Local Seismicity of Reservoir Areas Based on Digital Seismometric Observations

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***Abstract*— The work gives the results of seismometric observations in the region of operating reservoirs of Uzbekistan and analysis of the trend of variation of seismic activity, which is determined more descriptively in the case of digital registration of seismic events.**

Keywords*— *reservoir; digital network; seismicity; seismic activity; energy of earthquakes; oscillation spectrum; reponse of medium

I. INTRODUCTION

Long terms of reservoir operation, high frequency of change of their volume compared with the level of modern geodynamic motions, large volumes of water contained in them, intensive concentration of outflow of large volume of water from them in irrigation periods for limited periods of time – all of these contributes to disturbance of the regular original stress-strain distribution of canyon walls in the near deformation affected template zones of reservoirs. In the recent years, digital seismic monitoring has been becoming a new trend in the complex of research, which facilitates improving of safety and efficiency of reservoir operation. Monitoring is based on descriptive registration of seismic vibrations from small acts of brittle fracture in side rock masses [1,2,3]. Characteristics of fracture processes, such as their spatial attitude, released seismic energy, inelastic deformation in the focus area, are assessed by processing of obtained seismic records. Potential benefits of quantitative processing and interpretation of seismic events in reservoir areas have been known for a long time [4,5]. However, previous attempts to arrange plan-based seismic monitoring were unsuccessful, which was basically due to technical limitations. A number of new interesting results for this kind of observations have been obtained as of today. Such research is intended to be carried out for several medium-head reservoirs of Uzbekistan, such as Charvak, Gissarak and Tuplang, in the future.

II. RESEARCH SUBJECTS

Charvak reservoir (Tashkent Province, East Uzbekistan) is located in the nodal area of junction of the Chatkal, the Pskem situated the Koksuy rivers of Tashken geodynamic chain of West Tien Shan. The Chirchiq river, together with the Ugam river, practically begins from the dam site, which is the main source of fresh water of the whole irrigable and urban zone of Tashkent valley. The reservoir foundation is crossed with a number of seismically active ruptures, such as Pskom, Kumbel and Karzhantau. Major earthquakes with $M \geq 5$ occurred here: Buruchmulla (1959), Tashkent (1966), Denap (1974), Tavaksay (1977), Nazarbek (1980), Tashkent (2008). Seismicity of the area is estimated as 8-9 points of MSK-64 scale.

Gissarak reservoir (Qashqadaryo Province, Central Uzbekistan) is situated in the middle reaches of the Aksu, which springs from the mountains on the northern slopes of Gissar mountain ranges. The valley of the river, where the reservoir is located, is characterized by steep sides, steep course grades, relatively low preserving of terrace surfaces, and weak spread of young quaternary deposits. The foundation of Gissarak reservoir is located in the single tectonic unit and in the areas with 7 and 8 points' seismicity. Spatial arrangement of seismic sensors is known to be the primary element of seismic monitoring system. Arrangement of 24 seismic sensors in this region is designed to provide three-dimensional coverage of rocks, which are of interest from the viewpoint of stability. For that end, seismic sensors were placed both on the surface and on bench areas of the Gissarak reservoir pit, as well as in 100-250 m deep wells drilled beyond the open-pit edge of the earth-fill dam. The distance between seismic sensors if about 100-200 m, monitoring covering the volume of rocks with maximal lateral dimension 300-500 m. Electrical signal from seismic sensors are received at registering modules, where they are filtered, digitized and preprocessed.

Tupalang reservoir (Surkhondaryo Province, South Uzbekistan). The territory of Tupalang reservoir is situated in the southern part of Gissar mountain range, the near zone of South Tien Shan rupture, in the transition zone to Pamir region and bounded by mountain ranges – Surkhantau in the west and Machetli in the east. Major destructive earthquakes occurred in that region, such as Qarataq earthquake with intensity 9-10 points ($M \geq 7$, with the focus very close to the reservoir), Baysun earthquake with intensity 8-9 points (80-90 km south-west of the reservoir) and Chuyanchin earthquake (70-80 km north-east of the reservoir) with $M \geq 6$. Seismic research carried out in the period 1973-1981 and later demonstrated that the area is characterized by high seismicity, where earthquakes with 9 points' intensity ($M \geq 7$) are possible. Research in the territory of reservoirs established that earthquakes with intensity 7, 8 and 9 points ($M \geq 5$) tend to recur once in 300, 1,000 and 4,000 years. The dam site is located in the zone of 8 and 9 points' seismic intensity [5].

III. BASIC RESEARCHES

In 2007-2011, seismometric observations were updated by digital networking to estimate dam oscillations at Charvak reservoir, the volume of which at maximal filling is about 2 km3. It is over 120 m high and over 800 m long. 18 digital seismic stations are installed in the body of the dam and analysis of records for the updated "Charvak" ASOS. Checkpoints (CP) are equipped with high-sensitivity seismographs to record local and nearby earthquakes with increasing channels depending on the background noise of the 1st kind from 10,000. The range of passband periods is 0.2-1.2 s; gain-frequency characteristic of channels depends on the main part of the seismic spectrum of weak nearby and local earthquakes [6].

Engineering seismometric estimates on the temporary basis are represented by digital records at 20 CPs. With the transition to continuous engineering seismometric observations, the number of CPs was increased to 24 three-channel CPs. 12 of them in opposite sides and in the foundation remained in the same position. Sensitivity of recording channels of the seismic station in the standby mode is set for recording the velocity of weak soil oscillations from 1 to 5 points (Vx = 10s) and for stronger ones from 5 to 9 points (Vx = 1s). S - 5 -S with Ts = 4.5s (Ds =0.6; Dso= 0.02) were used as seismic detectors and GB-IV with Tg = 0.008 s (Dg = 0.7) as galvanometers. In the seismograms, maximal amplitudes of oscillations velocity A_{Max} (mm/s) and respective oscillation periods and duration are measured. Relative change of oscillation intensity $\delta_i=A_{max(i)}/A_{ma}$ has also been calculated, where I is the CP number. Determination of seismic properties of sandy clastic and rudaceous masses in the area of Charvak dam as experimental material at different loads and volumes of water was performed by several methods: recording of weak remote earthquakes; study of spectral characteristics of soils by analysis of microseisms and Nakamura method (HVSR) [7]. JSESAME and GEOPSY (in MATLAB 8.0 environment) were used for data processing. Method of registration of small energy earthquakes was used for quantitative assessment of relative changes of seismic intensity at sites with different physical mechanical properties of rudaceous masses. Based on Nakamura method, which is based on ellipticity of relay waves, and by means of measuring natural microseismic by three-component seismometers, characteristics of different clastic rock masses and cohesive soils up to the level of running soil were determined. Measurements were made at 12 checkpoints in the body of the dam. 28 earthquakes at distance from 10 to 550 km were registered. 17 earthquakes, which show dynamic displacements of low-frequency and high-frequency oscillations, were included in the analysis. Calculations of layer thickness from rudaceous masses to sandy clastic rocks were made using the following empirical equations: $h=156{\cdot}f_0^{\ -1,08}$ where h is thickness of layer of filling rocks, f_o is resonance frequency of each part of clastic rocks [6,7]. To determine velocity of S-waves V_s, the following expression was used [7]:

$$T = 4h/Vs;$$

where T is resonance period of each type of rock masses, h is thickness of each part of rocks, V_s is velocity of S-waves. To verify the validity of the equations, simultaneously recorded seismograms from three-component seismometers placed at different points of the body of the dam were analyzed. Calculation results show the variation range of V_s as 627-647 m/s. The dam consisting of fragments of rudaceous consolidated and sandy clastic less consolidated masses, special measurements were made on virgin soil. Increment of oscillation intensity (HSVR) here was 1.8. Table I gives the calculation results below.

TABLE I. INCREMENT OF INTENSITY ΔJ AND MAXIMAL ACCELERATIONS G

CP No	f_0	H, m	V_s, m/s	HVSR	L_k	ΔJ	g, m/c^2
1	0.76	35	655	2.3	9.3	+0.45	0.23
2	0.71	145	630	3.2	17.0	+0.73	0.29
3	0.71	152	586	5.2	33.7	+1.20	0.34
4	0.67	155	564	4.3	25.4	+1.03	0.31
18	0.64	123	569	3.2	13.7	+0.35	0.22
19	0.60	86	607	6.5	12,4	+0.25	0.18
20	0.83	42	623	3.2	5.8	+0.20	0.12
14	0.79	20	675	2.1	6.9	+0.01	0,01

Here, *f_o is resonance frequency of the mass, H is the thickness of rudaceous layer, Vs is velocity of S-waves, HVSR is relationship between spectra of horizontal components and vertical components, Lk is coefficient of seismic liquefaction of the mass. Intensity increment ΔJ; Maximal accelerations g, m/c^2

Coefficient of liquefaction of sandy clastic masses brought to the state of comprehensive compression at cyclic effect: $K_s=A_p^{\ 2}/F_p$ where A is H/V relationship, F_p is the basic frequency of the rudaceous mass. Thickness parameters by types of fragmentation obtained by HVSR method were used; accelerograms were calculated for registration points of units with most different physical mechanical conditions [6,7].

Using Nakamura method and physical mechanical characteristics from recorded data and with application of HVSR technology (Yoshito Nakamura's method), a velocity model of the body of the dam has been built (Table 2).

TABLE II. S-WAVES V_S (M/S) AND COEFFICIENT OF SOIL LIQUEFACTION K_L IN THE BODY OF THE DAM

H, m	Vs	K_L
16.31	527.89	0.193
21.40	538.63	0.289
30.30	562.57	0.775
47.62	571.49	1.241
68.94	587.37	1.742
96.37	602.13	11.239
162.84	625.99	2.630

Here, H is depth of reflecting borders, Vs is average velocity in the medium of S-waves, K_L is coefficient of soil liquefaction

Results of instrumental seismometric research demonstrate that maximum possible seismic accelerations are within the range 0.24-0.32 g, or 8.0-9.0 points. It should be noted that the body of the dam is covered with filling loose masses with density 1.4 g/cm^3, thickness of which comes up to 3.0 m. Custom measurements on virgin masses in natural condition showed intensity increment +0.5 (+0.3 g). Considering that filling layers of the area will be removed for objects, we can take maximum possible intensity of seismic impact as I=8.5, and maximum accelerations as 0.27 g. Number of earthquakes in 2008 and 2011 is quite small and it could be related to continuing seismic calm in this region. The only Tashkent earthquake on 22 August, 2008 (M=4.5; I=6-7 points) in the area of Charvak reservoir resounded with 3-4 points' oscillations.

In 2009, in line with the program of applied research, new digital stations were opened in Gissarak and Tupalang regions [8]. Opening of regional stations made it possible to distinguish between an earthquake and an explosion, to determine the exact time of wave arrival and time in the earthquake focus, energy class, epicentral distance and specify the total number of seismic events occurring in the regions of major hydroelectric complexes. Detailed study of seismicity of the territory under research revealed weak local earthquakes with K=8. Manifestation of those shocks has increased since October 1986 on tapes of seismic stations operating in standby mode and since May 2004 in digital records on the object of Gissarak reservoir. Those weak seismic shocks became active in March-May of 1987 and August and September of 2004, when water level in the reservoir rose over the mark H = 110 m.

Time-wise behaviour of parameter γ (slope ratio of return chart) is known to comply with the earthquake preparation theory [9]. It could be assumed that increase of γ is related to increase of weak seismicity in the area of the future strong earthquake, and subsequent decrease is caused by merging of ruptures and formation of larger ones. Value of slope of return chart γ for Gissarak region from the materials of observations in the period from 1968 to 1967 for the range of energy classes with K=10±14 is γ = 0.62±0.1. For the observation period from 1968 to 1971 for the range of K=9±13, value of slope of return chart is γ=0.53±0.08. This period includes design and survey work in Gissarak region. For the period from 1972 to 1983 for the range of K=9±12, value of γ is γ=0.57±0.06. Design and survey work were completed in that period and construction of the dam began. For the period from 1979 to 1985 for the range of K=8±12, γ=0.54±0.07. During construction of the hydroelectric complex, for the period from 1980 to 1986 for the range of K=8±12, γ=0.43±0.04. In the period of completion of the construction, for the period of the beginning of reservoir operation from 1985 to 1987, for the range of K=8±12, γ=0.42±0.05. During the beginning of reservoir filling, maximum filling in 1987, H=110 m. For the period from 1987 to 2010 for the range of K=8±12, γ=0.34±0.08 during regular operation of the reservoir.

The above-listed values of slope of return chart γ show that discrepancy of values γ lies within the limits of error, which allows one to believe that the average long-term value of parameter γ of return chart would not change considerably before a reservoir was built in the area. Thus, γ = 0.53±0.08 should be taken as the average long-term value of slope of return chart for Gissarak region. Value γ of return slope decreased abruptly for the last two intervals; filling of the reservoir and its adaptation began in that period (Table 3).

Comparison of values of return charts in separate time intervals: 1966-1973 (before the construction in the area of the reservoir), 1973-1983 (in the period of construction and beginning of filling of the reservoir) and 1987-2010 (operation period) demonstrates that the latter is characterized by decrease of the parameter from γ = 0.57 to γ = 0.34. Values of parameter γ obtained for different averaging periods show that seismic setting in the period including the first cycle of the beginning of the reservoir construction (1972-1983) differs from the second cycle of the reservoir filling (1985-1987) and the third cycle of the reservoir operation (1987-2010).

TABLE III. VALUES OF PARAMETERS OF RETURN CHART OF GISSARAK REGION

No	Observation periods	Class K	Value γ	Note
1	1968-1967	10÷14	0.62±0.1	Full interval long before the construction
2	1967-197I	9÷13	0.53±0.08	Period of design and survey work
3	I972-1983	9÷13	0,.57±0.06	Period of construction of the reservoir
4	1979-1985	8÷12	0.54±0.07	Period of completion of the construction
5	1980-1986	8÷12	0.43±0.04	Period of completion of the construction and beginning of operation
6	1985-1987	8÷12	0.42±0.06	Period of beginning of filling of the reservoir
7	1987-2010	8÷12	0.34±0.08	Period of regular operation of the reservoir

The second cycle of filling, which corresponds to the level of the reservoir H_{max}=110 m, is characterized by considerable decrease of average seismic activity in the region, which allows speaking of some dependence of seismic setting on the mode of the reservoir filling. It follows from the above-mentioned that changes in parameter γ, possibly related to preparation of a strong earthquake, occur in the region of Gissarak reservoir in the period of its filling and operation. Preparation of a strong tectonic earthquake in the region of reservoirs is known to be characterized by considerable decrease of parameter γ [9]. Before earthquakes with M=4.04÷4.6, γ decreases by 16%, before earthquakes with M=5.0, it decreases by 28%. It is also said that for earthquakes with M=3.09÷4.3 caused by the influence of the reservoir – abrupt stress removal – an inverse effect is observed, which is increase of parameter γ by 20%.

CONCLUSIONS

Analysis of obtained results shows that construction of the reservoir caused change in the relationship between the number of earthquakes of different energy and the return period. Return period of weak earthquakes K≤8 increased, and return period of earthquakes with с K≥9 reduced, which means that construction of a reservoir in the region led to rising of the degree of crustal heterogeneity, and stress removal was mainly due to small portions of energy.

Thus, based on the above-mentioned, the following can be said:

- After completion of construction of all studied and commissioned reservoirs, the beginning of filling of reservoirs influenced the average long-term value of parameters of seismic setting.
- There is a relationship between interval values of parameters of seismic setting and the operation mode of a reservoir. The initial period of filling of a reservoir

up to H=100 m and responding velocity gradient up to 0.3 m per day is characterized by decrease of slope γ compared with the average long-term value of the parameter. A sharp increase of the number of weak shocks is observed in the period of maximum filling, weak local earthquakes become active.

Construction of those reservoirs caused changes in the stress state of the area, which in its turn led to decrease of slope of return chart. For natural tectonic, low value γ corresponds to increase of threat of a strong earthquake, seismic energy unloading in small portions, at the high level of activity of weak shocks. Therefore, in the regions with reservoirs, reduction of slope of return chart can be considered as a sign of possible coming strong earthquake.

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