Remediation of the HPP "Višegrad" Dam

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Abstract: The hydropower plant "Višegrad" is located on the Drina River upstream of Višegrad. Many seepage occurrences have been observed since the construction. Over time, the measured quantities of seepage water under the dam body increased significantly: from 1.4 m^3/s (1990) to 14.68 m^3/s (2012). Investigations were implemented during 2008-2009 period to define the directions of groundwater movement. Repair design was developed based on subject investigations. Repair was implemented with continuous monitoring of the effects of installation, on a complex monitoring system, and real-time data processing in the mathematical model results of which were then used to adjust and direct the works. The works were carried out in 2 phases. The inert materials were installed in the first phase, while the consolidation was carried out in the second phase. The total water losses from the reservoir at the end of the repair works were reduced to 3.74 m^3/s. This paper presents the investigation activities carried out before and during the repair works, which facilitated the big success of works on the remediation of the HPP "Višegrad" dam.

INTRODUCTION

General information on the HPP Višegrad dam

The Višegrad hydropower plant is located on the Drina River, 2.7 km upstream from Višegrad. It was built between 1985 and 1989, when it was commissioned (Figure 1). The installed power of this hydropower plant is 3 x 10^5 MW, the installed discharge is 3 x 267 ~ 800 m^3/s, and the design average annual generation is 1.010 GWh. The reservoir backwater stretches along the Drina River upstream from the HPP "Višegrad" dam up to Gorazde and along the Lim River about 18 km upstream from the mouth to the Drina River. The maximum reservoir level of Višegrad is 336 masl. The tail water elevation is 285 masl. The total volume of the reservoir is 161x10^6 m^3, and the usable volume is 101x10^6 m^3. The average discharge of the Drina River on the Višegrad HPP profile is about 340 m^3/s.

***Figure 1**. HPP Višegrad Dam (with a working platform where the repair works were carried out in 2016)*

The HPP Višegrad dam is concrete, gravity dam. The 594 m long (325 m below the dam structure, 65 m in the left flank, 204 m in the right flank) and 50 to 130 m deep grout curtain is also an integral part of the dam.

Problems of seepage under the Višegrad HPP dam

A number of sources occurred on the foundation joint at the beginning of the construction of the HPP Višegrad dam, as early as in the dam foundation excavation phase. The occurrences of numerous sources in the Drina riverbed downstream of the dam were registered during reservoir filling at an elevation of 332.00 masl (4.0 m below the max. elevation). Immediately after the occurrence of seepage, the grout curtain was repaired in the block 5 zone along the width of 30 m and depth of 110 m. This included repair of 48 out of a total of 52 registered water penetrations, but the seepage has not stopped. Despite these works, measurements of the water quantity coming out of the sources downstream of the dam found that the quantity from the original 1.4 m^3/s (1990) increased up to 14.68 m^3/s (December 2012) (Figure 2).

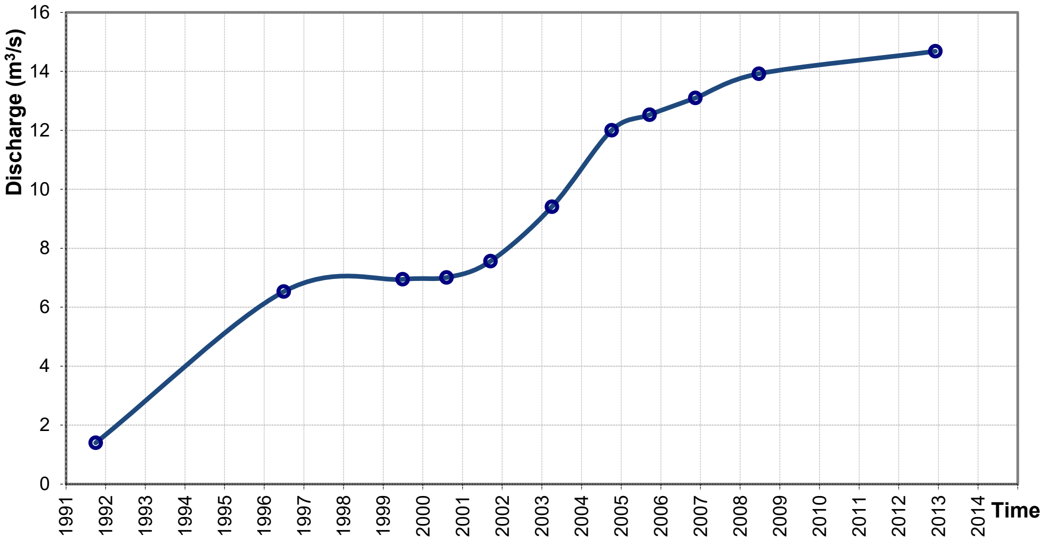

Figure 2. *Aggregate discharge at the sources in the Drina riverbed*

The investigations resulted in a conclusion that the water seepage under the HPP Višegrad dam is an extremely undesirable phenomenon. Further intensification can cause various harmful consequences, both in terms of water losses and in terms of dam safety.

Overview of activities implemented to solve the problem of seepage under the dam

Engineering-geological mapping of the foundation joint was implemented during the excavation works for the dam foundation and the riverbed downstream, when sources were first detected and recorded in the area of the dam foundation.

Seepage around and under the dam body was observed upon completion of the construction of the dam during the reservoir test filling. At that time, a dedicated investigation program was developed and implemented during 1990 and 1991. Implemented investigations included, among other things, measurements at the sources downstream of the dam (discharge, temperature, chemism), water routing in investigation boreholes and piezometers, diving-speleological investigations, water level measuring in piezometers, investigation drilling in the grout curtain zone.

Subsequently, the next significant investigation activity was carried out in 1996. The discharges of Uzamnicki Creek and Drina River were measured this time, including the interpretation of geological structure, analysis of grouting works, analysis of the level regime and physical and chemical characteristics of groundwater, reinterpretation of diving prospection, analysis of groundwater routing tests.

The following investigations were carried out at the end of June 1999. At this stage of the investigations, the number of sources in the Drina River bed and their geodetic surveying, hydrological measurement of the total quantity of seepage water at the sources, diving investigations and groundwater routing activities were implemented.

The beginning of seepage repair works under the Višegrad HPP dam began with the development of a design. During the 2008-2009 period, the Jaroslav Černi Water Institute from Belgrade successfully implemented unusually extensive investigations, which have helped to determine the general directions of water movement through the underground in the dam zone. Investigations included detailed geodetic surveys of the terrain surface and the reservoir bottom, geological mapping of the terrain surface and the investigation borehole cores, geophysical surveys on the terrain surface and in the wells, diving surveys upstream and downstream of the dam, marking tests and other investigation activities.

Dedicated surveys implemented for the needs of the Repair Design generated various quantitative information on watercourses, defined the boundary of the watertight rock under the dam body, the orientation spatial position and approximate size of the most significant underground channels, determined the velocities of water outflow at the sources, the velocity of influx at the Great Abyss and other significant parameters (discharges, pressures) that contributed to understanding the spatial position of underground flows and processes that take place under the foundations and in the flanks of the dam.

The concept was defined on the basis of all collected and processed data and the Repair Design was developed.

Repair works were carried out in the 2012 – 2014 period. Subject works included extensive investigations and real-time observations.

The decision to stop the works was made at the end of October 31, 2014, due to the exhaustion of financial resources, as well as the expiration of the agreed deadline for the implementation of repair works.

The works were continued during 2016 - 2018 in accordance with the repair concept within the implementation of the Design of terrain consolidation under the Višegrad HPP dam.

STUDY OF THE PROBLEM

Geological structure of the wider dam area

The area of the HPP "Višegrad" dam is very complex in geological terms. It is built of Triassic, Jurassic and Quaternary creations.

Medium-Triassic - Lower Triassic limestones and clasts ($T_{1,2kp}$) are the oldest fortified rocks on the investigation field. They are represented by a shifting marly and sandy limestones, marls, arenites and sandstones where limestones and marly limestones dominate. The subject rocks are well layered up to the banked state, often intensively contorted and tectonically broken. In this part of the terrain, this environment in hydrogeological terms is a watertight unit.

These sediments contain sediments of the middle and upper Triassic ($T_{2,3}$). Dolomite limestones ($T_{2,3dk}$) and dolomites ($T_{2,3d}$) are present. The limestone in some places is intensely tectonically fractured with wires of calcite. Dolomites are usually massive, rarely banked with very common and conspicuous occurrences of "grusification" and cataclysing. There are also open cracks there, as well as clear traces of karstification and water movement.

Hornstones and clays are present within the rock masses of middle – upper Jurassic age, serpentinites, basalts, diabases, and sandstones. These rocks are part of an ophiolitic mélange that is a heterogeneous creation, a chaotic structure.

The structural plan of the narrower dam area of the Višegrad hydropower plant is dominated by two units. Locally observed, the lower one (indigenous) consists of the Triassic limestone body, and the upper one (allochton) consists of the Jurassic melange. In broader terms, the Triassic limestone body is also a part of the Dinaric - ophiolitic melange and most likely represents the olistolite embedded in the melange during the subduction-collision processes in the subject terrains.

The middle–upper Triassic limestone body as the dominant one in the investigation area, as well as the environment in which the processes of water seepage in the dam domain take place, is inclined towards the southeast and sinks under the melange structures (Figure 3).

Generally speaking, the entire area southeast of Drina is lower in relation to the northwestern part, which resulted in preserved melange structures on the surface in that southeastern part of the terrain.

It was found that the tectonic assembly formed during the three main stages of formation. The first phase of tectogenesis-compression - closure of the Jurassic Ocean space and the formation of melange (Dinaric ophiolitic zone).

The second stage - the upper chalk is also tensional or transtensional. The third major phase of the formation of structures occurred in the older Paleogene.

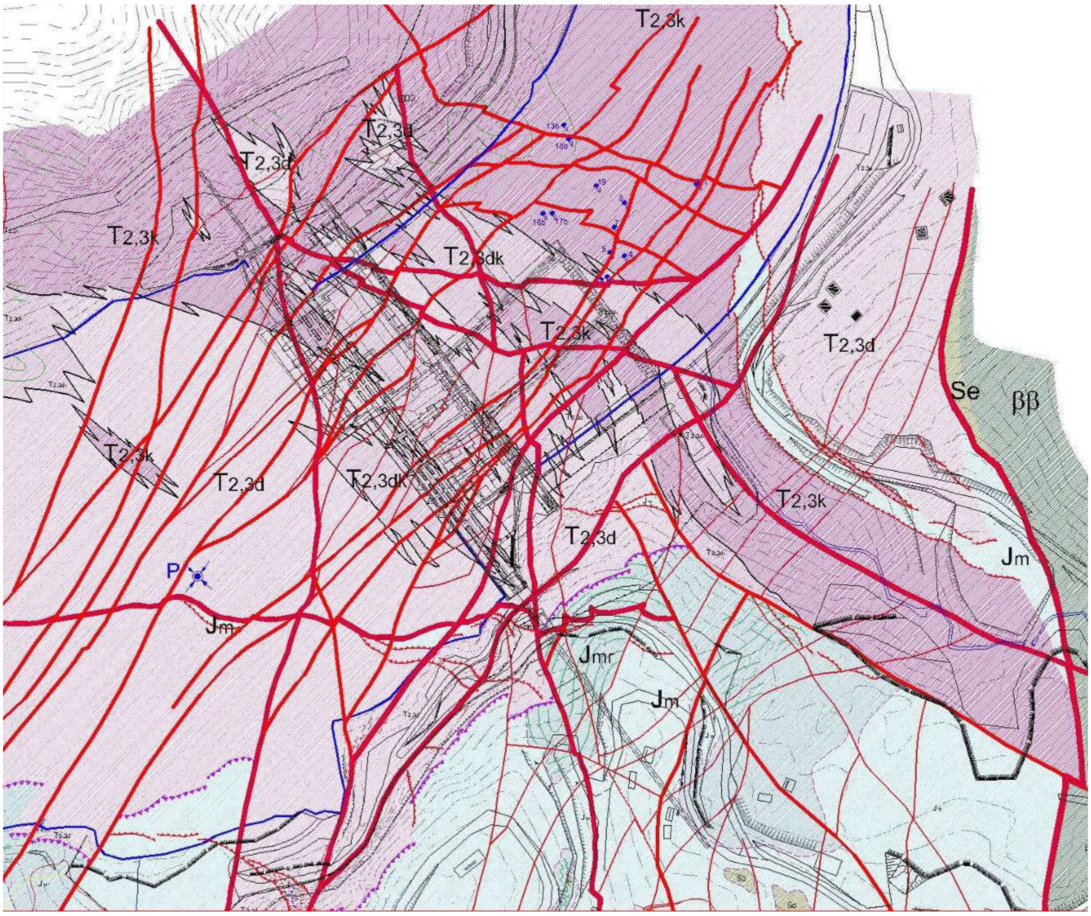

Figure 3. *Geological structure of the wider dam area*

The Drina River course and reservoir areas are in the area of an asymmetrical tectonic trench. It was created by the gravitational activity of the Drina fault located on the right bank in the Drina River bank hinterland, which was followed, successively, also by the lowered blocks of the accompanying faults primarily stretching NE-NW under the slope towards southeast but also towards the northwest (Figure 4).

Erosion process development

The Triassic limestone body is substantially damaged in tectonic terms in the narrower area of the dam. Many deformities of different orientation and type of faults and cracks, especially tension cracks, were noted. They are grouped into multiple systems according to spread, slope and cinematics.

Tectonic activities have led to the formation of complex rupture geometry where the main fault structures are connected by numerous rupture elements of lower order (faults and tension cracks), making this space tectonically very damaged.

From the aspect of seepage into the dam domain, unusually important are fault intersection zones and accompanying rupture elements, primarily tension cracks. These are also potential spaces for the development of (karst) erosion and the formation of caverns and therefore the possibility of water peeking under the dam.

In accordance with the lithological composition, the rocks of the lower and middle Triassic ($T_{1,2kp}$), which are characterized as watertight, are a watertight floor, i.e., the base of karstification, in this part of the terrain.

During the time prior to the reservoir filling, the karst forms under the local base level of erosion were predominantly filled with secondary material, and the erosion process took place along relatively small parts of the cracks, at small hydraulic gradients. With the construction of the dam and the reservoir formation, the hydraulic gradient increased dramatically, which led to a significant increase in flow rates and the development of the erosion process through rupture shapes under the dam body (Figure 5). The erosion involved the rinsing of milonite zones of larger rupture forms and Paleokarst structures filled with secondary material.

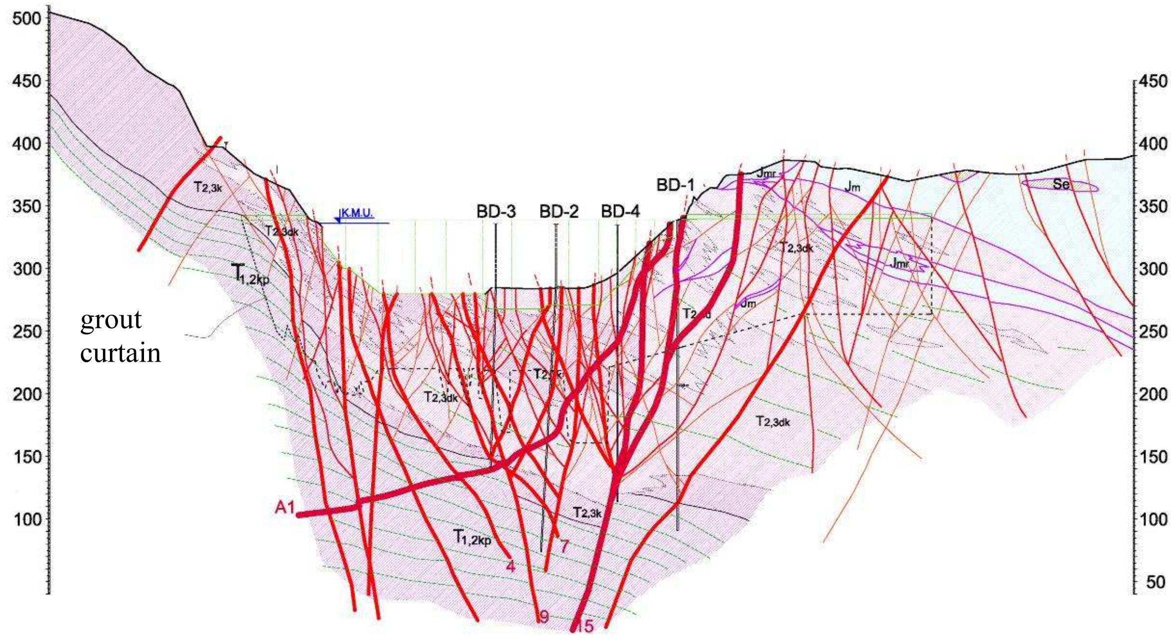

***Figure 4**. Geological profile along the borehole axis upstream of the dam*

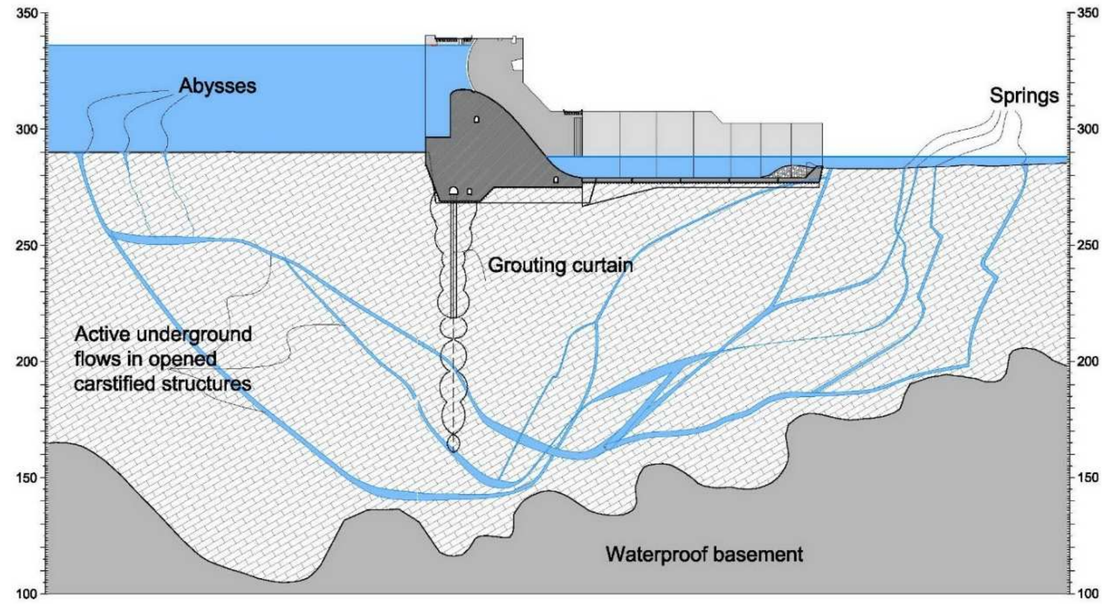

***Figure 5**. Process of the material rinsing under the dam body under the influence of the reservoir*

INVESTIGATIONS

Geological surveys

Geological terrain mapping

Detailed 1:50 to 1:1000 geological mapping of the dam site was carried out by Higrainženjering – Sarajevo for the purpose of developing the Preliminary Design and development of the geological layers required for the dam construction. No documents were found in the existing literature and databases on the results of detailed laboratory (primarily petrological, sedimentological and paleontological) investigations. Detailed engineering geological mapping of the foundation pit excavation was carried out during the construction of the dam. Also, the interpretation of geological structure was conducted during the surveys carried out in 1996.

Detailed and comprehensive surveys of geological structure were carried out within the framework of the seepage repair design development [1]. The results of previous surveys were systematized, then the surveys were performed via the remote detection method, by analyzing satellite and aerial images, on the basis of which a 1:5000 structural tectonic map was made for the dam site zone. Geological mapping was carried out by detailed study of the terrain surface, starting from the results of previous surveys. Petrological analyses of more than 200 representative rock samples were carried out within the framework of these investigations.

The entire interpretation and formation of the geological map was focused on finding logical connections between the geological structure of the terrain and its hydrogeological function. Particular attention was paid to the structural and lithostratigraphic elements of the narrowest dam region and the upstream riverbed.

The result was the conclusion that the dam was built on a large sliding leaf (olistoplake), with direct contact with melange structures located on the right side of the river valley. If we consider that in the later stages of tectonic shaping there was a significant breakdown of the terrain parallel to the riverbed, then it was understandable why the directions of seepage were similarly oriented. The high tectonization of the carbonate olistolite was particularly important along the fault intersecting the floor of the right dam flank on the right bank at an oblique angle. Its orientation substantially coincides with the orientation of the source in the river below the dams.

Investigation drilling

Investigations were implemented for the purposes of the Preliminary Design (1976 – 1977), mainly in the immediate area of the dam site, some of which were carried out during the conceptual design development, and most of them during the preliminary design phase, 58 investigation boreholes of a total depth of 4024 m were constructed within the development of the preliminary design (Figure 6).

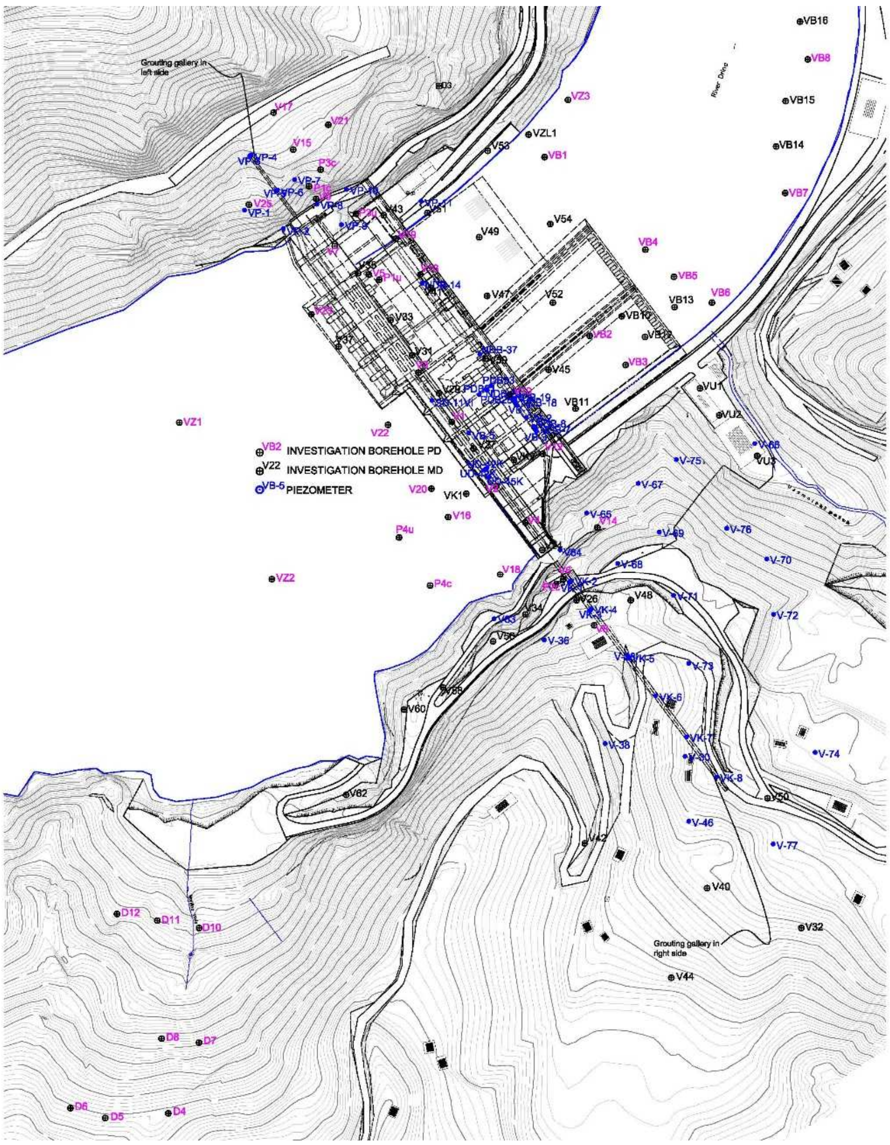

***Figure 6**. Locations of boreholes done within the Preliminary Design (ID), Main Design (MD) and piezometers*

Investigation drilling continued in the Main Design phase (1980 - 1981). Water permeability tests were performed in all boreholes in the cofferdam zone and bypass canal, as well as in the flanks of the river valley, 56 boreholes of a total depth of 3260 m were constructed during the development of the main design (Figure 7).

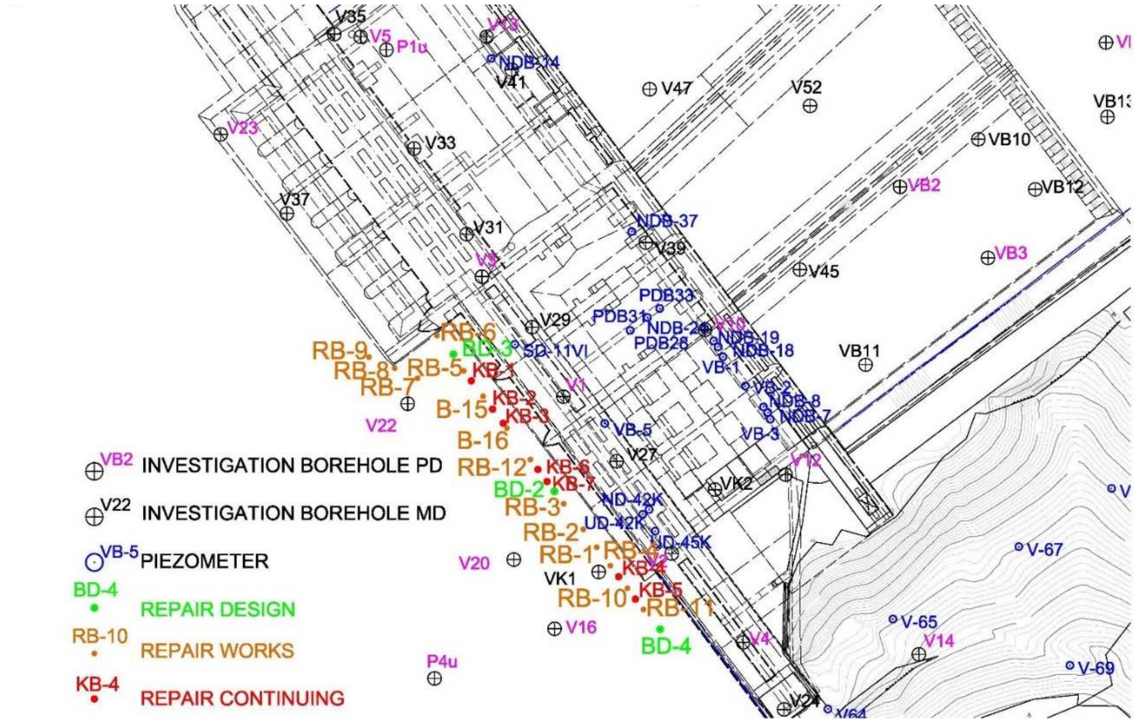

Figure 7. *Locations* of *boreholes done for the design and seepage repair works purposes*

1295 m long investigation drilling was also carried out for the purpose of assessing seepage through the grout curtain (1991).

Four investigation boreholes of a total depth of 930 m were drilled within investigations implemented for the purpose of developing the Seepage under the Višegrad HPP Dam (2008) Repair Design.

As part of the implementation of works according to the repair design, during the 2012 – 2014 period, a total of 14 boreholes from the pontoon located along the upstream face of the dam, with a total depth of 1733 m and 3 piezometer boreholes from the dam gallery, with a total depth of 697 m, were constructed (Figure 8).

Additional 7 boreholes of a total depth of 698 m were drilled within this design as part of the continuation of works in line with the repair concept, according to the Design of terrain consolidation under the Višegrad HPP dam.

The following investigations were implemented in all boreholes drilled in accordance with the repair concept applied for seepage under the Višegrad HPP dam: geological mapping, deviation measurement, geophysical logging measurements, video endoscopy imaging and VDP tests (Figure 8).

Figure 8. *Investigations in boreholes*

Geological mapping of the borehole cores examined in detail the structural - textural properties of the rocks, which are correlated with rocks of identical lithological type and age in the wider area of the dam. All fault zones and cracks have been registered and their intensity and position have been determined. Special emphasis is given to mechanical discontinuities that indicate recent water movements.

Significant caverns and zones with active water movement were isolated in all boreholes, as well as parts where the influence of reservoir water movement ceases.

Geophysical investigations

During the implementation of the investigations required for development of the Repair Design, extensive geophysical investigations were applied via various methods:

Self-potential method was applied to conduct measurements at the reservoir bottom. Based on the obtained results, several anomalous zones were isolated, which indicated potential sites of seepage or water loss.

The geo-electric scanning method according to the parameter of specific electrical resistance was applied to perform investigations in the wider area of the dam site. The depth of intervention ranged from 80 to 130-140 meters (Figure 9).

Based on the conducted investigations within the geo-electric scanning method, the positions of fault structures, through which the movement of water is most likely, have been indicated.

The method of seismic reflection was applied in detail in grouting galleries from the left flank of the dam, through the dam and along the right flank. Fault and other structures that can be significant from the point of view of water seepage were singled out based on the measured reflected seismic waves.

The "misse a la masse" method was applied to detect the spatial position of natural channels, upstream of the HPP "Višegrad" dam, which are assumed to facilitate the water loss from the reservoir.

Two significant seepage zones were detected: from the sinkhole to the right, in the direction of block number 5, and to the left, in the direction of the turbine segment of the dam, i.e., block number 9 (Figure 9).

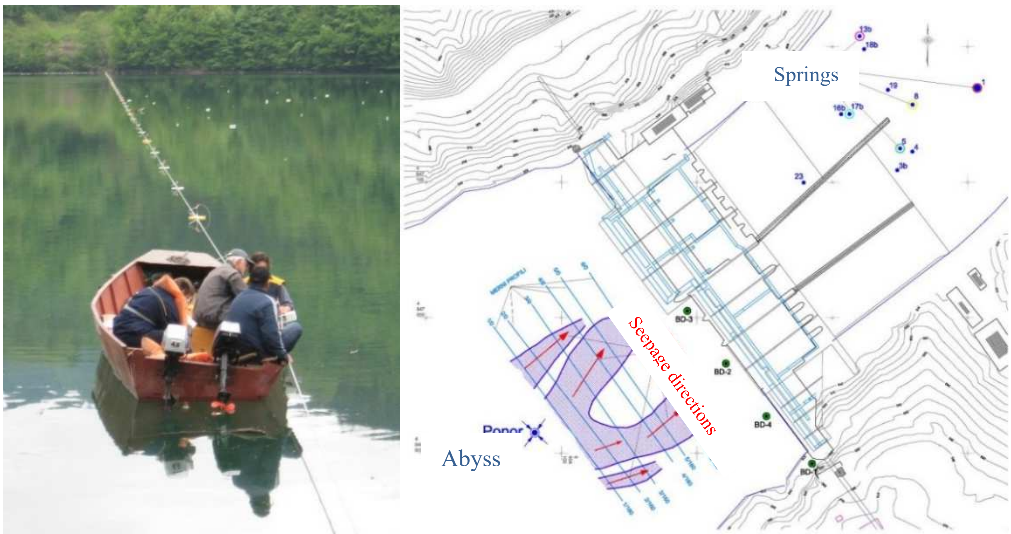

Figure 9*. Identification of groundwater movement directions in the zone upstream of the dam – geo-electric scanning and "misse a la masse"*

The following activities were conducted during the repair works:

Electrical resistance between boreholes

These investigations were conducted between 3 pairs of investigation benchmark boreholes from the pontoon along the face of the dam in characteristic periods. The results of these surveys were entered into a single monitoring system. Conclusions were made regarding the effects of the installation of materials on the appropriate cross-section by comparing the results of 2-time intervals. They were implemented during the analyses performed during the installation of materials (Figure 10).

Underwater investigations

Aiming to create a precise spatial definition of locations and characteristics of the occurrence of sinkholes upstream from the dam, and sources downstream, a significant scope of underwater investigations was carried out within the framework of the implementation of the Seepage Repaid Design.

Geodetic surveys included surveys of the terrain surface and detailed high-resolution bathymetric surveys of the reservoir bottom, part of the reservoir and the space downstream of the dam. These surveys determined the exact position of the facilities in the wider zone of the dam, which later served to create geological maps. In addition, deformations at the bottom of the reservoir were also detected. They indicated the zones where the subsequent investigations were carried out with more details.

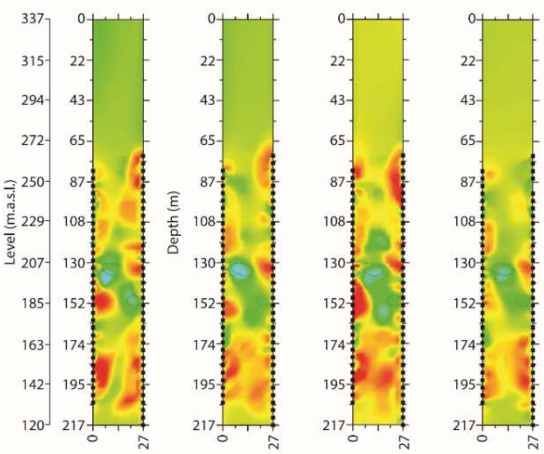

Figure 10. *Change in electrical resistance between boreholes during the repair works*

The thickness of sludge and underground structures was recorded and the velocities of water movement in the reservoir in depth were recorded, in segments of 0.5 m each, in the period when the HPP "Višegrad" power units were shut down.

Underwater camera imaging

For the purpose of finding possible zones of water sinking in the reservoir bottom, at the locations indicated by previous geophysical and bathymetric surveys, surveys of the reservoir bottom were performed with an underwater video camera with the aim of finding sink zones in the reservoir bottom area (Figure 11).

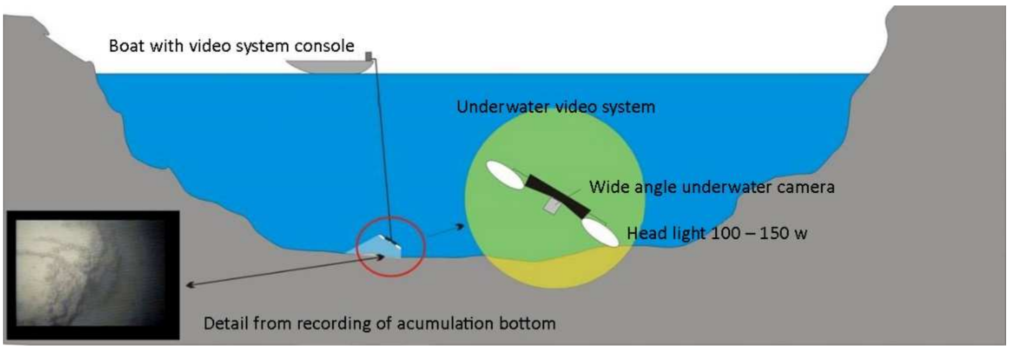

Figure 11. *Underwater video inspection system and technology*

A "great abyss", among others, was detected one the basis of the results of the underwater video camera investigations. Based on the recorded size of this abyss, as well as the behavior of the equipment used to conduct the survey, it was estimated that this location is of exceptional importance for the water seepage process under the dam body.

Measuring net was constructed to determine the characteristics of this abyss, which is lowered to the abyss. The position and speed of the water at the entrance to the abyss were then recorded using a purpose-built measuring console. This study found that the inlet changes from a slight channel slope into a steeper part, and the area of the irregular opening is 16 m^2. Further, the channel narrows after 5 - 6 m in depth to a fairly regular cylindrical shape, which is several meters long with an approximate diameter of 2.5 m or 5 m^2, but with significantly higher speeds (Figure 12).

Diving investigations were carried out at certain "perspective" points detected during the reservoir bottom imaging with an underwater inspection camera in order to directly determine whether there is a possibility of sinking and whether there are conditions for the marking tests.

In addition to the reservoir area, detailed diving surveys were performed downstream of the dam, with the aim of accurately sizing downstream sources and setting the optimal position of monitoring equipment.

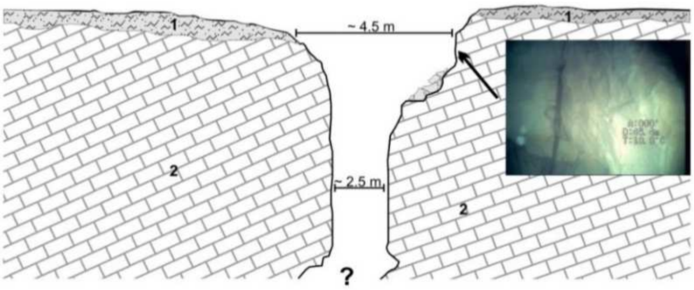

Figure 12. *Characteristic profiles of the inlet sink channel*

MONITORING

Monitoring, data collection and processing system development

Bearing in mind that sealing of carstified rock masses is not a routinely done operation, but a procedure that has the emphasized character of the "Learn as you go" principle, the concept has defined that it must be accompanied by extensive dedicated monitoring of both the implementation process and the effects on the groundwater flow state achieved during the implementation.

Implementation of works according to the adopted concept required monitoring of the effects of implementation and quality control of all implemented works, in the best possible way, in order to make the correct decisions during the execution of the process.

During the grouting on all sites, i.e., the installation of materials in the sinkhole and boreholes, in addition to monitoring the consumption of materials, the levels of groundwater in piezometers, water velocities at sources, as well as other relevant phenomena were monitored in real-time.

Appropriate dedicated software was developed for data collection and processing. It was used to establish an appropriate method of measured data processing and archiving aimed at monitoring changes at all times and performing required analyses (Figure 13).

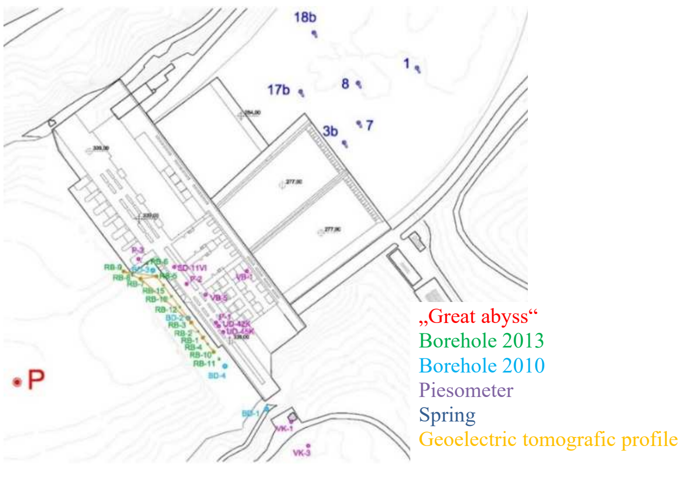

Figure 13. *Data acquisition system facilities*

By collecting and processing data in real time, data on changes in hydraulic processes were obtained in a timely manner during the very procedures for the installation of materials. Data facilitated conclusions after the analysis on the intensification of certain works or the necessity of certain modifications for the execution of subsequent works and activities (Figure 14).

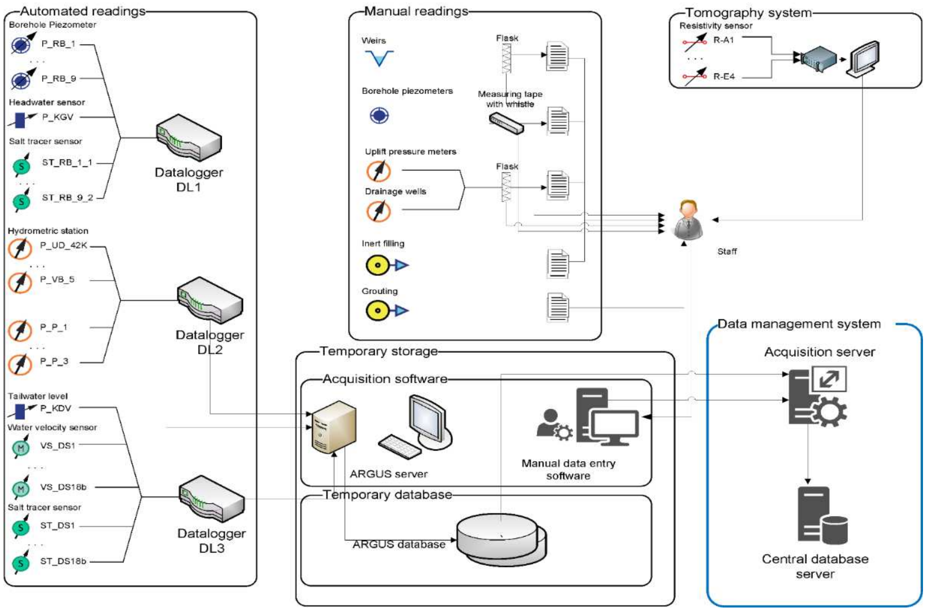

Figure 14. *Data acquisition system topology*

Groundwater level monitoring

The groundwater level in the piezometers has been measured within the regular observation of the dam, from the period of reservoir test filling. Observation of the groundwater level regime is performed twice a month (on 40 piezometers in the valley sides and 18 piezometers in the dam body). The existing piezometer network was mostly made up to depths of 40 – 80 m (to the level of the bottom of the riverbed downstream of the dam), which is well above the structures that served as a hydrogeological collector of the conductor, through which the water from the reservoir seepaged downstream of the dam.

As part of the implementation of activities under the Repair Design, an automatic system for monitoring groundwater levels in real time was established on 24 locations. Appropriate existing piezometers on the left and right bank, piezo boreholes in the gallery under the dam body and newly constructed boreholes were selected as monitoring facilities. Level measurements were performed in parallel with the observation of the head and tail water levels at the hourly and half-hourly intervals, respectively (Figure 15).

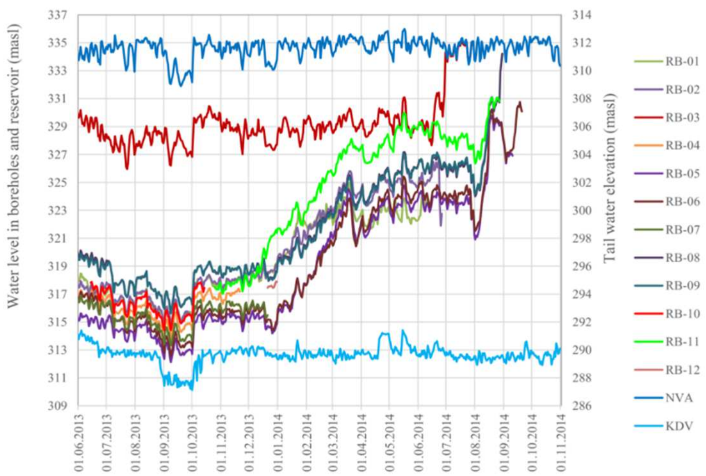

Figure 15. *Groundwater levels in the boreholes upstream of the dam during the execution of seepage repair works – part of the groundwater level monitoring system*

Monitoring of water velocities at sources downstream of the dam

Monitoring of water velocities at downstream sources started as part of the repair design development. Diving investigations were implemented with the aim of precisely locating the sources, determining their morphological characteristics and measuring the speed of water efflux. All outflow zones, i.e., all sources were subject to geodetic surveying (Figure 16). For each location, the size and spatial position were defined and the hydrometric measurement of water velocities at the outlet was performed (Table 1).

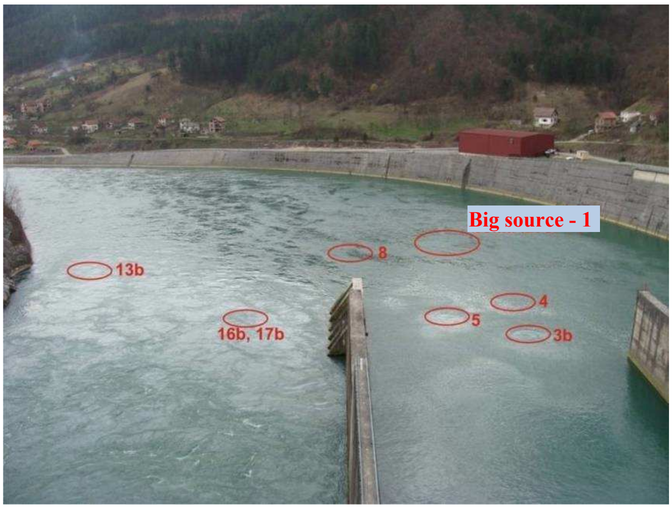

***Figure 16**. Locations of sources where hydrometric works were implemented*

***Table 1.** Measured velocities of efflux at downstream sources within the repair design development*

Name / designation of source	Efflux velocity m/s
Big source -1	3.979 - 4.300
3b	2.063 - 2.090
4	2.230
5	2.063 - 1.960
8	2.008 - 1.770
13b	0.820
16b,17b	2.156 - 2.370

As part of the works set in the repair design, water velocities monitoring system was developed at sources.

A selection of 6 characteristic locations was made based on previous measurements, where continuous monitoring of water at sources is possible (Figure 17).

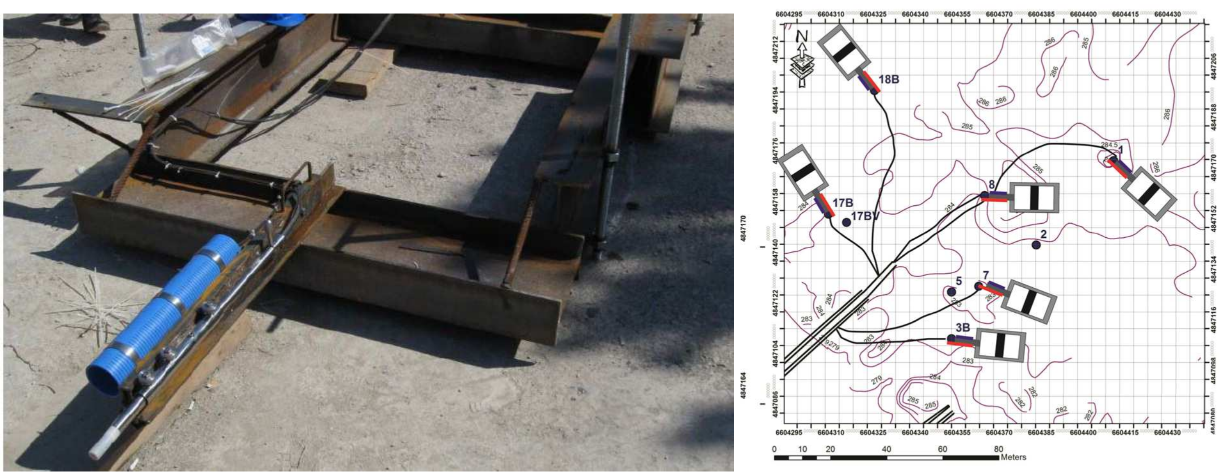

***Figure 17**. Water velocity measuring probes on the instrument holder*

A structure is designed and lowered into the river for the purpose of holding measuring instruments and placed precisely above each source. Electromagnetic probes were used to measure water velocities, as a type of measuring instrument, least sensitive to damage due to the rapid removal of solid materials at sources.

The probes are connected to a real-time data acquisition system (Figure 18).

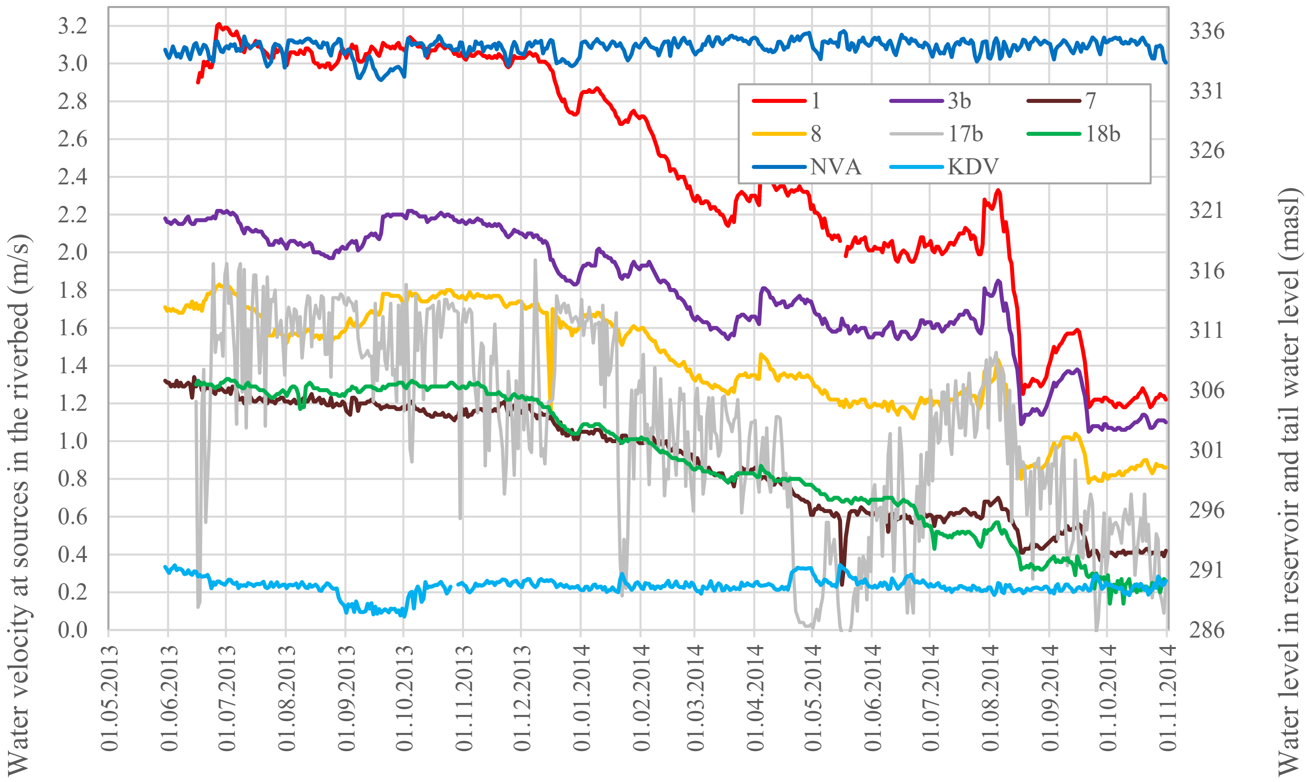

***Figure 18**. Water velocities at sources downstream of the dam*

Underground flow tracer test

The first tests of groundwater routing were carried out after the occurrence of seepage in the Uzamnicki Creek according to the "Program of groundwater connections identification with the source in the Uzamnicki Creek" (December 1989) by the dam designer. After this, the routing tests were carried out on several occasions also during 1990, 1996 and 1999.

As part of the development of the Seepage under the hydropower plant "Višegrad" Repair Design, the tracer tests with fluorescein sodium of underground channels in the dam zone were performed during 2009, a total of 16 tracer tests in boreholes and piezometers and 3 tracer tests in sinkholes upstream of the dam were performed (Figure 19).

The tracer tests with fluorescein sodium established the connection of the great abyss with the sources in the Drina riverbed downstream of the dam. The nature of the connection is such that, at each tracer test, the tracer first appeared at the source located in the left part of the riverbed (source number 17b in Figure 16), and then in the central part (sources 8, 7, 5, 3b and 4, as presented). A little later, but with the longest exit wave duration, the tracer appeared at a large source (no. 1). The last sources where the tracer appears are located downstream, towards the left bank (no. 13b and 18b). Tracer tests performed in boreholes and piezometers also identified underground connections to all sources downstream of the dam with the same order of tracer occurrence as in the sinkhole tracing.

Subject investigations were carried out to identify underground water connections between the reservoir and downstream sources in the Drina riverbed and Uzamnicki Creek.

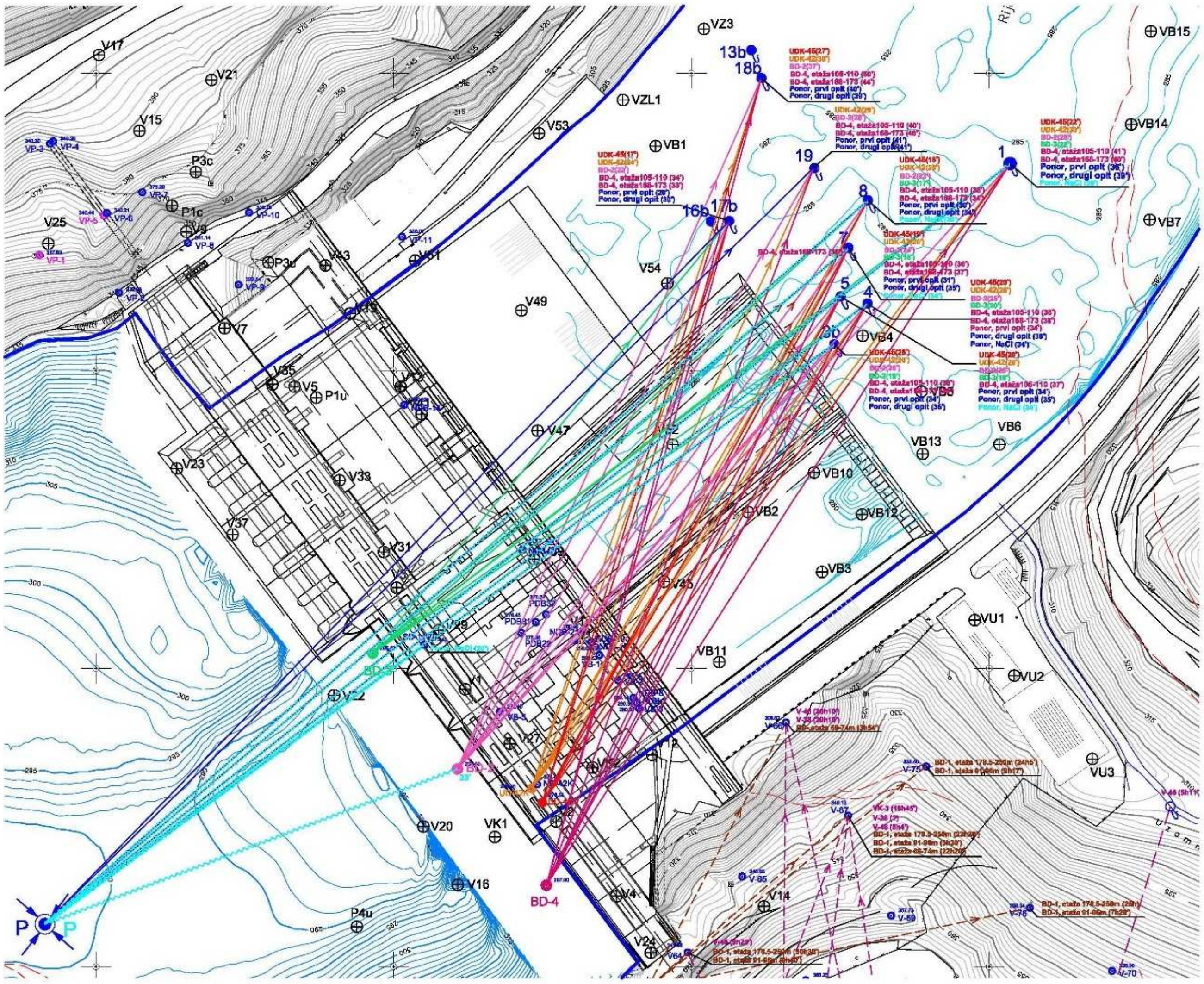

***Figure 19**. Connections of boreholes and sinkholes upstream of the dam with downstream sources identified within the repair design development*

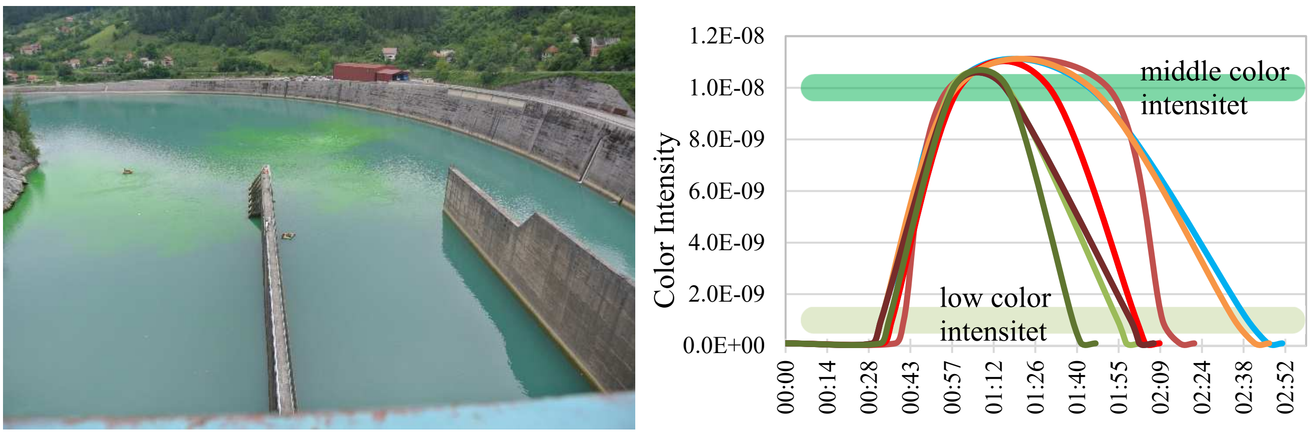

***Figure 20**. Appearance of dye on sources, tracer test with fluorescein sodium*

During the implementation of works according to the repair design (2013), a tracer test through the sinkhole and 10 tracer tests through the boreholes were conducted prior to the start of the installation of inert material in the sinkhole. Subject tests were conducted to set the zero state in the system of underground channels before the installation of materials.

Data on the tracer exit speed and their concentrations were implemented in the mathematical model (Figure 20).

Electrical conductivity monitoring

As part of the investigations done for the repair design development purposes, the sodium chloride tracer test was designed as an improvement of the tracer test, with permanent monitoring of the tracer exit.

Measuring points were placed in all four boreholes, on all storeys where the previous surveys detected the movement of water. Measuring probes were also installed at the locations of piezo boreholes in the gallery under the dam body, which have been identified to be connected to downstream sources. The third group of probes was placed at the sources in the Drina riverbed (sources 1, 3b, 4, 7 and 8).

This is how during the tracer testing the concentration of the tracer exits was monitored with significantly better accuracy.

Dedicated measuring probes were developed for the needs of the execution of works according to the repair design. They were adapted to the conditions of material installation and connected into the monitoring system (Figure 21).

Measurement of electrical conductivity with sodium chloride tracing – was observed in real-time, in 10 newly constructed benchmark investigation boreholes along the dam face and at 6 largest sources.

NaCl tracer tests were conducted at all characteristic moments of repair, at appropriate locations of tracer insertion. In total, 32 tests were carried out (Figures 21 and 22).

Figure 21. *Electrical conductivity measuring probe, NaCl tracer test*

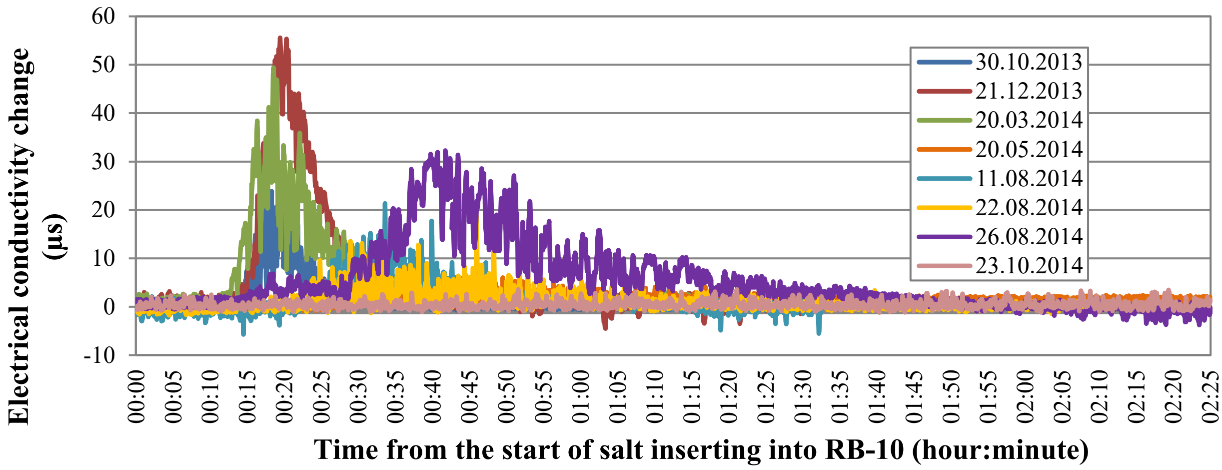

Figure 22. *Changes in electrical conductivity at source 17b during salt tracer test at different characteristic moments of material installation*

Electrical conductivity measuring probes in the grouting works phase provided significant data on the time of the cement mass arrival on the basis of which adjustments were made to the elements of the grouting regime.

Visual observations

During the repair works execution, visual observations of all phenomena that were relevant for the process of seepage repair, which could not be covered by the monitoring system and which were implemented in the overall analysis, were performed.

From the downstream side of the dam, material removal was observed at the downstream sources' sites, with a detailed record of the intensity of occurrences and a qualitative assessment of the type of material that was extracted (clay, sand, grouting mass). Sampling of material extracted at downstream sources was also carried out at characteristic moments (Figure 23).

Figure 23*. Visual observation of the source downstream of the dam (removal of clay and grouting mass) and sampling*

In the reservoir area, within the scope of visual observations, the most significant phenomena observed during the period of repair works were those detected during the airlift of the Great Abyss. A large number of locations were registered at this time where bubbles appeared, in the reservoir zone (Figure 24).

Subject phenomena of pressurized air outlets have been treated as potential zones of water influx into the system of underground channels.

All phenomena were subject to geodetic survey and the subject of later underwater investigations and served as a basis for defining the "nodes" of the mathematical model, as the location of the entry of water into the system of underground channels.

Figure 24*. Air outlet in the right flank of the reservoir zone*

Hydrometric measurements

Systematic regular measurements of total water seepage under the dam were carried out from 1991 to 2008 (the measured values are shown in the table).

Table 2. *Measurement of the total quantity of seepage waters downstream of the dam before the development of the repair design*

Date	Seepage Q (m^3/s)	Measurement done by
01/10/1991	1.40	RK "Ursus Spealeus" Foča
28/06/1996	6.53	Energoprojekt-Hidroinžinjering,Beograd
06/27/1999	6.95	HPP on Trebisnjica, Trebinje
05/08/2000	7.01	HPP on Trebisnjica, Trebinje
13/09/2001	7.56	Energoprojekt-Hidroinžinjering,Beograd
03/04/2003	9.41	Energoprojekt-Hidroinžinjering,Beograd
10/04/2004	12.00	Jaroslav Černi Institute, Belgrade
17/09/2005	12.53	Jaroslav Černi Institute, Belgrade
13/11/2006	13.10	HPP on Trebisnjica, Trebinje
21/06/2008	13.92	HPP on Trebisnjica, Trebinje

Immediately prior to the start of works according to the seepage repair design, a hydrometric measurement was performed on previously determined profiles (December 2012) to set the zero state. Total recorded discharge was 14.68 m^3/s.

After the repair works were aborted (02/11/2014), hydrometric measurement was performed downstream of the dam with the aim of identifying the effects of repair. The measured seepage under the HPP "Višegrad" dam for the given conditions was 4.47 m^3/s (Figure 25).

Figure 25*. Hydrometric measurement of total seepage downstream of the dam*

After all works were finished, the total discharge at the sources was not measured due to the unfavorable hydrological situation. The total discharge was obtained based on the results of the mathematical model to amount 3.74 m^3/s (as of 16/04/2018).

MATHEMATICAL MODEL

The basic task of model research of underground flows was to form a mathematical model of underground flows that would faithfully repeat the tests performed on the real system (in the field). Considering that several dedicated tests were carried out on the real system, which are diverse in nature (testing the sinking zone upstream of the dam, measuring the speed of vertical water flow at the sources, fluorescein sodium tracing, sodium chloride tracing, measuring the level of groundwater, etc.), it was necessary to develop model components for each observed phenomenon and to connect them to each other.

Model development

Spatial determinants of the model

Starting from the geological structure of the terrain or structural characteristics and the hypothesis that the process of erosion or movement of water through underground structures is predisposed to the position of fault structures, a model topology was formed consisting of possible underground flows. The subject topology is the starting set of connections and nodes that model the possible underground flows. It is necessary to determine which computing nodes and connections represent flows in the real system, as well as their sizes (cross-sectional area) and flow resistance.

The 3D geological model was created for the purpose of forming a network of potential karst channels stretching from the sinkhole to the source zone, i.e., from the set and potential feeding zone up to the precisely defined drainage zone of the karst waters.

One of the most expressive methods used for the formation of the karst channel network is the 3D model of fault elements "tectonics" in the zone between the surface topographic layer and the floor with the DEM obtained on the basis of previous and new added detailed investigation works. As a result of the resulting detailed geological and rupture 3D model, the geometric starting element for modeling the potential karst channels stretching has been clearly defined.

Roof layer, floor, as well as the fault network shown in 3D space, is the result of systematic research of all accessible investigation sites.

All spatial data such as geological maps and profiles as well as the position of the dam, grout curtains, grouting galleries and piezometers have been translated into digital form, namely each spatial entity has been defined with x, y and z a in the coordinate system.

Starting from the detailed development of separate layers, the formation of the basic model can be divided into three categories, as follows:

- Individual digitalization of faults, i.e., creating a 3D fault area that, in addition to the basic stretching registered in the 2D view, i.e., on the plan, but also provide the attribute of vertical spread, through depth and drop angle
- Formation of DEMs of the terrain surface and karstification base, as well as 3D models of individual faults that provide the starting point for 3D analysis as an output
- Final formation of a complex network of faults and DEMs in order to start the analysis and formation of a network of karst channels.

The formation of the karst canal network was implemented according to the principle of logical connection of the most likely possible directions using tectonics as a parameter of greatest safety when it comes to the initial phase of formation of karst channels during the process in a certain time interval.

After setting all elements in the 3D environment, a realistic spatial-oriented network of potential stretching of karst channels was obtained, which served as an input parameter for further mathematical modeling of the underground karst development.

Hydraulic model

A line hydraulic model of the flow under pressure was formed as the basis of the mathematical model of underground flows. The system of flows at both ends has set potentials, in the form of head and tail water elevations. System parameters are cross-sectional areas and flow resistances in all system elements. The results of such a hydraulic model are potentials, velocities and discharges in system elements (nodes and connections).

A mathematical model of transport of soluble materials was formed as an extension of the basic hydraulic model, which relies on the results of the hydraulic model (relies on known velocities and discharges in the system). The results of this model are travel times and dissolved matter concentration. The hydraulic model and the soluble matter transport model are coupled, thus forming a mathematical model of underground flows.

The results provided by the coupled model of underground flows can be compared with the measured sizes in individual elements of the system (water sinking velocities in the great abyss, measured water efflux velocities at sources and according to piezometric levels), according to the total balance of water seepage, as well as according to the measured times of travel and concentrations of tracers (fluorescein sodium or sodium chloride) between individual nodes of the system (input: sinkhole or borehole, outlet: borehole or sources). Comparison of these measured and calculated values indicates the level of compliance of the model and the real physical system (Figure 26 and 27).

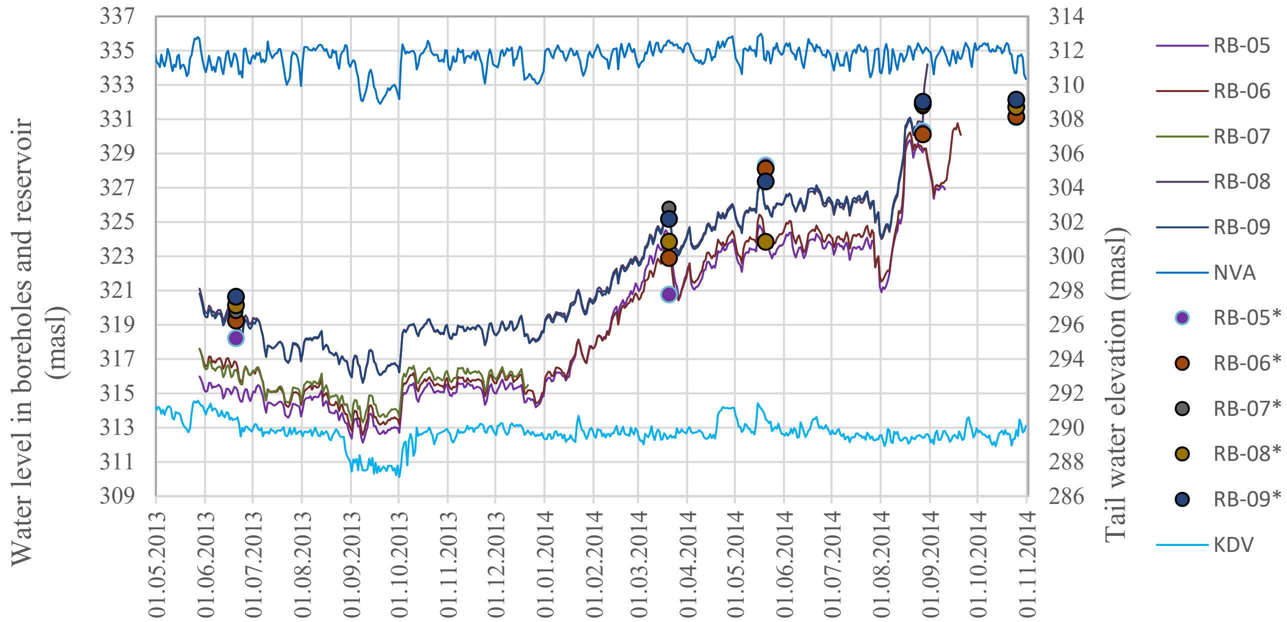

Figure 26. *Example of a comparative presentation of measured and calculated values of water level in investigation benchmark boreholes along the dam face (computing values tagged with *)*

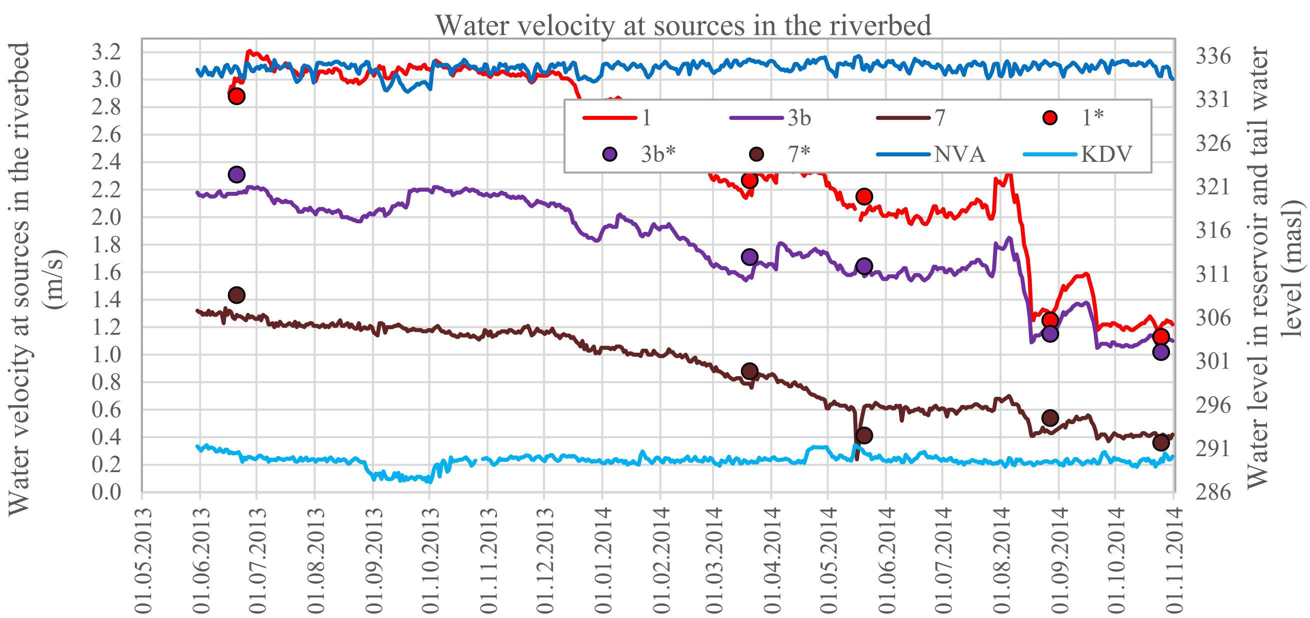

Figure 27. *Example of comparative presentation of measured and calculated values of water velocities at sources (computing values tagged with *)*

Estimation

The problem of flow hydraulics in underground tunnels caused by fault processes in the rock mass and erosion lies in the base of all this. Given the big tunnel lengths in relation to their transverse dimensions, it is possible to apply a linear flow model, without the danger that this could neglect some important processes. As will be shown later, due to the large dimensions of the tunnel cross-sections and discharges, the big Reynolds numbers indicate the extremely turbulent nature of the flow. The finite element method was chosen to solve the system of turbulent streaming equations in underground tunnels.

However, the full parameters of the model are not known, but it is necessary to perform their evaluation on the basis of the performed measurements. The hydraulic model is stationary and does not give the time dimension of the flow, so additional information on flow rates within the system was obtained through experiments of monitoring the spread of salt and paint, which were inserted into some of the system points. For this reason, it was required to develop an appropriate mathematical model that, based on the hydraulic computation, could determine the dynamics of salt and paint spreading via the finite element method. The discrete event system specification method (DEVS) was selected for the simulation of salt and color spreading. DEVS result is the dynamics of salt and color occurrence at individual points in the system.

After the completion of the hydraulic computation and the salt and paint spread computation, it is required to determine the deviation of the results obtained by mathematical models from the measured values and, on the basis of that, make the adjustment of the parameters in order to bring the model closer to the actual state. Using the corrected parameters, the entire process is repeated until a satisfactory degree of matching of calculated and measured values is achieved. The result are the most likely values of unknown system parameters, such as dimensions and shape of tunnels, roughness of walls and the like.

Bearing in mind the complexity of the model of seepage under the HPP "Višegrad" dam, it is clear that this problem involves several different physical processes, but again interconnected to the point that they cannot be observed independently.

By varying the parameters of the model of underground flows (dimensions of the karst channels and resistance along the underground flows), different results would be obtained, which more or less deviate from the measured values. The procedure of setting parameters of underground flows and hydraulic computation is by nature an iterative process. Considering the complexity of all models used and their interconnectedness, it is concluded that such a problem is impossible to solve without the implementation of appropriate algorithms. The procedure is essentially to solve an optimization problem that from a set of possible flows identifies those corresponding to real flows and identifies their sizes and hydraulic characteristics, while minimizing the difference between the computed and measured values. Therefore, an optimization platform based on genetic algorithms has been developed for the purposes of research via the mathematical model. Its task is to automate the entire process under the conditions of complex multi-criteria optimization [7].

Estimation of model topology and parameters

The mathematical model is formed on the basis of known physical dependencies that approximate the behavior of the actual system. However, the model does not possess certain parameters that influence the behavior of the model, thus these values are assumed within a set of possible values. Similarly, the topology of the model is not known, so a certain topology was assumed based on the available data.

The process of setting model parameters and topology based on the measured values of inputs and outputs to the system is called estimation, and it boils down to the optimization problem aimed at setting the parameters for which the model gives the best match of computation values with the measured values.

Depending on the assumed parameter values, the presented mathematical model may be more or less in line with the real behavior of the system. Known inputs and outputs to the system are used in the estimation process to determine the following parameters:

- widths and heights of cross-sections at the input and output of each of the network elements and
- Darcy friction factor for individual elements of the network.

Also, the topology of the model is of great importance for the model's accuracy and thus it is required to determine the main routes of water transport through the terrain.

This procedure selects the appropriate topology of underground flows, which is a subset of the initial topology set on the basis of the geological data analysis. In addition to deciding which elements will remain in the model, it is also required to determine their unknown sizes and hydraulic characteristics for these elements (computation directions of underground flow). The sizes of the flows should be sought within the limits dictated by the geological structure of the terrain, so the first step in the estimation of the model's topology and hydraulic characteristics is to set the limits of acceptable sizes of the computation flows. The term "acceptable sizes" refers to the maximum cross section width and height of the computation underground flow and indicates the values that are acceptable given the geological structure of the terrain.

The next step consists of processing and preparing all available and comparable measurements performed on a real system (detection of the sinking zone upstream of the dam, measuring the speed of vertical water flow at the sources, fluorescein sodium tracing, sodium chloride tracing, and measuring the level of groundwater). The data are systematized in a manner suitable for comparison with the computation values. An important step in the data preparation for comparison is also the determination of their reliability, which is the starting point for defining the target function that is minimized by the optimization algorithm.

When all subject activities have been completed, it is possible to initiate a parameter estimation procedure that involves a large number sequentially computations on the simulation model, which automatically implements an optimization algorithm based on the given parameters and input data.

Simulation on a hydraulic model with the adopted topology and characteristics of flows provides all hydraulic sizes. They serve as the base for analysis and definition of dominant directions of water movement under the dam body. The following figures show the results of the hydraulic computation according to discharges (first figure) as well as the real sizes of underground flows (second figure), Figure 28.

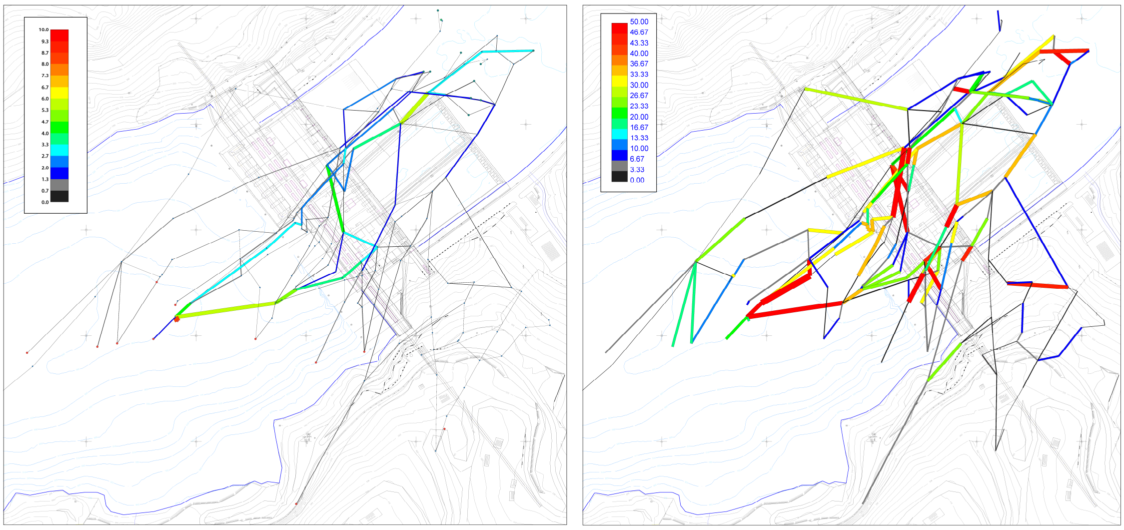

***Figure 28**. Results of discharge and size computations for underground flows*

The quality of the estimation is very good, given the complexity of the processes that have been modeled. By comparing the computed and measured values, according to the available observed data, we can observe very good matches.

Granular material transport and sedimentation model

A mathematical model and appropriate software were developed to compute the granular material sedimentation in underground streams in order to better plan the regime of granular material installation in underground cavities. The mathematical model of underground flows with the adopted parameters and the mass discharge of the material to be inserted and the characteristics of the grain (diameter and density) were used for computation purposes. Considering that the result of sedimentation computations is the quantity of deposited material in underground flows, and therefore the altered hydraulic characteristics of the tunnel, it is necessary to redo the hydraulic computation over the modified model and redo the sedimentation calculation with the new results. This entire iterative procedure is repeated until the desired sealing of a specific model segment is achieved. Upon completion of the computation, results show a gradual decrease of discharge through the system due to tunnel filling with inserted material.

Appropriate software was used to set the appropriate way of processing and archiving this data to monitor changes at all times, and to perform the required analyses. The analyses were performed on a purpose-made mathematical model, which was additionally calibrated with each new information.

REPAIR WORKS

Concept of repair works

The repair concept has been defined based on the results of the implemented investigations, as well as the requirement that the repair works should be conducted under the conditions of normal power plant operation, i.e., full reservoir and intensive water streaming in underground channels.

A distinct disadvantage is that, in the water-permeable zone of cracked and eroded, karstified limestones, located under the existing curtain, and above the water-resistant rock masses, additional "rinsing" due to the water streaming along about 40 m drop formed underground channels where high velocity water flows existed. Therefore, formation of cement stone, i.e., the hardening of the cement mass - the execution of grouting works, in such conditions, was practically impossible.

It was first required to slow down the water streaming (below 1 cm/s) through open cracks or caverns, and only then start grouting with masses that should harden and permanently fill the existing cavities.

Given the complexity and specific features of the problem, and the task of achieving permanent sealing of channels of defined underground flows in the existing conditions, it was necessary to come up with a solution that would provide good results via a combination of technologies and procedures, with constant adaptation of subsequent works in accordance with the results monitored on the previously established real-time monitoring system, which would indicate the achieved effects during the execution of each activity and enable timely decision-making, from the beginning to the end of the repair process.

Defining underground connections of the reservoir area with the sources downstream of the dam created conditions to reduce the water velocities in the underground channels by at least temporary grouting/installation of selected – inert materials.

According to the adopted concept, the installation of inert material should be carried out from reliable predefined locations, as the entrance to the karst system upstream of the dam, i.e., the existing grout curtain. Then, after velocities is reduced, permanent sealing is to be implemented under more favorable conditions (Figure 29).

The stage of primary filling of cavities to reduce streaming velocities consists of filling streaming channels with an inert "filler", which should be adapted to the shape and size of the space to be filled, but also to the procedure applied in the subject filling.

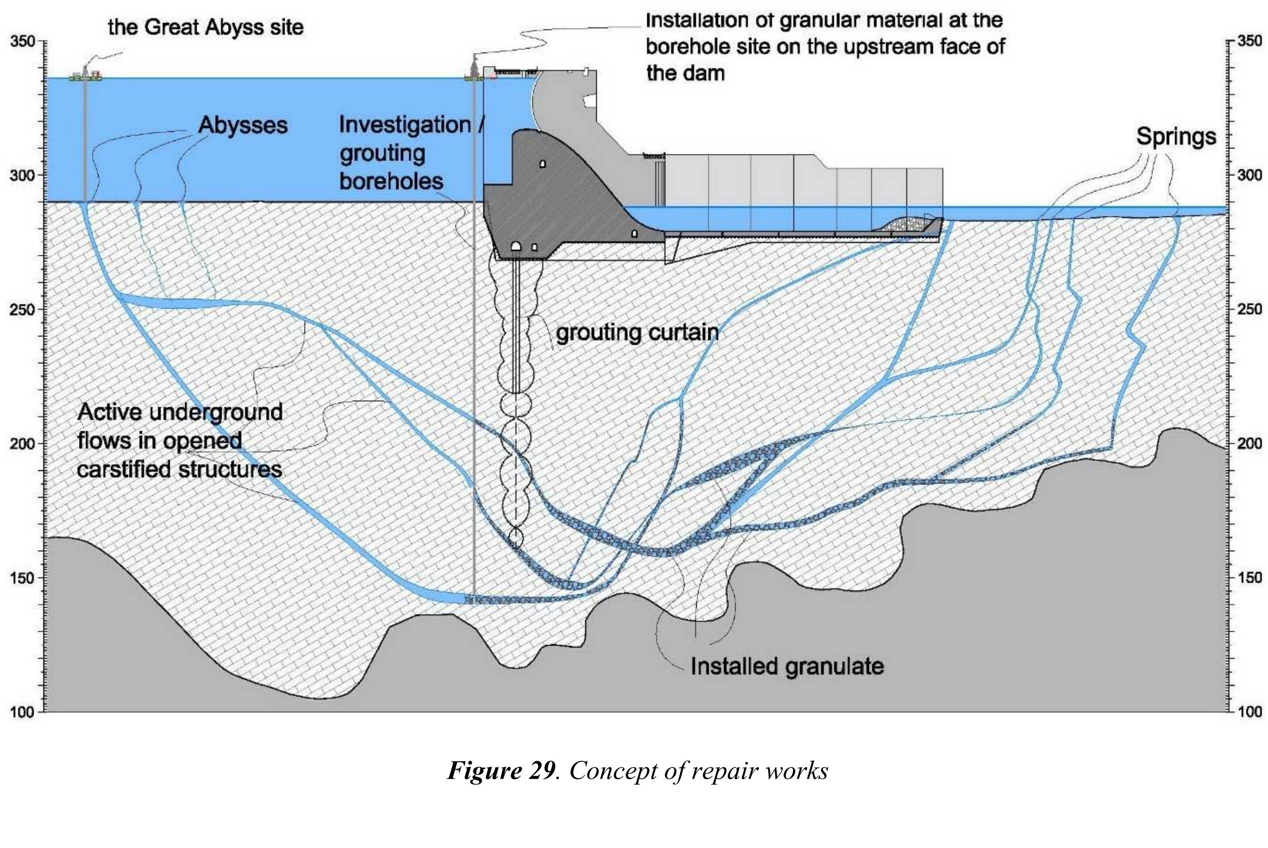

Figure 29. *Concept of repair works*

The insertion of large quantities of mineral aggregate into existing cavities inevitably reduces discharge profile and transforms the streaming through planar cavities into streaming through a porous medium, with cavities evenly distributed in the space, and thus reduces both the discharge profile and the water streaming velocity, and thus the reduction of the total discharge is significant.

The final permanent sealing phase included the implementation of the second phase works. In improved conditions after the completion of the first phase works, the second phase included grouting with respective masses that will fill the remaining cavities in the radius of activities and harden together with the already inserted inert material.

Installation of granular material

Filling of underground open structures, in accordance with the concept of repair, began with the installation of granular material at the Great Abyss site. A little over 1524 m^3 of granular material was installed in the abyss.

The installation of granular material continued at the borehole site on the upstream face of the dam in borehole RB-10. The initial phase of material installation was carried out as a test, in order to avoid congestion with the material. The material installation was carried out through the PQ cladded pipes of the drilling set, ∅122 mm in diameter, directly above the cavern which the material is installed. In the initial phase, 0-4 mm granular material was installed, at a very low speed, and over time, after the analyses, the installation speed was increased and adapted to the existing conditions. After the test installation, the mechanical installation of granular material was initiated with conveyor belts, first in borehole RB-10, and then in boreholes RB-4 and B-15. Through the PQ drilling set ∅122 mm, the maximum realized installation capacity was 4 m^3/h (Figure 30, left).

The expansions were then implemented after the significance of the underground structure in which the material was installed at these two locations was determined, first of the borehole B-15, and then RB-10 to a ∅500 mm diameter, with the aim of installing a larger quantity of material. Borehole B-15 was expanded to a total length of 51 m, i.e., to a depth of 101.5 m. The borehole RB-10 was expanded in the length of 109.9 m, i.e., to a depth of 167 m, measured from the elevation of 337 masl.

Larger diameters provided for a much faster installation of the granulate. Material jams occurred at higher installation speeds. The installation was carried out by gradually increasing the speed through expanded non-cased boreholes - from the initial test speed of 1 m^3/h, to a maximum of 22 m^3/h (Figure 30, right).

During 2013 and 2014, a total installed volume was about 37 000 m^3.

***Figure 30**. Installation of granular material through boreholes of smaller and larger diameter*

Additional quantities of granular material were installed after the works were continued during 2016 and 2018. The total quantity of granulate installed was about 46 777 m^3.

Grouting works

The final permanent sealing phase included the implementation of grouting works with respective masses that will fill the remaining cavities in the radius of activities and harden together with the already inserted inert material.

Grouting works were conducted via with different technologies for rock mass zones, i.e., boreholes or borehole sections, with different hydrogeological and geotechnical conditions.

In the zones with smaller cracks, final borehole grouting was conducted by ascending procedure, storeys 5 to 20 m, dense grouting cement masses, with additives on as needed bases.

Grouting in the zones of caverns and faults, with carstified channels and larger cracks, previously filled with granular material, was conducted in line with specific conditions, by a descending procedure.

In order to ensure good filling of cracks and sufficient radius of action, the choice of optimal grouting mass recipes and their changes during grouting was of particular importance.

The permeability and groutability of the rock mass of the subject storey were tested at the beginning of grouting of each storey.

During the three time periods of the binding materials installation, a total of about 8.5 thousand tons of cement were installed.

Material installation process management

The collection, analysis and processing of data obtained by the monitoring system, data on the installation of materials and other information recorded in the field were permanently performed during the repair works. Subject data were adequately analyzed via the presented mathematical models (Figure 31).

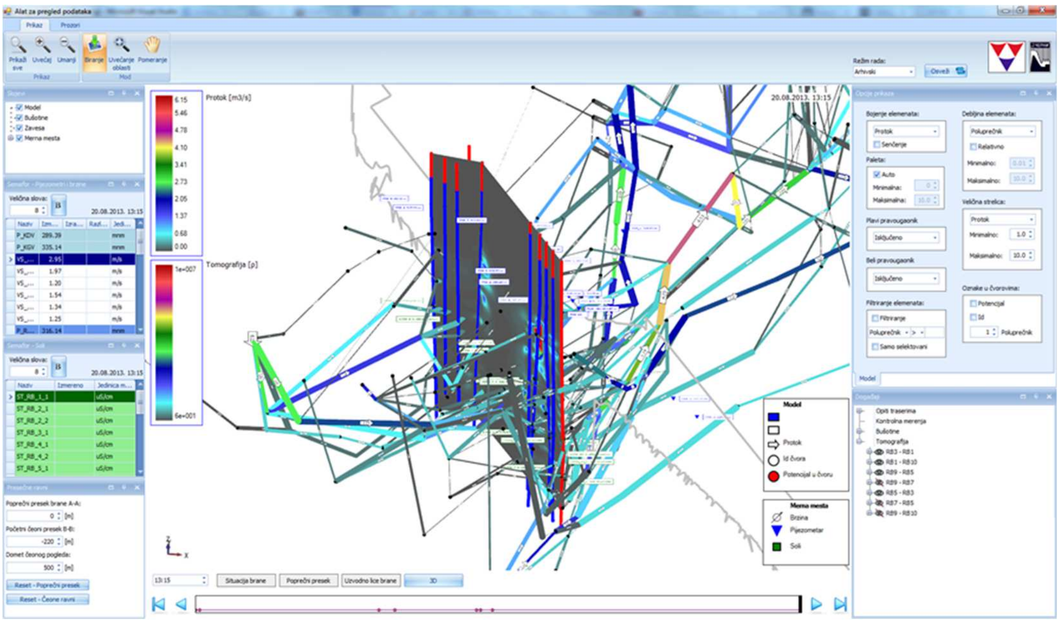

Figure 31. *User application for the system state monitoring*

During the installation of granular materials, the recipes (mixtures) of granulation were adjusted - the material that was installed at individual installation locations - based on the implemented computations, so that the material is taken to the farthest parts of the underground channel system, but also that no major quantity is brought out at downstream sources. A significant filling of the system of underground structures was achieved exactly with this adjustment of the granulation.

The exit of the grouting masses was monitored and the recipes were adjusted during the implementation of grouting works. The aim of the recipe adaptation was to have the binding materials installed as far away from the place of installation as possible, in order to bind as much granular material as possible.

EFFECTS OF REPAIR

The works carried out within the subject repair have largely achieved the preset goals. The total discharge was reduced from 14.6 m^3/s to 3.74 m^3/s (Figure 32). Reduction of seepage under the dam foundation was primarily achieved by installing granular material through the boreholes along the upstream face of the dam.

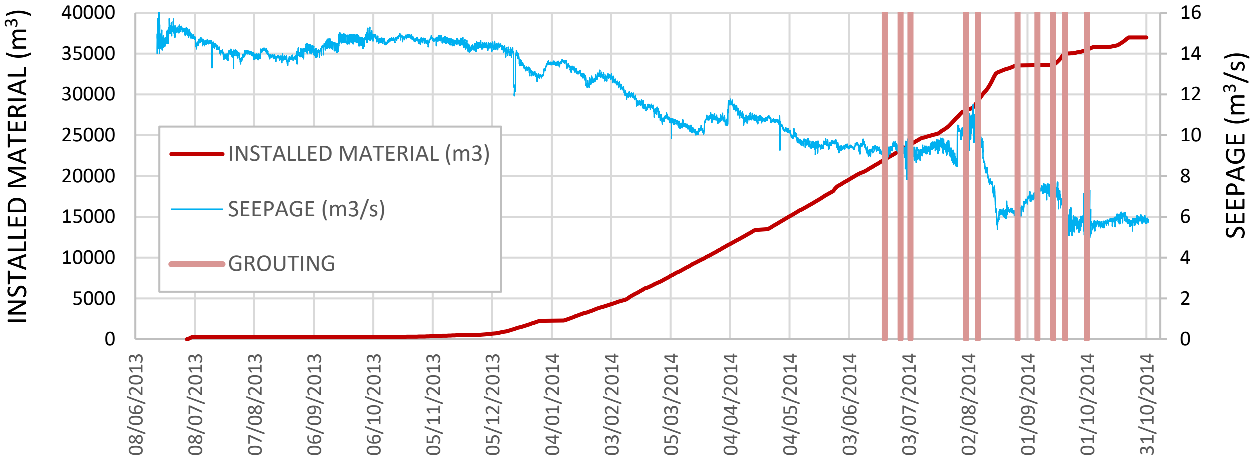

***Figure 32**. Effects of quantities of installed materials and achieved effects (2012-2014 period)*

The water velocities in the channels were reduced. After the repair in the zone below the dam structure there are no channels with a velocity higher than 0.5 m/s, while before the repair works there were channels with speeds over 1.3 m/s.

The discharges in the channels were stopped or reduced, in different channels to a different extent. Before the repair, there were several locations in the network with several individual channels with discharges over 2.0 m^3/s, and the maximum water discharge in the channel was over 5.5 m^3/s. After the repair works, the biggest discharges were in the same channels in which they were bid before the repair, but they were reduced several times. There were no channels with discharges greater than 1.2 m^3/s after repair (Figures 33, 34 and 35).

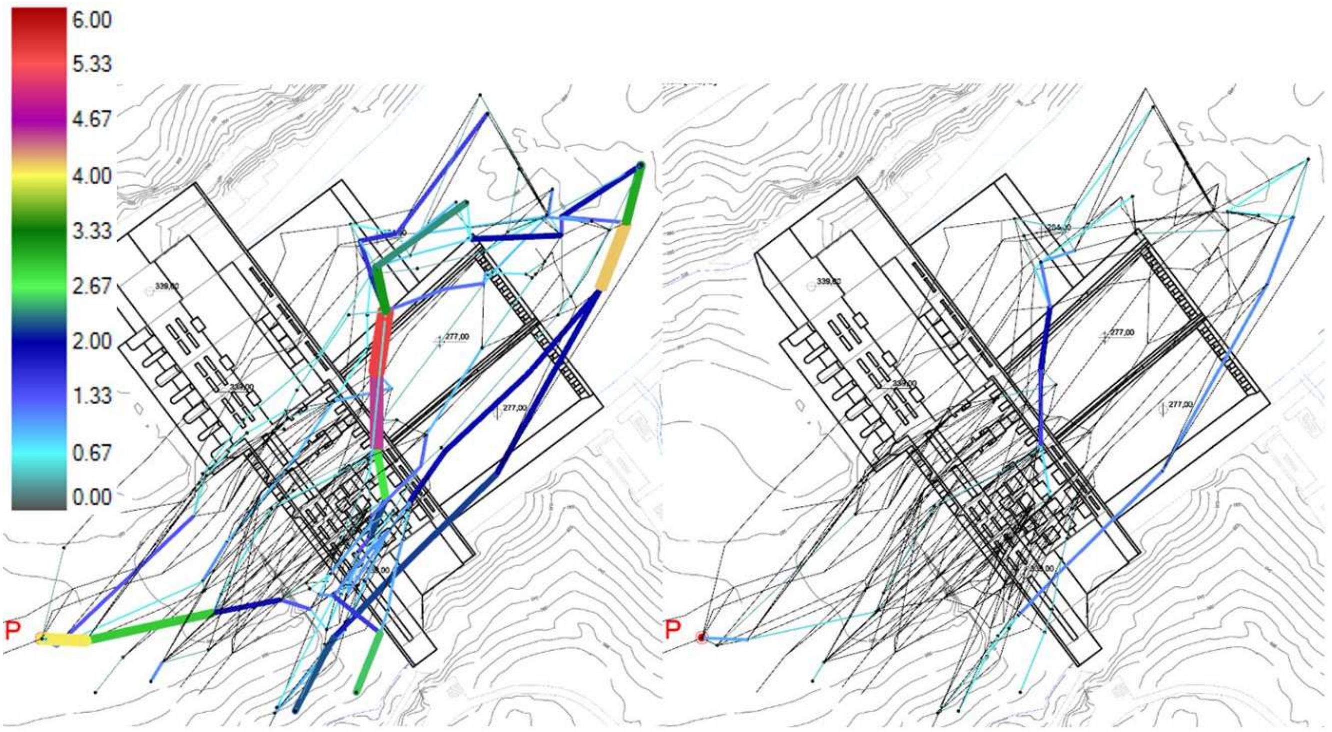

***Figure 33**. Layout of channels with water discharges (m^3/s) before and after repair*

Based on the sums of water discharges before and after repair – shown via layout and cross-section, one can be concluded that positive effects of discharge reduction were achieved in almost the entire channel system.

The best effects were achieved in the part of the channel system downstream of the sites where the mass installation was carried out. The most significant installation of granular material in the channel system, i.e., the largest quantities are installed in the channels drilled via the borehole RB-10, then B-15 and less via RB-4 in the channels at the site of the great abyss.

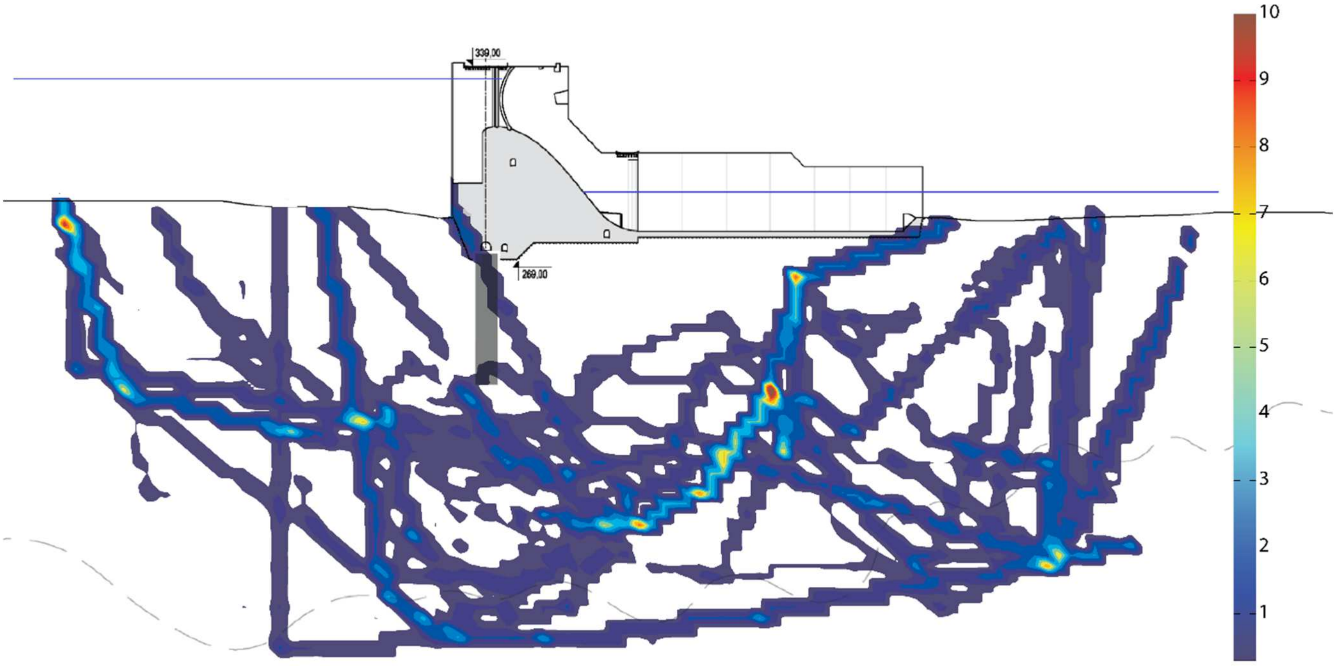

Figure 34. *Sum of water discharges in channels (m^3/s) before repair*

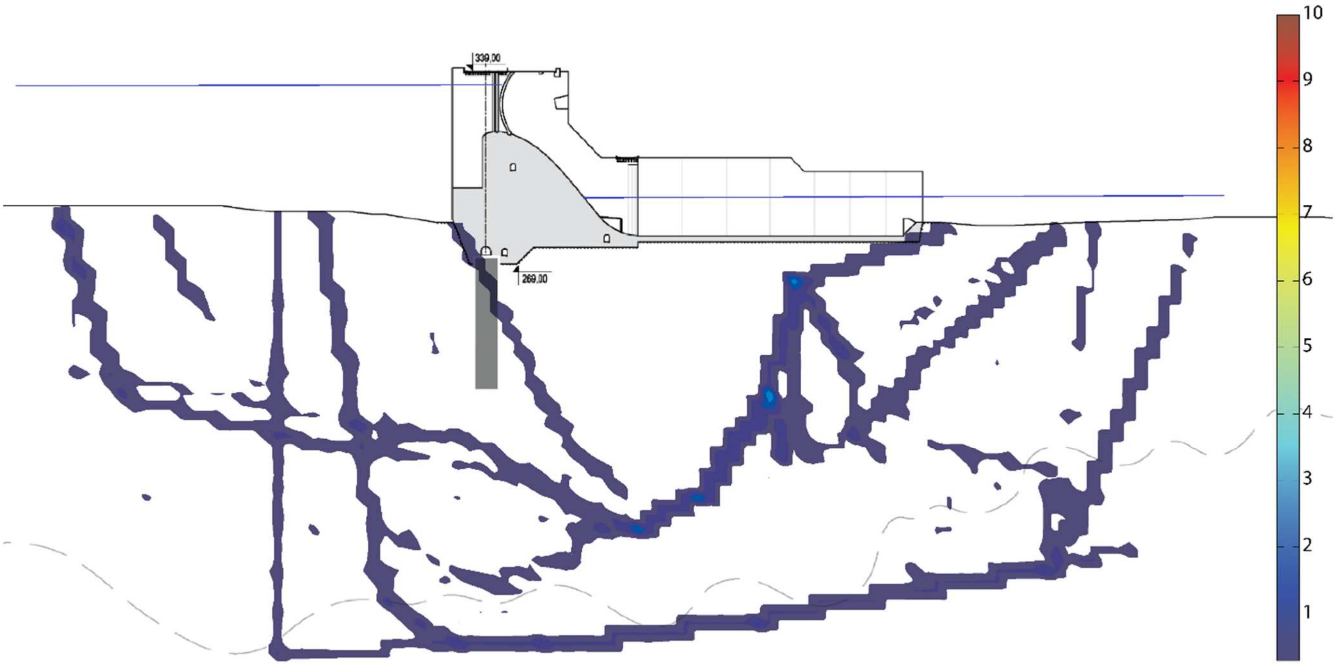

Figure 35. *Sum of water discharges in channels (m^3/s) after repair*

CONCLUSION

The Seepage under the HPP Višegrad Dam Repair Design is a pioneer undertaking in solving the problem of water seepage under (and around) high dams. Dedicated multidisciplinary investigations were carried out to define the directions of water movement under the dam body. The team of experts from the Jaroslav Černi Water Institute designed the concept of repair works, which included prior reduction of water velocities in underground channels, and then permanent binding of installed materials until the complete closure of structures which used to have an active water flow. Starting from the defined concept, the Institute developed the design documentation and made adjustments during the entire period of seepage repair works.

This concept of repair works could be successfully applied in other locations with similar problems.

However, the repair works were not implemented entirely in accordance with the Concept, due to various circumstances (financial, technical, etc.). The installation of binding materials was not done entirely in the part of the terrain where the granular material was installed, but it can be considered that the installed granular material is bound to the necessary extent only in the narrow zone of the dam body (part covered by the repair works).

Although at the time of writing this paper no indication of discharge increase over time has been detected in the remaining parts of the monitoring system, over time it can be expected that, in line with natural processes, there will be an intensification of the process of installed material rinsing and continued erosion due to the reservoir formation. Therefore, it is necessary to implement constant monitoring of all relevant phenomena both in the dam facilities and in the terrain around the dam and in the Drina riverbed downstream of the dam.

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PREFACE

Institute of Hydrology was established in 1947 within the Serbian Academy of Sciences. The Hydraulics Laboratory was established that same year within the Federal Ministry of Electricity, a predecessor of the later Hydropower Institute created in 1950. These two institutions were soon merged under the auspices of the Serbian Academy of Sciences into the Hydrotechnical Institute Eng. Jaroslav Černi. This Institute merged with the Serbian Water Management Institute in 1959 to create today's Jaroslav Černi Water Institute.

Over the past decades, the Institute has been the backbone of scientific research in the field of water in Serbia and the former Yugoslavia. The international scientific conference Contemporary Water Management: Challenges and Research Directions is organized to celebrate 75 years of the Institute's long and successful history. The Scientific Board selected 26 papers to provide readers with the best view of the current research results, as well as the further scientific research directions and potential challenges in the future. Selected papers are classified into six conference topics according to the corresponding research field, although one should note that most of the presented works is multidisciplinary, which is after all a characteristic of a modern problem-solving approach in the field of water. Hence, the chosen conference topics and corresponding papers represent only one possible way of classification of the presented works.

We wish to express our gratitude to the International Scientific Board and the Organizing Committee of this international conference for their efforts in selecting the papers, reviewing, and organizing the conference. We also wish to express our gratitude to all the authors of selected papers for the time they spent presenting the results of their research in a way suitable for this conference, and for contributing to the celebration of 75 years since the establishment of the Jaroslav Černi Water Institute. Respecting the importance of jubilee and wishing to express gratitude to previous generations of scientific workers, the Honorary Committee was also formed.

Following the path of previous generations, the Institute's present and future staff remain privileged, and under duty and obligation to continue and improve the scientific and research work of the Institute in the years and decades to come.

Belgrade, October 2022

Editors

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