Recurrence of earthquakes in the area of the Toktogul HPP cascade

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Abstract. A brief statistical analysis of the current seismicity of the Toktogul region of the Kyrgyz Republic is done. The analysis concerns the region where the Toktogul HPP cascade on the Naryn River is located, and covers the period from 1973 to 2021 years. The space-time distributions of earthquakes, accumulation characteristics, probability and recurrence of seismic events of various magnitudes are considered. According to the analysis results, the maximum magnitude of seismic events in the Toktogul region can be ~ 7.4, and the recurrence period of earthquakes with a magnitude of \( M \geq 7 \) and above \( T \geq 10 \) years is equal.

1. Introduction

The Toktogul HPP cascade of five hydroelectric stations was built in the lower reaches of the Naryn River in the Kyrgyz Republic. The first scheme for the hydropower use of Naryn River was developed by academician I.G. Alexandrov in 1931. It provided for the construction of 8 hydroelectric power plants with a total capacity of 1,868 MW and a regulating reservoir in the Ketmen-Tyubinskaya depression. In 1960, a new version of the scheme was developed. According to it the construction of 22 hydroelectric power plants with a total capacity of 6690 MW was planned on the Naryn and its tributaries. First of all, it was planned to build the Lower Naryn cascade of five stations - Kara-Suu (Toktogul), Kurpsai, Tash-Kumyr, Shamaldysai and Uch-Kurgan. Among them, according to its technical and economic indicators, the Toktogul HPP stood out with a large reservoir of complex purpose - in addition to generating electricity, it had irrigation significance.

One of the main factors that determined the requirements for the strength and stability of HPPs in the lower Naryn cascade was the level of seismicity of the territory on which they were built. These requirements were especially relevant for the Toktogul HPP, which was being built in the narrowest gorge section of the Naryn River with high steep banks at its outlet to the Fergana Valley. And, although the station itself was designed for a 9-point seismicity, the real danger during its construction and further operation were represented by numerous potentially unstable massifs identified at the site of the main structures of the hydroelectric power station [1-3]. The likelihood of spontaneous collapse of these massifs capable of damaging engineering structures and disrupting the normal operation of the hydroelectric complex increased during earthquakes. The increased seismicity of the region, which negatively affects the stability of the surrounding mountain slopes, required considerable additional material costs for their strengthening and monitoring. At the same time, the effectiveness of deterministic methods for assessing and predicting the stability of the structural elements of mountain slopes significantly decreased, since the stress-strain state, mobility and stability of steep mountain slopes, depending on many factors of natural and man-made nature, did not lend itself to strict accounting.

According to the IPZ of the USSR Academy of Sciences [1], the region is characterized by a 9-point seismicity. The recurrence rate of catastrophic earthquakes \( \geq 9 \) points in the area of the main
structures of the Toktogul HPP was estimated at 3000–15000 years. The high level of seismicity in the region is due to the presence of large deep faults as Talasso-Fergana, Karasui and others, located at a distance of 25-30 km to the north-east and south-west of the Toktogul hydroelectric complex. Directly, the section of the main structures of the hydroelectric complex is broken up by less large structural faults, such as the Karasuu thrust fault, the plane of which, within the site of the Toktogul hydroelectric power station, sinks to a depth of 4–5 km beneath the valley of the Naryn River [1].

![Figure 1](image.png)

**Figure 1.** a) epicenters of earthquakes within a radius of 300 km from the Toktogul HPP, b) distribution of earthquakes in depth.

The purpose of this article is a brief statistical analysis of the current seismicity of the Toktogul region from 1973 to 2021, where the Lower Naryn cascade of the Toktogul HPPs was built in the second half of the last century. The source of information is the regional catalog of seismic events, freely available on the US Geological Survey website (https://earthquake.usgs.gov/earthquakes/feed/). During the specified period of time, 1799 seismic events with a magnitude of 0-7.3 were recorded in the 300-kilometer vicinity of the HPP cascade, which fell into the analyzed sample. The magnitude of earthquakes was determined by body waves - 1454 events, by surface waves - 20, by the seismic moment - 97, in 228 cases the magnitude was not determined.
2. Results and discussion

In the Toktogul region of the Kyrgyz Republic, tens and hundreds of earthquakes of various magnitudes are annually recorded. Epicentral position of earthquakes registered in 1973–2021. Within a radius of 300 km from the Toktogul hydroelectric complex is shown in Figure 1a. The power plants of the cascade are marked on the map with asterisks, and individual earthquakes are marked with a circle with a radius proportional to the magnitude [4]:

\[ R \approx 10^{(0.43M-1.29)} \] (1)

The spatio-temporal distribution of seismicity, which is very uneven in the region, obviously reflects its structural features and the heterogeneity of the stress field formed under the influence of active tectonic faults. Most of earthquakes occur southeast and southwest of the cascade of the Toktogul HPPs within the Fergana Valley and the Alai Range. A small swarm of earthquakes northeast of the Toktogul hydroelectric power station is confined to the focal zone of the Suusamyr earthquake.

The strongest, recorded in the recent past, the Markansu (08/11/1974) and Suusamyr (08/19/1992) earthquakes with a magnitude of 7.3, occurred, respectively, at a depth of 9 and 27 km, in 94 km northeast and 264 km southeast of Toktogul Hydroelectric power station.

The focus of the Markansu earthquake was located on the border of the Northern Pamirs and Western Kun-Lun. Immediately after the Markansu earthquake, its aftershocks were recorded mainly to the west of the main event. Later, they began to occur across the location of the initial aftershocks. Few aftershocks with \( M \geq 4.4 \) were also observed to the east of the main event [5].

The seismic regime of the Toktogul region during the period from 1973 to 2021 is represented by the time flow of recorded earthquakes, shown in Figure 2a as a vertical bar with a height proportional to the magnitude, and by the cumulative dependences of events of various intervals of magnitudes in Figure 2b.

The Suusamyr earthquake that occurred in the area of the Pre-Aramsu marginal fault at the junction of the Aramsu inversion uplift and the Suusamyr depression was accompanied for a long time by numerous aftershocks of various strengths [6]. At the site of the Toktogul HPP, the Suusamyr earthquake was felt in the form of 7-point seismic vibrations and was accompanied by an intense rockfall from the surrounding mountain slopes. The main structures of the waterworks were not damaged during the earthquake. During the preparation and in the aftershock periods after these earthquakes, the regional seismicity increased markedly. The hypocenters of most earthquakes of this period in the region occurred at depths of up to 100 km, Figure 1b.

The regional features of the seismic regime of this period can be traced from the characteristic changes in the time dependences of the accumulation of earthquakes of different magnitude intervals, Figure 2b. In particular, a sharp increase of earthquakes numbers was noted in 1974, 1992, 2009 and 2016. In 1974 and 1992, it was caused by the Markansu and Suusamyr earthquakes and in 2009 and 2016 by seismic events of lesser magnitude. Shortly before the Suusamyr earthquake, the number of medium seismic events increased in the region. Then, after the main shock, the increased seismic activity caused by the unloading of the source area persisted for a rather long aftershock period, which ended with a relative deficit of high-energy events. After the Suusamyr earthquake, the background level of regional seismicity gradually increased until 2009.

The increase in the number of events with magnitude \( M < 5 \) after this earthquake was most likely caused by an intense redistribution of stresses in the region. At the same time, the accumulation of stronger events, the occurrence of which is not so sensitive to short-term variations in the stress-strain state, proceeded at an approximately constant rate. The period of aftershock activity of the Suusamyr earthquake ended with a series of relatively weak and medium-strength earthquakes in 2008-2009. After some time, the region was followed by another increase in the number of earthquakes and their magnitudes. The subsequent discharge of stresses in the form of a series of earthquakes was similar the strength in the region occurred in 2016.
Figure 2. a) sequence of seismogenic ruptures; b) accumulation of earthquakes of various magnitudes in the Toktogul region.

As observations show, seismicity is characterized by repeated occurrence of earthquakes in those places where they happened earlier. In particular, in the focal zones of earthquakes, earthquakes of the same magnitude are possible in the future. The frequency of their manifestation in a given territory is characterized by the recurrence of earthquakes. The frequency of occurrence increases rapidly with decreasing of earthquakes magnitude, but the energy released by them decreases more rapidly. Therefore, the elastic energy accumulated within a given territory is released mainly due to the relatively few earthquakes of large magnitude. Strong earthquakes are relatively rare because during the destruction of solids, large cracks are formed as a result of sequential enlargement and merging of
a number of smaller ones [7]. Accordingly, the number of seismic events naturally decreases with an increase in their magnitude, as it is evidenced by the distribution of earthquake magnitudes.

$$N(M) = dn/dM$$

(2)

where $M$ is the magnitude.

Figure 3a shows a histogram of the magnitude distribution of earthquakes in the Toktogul region recorded in 1973-2021. The distribution is the result of sorting the magnitudes of seismic events with an accuracy of 0.1. Their number increases in the region of low magnitudes, reaching a maximum at 4.5, and decreases with a further increase. This form of distribution is caused, on the one hand, by the skipping of energetically weak events due to the limited sensitivity of the seismic network, on the other hand, by the natural deficit of strong seismic events, which is caused by a natural decrease in their number with increasing magnitude, since cracks of a given size are formed by merging and sequential enlargement of some the number of smaller defects [7].

$$N(M) = N_0 - \gamma M$$

(3)

where $N_0$ is the number of zero-magnitude events.

The law of recurrence of earthquakes reflects the probability of occurrence of earthquakes of various magnitudes (energies). Statistically representative information corresponds to the drop-down portion of the repeatability graph. According to Figure 3b, for the Toktogul region, earthquakes starting from $M>4.5$ are statistically representative. A negative value of the slope of the repeatability graph $\gamma$, means that the frequency of tremors decreases as their magnitude increases. The value of the parameter $\gamma$ depends on the properties of the medium and the law of deformation (loading) at which the fracture process is realized [8]. The dependence (3) has a universal character and is valid in a wide range of energies of acts of destruction, including the processes of cracking (acoustic emission), rock bumps (seismic acoustics) and earthquakes [8-13].

In a number of works [8-13], a decrease in the slope of the recurrence graph before macro-fracture of samples, rock burst and strong earthquake was noted, which was given prognostic significance. The flattening of the $N(M)$ dependence during the preparation of a large earthquake is due to the intense coarsening of ruptures, which occurs at this time much more often than at the background level of seismicity characterized for the average stress-strain state established in this region. In the general case, the flattening of the recurrence graph before the formation of a relatively large discontinuity
(slip) is a characteristic manifestation of the fracture process at various scale levels from laboratory samples to rock bumps and earthquakes [7].

If seismicity is some resultant property of a given territory, which is formed under the influence of many factors, such as its stress-strain state, structure and properties of rocks, then the slope of the recurrence graph characterizing the level of seismicity of the territory can serve as its quantitative indicator. At the same time, a flat recurrence graph indicates an increased probability of occurrence of strong earthquakes, and, on the contrary, a steeper one says about the absence of such. For statistically representative data, a shallow recurrence graph indicates a higher probability of occurrence of strong earthquakes compared to more abrupt ones. Thus, the slope $\gamma$ of the recurrence graph allows us to evaluate and compare the seismicity of different regions of the earth's crust. Obviously, this remark is also true in relation to different periods of time for the same territory. Since the slope of the repeatability graph is calculated for statistically representative data, its value does not depend on the characteristics of the recording equipment, and therefore it can serve as one of the predictive parameters of seismicity.

To determine the maximum magnitude and the probability of occurrence of earthquakes of various strengths, in this work, we considered the reverse accumulation [11] of seismic events in magnitude. This dependence is obtained by summing the number of seismic events, starting with the largest values of magnitudes, in contrast to the construction of the known distribution function [14], starting with small values of magnitudes. The resulting dependence resembles the well-known distribution function constructed in the reverse order, which decreases from 1 in the region of minimum energies to 0 in the area of its maximum values. The descending branch of the inverse dependence of the accumulation of the number of events on the magnitude is rather accurately approximated by a linear dependence similar to the shown one by the equation (3). The approximating dependence, as well as the dependence in Figure 5, was obtained by the least squares method.

Equating to zero the left side of the regression equation (3), which approximates the dependence of the inverse accumulation of statistically representative seismic events, it is enough to calculate simply the maximum magnitude of earthquakes,

$$M^* = \frac{\lg N_0}{\gamma}$$

Figure 4. Inverse distributions function of seismic events by magnitude.

In Figure 4, $M^*$ corresponds to the abscissa of the intersection point of the approximating linear dependence by the zero ordinate, i.e. $M^*$ has the meaning of the maximum magnitude of a single seismic event. Due to its clear physical meaning, this parameter, along with the slope $\gamma$ of the earthquake recurrence graph, can be considered as another predictive parameter of seismicity. According to Figure 4, for the Toktogul region, the maximum earthquake magnitude can be $\sim 7.4$. To predict quickly the maximum magnitude of the expected seismic event, $M^*$ should be calculated for the current implementation of the process at the rate of receipt of instrumental information.

When calculating the probability $P(M)$ of occurrence of earthquakes of a given magnitude, it is sufficient to refer their number accumulated over a certain time to the total number of events over the
same period of time. The dependence of the probability of occurrence of earthquakes of various magnitudes and the corresponding regression equation, which makes it possible to calculate the probability of occurrence of an earthquake of a given magnitude in the region, are shown in Figure 5a.

Figure 5. a) The probability of occurrence and b) the recurrence period of earthquakes of various magnitudes in the Toktogul region.

Knowing the probabilities of occurrence of earthquakes of various magnitudes and the time for which they were recorded, it is possible to calculate their recurrence period by dividing this time by the corresponding probability. The dependence of the recurrence period of earthquakes of various magnitudes within a radius of 300 km from the Toktogul HPP is shown in Figure 5b. For earthquakes with magnitude \( M \geq 7 \) and above, the return period is \( T \geq 10^4 \) years.

3. Conclusions
1. A brief analysis of the modern seismicity of the Toktogul region of the Kyrgyz Republic with located there the hydroelectric power station of the same name is done.
2. The maximum magnitude of seismic events in the Toktogul region was determined, amounting to \( \sim 7.4 \).
3. Estimates of the probability of occurrence and recurrence of earthquakes of various magnitudes in the Toktogul region have been obtained.
4. For earthquakes with magnitude \( M \geq 7 \) and above, the return period is \( T \geq 10^4 \) years.

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