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Stress-strain state of highland dams under the influence of volumetric and seismic forces for sustainable water resources management and agrarian security

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Abstract. Ensuring the reliability of hydraulic structures, in particular highland dams, is of particular importance for sustainable water supply in the agro-industrial complex, especially under conditions of water scarcity and seismic activity. The purpose of this work was to evaluate the stress-strain state of highland dams taking into account the complex action of volumetric, seismic and hydrostatic loads to improve the reliability of water infrastructure serving agriculture. The Kolosov-Muskhelishvili method was used in the study to model stresses in elastic media taking into account the interaction of rocks, tectonic stresses and external loads. The peculiarities of stress redistribution in the dam massif under changes in the reservoir level and water saturation were analysed, and the influence of seismic effects on the formation of shear zones in isotropic rocks was revealed. It was found that in mountainous relief conditions horizontal stresses may exceed vertical stresses, which requires revision of design approaches. The combined effects of gravitational, seismic and hydrostatic forces on the stability of

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structures have been analysed. Special attention was paid to the influence of tectonic processes and relief on the stress state of the soil mass. The results of the study can be used in the design and operation of highland dams that provide water supply to reclamation systems and agricultural areas in earthquake-prone regions. Modern methods of mathematical modelling significantly increase the accuracy of engineering calculations and ensure the reliability of hydraulic structures, which is especially important for ensuring agrarian safety. The assessment of stress-strain state of structures serves as a basis for predicting their behaviour under various loads and taking effective measures to maintain stability. The practical value of the performed work lies in the use of the results by design and engineering survey organisations in the design and construction of highland dams, allowing designers to accurately predict the behaviour of hydraulic structures under various operating conditions, ensuring reliable and sustainable water supply in agriculture, especially in areas with increased seismic activity and complex engineering and geological conditions

Keywords: gravitational force; conformal mapping; initial stress state; boundary conditions; dam modelling; hydrostatic pressure; filtration processes

Introduction

Kyrgyzstan, located in a mountainous area, faces a special problem in water supply and irrigation of agricultural land. The accumulation of water resources is an essential part of hydropower and agro-industrial development, as it provides a stable water supply for agriculture and allows efficient use of water bodies for irrigation. To provide water resources, it is necessary to develop and operate reservoirs at different elevations. However, dam failure, especially in mountainous areas with large volumes of stored water, poses a serious threat to human life and can also lead to flooding of settlements and agricultural land.

The performance of dams in mountainous conditions has many characteristics, which makes the assessment of their stability a complex task, especially considering the specifics of agriculture and water management. As noted by U. Hansamali *et al.* (2025), the failure of dams and levees can be caused by a variety of factors, including seismic activity, the impact of water from reservoirs, and the design and materials of both natural and man-made dams. The location of dams relative to sea level is also important, which is directly related to the temperature regime and operating conditions of the dam during different seasons (Ouma *et al.*, 2022). These aspects need to be taken into account in the design and operation of hydraulic structures to ensure their long-term safety and minimise risks to agriculture and water supply.

However, dam failures in such high-altitude zones, as well as accidents at large hydroelectric power plants (HPPs) located in river canyons, pose a real threat to human life and safety, and can lead to massive destruction of settlements and agricultural lands. These problems become especially urgent in the conditions of complex geography of the country, where climatic conditions, seismic activity and geological features significantly affect the strength and stability of hydraulic structures (Montayev *et al.*, 2025). One of the most important tasks is to assess the stability of dams in mountainous areas, which requires consideration of many factors such as seismicity, temperature fluctuations, hydrostatic water pressure, water filtration through the dam body, and structural features. The stability of dams in such conditions is related to the preservation of structural stability, prevention of failure and deformation, which is key for the long-term operation of these facilities (Popov *et al.*, 2023).

M. Sainov (2022) has made a significant contribution to the study of the stress-strain state and stability of various types of dams. In his work, the influence of pore pressure on the fracture resistance of an ultra-high rock-fill dam with a central clay core is considered. Using numerical modelling techniques, the author investigates the stress distribution and identifies critical zones prone to crack formation. The results emphasise the importance of considering internal water head in dam design, especially under conditions of varying water saturation. The author also investigates the stress-strain state of a concrete dam with a concrete screen when the friction coefficient in the screen-sidewall contact zone is reduced. It is established that friction reduction leads to redistribution of stresses and potential reduction of stability of the structure. The author emphasises the need for accurate setting of boundary conditions when modelling structures of this type. In addition, M. Sainov (2023) summarises theoretical and practical aspects of the design, construction and operation of earth dams in a textbook intended for training specialists in hydraulic engineering. The manual covers a wide range of engineering solutions and contains a structured presentation of basic and applied principles applicable in real dam operating conditions.

In the work of S. Pari (2025) provides a probabilistic analysis of the stability of an earthen dam under steady-state seepage conditions. Special attention is paid to the influence of the clay core location on the overall stability coefficient. The author uses stochastic modelling techniques to account for uncertainties in the geotechnical parameters of the foundation and dam body. It is found that the displacement of the core from the centre of the structure can significantly reduce the stability of the structure, especially in conditions of prolonged saturation. The analysed studies reflect modern scientific approaches to the assessment of stress-strain state and stability of dams. E. Argal (2024) in his work analyses the causes of seepage, methods of controlling it and offers recommendations on how to improve the condition of a dam.

The purpose of the study of the stress-strain state (SS) of highland dams was to evaluate the distribution of stresses and strains in the dam structure to ensure its stability, safety and durability during operation. This included analysing the effects of external factors such as hydrostatic pressure, seismic activity on the dam structure. Objectives of the study:

- modelling of the stress-strain state of rock dams taking into account seismicity, temperature, water pressure in reservoirs, and geological features;
- analysing existing methods of calculating the VAT of dams in mountainous areas, taking into account the impact of various natural and geophysical factors;
- development of recommendations for strengthening the design of dams in mountainous areas to ensure their long-term stability and safety for the population and agriculture.

This study can make it possible to solve the complex problem of dam stability in mountainous conditions, which is an important step to ensure the reliability of hydraulic structures, minimise risks for the population, safety of irrigated lands and stable water supply in agriculture.

Materials and Methods

The Kolosov-Muskhelishvili analytical method for modelling the stress-strain state of a mountain dam taking into account various natural and anthropogenic factors, described in detail in R. Abdikarimov *et al.* (2011). The application of this method made it possible to conduct a comprehensive study of the influence of hydrostatic, thermal and seismic loads on the stability of the structure, as well as to determine the critical stress zones and develop recommendations for structural optimisation taking into account the developments presented in the study by N. Kobeleva (2017). The stability of the dam under various external influences was assessed. The most vulnerable sections of the structure subjected to maximum stress were identified according to the methodology described in E. Askarbekov *et al.* (2019). The proposed methodology made it possible to assess the stability of the dam under the combined effects of natural factors.

Analytical modelling of highland dams was carried out by using the mapping functions $\omega(\zeta)$ and deriving relations for the complex potentials $\Phi(\zeta)$ and $\Psi(\zeta)$ based on the given boundary conditions (1):

$$\Phi(t) + \overline{\Phi(t)} + \frac{1}{\omega'(t)}\{\overline{\omega(t)}\Phi'(t) + \omega'(t)\Psi(t)\} = N(t) + \mathrm{i}T(t). \quad (1)$$

In the present study, a semi-infinite region corresponding to the centre plane of the dam was considered, with two characteristic protrusions on the contour taken as the initial points of the mapping ($\zeta = 0$) (Baialieva *et al.*, 2023). This approach allowed us to precisely set the geometry of the computational domain and ensure correct imposition of boundary conditions. The creation of the mapping function consisted of two steps: 1) selection of the general form of the mapping function; 2) development of a technique for selecting the values of the parameters of this function a (to = 1, 2, 3). The general form of the function representing the proposed class is shown as (2):

$$z = \omega(\zeta) = \frac{a\zeta + \sum_{k=0}^{3} a_k \cdot (\zeta - i)^k + b_1}{(\zeta + t_0 - i)}, \quad (2)$$

where z $x = +$iy; $i = \sqrt{-1}$; b_1, α, t_0 are constants, a (to = 1, 2, 3) are complex constants.

The second part of the problem was solved by graphical packages in MATCAD #14 to vary the constants in the parametric equations, which follows (2) when $\zeta = t$:

$$x(t) = \frac{f_1(t)}{(t^2+1)^3} + \frac{b_1(t+t_0)}{[(t+t_0)^2+1]}$$
$$y(t) = \frac{f_2(t)}{(t^2+1)^3} + \frac{b_1}{[(t+t_0)^2+1]}. \quad (3)$$

The proposed mapping technique differs from the previously known one in its flexibility, clarity and high operability in modelling dam shapes (Mirsaidov *et al.*, 2013). After creating the dam computational model (Fig. 1), i.e. when all parameters $\omega(\zeta)$ in (2) are determined, the equation (1) was integrated and its conjugate equation in closed form under given arbitrary external loads to calculate the stress state of the semi-infinite region.

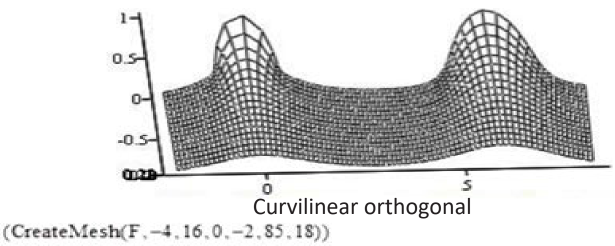

Figure 1. Dam model

Source: B. Zhumabaev & K. Ismailova (2005)

The formulated boundary value problem (1) was solved by constructing relations of two complex potentials $F(\zeta)$ and $\Psi(\zeta)$ in the form:

$$\overline{\omega'}(\zeta)F(\zeta + \overline{\omega}(\zeta)\, F'(\zeta) + k_1/(\zeta+i)^2 + 2k_{(2)}/(\zeta+i)^3 +$$
$$+3k_{(3)}/(\zeta+i)^4 + \kappa_4/(\zeta+_{t(0)}+i)^2 +$$
$$+\omega'(\zeta)\Psi(\zeta) = A(\zeta);$$

$$(\omega'\zeta)F(\zeta) - \overline{\kappa_1}/(\zeta-i)^2 - 2\overline{\kappa_2}/(\zeta-i)^3 -$$
$$-3\overline{\kappa_3}/(\zeta-i)^4 - \overline{\kappa_4}/(\zeta+_{t(0)}-i)^2 = B(\zeta), \tag{4}$$

where $A(\zeta)$ and $B(\zeta)$ depend only on the external loads N and T and are computed as Cauchy type integrals:

$$A(\zeta) = \frac{1}{2\pi i}\int \frac{(N+iT)\overline{\omega'(t)dt}}{1-\zeta} \quad \mathrm{B}(\zeta) = \frac{1}{2\pi i}\int \frac{(N-iT)\omega'(t)dt}{1-\zeta}, \tag{5}$$

where ζ belongs to the lower half-plane, $\eta = 0$ in the plane of the omnipotent complex variable $\zeta = \xi + i\eta$.

The operator $\omega(\zeta) = a\zeta + \omega_0(\zeta)$ is instantiated as:

$$\omega_0(\zeta) = \sum_{e=1}^{3} \frac{a'_e}{(\zeta-i)^e} + \frac{b_1}{\zeta+t_0-i}. \tag{6}$$

The general model of the stress state of surge dams as a sum of three stress fields:

$$\sigma x^0 = \sigma(x)^{(n)} + \sigma(x)^{(p)} + \sigma(x)^{(c)},\ \sigma(y)^{(0)} = {}^{\sigma(y)(n)} +$$
$$+ {}_{\sigma(y)}{}^{(p)} + {}_{\sigma(y)}{}^{c},\ \tau_{(y)}{}^{(0)} = \tau^{(y)(n)} + \tau^{(y)(p)} + \tau^{(y)(c)}. \tag{7}$$

This stress field is defined as the integral of the inhomogeneous differential equation of equilibrium for the half-plane (Zhumabaev & Ismailova, 2005):

$$\frac{\partial\sigma_{\tilde{0}}^{\tilde{\iota}}}{\partial\tilde{0}} + \frac{\partial\tau_{\tilde{0}\,0'}^{\tilde{\iota}}}{\partial 0'} + \rho_{\tilde{0}} = 0, \frac{\partial\tau_{\tilde{0}}^{\tilde{\iota}}}{\partial x} + \frac{\partial\sigma_{0'}^{\tilde{\iota}}}{\partial 0'} + \rho_{0'} = 0, \tag{8}$$

where $\rho_x = \gamma k_c \sin\delta$; $\rho_y = \gamma(1 - k_c\cos\delta)$ are the horizontal and vertical components of the volume force; g – gravitational acceleration; k_c – seismicity coefficient.

The integrals from (8) have the form

$$\sigma_x^i = A_1 y;\ \sigma_y^i = A_2 y;\ \tau_{xy}^i = A_3 y, \tag{9}$$

where $A_1 = \lambda\gamma(1 - k_c\cos\delta)$; $A_2 = \gamma(1 - k_c\cos\delta)$; $A_3 = k_c \cdot \gamma\sin\delta$; λ is the coefficient of lateral spreading.

The initial stress state of rock dam arrays under the action of the above forces is represented as the sum of the first two stress fields (7) with upper indices "n" and "p" and satisfies the boundary conditions on the contour:

$$X(n)^{(*)} = (\sigma(x)^{(p)} + \sigma(x)^{(p)})\cos(n, x) +$$
$$+ (\tau(x)^{(p)} + \tau(x)^{(p)})\cos(n, y) = 0;$$

$$U(n)^{(*)} = (\tau(hu)^{(p)} + \tau(hu)^{(p)})\cos(n,x) +$$
$$+ (\sigma(y)^{(p)} + \sigma(y)^{(p)})(\cos)(n, y) = 0, \tag{10}$$

where n is the direction of the external normal at the contour point under consideration.

Condition (10) contains the sum of fictitious loads N and T and load-force. The latter arises from the first stress field (9) at the contour points. Denoting by F_1 and F_2, the boundary conditions are obtained:

$$F_1(t) = \left[\omega_0(t) - \overline{\omega_0(t)}\right] \cdot [T_5 + T_6\overline{\omega'_0(t)} + T_7\omega'_0(t)]$$
$$F_2(t) = \left[\omega_0(t) - \overline{\omega_0(t)}\right] \cdot [T_2 + T_3\overline{\omega'_0(t)} + T_4\omega'_0(t)], \tag{11}$$

where

$$T_2 = -\alpha\frac{iA_2 + A_3}{2};\ T_3 = -i\frac{A_1 + A_2}{4};\ T_4 = i\frac{A_1 - A_2 + 2iA_3}{4};$$
$$T_5 = \alpha\frac{iA_2 - A_3}{2};\ T_6 = i\frac{A_1 + A_2}{4};\ T_7 = -i\frac{A_1 - A_2 - 2iA_3}{4}.$$

The solution of this boundary problem on the initial stress state of the surge dams is given by calculating the Cauchy type integrals in (5) from the boundary conditions in (11). They are of the form:

$$A(\zeta) = -\frac{1}{2\pi i}\int F_1(t)\frac{dt}{t-\zeta} = [T_5 + T_7\omega'_0(\zeta)] \cdot \omega_0(\zeta) +$$
$$+T_6\left(\sum_{k=1}^{3}\frac{C_k}{(t-i)^k} + \frac{C_4}{t+t-i}\right) -$$
$$-T_7\left(\sum_{k=1}^{4}\frac{S_k}{(t-i)^k} + \frac{S_5}{t+t-i} + \frac{S_6}{(t+t-i)^2}\right)$$

$$\mathrm{B}(\zeta) = -\frac{1}{2\pi i}\int F_1(t)\frac{dt}{t-\zeta} = T_3\omega_0(\zeta)\omega'_0(\zeta) +$$
$$+T_2\omega_0(\zeta) + T_4\left(\sum_{k=1}^{3}\frac{C_k}{(t-i)^k} + \frac{C_4}{t+t-i}\right) -$$
$$-T_3\left(\sum_{k=1}^{4}\frac{S_k}{(t-i)^k} + \frac{S_5}{t+t-i} + \frac{S_6}{(t+t-i)^2}\right). \tag{12}$$

The stress-strain state of the upland dam, when the depression between the mountains is filled with water, experienced the action of external load (influence of the reservoir (Fig. 2).

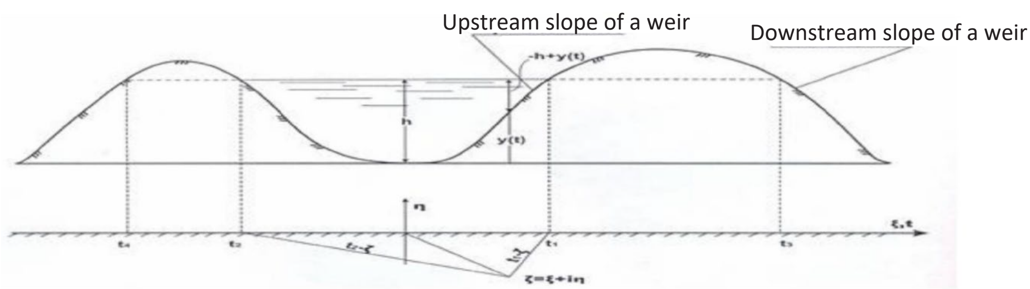

Figure 2. Calculation scheme of the reservoir

Source: B. Zhumabaev & K. Ismailova (2005)

In this case, the solution of the problem on the influence of the reservoir on the stress-strain state of the dams according to the boundary conditions $F_1(t) = N(t)\omega'(t)$ and $F_{(2)}(t) = F_{(1)}(t)$ were determined by the relations:

$$A(\zeta) = \left[r_0 + \sum_{k=1}^{7}\frac{r_{1k}}{(\zeta+i)^k} + \sum_{k=1}^{3}\frac{r_{2k}}{(\zeta-i)^k} + \sum_{k=1}^{3}\frac{r_{3k}}{(\zeta+t_0-i)^k} - \frac{r_{41}}{\zeta+t_0+i}\right] \ln\frac{t_1-\zeta}{t_2-\zeta} + \sum_{k=1}^{7}\frac{c_{1k}}{(\zeta+i)^k} + \sum_{k=1}^{3}\frac{c_{2k}}{(\zeta-i)^k} + \sum_{k=1}^{3}\frac{c_{3k}}{(\zeta+t_0-i)^k} + \frac{c_{41}}{\zeta+t_0+i}$$

$$B(\zeta) = \left[R_0 + \sum_{k=1}^{7}\frac{R_{1k}}{(\zeta-i)^k} + \sum_{k=1}^{3}\frac{R_{2k}}{(\zeta+i)^k} + \sum_{k=1}^{3}\frac{R_{3k}}{(\zeta+t_0-i)^k} + \frac{R_{41}}{\zeta+t_0+i}\right] \ln\frac{t_1-\zeta}{t_2-\zeta} + \sum_{k=1}^{7}\frac{S_{1k}}{(\zeta-i)^k} + \sum_{k=1}^{3}\frac{S_{2k}}{(\zeta+i)^k} + \sum_{k=1}^{3}\frac{S_{3k}}{(\zeta+t_0-i)^k} + \frac{S_{41}}{\zeta+t_0+i}. \quad (13)$$

The initial stress state was determined for the selected computational model. All relations required for the calculation of stress components were algorithmised in MATCAD environment.

Results and Discussion

The modelling results satisfy all the conditions of the problem on the influence of the reservoir on stress redistributions in the massifs of the upland dams. Stress values are presented in relative values. This circumstance allows to reflect more objectively the established regularities of stress distribution. The use of the Kolosov-Muskhelishvili method in calculations allows to improve the design of dams, taking into account the interaction of materials and soils, which contributes to a more accurate and efficient approach in construction, it also allows to identify potential zones with high stresses and deformations at early stages and take timely measures to strengthen the structure and prevent failures (Botokanova & Isaeva, 2024). It is based on the classical theory of elasticity and complex potentials, which guarantees theoretical validity of calculations and applicability in engineering practice for modelling the stress-strain state of dams. This method has proven its effectiveness in modelling complex hydraulic structures such as mountain dams, where the interaction of materials and external factors is crucial for the stability of the structure (Nikolaevsky, 2012). Thus, the results of the study have significant practical value for the design and operation of mountain dams, and the methodological correctness is ensured by theoretical validity of the method and its integration with modern numerical methods (Botokanova, 2024).

In the work of B. Zhumabaev & K. Ismailova (2005) performed an in-depth mathematical analysis of the stress state of rock massifs of canyons in the zone of reservoir formation. Particular attention was paid to the influence of water pressure regime on the redistribution of stresses near the surface of the canyon, taking into account the different orientation of the slope of the layering of the geological massif. On the basis of the developed mathematical model private analytical solutions describing the stress state of rock massifs under different variants of load combinations are obtained. The following types of combined effects are considered: joint action of gravitational and hydrostatic loads; simultaneous effect of gravitational, seismic forces and hydrostatic loads; superposition of gravitational, horizontal tectonic and hydrostatic effects. The results of the analysis show that water saturation of the massif and changes in the reservoir level lead to significant local redistributions of stresses, especially in zones of disturbed layering and on sloping slopes (Fig. 3).

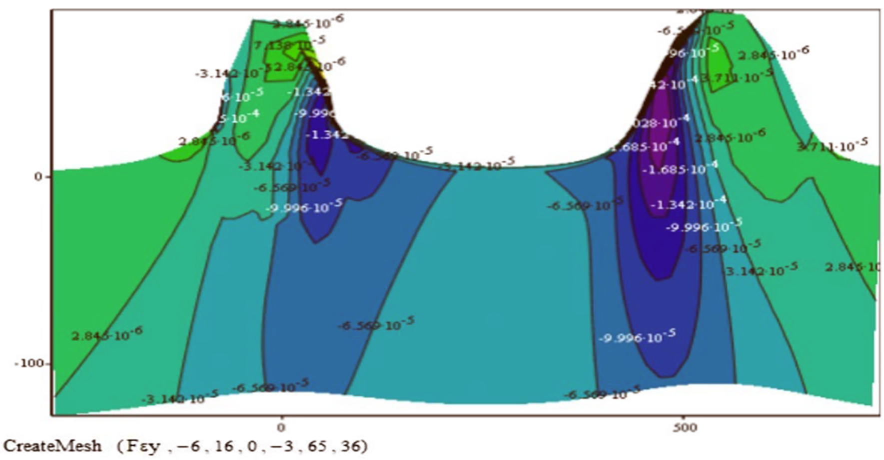

Figure 3. Stress components

Source: B. Zhumabaev & K. Ismailova (2005)

It has been found that when hydrostatic pressure increases in combination with seismic effects, the probability of shear deformations in weakly cemented layers increases (Baialieva *et al.*, 2023). Under the action of horizontal tectonic stresses, additional hydrostatic pressure favours the activation of already existing dislocation zones and fracturing. B. Zhumabaev & K. Ismailova (2005) focus their research on the stress-strain state of dams, especially in mountainous areas. They consider the influence of physical and mechanical properties of materials, water pressure, temperature and seismicity on the behaviour of dams. Particular attention is paid to the evaluation of filtration processes in the dam body and their influence on the deformations and stability of the structure. B. Zhumabaev & K. Ismailova (2005) offer a methodology for calculating the VAT of rock dams, which takes into account both static and dynamic loads, as well as seasonal temperature fluctuations, which is especially important for frozen and seismically active regions. Their work emphasises the use of multilink models to more accurately account for the interaction of various factors such as water filtration, changes in geology and heat transfer, which improves the accuracy and reliability of the calculations.

Conclusions of B. Zhumabaev & K. Ismailova (2005) confirm the need to integrate the water storage factor into geomechanical calculations, especially in the design and operation of reservoirs in complex engineering and geological conditions. As part of the research conducted by K. Abdyldaev (2015), a comprehensive analysis of the stress-strain state of rocks in mountainous terrain was carried out. Particular attention is paid to the identification of the relationship between tectonic processes, gravitational forces and redistribution of horizontal stresses in the massif. Based on analytical calculations and modelling, it was found that in zones of complex relief the maximum horizontal stresses significantly exceed the values predicted by classical theories of elasticity for flat conditions (Baialieva, 2015). This is due to a combination of the following factors: the effects of redistribution of the massif weight in the presence of height differences; directional tectonic compression, characteristic of active mountainous regions of Central Asia; local redistribution of stresses in the zones of slope bends and contacts of rocks of different stiffness.

K. Abdyldaev (2015) also revealed that in some cases horizontal stresses can reach values comparable to vertical stresses, and in some zones even exceed them. This effect is enhanced in the presence of pre-formed tectonic disturbances, faults and weak interlayers. The analysis confirmed that the traditional approaches of VAT calculation, based on the assumption of homogeneity of the stress field, are unacceptable for engineering calculations in mountain conditions. Ignoring spatial variability of stresses can lead to underestimation of risks of deformation processes (landslides, slope failures) during construction of hydraulic structures, dams and mountain roads. The work of K. Abdyldaev & A. Toktosunov (2017) demonstrates the necessity of complex consideration of tectonic and gravitational factors in modelling of VAT in massifs with mountainous relief and underlines the relevance of application of three-dimensional geomechanical models based on real geological and structural data.

The analysis of the stress-strain state of the soil massif in the area of the Ust-Ilimskaya HPP construction was based on a comprehensive study of geological conditions, including relief and tectonic features. A significant contribution to the study of these processes was made by N. Bondarchuk *et al.* (1978) and other specialists engaged in the assessment of stresses in the base of hydraulic structures. In the process of research it was established that against the background of general gravitational loading the massif experiences a significant influence of horizontal tectonic stresses. The latter are caused by both ancient tectonic processes associated with the formation of the Siberian platform and active modern deformations of the Earth's crust within the southern margins of Siberia.

The relief of the Ust-Ilimskaya HPP territory, characterised by alternation of river terraces, erosion scarps and slopes, additionally increases the unevenness of stress distribution. As calculations on the basis of elastic-plastic models have shown, areas of increased horizontal compression and vertical tension are formed in the zones of slope bends, which leads to localisation of plastic deformations and reduction of bearing capacity of the massif (Bychkov, 1981). The influence of the reservoir filling process is of particular complexity. Reservoir filling leads to an increase in pore pressure, changes in effective stresses and, as a consequence, to redistribution of stress fields in the coastal zone (Kasparyan *et al.*, 2006). According to the studies, as a result of water level rise by 20-30 m, redistribution of horizontal stresses occurs up to the depth of 100-150 m, which is accompanied by an increase in the risk of landslide deformation formation on coastal slopes.

The work of C. Li *et al.* (2020) confirms that in conditions of high reservoirs of similar type, the character of stress changes depends significantly on the shape of the base relief, the depth of tectonic faults and the nature of watered rocks. According to field observations and theoretical modelling, the greatest redistribution of stresses is recorded within the coastal slopes composed of poorly consolidated or disturbed tectonic rocks, where additional load from the reservoir can initiate slow creeping deformations or rapid failures such as rockfalls and landslides (Khusanov & Khaydarova, 2019). These results are relevant not only for the conditions of the Ust-Ilimskaya HPP, but also for the design of new large hydraulic structures in regions with pronounced relief and active tectonics. Thus, the works of these scientists are of great practical importance for the design and operation of dams in mountainous areas such as Kyrgyzstan. Given the high seismicity and difficult climatic conditions, the development of effective methods for calculating the VAT of dams, taking into account all these factors, becomes a key aspect for ensuring the safety of hydraulic structures and preventing potential failures.

Conclusions

In the course of the study, a methodology was developed for calculating the stress-strain state (SS) of upstream dams, taking into account the influence of volumetric forces and changes in this state before and after filling the reservoir. This approach allowed a more accurate prediction of the distribution of stresses arising in the dam structure, which is of key importance for ensuring its durability and stability, especially in the context of hydraulic structures serving agriculture. The analysis showed that horizontal stresses reach their maximum values in the contour part of the reservoir bowl, along the loaded section. At the same time, small tensile stresses are observed in the area just above the level of the reservoir mirror, and the compressed section occurs only in a small part of the dam massif, where the thickness of this zone is about 1.1-1.15 of the dam height. A zone of tensile stresses is formed along the depth of the reservoir, the intensity of which gradually decreases. Vertical stresses show a similar pattern, but their decrease is somewhat slower in depth.

Particular attention is paid to the tangential stresses, which reach their maximum values in the zone of slope inflection, as well as in the contour part of the dam localised at the base. These data are critical for analysing potential weakening zones of the structure and minimising failure risks. Application of the Kolosov-Muskhelishvili method makes it possible to take into account a wide range of factors affecting the stability and stability of dams, such as hydrostatic pressure, seismic activity and geological conditions. This method significantly improves the accuracy of predicting the behaviour of structures and helps to optimise the design and operation of hydraulic structures. Thus, the performed VAT calculations have become an important step in ensuring the reliability of upstream dams used in agricultural and water management. Taking into account complex loads, including seismic and gravitational forces, as well as peculiarities of canyon slopes in reservoir zones, allows increasing the stability of structures to various external influences. Prospects for further research are aimed at developing more detailed models that will take into account the effects of climate change, seasonal temperature fluctuations and other factors, as well as improving calculation methods to ensure the long-term safety of water management facilities and minimise risks to agriculture, which depends on the stability of water supply.

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Conflict of Interest

The authors are interested in the publication of this article, there is no conflict of interest.

References

[1] Abdikarimov, R.A., Eshmatov, Kh., Bobanazarov, Sh.P., Hodzhayev, D.A., & Eshmatov, B.Kh. (2011). Mathematical modelling and calculation of hydraulic engineering constructions such as dam-plate in view of hydrodynamical pressure of water and seismic loading. *Magazine of Civil Engineering*, 3, 59-70.

[2] Abdyldaev, K.K. (2015). Analysis of the stress-strain state of rocks in mountainous terrain. *Bulletin of Geomechanics*, 2, 10-18.

[3] Abdyldaev, K.K., & Toktosunov, A.B. (2017). Modelling the influence of tectonic stresses on slope stability in mountainous regions of Central Asia. *Geomechanics and Engineering Geology*, 4, 35-42.

[4] Argal, E.S. (2024). Control of filtration at the base of the western dam of the tailings dump of Udokan Mining and Metallurgical Works. *Power Technology and Engineering*, 57, 858-863. doi: 10.1007/s10749-024-01748-4.

[5] Askarbekov, E.B., Zhumabaev, B., & Zhamangapova, A.K. (2019). Calculation of stresses of massifs around a chamber with a rectangular cross-section in the field of action of gravitational and tectonic forces. *Bulletin of the Kyrgyz-Russian Slavic University*, 19(12), 3-10.

[6] Baialieva, J.A. (2015). Stress and strain state near relented in mountain slope. *Bulletin of the Kyrgyz State University of Construction, Transport and Architecture*, 15(9), 59-66.

[7] Baialieva, J.A., Ismailova, K.D., Abdygaziev, K.K., Zhamangapova, A.K., & Dyikanova, A.T. (2023). Assessment of the strain-stress distribution in the vicinity of conceding mountainside's scarp using mathematical modelling. In E.G. Popkova (Ed.), *Sustainable development risks and risk management* (pp. 375-380). Cham: Springer. doi: 10.1007/978-3-031-34256-1_65.

[8] Bondarchuk, N.F., Bychkov, B.I., & Ushakov, V.V. (1978). Study of the stress state of the foundation of the Ust-Ilimsk hydroelectric power station taking into account the geological features of the region. *Hydrotechnical Construction*, 4, 25-30.

[9] Botokanova, B.A. (2024). Study of the stress state of rocks around a hydrotechnical tunnel located in a mountain range mineral enrichment. *Mine Surveying and Subsurface Use*, 4(132), 30-34. doi: 10.56195/20793332202443034.
[10] Botokanova, B.A., & Isaeva, G.S. (2024). Stress-strain state of rock massifs around tunnels located in a dip-layered massif. *Mine Surveying and Subsurface Use*, 6(134), 12-18. doi: 10.56195/20793332_2024_6_12_18.
[11] Bychkov, B.I. (1981). Modelling of stress redistribution in the dam foundation during reservoir filling. *Engineering Geology*, 5, 30-36.
[12] Hansamali, U., Makumbura, R.K., Rathnayake, U., Azamathulla, H.M., & Muttil, N. (2025). Leaky dams as nature-based solutions in flood management. Part I: Introduction and comparative efficacy with conventional flood control infrastructure. *Hydrology*, 12(4), article number 95. doi: 10.3390/hydrology12040095.
[13] Kasparyan, E.V., Kozyrev, A.A., Iofis, M.A., & Makarov, A.B. (2006). *Geomechanics*. Moscow: Vysshaya Shkola.
[14] Khusanov, B., & Khaydarova, O. (2019). Stress-strain state of earth dam under harmonic effect. *E3S Web of Conferences*, 97, article number 05043. doi: 10.1051/e3sconf/20199705043.
[15] Kobeleva, N.N. (2017). Methodological features of constructing predictive mathematical models for studying deformations of high dams. *Bulletin of Siberian State University of Geosystems and Technologies*, 22(2), 55-66.
[16] Li, C., Tang, H., & Wang, Y. (2020). Study on the deformation mechanism of reservoir landslides considering rheological properties of the slip zone soil: A case study in the Three Gorges Reservoir Region. *Sustainability*, 12(16), article number 6427. doi: 10.3390/su1216166427.
[17] Mirsaidov, M.M., Sultanov, T.Z., & Sadullaev, Sh.A. (2013). An assessment of stress-strain state of earth dams with account of elastic-plastic, moist properties of soil and large strains. *Magazine of Civil Engineering*, 40(5), 59-68. doi: 10.5862/MCE.40.7.
[18] Montayev, S., Shinguzhieva, A., Adilova, N., Karshyga, G., & Abdikerova, U. (2025). Methods of increasing the seismic resistance of metal structures. *Architectural Studies*, 11(1), 118-130. doi: 10.56318/as/1.2025.118.
[19] Nikolaevsky, V.N. (2012). *Collected works. Geomechanics (Vol. 3). Earthquakes and crust evolution*. Moscow: Gostekhizdat.
[20] Ouma, Y.O., Moalafhi, D.B., Anderson, G., Nkwae, B., Odirile, P., Parida, B.P., & Qi, J. (2022). Dam water level prediction using Vector AutoRegression, Random Forest Regression and MLP-ANN models based on land-use and climate factors. *Sustainability*, 14(22), article number 14934. doi: 10.3390/su142214934.
[21] Pari, S.A.A. (2025). Effect of clay core location in earth dam on probabilistic stability analysis in steady-state condition. *Indian Geotechnical Journal*. doi: 10.1007/s40098-025-01191-w.
[22] Popov, V., Voitsehivskiy, O., & Kryklyva, K. (2023). Seismic resistance of a large methanol storage tank. *Modern Technologies, Materials and Structures in Construction*, 20(1), 6-18. doi: 10.31649/2311-1429-2023-1-6-18.
[23] Sainov, M.P. (2022). Stress-strain state of CFRD with a decrease in friction at the face-sidewall contact. *Magazine of Civil Engineering*, 115(7), article number 11506. doi: 10.34910/MCE.115.6.
[24] Sainov, M.P. (2023). *Earth dams: A textbook for secondary vocational education*. Moscow: Profobrazovanie.
[25] Zhumabaev, B., & Ismailova, K.D. (2005). Influence of a reservoir on the stress-strain state of a dam. *Bulletin of the Kazakh Academy of Transport and Communications named after M. Tynyshpaev*, 4, 26-33.

Суу ресурстарын туруктуу башкаруу жана айыл чарба коопсуздугун камсыз кылуу максатында көлөмдүк жана сейсмикалык күчтөрдүн таасири астында бийик тоолордогу дамбалардын стресс-деформациялык абалы

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Аннотация. Гидротехникалык курулмалардын, атап айтканда, бийик тоолордогу дамбалардын ишенимдүүлүгүн камсыз кылуу агроөнөр жай комплексинде, өзгөчө суунун тартыштыгынын жана сейсмикалык активдүүлүктүн шарттарында туруктуу суу менен камсыз кылуу үчүн өзгөчө мааниге ээ. Бул иштин максаты айыл чарбасын тейлеген суу чарба инфраструктурасынын ишенимдүүлүгүн жогорулатуу үчүн көлөмдүк, сейсмикалык жана гидростатикалык жүктөрдүн комплекстүү аракетин эске алуу менен бийик тоолордогу дамбалардын чыңалуу-деформациялык абалын баалоо болгон. Изилдөөдө тектердин өз ара аракеттенүүсүн, тектоникалык чыңалууларды жана тышкы жүктөрдү эске алуу менен серпилгич чөйрөлөрдөгү чыңалууларды моделдөөгө мүмкүндүк берүүчү Колосов-Мусхелишвили ыкмасы колдонулган. Суу сактагычтын деңгээлинин жана сууга каныккандыгынын өзгөрүшү менен плотина массивиндеги чыңалуулардын кайра бөлүштүрүлүшүнүн өзгөчөлүктөрү талдоого алынып, изотроптук тоо тектериндеги жылышуу зоналарынын пайда болушуна сейсмикалык таасирлердин таасири аныкталган. Тоолуу рельефте горизонталдык чыңалуу вертикалдуудан ашып кетиши мүмкүн экендиги аныкталды, бул долбоорлоо ыкмаларын кайра карап чыгууну талап кылат. Конструкциялардын туруктуулугуна гравитациялык, сейсмикалык жана гидростатикалык күчтөрдүн биргелешкен таасирин талдоо жүргүзүлөт. Топурак массивинин стресс абалына тектоникалык процесстердин жана рельефтин таасирине өзгөчө көңүл бурулат. Изилдөөнүн натыйжалары сейсмикалык кооптуу региондордогу мелиорация системаларын жана айыл чарба аймактарын суу менен камсыз кылуучу бийик тоолуу дамбаларды долбоорлоодо жана эксплуатациялоодо колдонулушу мүмкүн. Математикалык моделдештирүүнүн заманбап методдору инженердик эсептөөлөрдүн тактыгын олуттуу түрдө жакшыртат жана гидротехникалык курулуштардын ишенимдүүлүгүн камсыз кылат, бул айыл чарба коопсуздугун камсыз кылуу үчүн өзгөчө маанилүү. Конструкциялардын чыңалуу-деформациялык абалын баалоо алардын ар кандай жүктөмдөрдөгү жүрүм-турумун болжолдоо жана туруктуулукту сактоо боюнча натыйжалуу чараларды көрүү үчүн негиз болуп саналат. Аткарылган иштердин практикалык баалуулугу долбоордук-инженердик изилдөө уюмдары тарабынан бийик тоолуу дамбаларды долбоорлоодо жана курууда натыйжаларды пайдаланууда, долбоорлоочуларга ар кандай эксплуатациялык шарттарда гидротехникалык курулмалардын жүрүм-турумун так болжолдоого мүмкүндүк берет, айыл чарбасында, өзгөчө сейсмикалык активдүүлүк күчөгөн жана татаал инженердик-геологиялык шарттарда сууну ишенимдүү жана туруктуу камсыз кылууда

Негизги сөздөр: гравитация; конформдык карта түзүү; баштапкы стресс абалы; чек ара шарттары; дамбаны моделдөө; гидростатикалык басым; фильтрация процесстери

Напряженно-деформированное состояние нагорных плотин под воздействием объемных и сейсмических сил в целях устойчивого управления водными ресурсами и аграрной безопасности

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Аннотация. Обеспечение надежности гидротехнических сооружений, в частности нагорных плотин, имеет особую значимость для устойчивого водообеспечения в агропромышленном комплексе, особенно в условиях дефицита водных ресурсов и сейсмической активности. Целью настоящей работы была оценка напряженно-деформированного состояния нагорных плотин с учетом комплексного действия объемных, сейсмических и гидростатических нагрузок для повышения надежности водохозяйственной инфраструктуры, обслуживающей сельское хозяйство. В исследовании использован метод Колосова-Мусхелишвили, который позволяет моделировать напряжения в упругих средах с учетом взаимодействия горных пород, тектонических напряжений и внешних нагрузок. Были проанализированы особенности перераспределения напряжений в массиве плотины при изменении уровня водохранилища и водонасыщении, а также выявлено влияние сейсмических воздействий на формирование сдвиговых зон в изотропных породах. Установлено, что в условиях горного рельефа горизонтальные напряжения могут превышать вертикальные, что требует пересмотра проектных подходов. Проведен анализ комбинированных воздействий гравитационных, сейсмических и гидростатических сил на устойчивость сооружений. Особое внимание уделено влиянию тектонических процессов и рельефа на напряженное состояние грунтового массива. Результаты исследования могут быть использованы при проектировании и эксплуатации нагорных плотин, обеспечивающих водоснабжение мелиоративных систем и сельскохозяйственных территорий в сейсмоопасных регионах. Современные методы математического моделирования значительно повышают точность инженерных расчетов и обеспечивают надежность гидротехнических сооружений, что особенно важно для обеспечения аграрной безопасности. Оценка напряженно-деформированного состояния сооружений служит основой для прогнозирования их поведения под различными нагрузками и принятия эффективных мер по поддержанию устойчивости. Практическая ценность выполненной работы заключается в использовании результатов проектными и инженерно-изыскательскими организациями при проектировании и строительстве нагорных плотин, позволяя проектировщикам точно прогнозировать поведение гидротехнических объектов в различных эксплуатационных условиях, обеспечивающих надежное и устойчивое водоснабжение в сельском хозяйстве, особенно в районах с повышенной сейсмической активностью и сложными инженерно-геологическими условиями

Ключевые слова: сила гравитации; конформное отображение; начальное напряженное состояние; граничные условия; моделирование плотин; гидростатическое давление; фильтрационные процессы