Seismicity caused by hydrological regime of large reservoirs

Lutfulla Khamidov[*], *Farkhod* Artikov, *Khayrulla* Khamidov, *Barno* Ganieva and *Sadoqat* Anvarova

Institute of Seismology named after G.A. Mavlyanov, Academy of Sciences of the Republic of Uzbekistan, Tashkent, Uzbekistan

Abstract. By the analysis of the results of assessing the deformations of the base with a change in the hydrological regime of reservoirs, it is stated that during the operation of large reservoirs, its base and coastal slopes are located in the field of compression and tension loads of the corresponding intensity of the base bending amplitudes with a variation in water volume. It is shown that mountain massifs deformations at large reservoirs' bases can correspond to limiting tectonic focal deformations, which directly affect the regular stress-strain state and background geodynamic movements near the lying seismically active layer of the earth's crust. The study aims to identify the conditions for developing local geodynamic processes in the zones of deformational influence of large reservoirs, solving problems of mathematical physics for specific seismically active fault zones crossing the foundations of large hydraulic structures. An analysis of the results of processing the observed earthquake frequency, elastic displacements in the near zones of reservoirs, and estimates of local deformations shows the influence of changes in the hydrological regime in reservoirs on the activation of weak local earthquakes. It is explained that they are non-linear in nature and are associated with other influencing factors: additional load, the presence of local and active tectonic faults, flooding, and changes in pore pressure.

1 Introduction

From the history of the past hundred years, many examples of violations of geodynamic equilibrium in the zones of influence of large water reservoirs can be cited [1]. An earthquake caused by a reservoir is the main local indicator of the violation of this balance. It is especially sensitive in zones of active influence of reservoirs located in non-tectonic active regions [2]. Ensuring the seismic safety of zones of influence of reservoirs has become increasingly important in analyzing man-made seismic disasters in the last decade. They are mainly due to shallow local geodynamic processes and variations in the stress-strain state of the earth's crust materials, which change during the operation of reservoirs. Similar processes occur both regardless of human activity and depending on the levels of anthropogenic impacts. Seismicity caused by the reservoir in terms of its destructive

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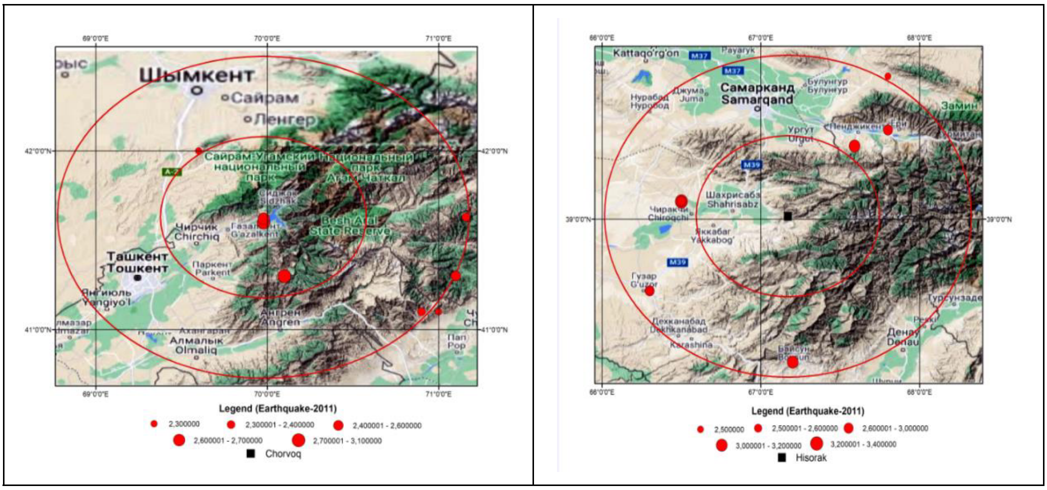
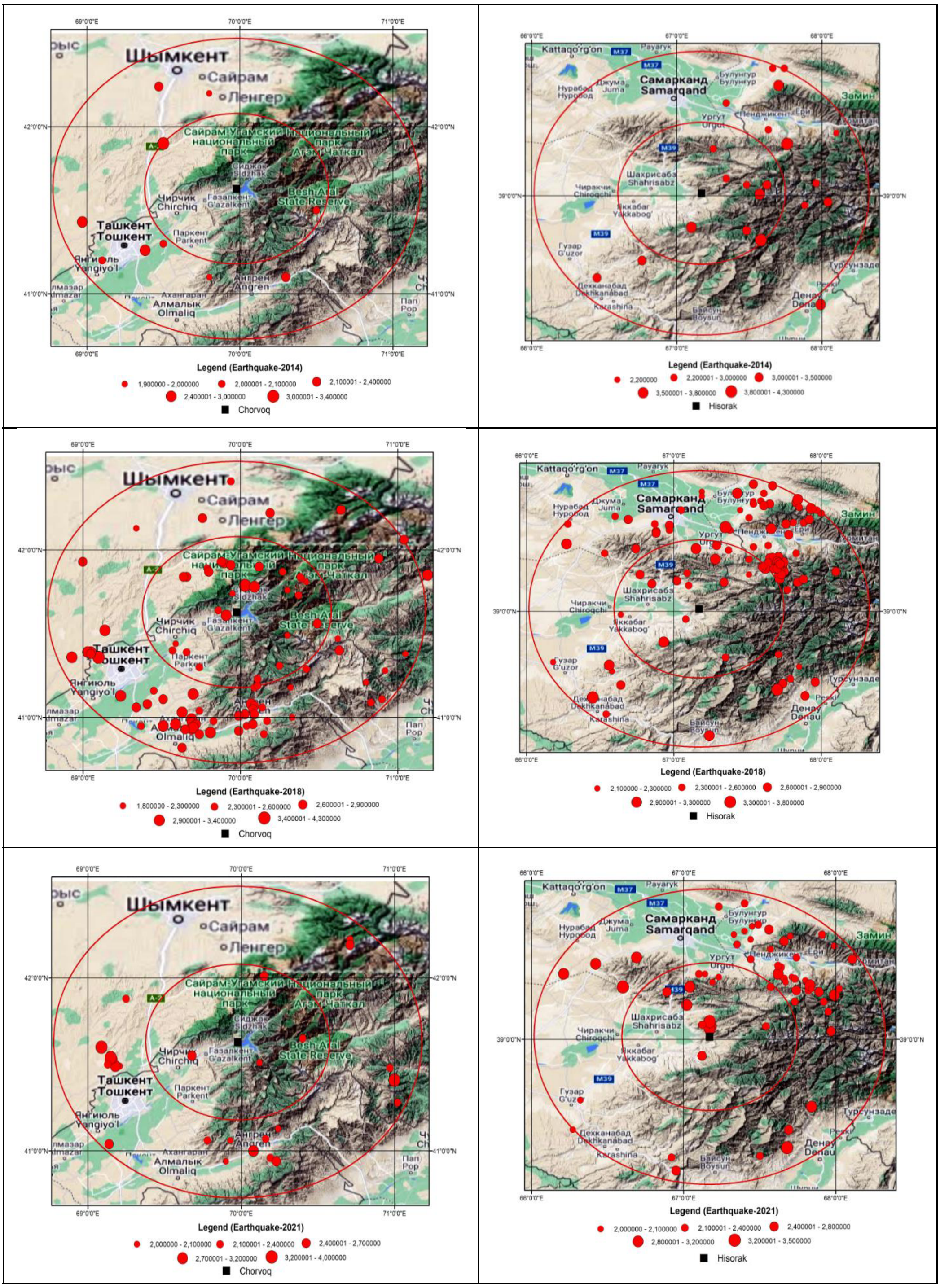
[*] Corresponding author: hamidov_l@mail.ru

consequences and the number of human casualties is not the last among other natural disasters [3].

Therefore, a lot of attention is paid to these problems worldwide. Especially in countries with seismic zones, the activity significantly exceeds the level of regularity of geodynamic equilibrium [4]. Seismic zones located in the western Tien Shan, the Fergana Valley, and southern Uzbekistan, including the eastern parts of the Tashkent and Andijan regions with a high population density, where several large reservoirs are operated, are of particular danger for the seismically hazardous regions of Uzbekistan [5].

Changes occurring in the materials of the earth's crust under the influence of human engineering and economic activities are not so noticeable [2]. However, there is several evidence of the negative impact of large hydraulic engineering structures on deformation-seismic regimes [3,4,5]. On large reservoirs of the world, such as Koina (India), Kariba (Zimbabwe), Mid (USA), Toktogul (Kyrgyzstan), and others, the rate of vertical movement of the earth's crust is 7-10 mm/year [6,7]. The value of bed bending is directly proportional to the specific water load per unit area of the bottom. On reservoirs with a pressure of hundreds of meters (Ingur - 410, Nurek - 273, Sayano-Shushensk - 212, Toktogul - 180 m, Charvak - 168 m, Tupalang - 165 m, Hissarak - 145 m, Andijan - 115 m) the surface of the earth can bend down by 2.0-2.5 cm [6,7,8,9]. Local earthquakes that occur when the reservoir is filled have insignificant magnitudes - less than 2 - 2.5, shocks with a magnitude of 3.5 - 5.0 occur less often and very rarely 6 - 6.5. Devastating consequences were observed only in a few cases: in the area of the Mead (USA), Kremasta (Greece), Koina (India), and Kariba reservoirs in Africa [6,10,11]. The use of digital stations in the location of weak earthquakes made it possible to compile a fairly stable picture of the distribution of sources over the area close to large reservoirs [12, 13] (examples are shown in Figure 1).





1 - locations of the Charvak and Hissarak reservoirs;
energy class, respectively: 2 - K≤9; 3- K≤10; 4- K≤11; 5-K≤12.

Fig.1. Distribution of weak earthquakes for the Charvak and Gissarak reservoirs by years

Evaluation of the nature of the manifestation of man-made earthquakes has come a long way since their appearance. It has become an integral part of the interpretation of seismicity in the vicinity of especially important and large reservoirs [14,15]. They are also used in our studies for seismic and geophysical forecasts of the geodynamics of reservoir influence zones. This made it possible, along with obtaining reliable digital data from field observations, to identify the current state of the local seismicity of each large reservoir separately with possible differences in the operating mode [10,11].

Analysis of the results of deformation assessment and geodetic measurements in the near zones of the reservoirs of Uzbekistan revealed that during the operation of large reservoirs, its base and coastal slopes are in the field of action of sufficiently low-frequency compression and tension loads of the corresponding intensity of the base bending amplitudes with varying water volume. The deformations of the base corresponded to the limiting tectonic focal deformations, which directly affect the regular stress-strain state and background geodynamic movements near the lying seismically active layer of the earth's crust [14-16].

2 Methods

Problems of mathematical physics for specific seismically active fault zones have been posed and solved. The stress-strain state of the earth's crust is modeled for the near zones of large reservoirs in Uzbekistan. It was assumed that violations of isostatic equilibrium during the operation of the reservoir are the main force source that changes the state of lithostatic equilibrium in faults, in which, as a rule, forces that are quite commensurate with seismotectonic stresses are accumulated. Therefore, within the limits of linear physical and geometric relationships, considering the pre-stressed state, the problems of mathematical physics are set for specific seismically active fault zones (zone of influence of the reservoir). The calculation module is based on the 2D-Kelvin and 3D-Kupradze displacement tensors for one concentrated load as a component of the source model of the upcoming earthquake in the field of acting quasi-geostatic forces [17]. It is assumed that a rigid elastic half-space with softer plane-parallel layers layered on top is weakened by several non-orthogonal (in a particular case, orthogonal) cylindrical in homogeneities of great length. It experiences longitudinal shear throughout its entire length (compression at infinity is given as a uniform deformation) and vertical pressure from the weight of the reservoir.

Let us assume that a half-space with internal cylindrical stress concentrators and a piecewise-homogeneous weighty medium is in a plane-deformed state. Then, choosing the center of rectangular Cartesian coordinates so that one axis is directed along the axis of the concentrator, and the rest - according to the condition for choosing the right system, we arrive at a static problem for the Lamé equilibrium equation [17]:

$$(\lambda+\mu)grad(div\mathbf{W})+\mu\nabla^2\mathbf{W}=-mgh; \qquad (1)$$

where $\mathbf{W}\{u,v,w\}$: $u=u(x,y,z)$; $v=v(x,y,z)$; $w=w(x,y,z)$ displacement components; λ,μ - Lame elastic constants; with border conditions: $\sigma^{(i)}_{nn}=\sigma^{(i+1)}_{nn}$; $\mathbf{W}^i_1 = \mathbf{W}^i_2$; $\sigma^{(i)}_{ns}=\sigma^{(i+1)}_{ns}$; for combinations and plots of hub groups; $\sigma^{(i)}_{nn}=\sigma^{(i+1)}_{nn}$;$\mathbf{W}^i_1 = \mathbf{W}^i_2$;$\sigma^{(i)}_{nn}=k\sigma^{(i)}_{ns}$ - where $\sigma^{(i)}_{jj}$ - *jj*- th components of stresses in the i-th concentrator; k - Coulomb coefficient (static friction). on the free surface. $\sigma_{nn}=0$; $\sigma_{ns}=0$; at the boundary with the base of the reservoir, there is a quasi-static load from the pressure δg_v of the weight of the volume

$$\delta g_v = \frac{1}{4\pi\mu T}\sum_{k=1}^{m}(P_k \Delta S_k \Delta t_k / S_k^2); \qquad (2)$$

where $\pi \approx 3.14$; μ - shear modulus; T is the total load unloading time on the base; P_k is the pressure on the base at; S_k is the difference in the change in the mirror area with increasing k from different Δt_k ; Δt_k - intervals from loading to unloading (or vice versa) time (always T>Δt_k); S_k^2 - changing the area of the mirror. Additional (local) stresses appear due to the presence of several discontinuities:

$$\sigma_{pq}=\sigma^{0}_{pq}+\sigma^{*}_{pq}+\sigma^{**}_{pq}+\delta g_{v} \quad ; p\sim q\sim (1,2,3,...). \qquad (3)$$

Displacements are calculated according to the "reservoir + base" scheme for given boundary conditions. Points x_i, y_i, z_i corresponded to the point of displacement from the starting point along the i - th discontinuity site with a voltage drop $\Delta\sigma$. The stress concentration and additional distribution of forces in the zones close to the faults were determined according to the "reservoir + base" scheme so that the energy had the value of the potential corresponding movement [7,17,18]. The function $\sigma_{ij}(u,v,w)$, satisfying the Lame equation for a half-space for the identified concentrated forces (P,Q,N) and with the corresponding δg_v and $\Delta\sigma_i$, gave a picture of the 2D field of the stress-strain state [7,13,17]. Figure 2 shows an example of calculating the pressure variation (longitudinal stresses $\Delta\sigma$) on rocks for 12 months of 2016, 2017, and 2018 in the zone of the possible influence of the Gissarak reservoir. Using the Saint-Venant principle, it is assumed that the points (x_0,y_0,z_0) and (x_{0j},y_{0j},z_{0j}) of application of the concentrated force will be in the middle of the discontinuity [17,19]. Comparing shear stress fields with the current geodynamic setting shows a good similarity [20].

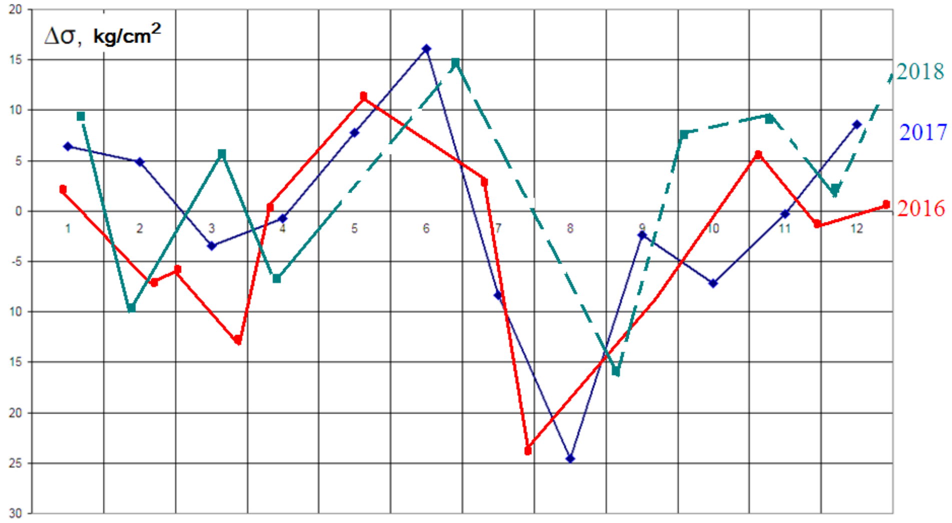


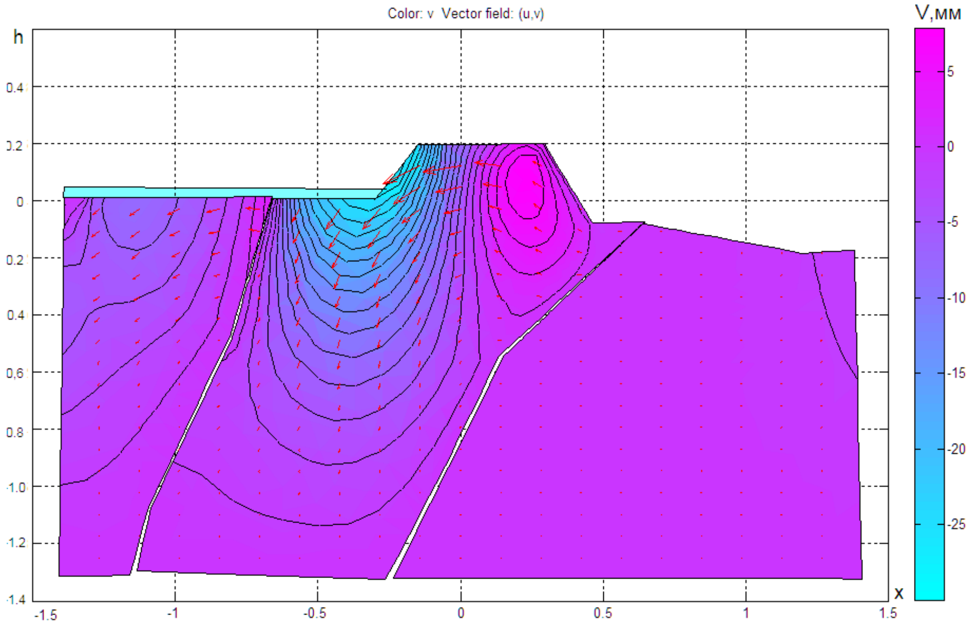
Fig. 2. Calculations of pressure variations (stresses Δσ) on rocks for 12 months (2016, 2017, 2018) in the zone of possible influence of the Gissarak reservoir

Test calculations made it possible to determine the options for setting the boundary value problem of mathematical physics for assessing the local stress-strain state of the earth's crust and to develop the basis for the scheme for its implementation. At the same time, it was found that additional stress concentrations in disturbance zones of the same scale (size) can be localized close to each other, and the variation in the total volume of reservoirs can most likely compensate for pressure in nearby areas in the loading and unloading areas.

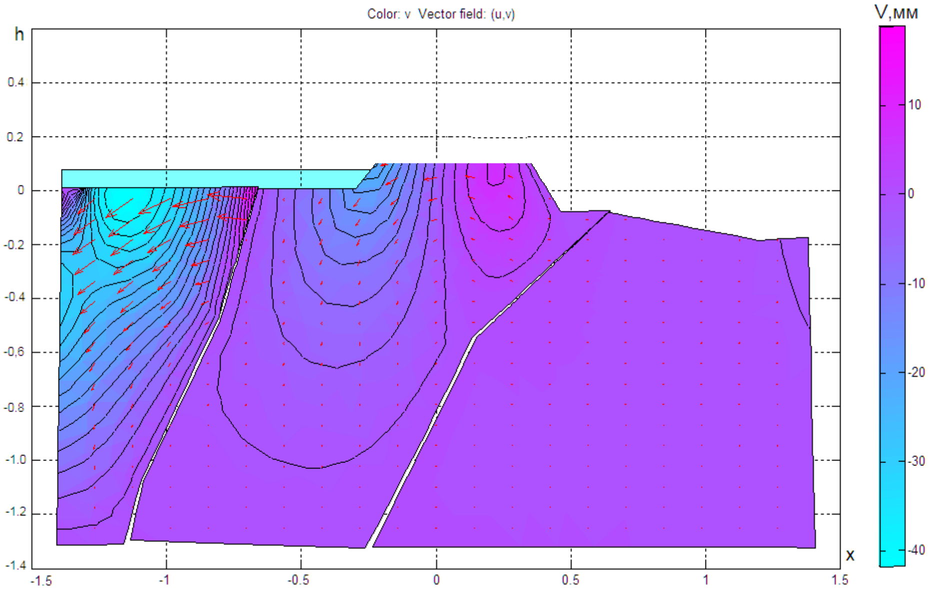
3 Results and Discussion

Based on the developed algorithms and software calculations, the results of primary numerical determinations of stress and strain fields in zones of active influence of reservoirs are analyzed (calculation programs were compiled in the C^{++} environment) [17,21,22]. Engineering-geodynamic changes on the coastal slopes and possible stress distributions have been studied. Relationships between the level of the stress-strain state and the operating conditions of technogenic objects are determined using the example of high-pressure and large reservoirs in Uzbekistan. The range of change of piecewise uniformities in the composition of the array, on the boundary of which stresses are concentrated, are distinguished by a certain in homogeneity of physical and mechanical properties. Four load levels are experimentally assigned to determine the effect of mass in homogeneity on displacements, strains and stresses. This formulation made it possible to establish the relationship between deformation and vertical loads concerning piecewise in homogeneities. Figure 3 below shows the depth distribution of vertical displacements at loads between 2 and 10 bar.

Comparison of the results of the vertical displacement fields obtained by us along the depth of the reservoir base at different loads shown in Figure 3 with the data on the displacement of the earth's crust as a result of variable loads in the Chirkey reservoir obtained by A.V.Deshcherevsky, Sh.G.Idarmachev, and I.Sh.Idarmachev, in their work, shows a satisfactory agreement [23-25].



a)



b)

Symbols: a is at 2 bar (20m); b-10 bar (100 m.); h is depth of the scheme, where step Δh,m=0.2x2000m=400m.; x is the width of the scheme, where the step is Δx,m=0.5x2000m=1000m.; V, mm is gradation along isolines of equal vertical displacement

Fig. 3. Depth distribution of vertical displacements at a water height of 20m (a) and 100m (b) in the reservoir

As revealed above, the parameters of each reservoir, being quite diverse, affect the earth's crust with the same force - a variation in pressure on the underlying mountain ranges [17,21,22,23,24]. As a result of the calculation according to the model (1), (2), and (3), data processing [8,9,13,17], materials from literary sources [2,5,6,7,11,23,25], and personal research [17,21,26,27] we compiled Table 1 for the reservoirs, where significant changes in the background seismicity in the near zone were observed during operation. Based on the data analysis, we compiled graphs of the relationship between different indicators for all reservoirs according to Table 1.

Figure 4 shows the relationship between N_{fon} (average local background of the number of earthquakes per year within a radius of 50 km from the object), N (long-term average background number of earthquakes per 10 years), and Δn (difference in the number of earthquakes) during the operation of eleven high-pressure reservoirs. The dependence shows that reservoirs with a moderate base pressure of up to 11.5 bars are operated more frequently than reservoirs with a base pressure of 14.0 to 30.0 bars [26].

An additional deformation field is formed due to the variation of the indicated pressures on the bases and form displacements or stresses [8,21]. In the zone of objects, the depth of most seismic events did not exceed 10 km. The hypocenters of these earthquakes correspond to the zone where the depth of the reservoir was the greatest, and some sources coincided with the intersections of seismically active faults in this area. Data from a number of other reservoirs were used to analyze the change in non-background numbers of earthquakes.

Table 1. Variation in pressure and number of earthquakes in zones of influence of reservoirs

№	*A*	*ΔH*	*ΔP*	*ΔT*	*n*	N_{fon}	*N*	*Δn*
1	Xinfeng River (Chinese)	30	0,304	2	12	54	3,5	19
2	Capanda (Angola)	32	0,324	2	3	18	3,2	-14
3	Kariba (Zambia, Zimbabwe)	35	0,355	2	12	58	4,3	15
4	Tupalang (Uzbekistan)	38	0,365	2	5	24	2,9	- 5
5	Hissarak (Uzbekistan)	40	0,405	3	3	11	0,9	2
6	Andijan (Uzbekistan)	43	0,426	2	8	18	1,3	5
7	Kremasta (Greece)	45	0,456	2	3	8	0,6	2
8	Charvak (Uzbekistan)	50	0,537	2	8	16	0,9	7
9	Sayano Shushensk (Russia)	58	0,588	3	11	38	2,6	12
10	Mid (Colorado, USA)	60	0,608	3	18	63	4,6	17
11	Inguri (Georgia)	80	0,811	4	6	11	2,4	-13

Symbols in table 1: ΔH (m) is averaged water level variation for Δt (month); ΔP (bar) is pressure variation on the base; ΔT is the average amount of pressure variation during operation; n is average number of earthquakes with energy class 9≤K≤15 until the next volume variation where K=LgE (E-earthquake energy);

The gradual variation of the hydrological regime with loading or unloading from reservoirs as a percentage of the total volume creates different pressures on the bases during the annual cycle. On average, a 5% reduction in volume corresponds to a pressure reduction of 0.05 bar. 6% corresponds to - a decrease of 0.1 bars; 7% corresponds to a decrease of 0.15 bars. In reality, it corresponds to the dynamics of water pressure variations throughout the year. The number of earthquakes in the near zone, for example, the Charvak reservoir in 2014, with 5%, 6%, and 7% variation in water volume concerning the total volume per weight of the active operation cycle, as well as the change in energy classes over the same period, show a significant stress relief accompanied by 43 earthquakes with energy class 7≤K≤9 in the zone with radius up to R=50 km. A change in their number is observed mainly when the water column (or pressure on the base) changes from 0.1 to 0.15 bar. This zone is 6% and 7% percent variation [26,27].

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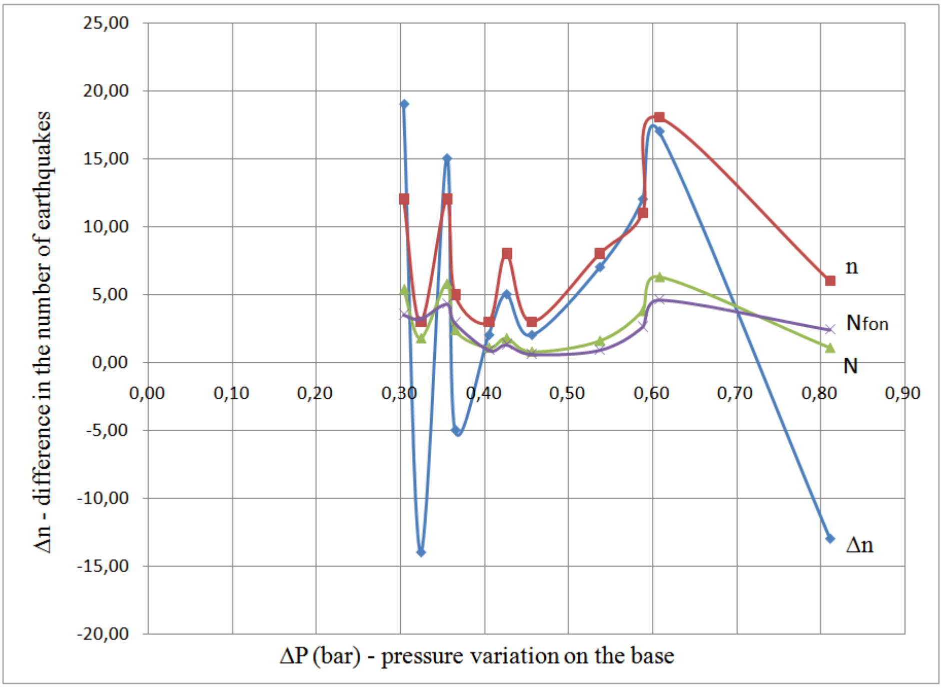

Fig. 4. Dependence on pressure variation (ΔP) of the average local background of the number of earthquakes per year within a radius of 50 km from the object ($N_{fon}/10$), the long-term average background number of earthquakes per 10-year unit (N), the difference in the number of earthquakes (Δn) and the average the number of earthquakes with an energy class of $9 \leq K \leq 15$ until the next pressure variation (n)

The pressure on the base of reservoirs at the maximum operational limit can be chosen as the ratio $P = F/S^2$, where F is the force of gravitational weight, and S^2 is the area of the base where this force acts. The deformation bending of the base - ζ_i at the operating pressure P was chosen by us partly from the literature data and partly from the empirical connection [21,26]. Deformation variations $\Delta\varepsilon_{\zeta}(\zeta_i) \cdot 10^{-5}$- calculated relative to the depth of 5-15 km of the earth's crust at the base of the reservoirs (in averaged values). At these depths, in the radius indicated above, a seismogenic layer is distinguished. The main sources of local earthquakes are identified precisely at these depths.

4 Conclusions

The analysis of the results obtained in the near zone of the reservoirs shows that during the operation of large reservoirs, its base is in constant compression and tension loads of the corresponding intensity of the base bending amplitudes from volume variation.

Deformations of the base can correspond to limiting tectonic focal deformations that directly affect the regularity of the stress-strain state and background geodynamic movements of the nearby seismogenic layer of the earth's crust (within the zone of active influence of reservoirs). These deformations are the main exciter outside of background seismic events in neotectonic structures, at least in the band of low energy classes.

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References

1. Gabriel-Martin I.; Sordo-Ward A.; Garrote L.; Granados I. Hydrological Risk Analysis of Dams: The Influence of Initial Reservoir Level Conditions. *Water.* **11,**(46) (12019)
2. Ren M.; He X., Kan G., Wang F., Zhang H., Li H., Cao D., Wang H.; Sun D., Jiang X.; Wang G.; Zhang Z. A Comparison of Flood Control Standards for Reservoir Engineering for Different Countries. *Water.* **9***,* 152 (2017)
3. Martin Wieland Safety Aspects of Sustainable Storage Dams and Earthquake Safety of Existing Dams// J. Engineering, **2**(3), pp.325-331 (2016)
4. Artikov T.U., Ibragimov R.S., Ibragimova T.L., Mirzaev M.A., Artikov M.T. Revealing of seismic activation interrelationships in various seismoactive zones // Geodesy and Geodynamics. **5**(6), pp. 351-360 (2015)
5. Chopra Satinder and Marfurt Kurt Seismic Attributes – a promising aid for geologic prediction. REC@RDER Canadian Society of Exploration Geophysicists. **31**, (2006)
6. L. Hamidov. Local Seismicity of Reservoir Areas Based on Digital Seismometric Observations. IV International Conference "Problems of Cybernetics and Informatics" (PCI'2012), **III**, pp.85-89, Azerbaijan (2012)
7. L. Khamidov, M. Turapov, S. Mahkamov, F. Artikov and Sh. Suyunov. Tracking the local seismicity level in the active influence zone of the southern Uzbekistan reservoirs. In E3S Web of Conf. **264**, (2021)
8. Alimukhamedov I.M., Shukurov Z.F., Khamidov Kh.L., Ziyomov B.Z., Fakhriddinov Zh.F. Indicators of local geodynamic activity of the earth's crust of reservoir zones. Geology and Mineral Resources, **3**, pp.37-42 Geologiya i mineralnie resursi, Tashkent (2014)
9. Telesca, L. Analysis of the cross-correlation between seismicity and water level in the Koyna area of India, Bull. Seismol. Soc. Am. **100**(5A), pp. 2317–2321 (2010)
10. Durá-Gómez, I., and P. Talwani. Hydromechanics of the Koyna-Warna region, India, Pure Appl. Geophys. **167**, pp.183–213 (2010)
11. Sumei Liu, Lihua Xu, Pradeep Talwani. Reservoir-induced seismicity in the Danjiangkou Reservoir: a quantitative analysis adeep Talwani. Geophysical Journal International. 85, pp.514-528 (2011)
12. Kh.L. Khamidov Assessment of strain effect of strong-motion (focus) zones of earthquakes on earth's surface displacement. J.Geodesy and Geodynamics, **8**, pp. 34-40 (2017)
13. De Matteis, R., E. Matrullo, L. Rivera, T. A. Stabile, G. Pasquale, and A. Zollo (2012). Fault delineation and regional stress direction from the analysis of background microseismicity in the southern Apennines, Italy, Bull. Seismol. Soc. Am. 102, no. 4, 1899–1907
14. Stabile T.A., Giocoli A., Lapenna V., Perrone A., Piscitelli S. and Telesca L. Evidence of Low-Magnitude Continued Reservoir-Induced Seismicity Associated with the

Pertusillo Artifificial Lake (Southern Italy). Bulletin of the Seismological Society of America, 104(4), (2014)

15. Talwani P. On the Nature of Reservoir-induced Seismicity. *Pure appl. geophys.* **150,** pp. 473–492 (1997)
16. Khamidov Kh.L., Ganieva B.R., Anvarova S.G., Zhumaev D.D. Numerical calculation of crustal stresses reservoir foundations. 8th International Scientific Conference of young scientists and students on "Innovations in geology and geophysics", ANAS Geology and Geophysics Institute, Baku, Azerbaijan. (2021) pp.74-76
17. El Hariri M., R. A. Abercrombie C. A. Rowe and A. F. do Nascimento The role of fluids in triggering earthquakes: Observations from reservoir induced seismicity in Brazil, Geophys. J. Int. **181**(3), pp.1566–1574 (2010)
18. Yarmukhamedov A.R., Denisov R.I., Karimov N.T., Alimukhamedov I.M. and others. The latest and modern tectonic activity of the earth's crust in the area of the Shurtan deposit and the epicentral region of the Kamashi-Ertepa earthquakes. Geology and Mineral Resources. **1**, pp. 37-45 Tashkent (2002)
19. Ibragimova T.L., Ibragimov R.S., Mirzaev M.A., Rebetsky Yu.L. The current stress of earth's crust in the territory of Uzbekistan according to focal earthquake mechanisms // Geodynamics and Tectonophysics. **12**(3), pp. 435-454 (2021)
20. Khamidov L.A. Linear model of stress concentration in the faults of the earth's crust, located in the near zone of the deformation effect of large reservoirs. Problems of seismology, 1, pp.41-51 Tashkent (2019)
21. Savich A.I., Gaziev E.G. Influence of cracked water in rock foundations on their stress-strain state. Geomechanics in mining.- Proceedings of the All-Russian scientific and technical conference,: IGD Ural Branch of the Russian Academy of Sciences (2014) pp.25-35
22. Deshcherevsky A.V., Idarmachev Sh.G., Idarmachev I.Sh. Influence of seasonal changes in the water level in the Chirkey reservoir on the apparent resistance of the rocks of the Khadum dome, located in its vicinity. Geology and Geophysics of the South of Russia, 10(4), pp.101-112
23. Tashlykova T.A., Ryashchenko T.G. Excited seismicity during the creation of reservoirs: analysis of the first facts and possible causes. Engineering protection. **6**, pp. 98–104 (44-52) 2015
24. I.Sorin Leoveanu Computer fluid dynamics determination of inside fluid reservoirs movements and walls loads during earthquakes. Buletinul AGIR nr. **2**, (2013)
25. Khamidov Kh.L., Artikov F.R., Khamidov L.A. Calibration of seismic station channels in Gissarak and Tupolang reservoirs and monitoring of seismic events in their near zones. International Journal of Geology, Earth & Environmental Sciences, **11**, pp. 164-173 (2021)
26. Khamidov L.A., Alimukhamedov I.M., Artikov F.R., Khamidov H.L. Parameters of local geodynamics of the near zones of reservoirs. J. Problems of seismology, 2(1), pp.64-80 (2020)