Shear and filtration strength of foundation of channel type hydropower plant building

Masharif Bakiev[1], *Nodira* Babajanova[1], *Kakhramon* Babajanov[2], and *Khojiakbar* Khasanov[1*]

[1]"Tashkent Institute of Irrigation and Agricultural Mechanization Engineers" National Research University, Tashkent, Uzbekistan
[2]GUP «Suvloyiha» Tashkent, Uzbekistan

Abstract. The purpose of the study was to analyze the foundation's filtration strength and the HPP building's shear stability after 38 years of operation as part of the Tuyamuyun hydroelectric complex on the Amudarya River. The analysis was carried out based on field data obtained with the help of 16 piezometers installed in two alignments within the block of the HPP building and vertical drainages in the grassland. The constructed graphs of water pressure fluctuations in piezometers coincide with the nature of the change in the water level in the upper and lower pools. The actual gradients did not exceed the allowable gradient for the shaly sand interlayer and limestone bedding fracture filler. Comparison of the maximum natural gradients and those calculated from model studies using electrohydrodynamic analogies. The stability of the HPP building block is estimated by the maximum piezometric pressure and compared with analytical calculations, and the safety factor is 2.303. In this way, the base's filtration strength and the structure's shear stability are ensured in the entire range of changes in the operating mode of the pressure front of the HPP building block.

1 Introduction

Nowadays, 55 reservoirs and 25 mudflow reservoirs have been built and operated in the Republic of Uzbekistan; it is also planned to build and reconstruct more than 20 reservoirs [1–4]. Many existing water reservoirs have been operated for more than 40 years; during this period, they were intensively silted up and lost a significant useful volume. The problem of silting reservoir hydroelectric facilities in Uzbekistan, particularly the Akdarya reservoir, was considered. Using the geostatic method, a method was developed to determine the useful volume [5–7]. In [8–10], the issues of silting control and the problems of cleaning reservoirs from sediments, and methods for preserving the useful volume by creating nano-reservoirs, ponds, reservoirs, and hydraulic washing of sediments are considered. Studies [11, 12] consider the issues of siltation of the Krasnodar reservoir using digital elevation models and bathymetric surveys. The authors' approaches are consistent with the results of our research.

* Corresponding author: kh.khasanov@mail.ru

Research works [13–16] are devoted to studying issues of modeling scenarios for managing the regime, water quality, and its changes during operation. Dr. V.A.Duhovny, in research works [17–19], presents studies on the assessment of water resources and regulation of the flow by reservoirs and hydroelectric power plants on the Amu Darya River and its tributaries. The water resources of the Central Asian republics and Afghanistan have been assessed. Surface runoff of the Amu Darya River basins[20,21]. Some books [22–24] give general questions and methodology for assessing the safety of hydraulic structures.

Research works [25] assessed the current state of silting in the Channel reservoir of the Tuyamuyun hydroelectric complex and, using GIS technologies, developed ways to increase the useful capacity. The book [26,27] is devoted to developing a methodology for conducting field studies of filtration in reservoir earth dams.

Research works [28] develop safety criteria for a medium-pressure hydroelectric complex, considering the time factor, silting of the drainage, and channel processes. The issues [29] of management of the cascade of reservoirs on the Belaya River with the introduction of certain changes in the design mode of operation are considered. The task was implemented on a mountainous section of the river and is not suitable for the conditions of flat rivers [30,31].

The filtration safety of the gypsum-based concrete gravity dam has been evaluated. The developed equipment was tested at the base of the arch dam of Miatlinskaya HPP [32]. The proposed method can be used when dried soil is present in the base and when their leaching occurs. In [33,34], the steady-state seepage in soils under the dam is solved by a numerical method. The papers [35–37] use various reliability assessment models for gravity concrete dams for the body of a deterministic or probabilistic method and the basis of a probabilistic approach during the periods of design, construction, and operation. The foundation of Zagorskaya GAES-2, under the compensatory injection of a special solution, provided a numerical solution to the problem of the stress-strain state of the base by the method of finite elements [38,39]. The purpose of the study was to assess the shear stability and filtration strength of the foundation of the building of the channel-type HPP of the Tuyamuyun hydroelectric complex, according to field studies. The objectives of the research are:

- assessment of the filtration strength of the base of the HPP building
- shear stability assessment of the HPP building

2 Method

Field studies and their results were processed according to the generally accepted methodology [26]. The total length of the pressure front is 330 m, including the HPP building - 110 m. According to the project, 61 pressure and non-pressure piezometers are installed on all structures (Fig. 1).

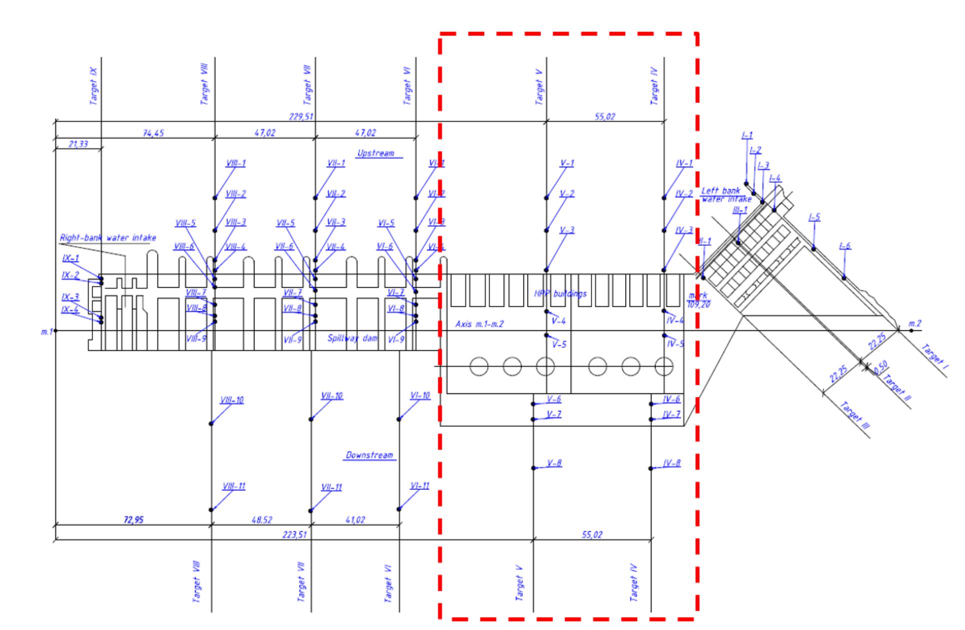

Fig. 1. The layout of piezometers at the base of concrete structures.

In the anti-filtration contour of the HPP building, a 56.8 m long downcast and a 14.6 m long upper tooth of the construction block take part. To remove the filtration pressure at the base of the structure, belt drainage is arranged behind the upper tooth, which is unloaded under the downstream level. Good vertical drainage is arranged to unload excess filtration pressure in the sand layer. Vertical drainage is in the downstream of the structures of the pressure front – the right-bank water intake, the spillway dam, the hydroelectric power station building, and the left-bank water intake. Well, the spacing is 3.0 m. Wells, cutting through limestones and sandstones, are deepened to the full thickness of the sands. The removal of filtration water from the sand formation is carried out by a filter column.

Considering the increased aggression of groundwater to metal, the filter column is made of polyethylene pipe with a diameter of 80 mm. The length of the perforated working part of the column located in the sands is 30 m. The sand of the Dzhumin quarry and the Saryassy gravel plant was used as a filter material. To monitor the filtration pressure, embedded pressure piezometers were installed in 9 sections at the base of the concrete structures of the pressure front. The piezometers are in a downcast position, directly at the base of the building block and under the water break plates. Downward piezometers were installed to measure the pressure in the weakly cemented sands.

During the period under review, measurements were made using 16 piezometers in two sections 4 and 5 of the blocks of the HPP building.

3 Results and Discussions

An assessment of the pressure front of the HPP building's piezometric curves indicates that changes in the water pressure in the impervious circuit piezometers generally fit the trend of changes in the water level (pressure) in the upstream and downstream (Fig. 2, 3).

 https://doi.org/10.1051/e3sconf/202336503025

Piezometers located at the junction of the spillway apron-construction show the efficiency of the spillway apron - 0.357H at the calculated reduced pressure of 0.457H for the block of the station building.

Tables 1 and 2 compare the measured value at the maximum upstream water level (UWL) during the period under consideration with the maximum values of piezometric pressure to determine the flow pressure in the foundation of the HPP building. Absolute levels and reduced piezometric pressures are used in the comparison.

According to the tables, as of 19.08.2019, the HPP building's determined and maximum values are determined at upstream water level (UWL) -130.00 and downstream water level (DWL) -112.58 with a head of 17.42 m.

The critical suffusion gradient for limestone bedding crack filler is $J_{cr} = 2.0$. The permitted critical gradient for the layer of clayey sand separating the limestone layer is $J_{cr} = 0.7 - 0.8$ in the loose state and $J_{cr} = 0.9 - 1.0$ in the compacted condition.

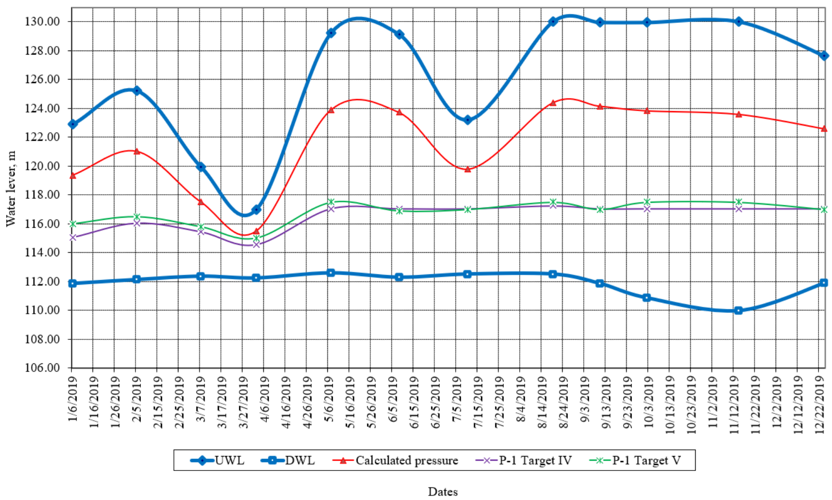

Fig. 2. Chart that shows differences in water pressure in piezometers No. 1 (targets IV, V)

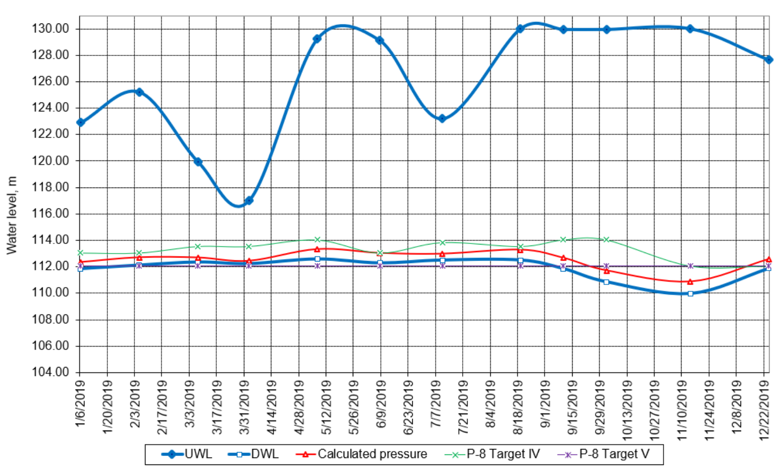

Fig. 3. Chart that shows differences in water pressure in piezometers No. 8 (targets IV, V)

The clayey sand interlayer filler and the bedding crack filler are factors for the HPP building. The clayey sand interlayer has a length of 14.5–18.0 m, and the drawings show that it runs from the top of the P-2 piezometer to the bottom on the sloped face of the HPP building block. The pressure difference Z=1.00 and 2.10 m. The actual average gradient is:

$$J_{cr} = \frac{Z}{L} = \frac{2.1}{14.5} = 0.145 < J_{add} = \frac{0.7}{1.25} = 0.56 \tag{1}$$

Thus, during the period under consideration, the actual gradients did not exceed the allowable gradient for the interlayer filler material.

For the filler of cracks in limestones, the length of the impervious contour from P-3 to P-4 is considered. This length is equal to L=14.5 m. The maximal drop is Z = 117.82 - 117.23 = 0.59 m, as shown in Table 1.

Maximum gradient:

$$J_{cr} = \frac{Z}{L} = \frac{0.59}{14.5} = 0.04 < J_{add} = \frac{2.0}{1.25} = 1.6 \tag{2}$$

The maximum difference in the beginning section of the spillway apron to P-1, is:

$$Z = 130.0 - 117.5 = 12.5\,\text{m} \tag{3}$$

$$l = 21.5\,\text{m} \tag{4}$$

$$J_{cr} = \frac{Z}{L} = \frac{12.5}{21.5} = 0.58 < J_{add} = 1.6 \tag{5}$$

In conclusion, the maximum effective gradient did not go above the allowed gradient for the limestone crack filler during the review period.

Table 1. Maximum piezometric pressures along the HPP building's transverse sections.

Target	Number of piezometers								
	P-1	P-2	P-3	P-4	P-5	P-6	P-7	P-8	P-9
Target IV	117.25	117.96	117.51	117.03	113.69	105.20	113.15	114.05	-
Target V	117.50	117.21	117.82	117.23	117.02	112.71	111.15	112.05	-
Calculated values, IV-V	124.40	121.78	120.50	113.41	112.91	114.25	113.83	113.33	-

The given pressures in piezometers according to field measurements are determined by the formula:

$$P = \frac{Lev.P - Lev.DSWH}{Lev.USWH - Lev.DSWH} \text{ in fractions of the pressure.} \tag{6}$$

The results of the calculations are summarized in Table 2.

Table 2. Piezometric reduced pressures at their maximum along the targets of structures

Target	Number of piezometers								
	P-1	**P-2**	**P-3**	**P-4**	**P-5**	**P-6**	**P-7**	**P-8**	**P-9**
Target IV	0.268	0.309	0.283	0.255	0.064	-	0.033	0.084	-
Target V	0.282	0.266	0.301	0.267	0.255	0.007	-0.082	-0.03	-
Calculated values, HHP	0.679	0.528	0.455	0.048	0.019	0.096	0.072	0.043	-

Model studies determine the calculated values by the electrohydrodynamic analogies (EGDA) method for an isotropic base by the Hydroproject Institute. The filtration strength of the formation under the limestones was monitored by measuring the piezometric pressure in the sand formation and the filtration flow rate at the wells of the vertical drainage of the HPP building. As seen from Fig. 4 and 5, the flow rate of wells in the first row is 0.85 l/sec, and in the seventh row is 0.10 l/sec and is significantly less than calculated by EGDA. It varies depending on the time and the current pressure.

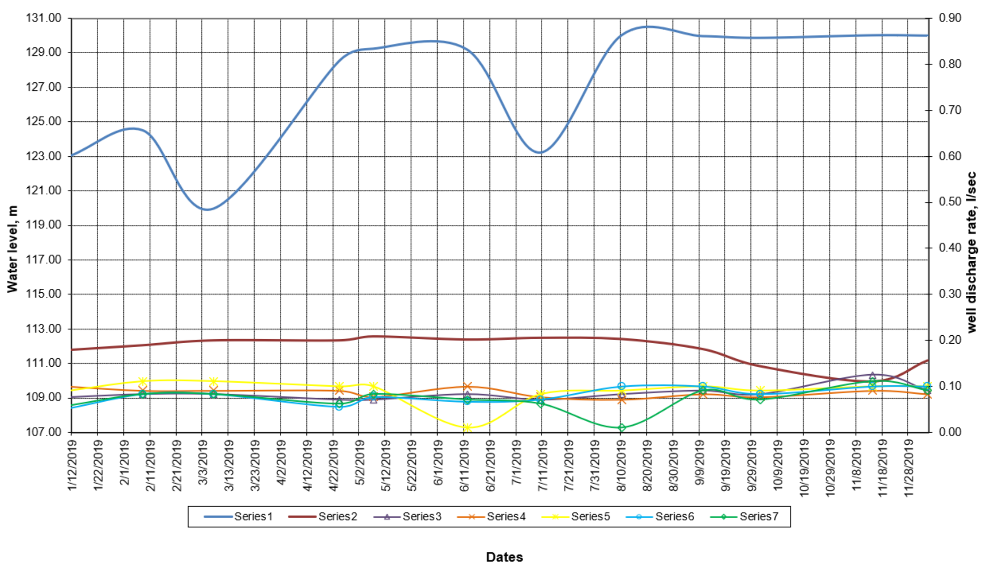

Fig. 4. Flow rate graphs for the Tuyamuyun HPP's vertical drainage wells

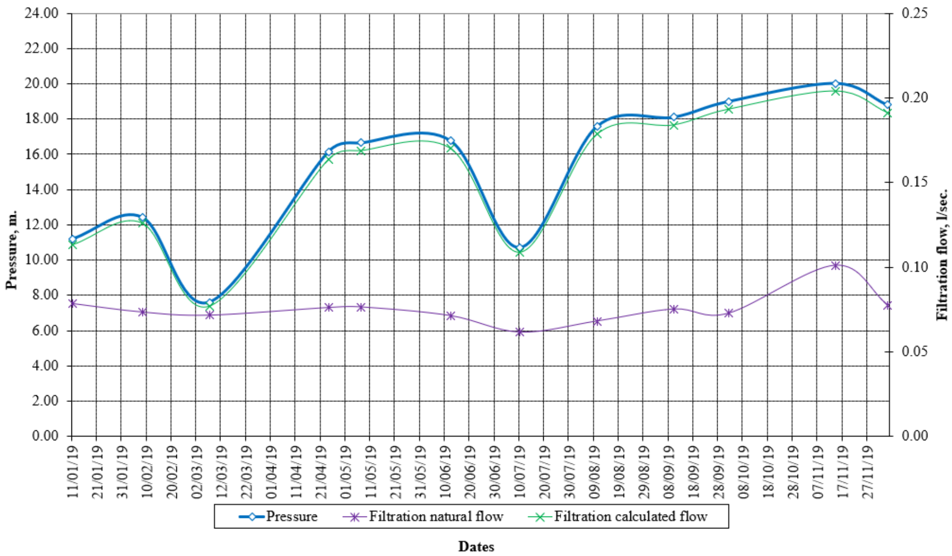

Fig. 5. A chart shows the generalized values of the seepage flow rates of the HPP building's vertical drainage over time.

The maximum gradient for the observed period in the sands was obtained:

$$J_{cr} = \frac{Z}{L} = \frac{130.0 - 112.83}{105.0} = 0.163 \tag{7}$$

Permissible critical sand gradient (8), which satisfies the filtration strength.

$$J_{cr} = \frac{Z}{L} = 1.6 \tag{5}$$

The curves of the HPP building's piezometric levels for 2019 are compared to the calculated curves and similar curves from 2017 using the transverse profiles (Figs. 6, 7). The HPP building's targets 4 and 5 created curves demonstrate that the 2019 piezometric levels do not surpass the indicators calculated for the same levels. The pressure piezometer readings within the HPP building for 2017 are higher than those of the same equipment at their highest readings. This is directly related to the high-water levels upstream and the structure's long-standing NWL.

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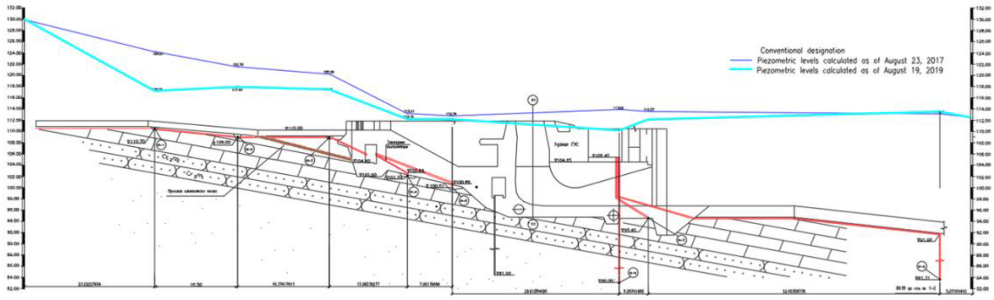

Fig. 6. Curves of piezometric levels. HPP building. Target IV

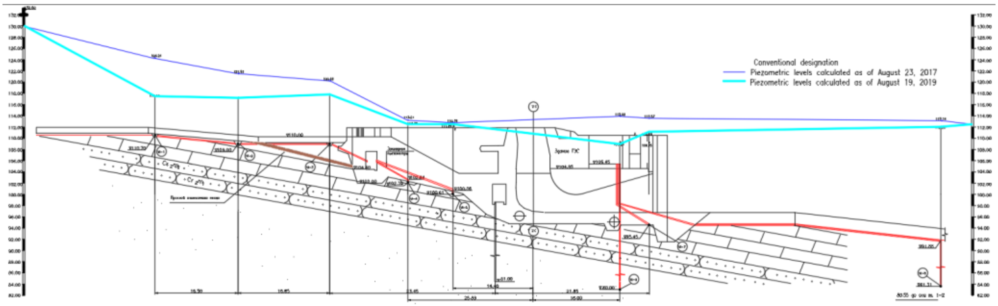

Fig. 7. Curves of piezometric levels. HPP building. Target V

The maximum piezometric pressures for the reporting period were selected and summarized on the transverse profiles for the HPP building block to assess the shear stability of structures (Fig.8). The summary maximum piezometric curve for 1995–1996 is shown in the same profile, and the maximum values of piezometric pressures were also selected for the sections. The stability of the structure under equally acting other loads and influences depends only on the degree of participation in the work of the spillway apron, vertical and horizontal drainage.

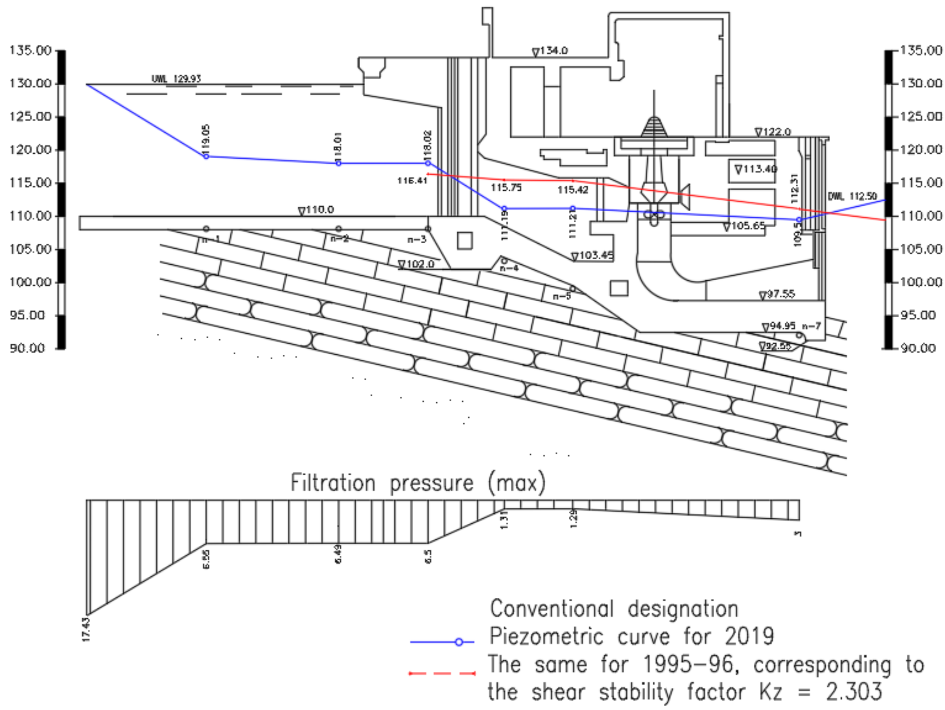

Fig. 8. Scheme for assessing shear stability of the power plant building.

It was compared to the calculated data from the Hydroproject performed in 1996 to determine the impact of silting of the run-of-river reservoir on the stability of the HPP building. The stability factor for the HPP building for this period is greater than the values for the period under consideration, the other parameters used to determine stability remain unchanged, and in conclusion, the stability factor is 2.303, respectively. Thus, the block of the station building, according to field measurements of piezometric pressure, is resistant to shear.

The Tuyamuyun hydroelectric earth dam's reliability and safety have been assessed in previous studies [40–42]. It provides the results of research into the HPP building's filtration reliability and safety based on field observations. The survey covers HPP buildings with a width of 110m. As is known, the main criterion for evaluation is assessing the foundation soil's strength [32]. Chosen the maximum values of the filtration pressure and the reduced heads. For the HPP building, the filtration strength of the filler of the clayey sand interlayer and the filler of bedding cracks was considered. The calculated gradients are between 0.145 to 0.56 for interlayer filler material, 0.04 to 1.6 for crack filler in limestone, and 0.163 to 1.6 for crack filler in the sand. By measuring the piezometric pressure and the filtration flow in the wells of the vertical drainage of the HPP building and comparing results with the calculation data using the electrohydrodynamic analogies (EGDA) method, the filtration strength of the formation under limestones was calculated. The HPP building block's shear stability factor is at 2.303, the same as it was in 1996. The HPP building's reliability and safety are ensured in all scenarios.

The purpose and objectives of the studies set in the work have been implemented, and the filtration strength of the base and the shear stability of the channel-type HPP building have been evaluated. Systematic monitoring of the operation of the constructed structures helps to increase their operational reliability and safety, as well as to improve the design of similar structures in the future.

Further studies should be carried out in conditions of silting of the run-of-river reservoir and in conditions of formation of non-stationary filtration at the base of the structure.

4 Conclusions and Recommendations

The piezometric network of the HPP building in two sections is represented by 16 piezometers.

The foundation of the HPP building is made of limestone (fracture filler and clay layer) that meets the requirements of filtration strength. The gradients acting in the base did not exceed the allowable gradients for the rock base.

In-situ seepage flow rates for vertical drainage wells of the HPP building did not exceed the calculated values.

The shear stability of the HPP building block remains the same as in 1996 and is equal to 2.303.

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