 2021, pp. 265–273. doi: 10.1007/978-3-030-72404-7_26

[23] T.R. Rashidov and D.A. Bekmirzaev, “Seismodynamics of pipelines interacting with the soil,” *Soil Mech. Found. Eng.*, vol. 52, no. 3, pp. 149–154, 2015.

[24] R. Khujakulov, M. Zaripov, and U. Normurodov, “Subsidence deformations of the foundations of hydraulic structures,” *E3S Web Conf.*, vol. 264, p. 03069, 2021. doi: 10.1051/e3sconf/202126403069

[25] R. Khujakulov, “Stresses in subsidence bases of flutbet models under the moisturizing conditions,” *IOP Conf. Ser.: Mater. Sci. Eng.*, vol. 1030, p. 012138, 2021. doi: 10.1088/1757-899X/1030/1/012138

[26] R. Khujakulov et al., “Determination of calculating stresses on the depth of loess grounds of hydraulic structures,” *IOP Conf. Ser.: Mater. Sci. Eng.*, vol. 1030, p. 0121331, 2021. doi: 10.1088/1757-899X/1030/1/0121331

[27] R. Khujakulov, “Interaction of hydraulic structures and their subsidence bases,” *AIP Conf. Proc.*, vol. 2612, p. 020038, 2023. doi: 10.1063/5.0113983

[28] R. Khujakulov and G. Samandarova, “Dependence of stress-strain state of hydraulic structures on infiltration moistening of foundation soils,” *E3S Web Conf.*, vol. 401, art. no. 01046, 2023. doi: 10.1051/e3sconf/202340101046