Large arch dam safety management: Grančarevo Dam case study

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Abstract: Dams are structures whose safety must be given extreme attention, because any damage and demolition of dams could have unfathomable and catastrophic consequences on society and the economy. This paper presents the modern concept of safety management of arch dams with application to the Grančarevo Dam, which is based on the following significant postulates: data management, development of mathematical models for the analysis of thermal, filtration and stress-deformation processes and interaction of mathematical models with results of dam monitoring in order to be able to estimate the condition of the dam and evaluate its safety. The Grančarevo Dam is an arch dam that forms the largest reservoir in the Balkans, with a water volume of about 1.3 billion m^3. By applying the safety management system of the Grančarevo Dam, a three-dimensional FEM model of the dam and the surrounding rock mass was formed, and the state of thermal, filtration and stress-deformation processes was determined by applying the FEM model. As part of the stress-deformation processes, attention should be drawn to the fact that the damage to the right side of the dam has been determined and that the safety of the right side of the dam has been compromised.

INTRODUCTION

Dams are structures that have a significant impact on the economy and society. These structures form reservoirs that generate electricity, water supply, irrigation, sports, recreation, and other purposes. Dam damage or breakage (a rare occurrence) could have catastrophic effects on society and the economy, primarily in the loss of human lives. Dams are structures that are most often in operation for several decades. Long periods of exploitation can lead to the appearance of specific changes in dams, such as damage in the concrete structure, the appearance of cracks, damage in the rock mass, in the drainage system, in the grout curtain, which overall adversely affect the safety of the dam in interaction with rock mass and water. Due to its importance and enormous impact on society, the dam's safety must be ensured and monitored throughout its exploitation period. The arch dams that are the subject of this paper have specificities that require somewhat different approaches to monitoring and managing their safety compared to other types of dams. Arch dams are usually located in canyons formed of solid rock masses and exhibit two distinct types of behavior under load: arched and cantilevered. Compared to other concrete dams (for example, gravity dams), they differ in geometry, stress-deformation behavior, and how to transfer the load to the surrounding rock mass. Unlike gravity dams, where the load-bearing capacity is achieved by the massiveness of the concrete structure and friction on the foundation rock, arch dams reach the load-bearing capacity through their compact arch geometry that interacts with the rock mass, where the rock mass must have exceptional mechanical properties.

One of the significant problems and challenges regarding arch dams during construction and exploitation is the appearance of cracks. Various arch dams' structural cracks affect their integrity and safety. There are multiple examples around the world where cracks appeared on arch dams, either during exploitation or construction. In the 1960s, two extremely thin arch dams in France, La Gage, and Tolla had severe problems with the appearance of cracks [1]. At the La Gage Dam, cracks appeared on the face of the dam during the filling of the reservoir, which caused the dam to be abandoned. At the Tolla Dam, cracks appeared on the dam's downstream slope when the reservoir level was 20 m lower than usual, which required remedial measures to strengthen the dam [2]. At the Kolnbrein Dam in Austria, cracks were also observed on the upstream slope (face) of the dam, which caused significant leaks (as much as 200 l/s) and required serious remedial measures that cost about 190 million dollars [1]. At the Daganshan Dam in China, cracks were observed in the dam galleries before the reservoir was filled, and it was determined that they had been caused by the dam's weight [2].

Other phenomena and problems can threaten the safety of an arch dam, such as a problem with the dam's foundations. The Malpasset Dam in France collapsed in 1959 due to the left bank's low shear strength, caused by the rock mass's weak mechanical properties and mud-filled cracks [3]. At the Pacoima Arch Dam in the USA, due to an earthquake, there was a several mm gap between the dam's foundation and the rock mass. These gaps were repaired by installing prestressed anchors, but after a second earthquake, the anchors cracked [2]. In October 1960, a large landslide occurred in the reservoir of the Vaiont Dam in Italy; it led to an overflow of 50 million cubic meters of water, which killed about 3000 people [2].

Cracks in a dam and any other damage are monitored during the construction and operation of the facility. A system for monitoring and tracking during construction and operation must be installed on dams. Based on dam monitoring and other methods, conclusions are made about the condition of a dam and its safety. The importance of monitoring in the safety management of arch dams is massive. For example, we should mention the Malpasset Dam [3], which collapsed in 1959, and the available monitoring results were not analyzed. Yet the corresponding anomalies could have been observed, and the disaster could have been avoided.

The abovementioned damage and cracking of arch dams cannot be fully predicted. Still, the risk of their occurrence can be reduced through systems for continuous monitoring and managing dam safety. A dam's safety implies that it is always in a condition where it can fulfill all its designed functions without adverse consequences for people, the environment, or property. Over time, the operating conditions of the dam, the characteristics of the materials from which the structures were built, and the characteristics of the geotechnical mediums in which the structures were built change. Over time, the relationship of professional and social factors to safety criteria and risks (hydrological, seismotectonic, and others) changes, with occasional changes in standards and legal norms (especially about criteria and standards from the time of design and construction of the structure). In practice, the safety of dams must be managed throughout their entire operational life.

In world practice, different countries have different approaches to dam safety management. For example, the USA, Canada, Australia, and Argentina have separately enacted legal frameworks at the national level that apply to dam safety management activities. These laws include all the details for dam safety management. In South Korea, legal acts define the obligation of the respective institutions and organizations to carry out appropriate control and inspection of dams, with the preparation of adequate reports [4].

In South Korea, for example, their dam management organization has formed a Dam Safety Management System that applies to all dams. It defines detailed activities, warnings, reports, and work processes of all groups, from field engineers, office engineers, and dam safety experts, and central control of all information and databases [4]. Switzerland also implements a dam safety management system that includes a mandatory periodic visual inspection of dams and reservoirs and review of the results, preparation of annual dam safety reports, and detailed examination by an independent expert every five years [5].

This paper presents the modern concept of dam safety management with an example of the application of such a system to the safety management of the Grančarevo Dam. The Grančarevo Dam is one of the essential hydroelectric facilities in the Balkans (Figure 1); it forms the "Bileća" reservoir with a volume of approximately 1.3 billion cubic meters of water. It was built almost 55 years ago as the first step of the hydroelectric system on the Trebišnjica River. It is located 18 km downstream from the river's source and 17 km upstream from the town of Trebinje.

The Grančarevo Dam is a double curved arch dam with a more pronounced vertical curvature. The building height of the dam is 123 m, the lowest point of the dam's foundation is 280 meters above sea level, and the dam crown is 403 meters above sea level. The body of the dam consists of 31 blocks, and the surfaces that are in contact with each other were grouted after the dam was concreted. Thus, the concrete mass was brought to a state where it acts as a monolithic unit. The dam was designed with a perimeter joint, which follows the shape of the valley and separates the foundation from the body of the dam, which is symmetrical. The water-holding capacity of the rock mass in the barrier profile, as well as the interaction of the dam and the barrier structure, were ensured by grouting and drainage works, which formed a grout curtain with a length of 664 m and an area of 60,000 m^2. The main characteristics of the formed reservoir "Bileća" are as follows: the level of a maximum backwater – 401.31 masl, level of a normal backwater – 400.00 masl, minimum working level – 348.00 masl, the energy value of the reservoir – 1010.7 GWh.

Nowadays, the Grančarevo Dam is of great interest to experts and the general public because a few years ago, cracks were noticed in the right flank on the downstream slope, about which research was carried out. A project for the remediation of the right side was carried out (Jaroslav Černi Water Institute, 2020).

Figure 1. *Grančarevo Dam*

SAFETY MANAGEMENT CONCEPT OF ARCH DAMS

Objectives of dam safety management

The concept of dam safety management in the general sense, and therefore of arch dams, has as a general objective to enable continuous maintenance of the existing safety of the dam, its improvement in case of need, and timely prevention of safety threats.

To fulfill the general goal of the concept, it is necessary to establish a dam safety management system that should ensure the fulfillment of the following partial goals:

- Continuous monitoring of all relevant information and efficient implementation of all procedures related to dam safety by expert services at the dam.
- Facilitating timely decision-making regarding dam safety by management and competent institutions.
- Formation of a single information system for data management, unification of safety criteria, unification of technology, and harmonization of the work organization of professional services related to dam safety.
- Effective implementation of periodic (annual) inspections with control computations and preparation of relevant reports on technical monitoring with safety analysis and assessment of the dam's condition by an authorized institution.
- Transparent control of the dam safety management process by competent institutions.
- Informing the public about relevant issues related to dam safety.

Procedures and processes for managing the safety of dams must be constantly improved in the field of technical monitoring, in the way of data management, as well as in the ways of using data in the procedures for determining the safety of structures and thus determining the optimal way of their maintenance.

The functionality of the Dam Safety Management System

The dam safety management system includes the following functionalities:

- A system for measurement, collection, acquisition, and archiving all relevant data and information observed at the dam.
- A system for data analysis through various applications that can enable access to data, based on which quality control and validation can be performed, based on which historical series of measured data can be reviewed, and statistical models can be formed.
- Appropriate mathematical FEM models for modeling thermal, filtration, and stress-deformation processes. In the case of mathematical models, there is an interaction between individual processes so that thermal fields, as a result of thermal processes, and filtration forces, as a result of filtration processes, are used in the model of stress-deformation processes as a load.

- Estimation of the state of thermal, filtration, and stress-deformation processes implies that the formed FEM model should be brought to a state where it describes the dam's behavior as realistically as possible, a behavior that corresponds to the condition observed.
- Adequate criteria for assessing dam safety based on appropriate legal frameworks and rules of the profession.

Software-hardware structure for safety management support of the Grančarevo Dam

To support the safety management of the Grančarevo Dam, a set of software/hardware components was formed, grouped into a system for measurement and data collection, acquisition server, central database server, central computation server, user subsystem for data analysis, user subsystem for condition and process analysis, and admin tools. Figure 2 shows the current software-hardware structure for the support of the Grančarevo Dam Safety Management System.

System for measurement and data collection

The measurement and data acquisition system include all measurement and acquisition equipment and all equipment and software for temporary data storage. Equipment and software for temporary storage serve the purpose of storing all measurement data, both data originating from the automatic acquisition process and manually recorded data. These first data are downloaded using software from the measuring equipment manufacturer.

If necessary, the intended software also performs a certain level of processing of the measured data, which is specific to the given equipment. Data collected on computers with the intended software can be temporarily archived as text files or databases. For manual entry, an application enables the entry of data relevant to safety management, which is not covered by automatic acquisition systems on existing measurement and data collection systems.

Acquisition server

The acquisition server is a set of hardware/software components connected into a single unit that is used for downloading, validating, and preparing the data temporarily stored on the measurement and data collection system to send the data to the central database server. If the measurement and data collection system are incomplete, i.e., if the equipment and software for temporary storage are not implemented fully, the acquisition server takes over their role (direct communication with equipment and devices for measurement and acquisition). The acquisition server consists of the following elements: a data reception and validation layer and a data layer.

Central database server

The central database server is a set of hardware/software components connected into a single unit that coordinates, distributes, synchronizes, stores data, and manages access to data and services. The central server is located in the center of the information and communication infrastructure of the system, and all the other system elements communicate with it to a certain extent. The central computation server uses data from the central database server, the user subsystem for data analysis, and the user subsystem for condition and process analysis.

User subsystem for data analysis

The user subsystem for data analysis is a set of user applications used for searching, accessing, downloading, and analyzing historical, i.e., archival measurement data and tracking measurement data in real-time alongside the results of statistical models. All user tools are modern, graphically-oriented applications enabling intuitive operation and data exchange with other commercial user applications. The user data analysis subsystem includes a user tool for viewing historical data, a user tool for monitoring real-time data, a user tool for expert data analysis, and a user tool for creating reports on measurement data.

Central computation server (Mathematical models)

The central computation server is a set of hardware/software components connected to a single entity that provides the infrastructure necessary for using mathematical models to monitor and analyze dam facilities' safety. Due to the specificity and complexity of the calculations performed with physically based models (FEM models), the hardware platform of the central computation server and the system software should enable the parallelization of computations and have the possibility of periodic upgrades.

Within the central computation server, computation is performed on FEM models using appropriate numerical solvers, measurement and computation data integration, and calculation management. Calculations on FEM models are performed using numerical modules that ensure safe implementation of individual and compound FEM calculations and unified access to results. There are special numerical modules for the simulation of thermal processes, filtration processes, and stress-deformation processes. Computations are carried out on a single finite element grid, which analyzes all processes. Given that there is a whole system of observations and measurements at the dam, the measurement data is integrated with the data obtained based on the results of calculations using the FEM model for the corresponding processes.

User subsystem for state process and safety analysis

The user subsystem for state process and safety analysis is a set of user tools specifically created to solve realistic problems in dam safety management. The tools work with the computation server, that is, with FEM models. The functions of the tools refer to the assignment of tasks for the analysis of the condition of and processes in the dam (including the assignment of all necessary input data, as well as instructions for computing) and downloading, processing, displaying, and analysis of computation results.

The user subsystem for condition and process analysis within the Grančarevo Dam safety management system includes a user tool for estimating the dam's condition and a user tool for analyzing the safety of the barrier structure. All the user tools are modern, graphically-oriented applications that enable intuitive operation and data exchange with other commercial user applications.

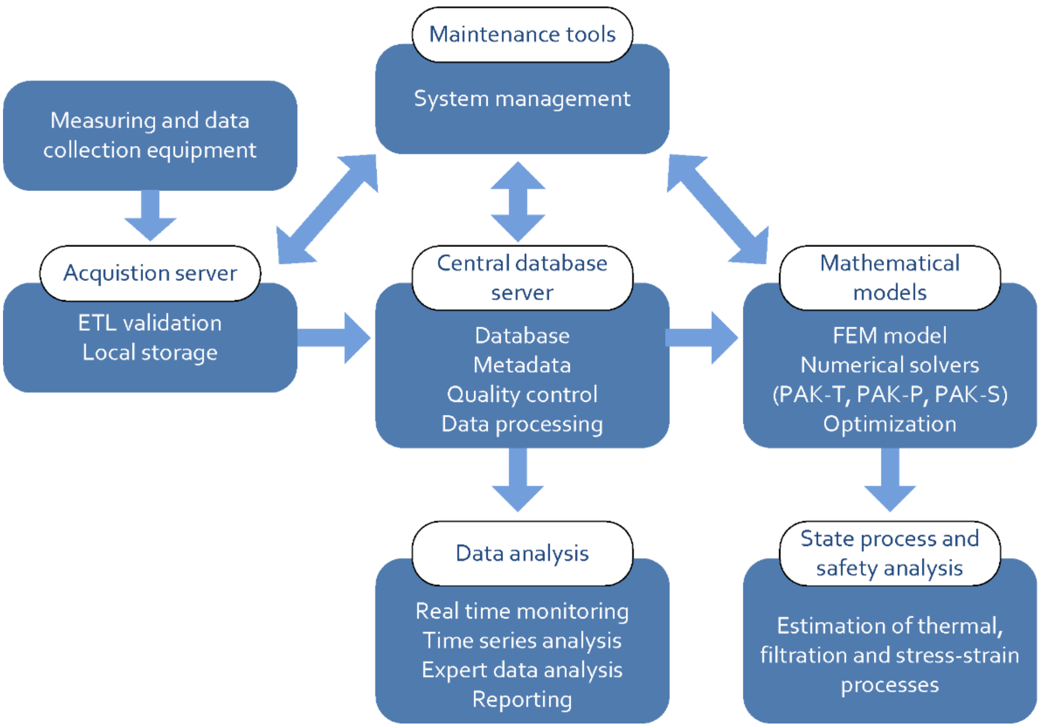


Figure 2. *Software-hardware structure for safety management support of the Grančarevo Dam*

DATA MANAGEMENT

Types of measurement

At the Grančarevo Dam, the following observations are made within the monitoring system:

- Meteorological and hydrological observations – the water level in the reservoir, tailwater level, air temperature, water temperature in the reservoir, precipitation, air humidity, atmospheric pressure, water evaporation, wind strength and direction, and soil temperature.
- Observation of water filtration - uplift and water table in the foundations of the dam, the water table in the broader area of the dam, flow of seepage water at drainage boreholes, hydrometric stations, and deep drainage piezometers, flow at springs, and total seepage through the dam profile.

- Geodetic observation of the dam and the surrounding terrain - horizontal displacement (alignment and microtriangulation), vertical displacement (precise leveling).
- Observation of the dam structure - concrete temperature, relative horizontal movement of the dam body, change in slope of the dam body, work of perimeter joints, work of radial joints, work of cracks, the stress in the foundation zone, on the upstream and downstream slopes of the dam, deformation in concrete.
- Observation of rock deformation in the foundation zone (long foundation bars - slitometers, inverted plumb line, invar tapes, rock extensometers, monitoring in the inspection tunnel - clinometer, deformeter).
- Observation of the anchor field - the force in the prestressed anchors and the change in the length of the measuring bases.
- Seismic observation (seismograph and accelerographs).

Equipment and devices for measurement and acquisition are represented by different measuring instruments, from instruments with fully automated measurement, reading, and data transfer procedures to instruments with manual reading and recording results, which require their subsequent manual input into the system.

The total number of active measuring points on the dam and the surrounding area is 549 (without geodetic measurements), of which 376 are performed manually, and 246 are performed electrically, that is, automatically. Specific measuring points are observed in both ways (in the total number of measuring points, they are counted as one measuring point). 141 geodetic points are included in the complex geodetic network on the dam and the surrounding terrain (they are in the database), and geodetic measurements and processing result in a total of 272 series of point displacements in one of 3 directions (X, Y, and Z).

Data acquisition, processing, and storage

The system used for automatic acquisition and storage of measurement data is the Sentinel software (with a Microsoft Access database), from where they are then, using specially developed procedures, imported into the central database of the Safety Management System (where they are further archived and used). Data from the Sentinel database is automatically downloaded regularly, based on previously developed patterns, by reading CSV files that are periodically created.

Using the manual input tool, frequent data entry is performed through a web-based interface with programmable predefined electronic forms equivalent to paper forms for recording measurements. During manual entry, with the help of this tool, pre-defined mechanisms of preliminary validation of the entry are applied, which prevents data entry with a gross error. For mass data entry, the tool forms patterns for reading data files and validation at the level of interpretation of the data read from the files. This tool functionality proved to be very practical when, due to technical limitations, it is impossible to provide fully automatic data transfer from individual loggers or divers.

Archival measurement data from earlier databases (mostly Excel files) were downloaded and consolidated in the central database. The system processes all the collected data, i.e., calculation of engineering values from measured values and, as necessary, aggregation of data (average, maximum and minimum values) according to a specific time step (daily, monthly, yearly).

Quality control of measured technical data

The measured technical data, in addition to the value of the quantity, also has attributes that include a record of the conditions under which the measurement was performed, the time when the measurement was performed, information about the measuring instrument, information about the state of the measuring equipment and other relevant information. One of the more critical attributes is information about the quality of the data itself. This attribute is calculated in the Quality Control of Measured Technical Data (hereafter QCMTD). QCMTD occupies an important place in the Safety Management System. It is carried out after the data acquisition process and its validation before entering the data into the central database with all the accompanying attributes. The task of data validation is to roughly evaluate and assess whether the data quality can and should be determined in the QCMTD process (if satisfied with the required data format).

In the QCMTD process, the following quality attributes are attributed to each piece of data: quality rating (in the range 0-1), a measure of the reliability of the quality assessment, and a diagram or list of methods by which the quality assessment was carried out. Figure 3 shows an example of a series before and after the application of QCMTD.

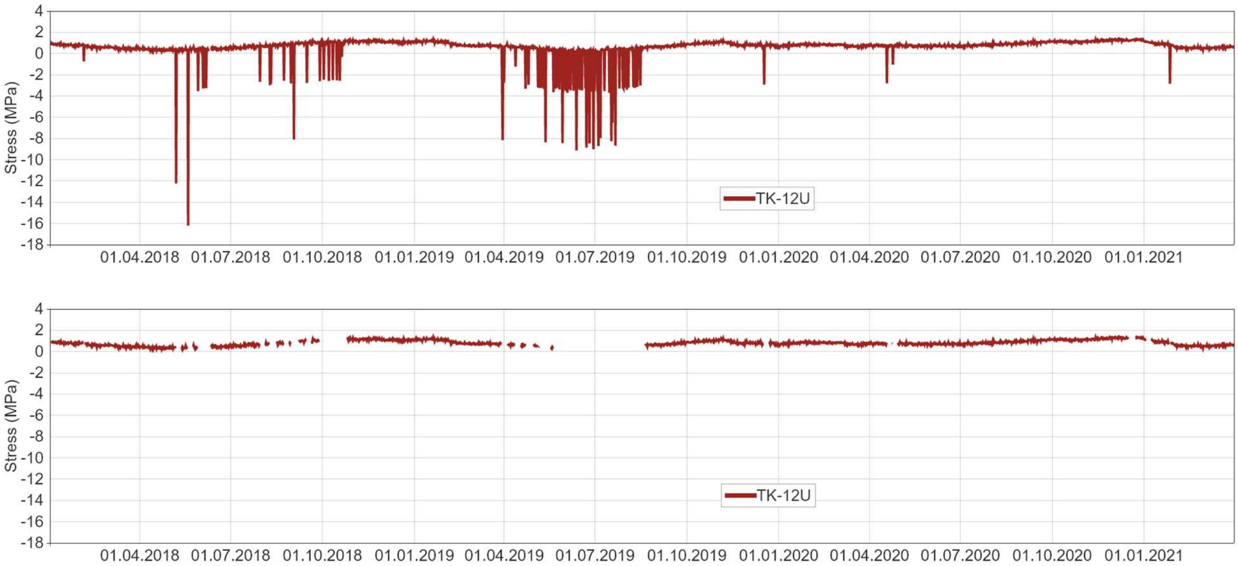


Figure 3. *Measured stress values in the foundation joints before and after the application of QCMTD*

Statistical modeling

Statistical models establish a connection between indicators of the dam's behavior (observed quantities - displacements, deformations, stresses, etc.) and indicators representing external influences that affect the structure (primarily, external temperature and the water level in the reservoir). Statistical models are used in the dam management process to determine whether the dam is behaving normally and whether individual measured values are within the expected ranges.

Figure 4 shows the expected values obtained based on the statistical model and the measured values of relative displacement of the rock mass in the foundation zone. It can be seen how the statistical model outside the expected ranges obtains the measured values of relative displacement in the last two years. Figure 5 shows the typical values based on the statistical model and the measured value of uplift at one measuring point.

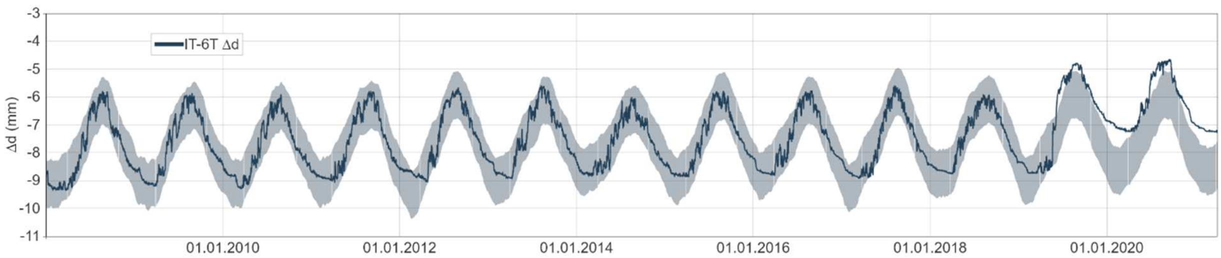


Figure 4. *Statistical model (expected values) and measured values - relative displacement (deformation of the rock in the foundation zone) in the direction of the invar strip IT-6T*

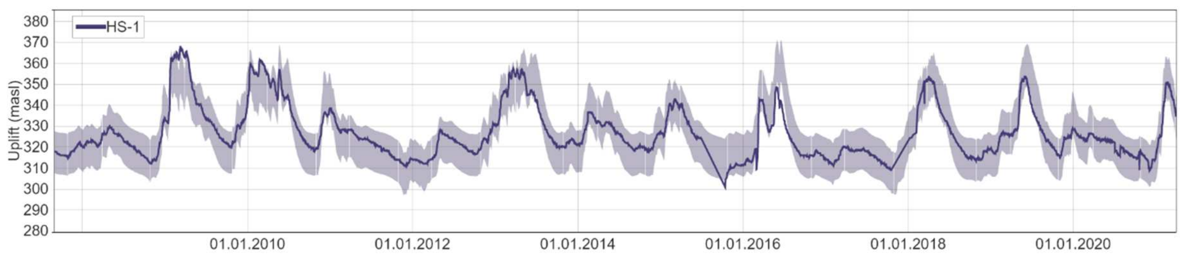


Figure 5. *Uplift (expressed as the corresponding water level), measured by a piezometer with a manometer HS-1*

Data review

It is possible to review data through the user tool for viewing historical data and a tool for viewing data in real time, which are located within the software-hardware structure (Figure 1) within the user subsystem for data analysis. With the tool for viewing historical data, the user can view the entire systematized system of technical observation with an organized and straightforward overview of all the measurements performed on the dam, starting from the construction period of the facility. In the tool, interactive graphics are available with the precise locations of all measuring points, as well as all available data series in the system with a defined convention, characteristics of the equipment used with accompanying documentation (catalogs, user instructions, photos...) and records of when which equipment was introduced in into the system, serviced or archived, if it is no longer used for any reason. An example of one work screen of the mentioned tool is given in Figure 6.

Figure 6. *The relative displacement of the central Block 17 in the radial and tangential directions*

The tool for viewing data in real-time enables the review of current measurement values at the dam and measurements in the recent past. It is used for daily, regular monitoring of the facility's state. The tool signals when specific measurements have been interrupted (in the case of missing data according to the previous collection dynamics), when the measurements are of poor quality (according to previously defined and implemented procedures and criteria), and when the measurements are outside the expected measurement ranges, calculated based on a statistical analysis of measurements from the previous period. An example of the practical use of statistical models from the tool in question is given in Figure 7.

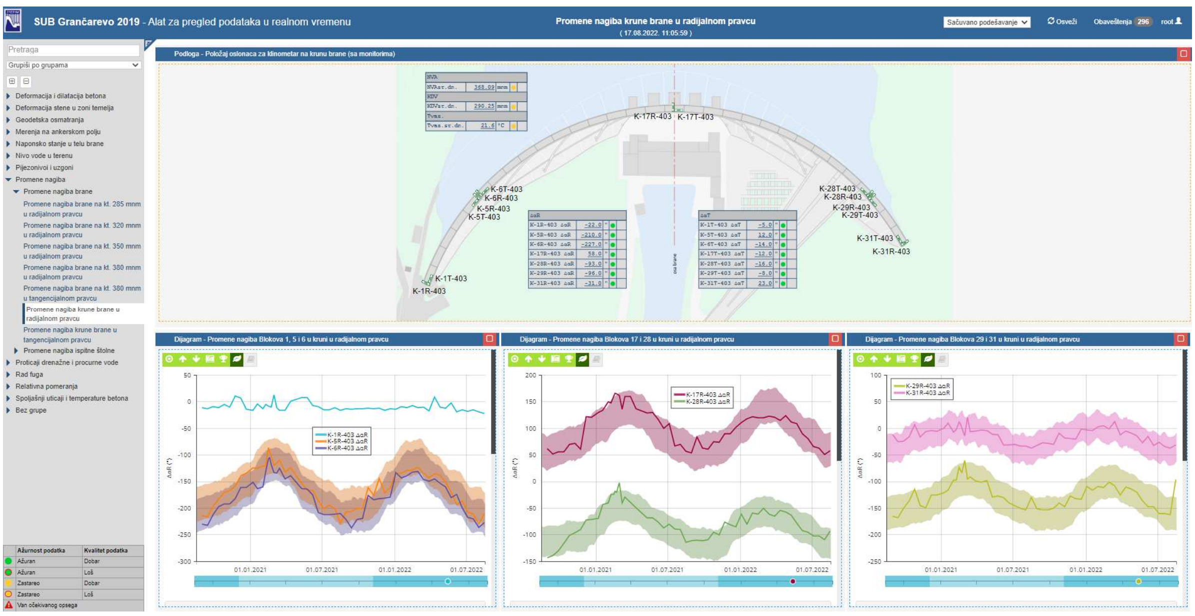


Figure 7. *Changes in the slope of the dam crown in the radial direction*

MATHEMATICAL MODELS

FEM model of the Grančarevo Dam

Different types of loads influence arch dams, the most important of which are the weight of the structure itself and the surrounding rock mass, temperature effects, hydrostatic water pressure and filtration forces, effects of seismicity, waves, and other relevant effects. Based on the loads to which they are exposed, three types of processes are analyzed at the dams: thermal, filtration, and stress-deformation. Thermal processes study the temperature fields in the body of the dam for various external temperature conditions. In the case of filtration processes, potential fields, uplift, and filtration speed are analyzed for various conditions of external water loads. Stress-deformation processes analyze displacement, deformation, and stress fields, considering the interaction with thermal and filtration processes.

In the case of arch dams, these processes are most often simulated using mathematical models based on the finite element method [6-10], which considers the arch dam's actual structure and surrounding terrain, as well as other functionalities. For the simulation of all relevant processes at the Grančarevo Dam, a three-dimensional FEM model of the Grančarevo dam was created (Figures 8 and 9) that integrates the structure of the concrete construction of the dam, the terrain, the grout curtain, the drainage boreholes, and the anchor field. The model covers terrain 500 m downstream and 250 m upstream. The lateral boundaries are 600 m from the axis of the dam. The lowest elevation of the model is at 0 masl. A detail of the concrete structure of the dam and grout curtain is shown in Figure 8b. The finite element grid is created using tetrahedral finite elements with intermediate nodes (with 10 intermediate nodes per element). The FEM model consists of 1021695 nodes and 718920 elements.

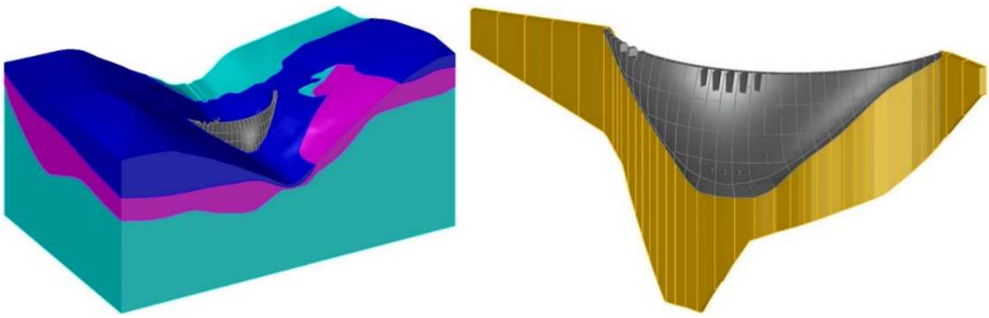


Figure 8. *3D view of the structure of the dam and the rock mass (a) and the structure of the dam and the grout curtain (b)*

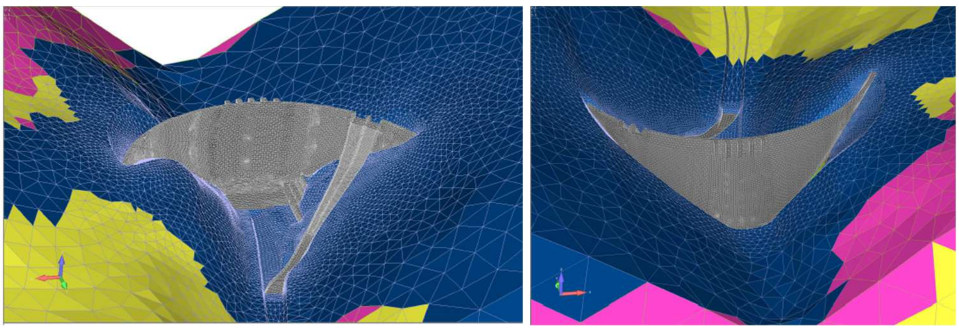


Figure 9. *FEM model of the dam and the surrounding rock mass*

The FEM model is divided into an appropriate number of quasi-homogeneous zones so that all details can be considered when simulating all relevant processes at the dam. In the FEM model, the concrete part of the dam is divided into a total of 91 quasi-homogeneous zones (62 zones in the body of the dam and 29 zones in the perimeter). An appropriate division was made according to the height of the dam blocks. Each dam console is divided into at least one zone (blocks closer to the dam's sides); for example, the central console is divided into 4 zones by height. The grout curtain is divided into 36 quasi-homogeneous zones (below each block of the dam, the grout curtain is defined as a separate quasi-homogeneous zone) (Figure 8b). The spillway and the anchor field wall are treated as one zone. Drainage boreholes are modeled as 1D finite elements, and each borehole is modeled separately (41 drainage boreholes are modeled in total). The surrounding terrain is divided into three quasi-homogeneous rock mass zones.

The formed FEM model of the Grančarevo Dam is used to simulate all relevant processes, considering the interaction between the mentioned processes. It is necessary to know the parameter values of all the processes. The parameters are defined for each quasi-homogeneous zone in the model. In most cases, they are determined using the FEM model and based on the results of the technical observation of the respective processes.

Modeling of thermal processes

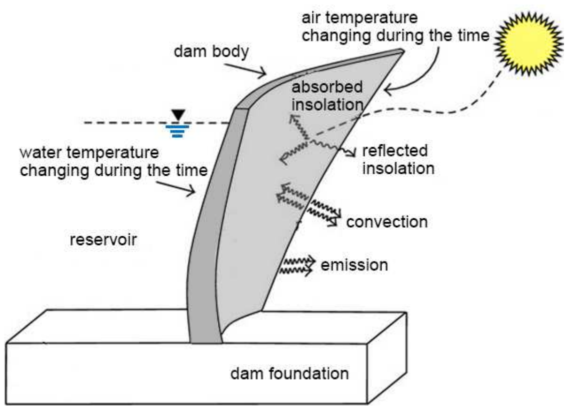
Modeling of thermal processes implies applying the FEM model of the dam, the appropriate solver for executing the FEM model, parameters of thermal processes, and boundary conditions to obtain the thermal field at any integration point in the model. Thermal processes are essential in arch dams to determine the stress-deformation state and assess the dam's safety. However, to determine the stress-deformation states, it is necessary to know the temperatures of the concrete part of the dam. Temperature effects on deformations in part of the rock mass can be disregarded because the rock in the foundation is largely isolated from seasonal temperature changes.

An important fact related to temperature effects is the presence of the delay effect of the concrete temperature in relation to the ambient temperature. This effect is also visible in the results of auscultation measurements on thermometers in concrete. For example, at some point in time, the temperature on the dam's surface is significantly different from the concrete's. This delay can be of several days, weeks, or even months and usually depends on the massiveness of the concrete structure. In this sense, the analysis of thermal effects must be performed for non-stationary conditions in which the time component is considered. Thus, the effect of the delay is also taken into account. A seven-day time step was adopted for the thermal analysis at the Grančarevo Dam.

To model thermal processes, it is necessary to know the appropriate external thermal influences, which include air temperatures, water temperatures, and solar radiation. Figure 10a shows all the ways of heat exchange between the concrete body of the arch dam and the surrounding area. The air temperature is set as a boundary condition on all non-wetted surfaces in the model (red in Figure 10-right). The water temperature is set as a boundary condition on the wetted surfaces of the model (green in Figure 10-right) according to Bofang's distribution by accumulation depth [11]. In addition, the transition of water temperature to concrete and air temperature to the concrete are also set. Solar radiation is applied to non-wetted concrete surfaces via a constant temperature flux condition that depends on the intensity of the radiation and the angle at which the sun's rays fall on the dam. All boundary conditions are set based on observed air temperatures, water temperatures, and solar radiation for a given location. Given that non-stationary calculations are being analyzed, thermal boundary conditions are assigned to the FEM model of the dam in the form of a series with a seven-day step.

In addition to the given thermal boundary conditions, for modeling thermal processes, it is necessary to know the corresponding parameters, which include: the specific heat capacity of concrete (c_p), coefficient of heat conduction (k), coefficient of heat transfer from air to concrete (h_a), coefficient of heat transfer with from water to concrete (h_{wc}), correction coefficient of measured radiation, the temperature in the foundation of the dam (T_r), coefficient of heat transfer from rock to concrete (h_{rc}), and specific heat of the rock mass in the foundation of the dam (c_r).

The values of the parameters of thermal processes must be determined for the realistic observed conditions in the field that correspond precisely to the Grančarevo Dam. The parameters are determined by applying the FEM model and the observed temperature measurement results at the dam by searching for the optimal combination of thermal parameters so that the best matches between the measurement results and the calculation results are obtained. The numerical solver PAK-T [12,13] is used to execute the FEM model during the simulation of thermal processes at the Grančarevo Dam.



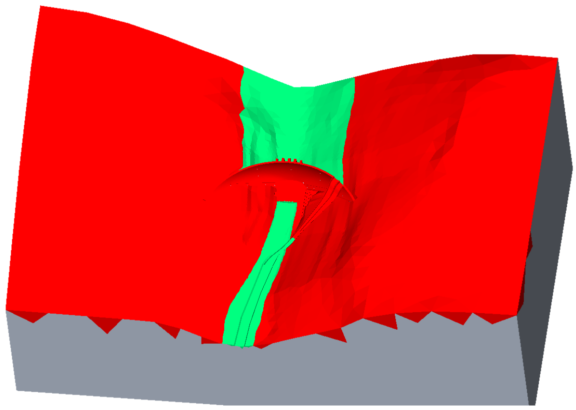


Figure 10. *Heat exchange between the dam and surroundings (left), given thermal boundary conditions on the FEM model (right)*

Modeling of filtration processes

Modeling of filtration processes involves the application of the FEM model of the dam, the appropriate solver for executing the FEM model of filtration processes, parameters of filtration processes, and boundary conditions to obtain the field of filtration quantities at any integration point in the model.

As a result of modeling filtration processes, the potential field, filtration speed, gradients, and uplift are obtained at any integration point in the FEM model and the flows on any surface in the model. Due to the significant interaction of filtration processes with rock mass, these processes are analyzed in both concrete and rock mass. When analyzing the observation results of the water table and flow, no delay in the measurement values was observed depending on seasonal changes. As a result, the assumption that the filtration field can be analyzed for stationary boundary conditions was adopted.

From the boundary conditions in the FEM model, the water levels at the boundaries of the model and on the wetted surfaces of concrete and rock mass are set. Based on the analysis of the measured water tables in the rock mass on the boundaries of the model, it was determined that variable boundary conditions must be set. On the upstream wetted surface of the rock mass and concrete, the headwater potential was set; on the downstream wetted surface of the rock mass, the tailwater potential was set (Figure 11). On non-wetted surfaces, the boundary condition of free draining is given [14].

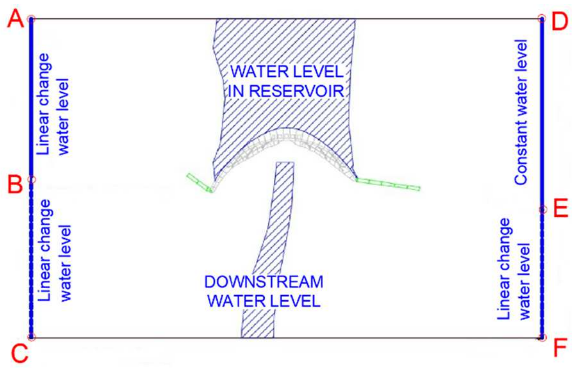


Figure 11. *Filtration boundary conditions at given potentials (water levels at model boundaries are defined at points A, B, C, D, E, and F)*

To perform filtration calculations, it is necessary to define the values of the filtration process parameters. For each quasi-homogeneous zone in the model, the value of the filtration coefficient must be determined. Given a large number of quasi-homogeneous zones (concrete, rock, grout curtain, drainage boreholes), appropriate assumptions were introduced about grouping zones with similar filtration characteristics into one zone with one value of the filtration coefficient. In this sense, the rock mass is divided into three quasi-homogeneous zones, the concrete structure of the dam is treated as one quasi-homogeneous zone, the grout curtain is divided into 8 quasi-homogeneous zones, the drainage boreholes are divided into less drainable and more drainable, and drainage boreholes that simulate the source have been introduced (6 groups in total). The parameters also include the variables used to determine the lateral boundary conditions (six parameters). Based on the grouping of individual zones, with assumptions justified in engineering, it is concluded that it is necessary to determine 27 parameters for modeling filtration processes.

The FEM model and the results of observing the water table and flow determine the parameters of filtration processes. The process involves performing many computations and finding the optimal combination of parameter values (27 values) to obtain minimal deviations between the measurement and computation results.

The numerical solver PAK-P [14,15] is used to execute the FEM model during the simulation of filtration processes at the Grančarevo Dam.

Modeling of stress-deformation processes

Modeling stress-deformation processes on the dam includes applying the FEM model, the appropriate numerical solver, boundary conditions, and parameters to determine the fields of displacement, stress, and deformation and the dam's safety. Stress-deformation processes are coupled with thermal and filtration processes. Based on temperature fields, thermal deformations are obtained when modeling stress-deformation processes. Additionally, filtration forces resulting from modeling filtration processes are used as a vector of nodal forces when modeling stress-deformation processes.

The state of stress-deformation processes depends on the applied constitutive model of the mechanical behavior of the rock mass and concrete. These models can range from simple elastic to complex models with hardening and damage in stiffness and strength. Due to the significant development of computers and software, the application of more complex models is more expedient. Various researchers have dealt with applying these complex damage models to model arch dam behavior [16-20].

To define the mechanical behavior of the rock mass and concrete at the Grančarevo Dam, the elastoplastic constitutive model of materials with plastic damage was applied [18, 21-23]. Using this constitutive material model, the most complex stress-deformation state in the material can be simulated in the form of damage in strength and stiffness. Based on various examples from world practice, the appearance of cracks and damage is frequent, especially in the concrete structure of an arch dam, so this constitutive model is a rational solution for simulating such damage and phenomena.

In the theoretical formulation of constitutive models with damage, a stress drop and material stiffness drop are taken into account as a function of a variable called damage or degradation, which is associated with the development of plastic deformations. Due to the occurrence of damage to the material, the elastic constitutive matrix changes depending on the damage in the material by correcting the value of the modulus of elasticity according to the following relation:

$$\mathrm{E} = (1 - \mathrm{d}) \cdot \mathrm{E}_0 \quad (1)$$

where *d* is the damage (degradation), variable, and E_0 is and the initial modulus of elasticity without damage.

The following relation defines the expression for stress:

$$\boldsymbol{\sigma} = (1 - \mathrm{d}) \cdot \bar{\boldsymbol{\sigma}} \quad (2)$$

where $\bar{\boldsymbol{\sigma}}$ is the effective stress at which there is no damage and which is defined by the following relation:

$$\bar{\boldsymbol{\sigma}} = \mathbf{C}^{\mathrm{e}} \cdot (\boldsymbol{\varepsilon} - \boldsymbol{\varepsilon}^{\mathrm{p}}) \quad (3)$$

where $\boldsymbol{C}^e$ is the elastic constitutive matrix without damage.

During the deformation, there is a change in the material's stiffness as a result of the development of plastic deformations and degradation. For the sake of illustration, the stress-deformation dependence is shown in the uniaxial pressure test (Figure 12a) and in the uniaxial tension test (Figure 12b), where the unloading after reaching the peak strength is also analyzed. It is observed that the unloading develops along a line that has a smaller slope, that is, less stiffness compared to the initial upward part of the curve. The slope of the unloading line depends on the previously realized value of variable degradation in the material and the value of the initial modulus of elasticity.

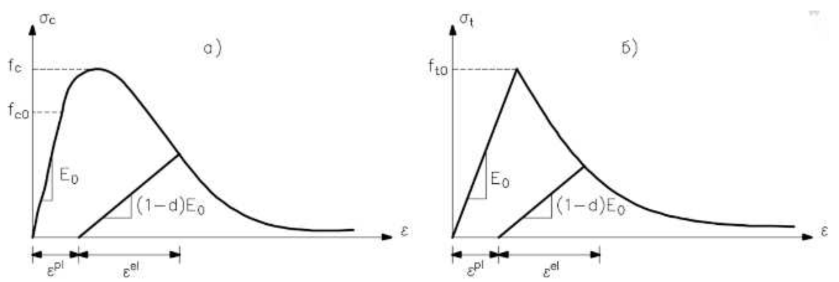


Figure 12. *The behavior of the damage plasticity model during uniaxial pressure a) and uniaxial tension tests b)*

16 parameters define the mechanical behavior of the materials using the damage plasticity model. The behavior of the materials in the elastic domain is determined by the initial modulus of elasticity and Poisson's coefficient. Material failure under uniaxial loads is defined by compressive and tensile strength. The capacity of plastic deformation after reaching material failure is determined by the compressive and tensile fracture energy and the degradations that define the shape of the deformation curve. The material's behavior under a complex stress state is regulated by the friction parameter that determines the slope of the flow function in the meridian plane and the parameter that defines the shape of the flow function in the deviatoric plane. The dilatancy parameter regulates the plastic deformation capacity. Other parameters have no physical meaning, but they regulate the numerical algorithm [24].

The parameter values of the damage plasticity model must be determined for each quasi-homogeneous zone, which is a highly complex task because there is a large number of quasi-homogeneous zones in the model and a large number of parameters, yet a limited number of data points based on which these parameters would be determined. According to the definition of the model, for each parameter, it would be necessary to have appropriate tests of uniaxial compression, tension, cyclic pressure, cyclic tension, triaxial compression, and others. However, it is practically impossible to have such experiments on the scale of the dam facility. Different approaches and methods for defining parameter values must be applied. Similar to thermal and filtration processes, specific parameters can be determined using the FEM model and technical monitoring results in stress-deformation processes. However, most parameters that define material failure cannot be determined based on monitoring results because, fortunately, the dam is not in failure. So, some other methods and approaches must be applied for these parameters (literature data, in situ failure tests, etc.).

The numerical solver PAK-S was used to model the stress-deformation processes at the Grančarevo Dam [25, 26].

STATE ESTIMATION AND SAFETY ASSESSMENT OF GRANČAREVO DAM

General outline related to dam state estimation

As is well known, dams are structures that have been in operation for several decades and are exposed to various physical and mechanical processes. As a result, there is often a change in the properties of the rock and concrete materials; there is degradation in the materials, the appearance of cracks, erosion of the rock mass, damage to the grout curtain, and so on. All these processes change the thermal, filtration, and stress-deformation processes in relation to the state when the dam was built. As a result of these changes, there may be a change in the degree of safety of the dam. As for thermal processes and conditions, they change slowly because the thermal properties of concrete also change slowly. Filtration processes can change relatively quickly due to damage to the grout curtain, blocking drainage boreholes, deterioration, and erosion of the rock mass, which creates predefined water paths and increased seepage. The most common indicators of a change in condition are changes in the results of observation of filtration parameters (water table and flow), and visual defects can also often be observed.

A change in the stress-deformation states is a frequent phenomenon in arch dams, and it has a highly negative effect on the condition of the dam and its safety. Such phenomena are manifested most often in the appearance of cracks, sliding blocks in the rock mass, rock breakage, and other phenomena. Such occurrences require a mandatory condition estimation based on which attitudes and measures are defined for bringing the dam to a satisfactory condition.

The concept of the Dam Safety Management System has as its ultimate goal the establishment of a connection between the mathematical FEM models of the dam and the results of technical monitoring of all processes to obtain calculation indicators on the dam that best correspond to the current state of the dam. As previously stated, there is an extensive system of technical monitoring of various quantities at the Grančarevo Dam: temperatures, water tables, flows, displacements, inclinations, and dilatations. All these quantities have been observed for many years and are suitable for estimating the dam's relevant processes. In this way, the model can be considered adequate and suitable for coming to conclusions about the state of the dam and its safety and decisions about possible preventive measures.

Based on all measurements and the application of the FEM model, the values of the parameters of individual processes are determined, based on which the states of individual processes in the entire structure of the dam and the surrounding rock mass are obtained, and based on which the safety of the dam is determined. The parameter values of individual processes are determined based on discrete measured quantities, and based on parameters and boundary conditions, the dam's current condition and safety level are determined.

A general algorithm for determining the parameter values of thermal, filtration, and stress-deformation processes

For all processes analyzed on the dam, it is necessary first to determine numerical values of the parameters that describe the model's behavior during the considered process. This procedure represents a systematic search for the optimal combination of parameter values of individual processes to obtain minimal deviations between the measurement results and the computation results obtained by the FEM model. Considering the large number of computations that need to be performed in that case, this procedure is defined as an optimization problem that is solved by optimization algorithms, such as the NSGA-II algorithm [27]. The optimization algorithm defines the number of variables for which values (parameters) is determined, search areas for individual parameters, criterion functions that define deviations between measurement and computation results, and limit functions if they exist.

In the general case, in the optimization algorithm, it is necessary to determine the minimum of the criterion function $K_s(x),\ s = 1,2,\ldots,S$ so that the following relations are satisfied:

$$g_j(x) \le 0 \quad j = 1,2,\ldots,J \tag{4}$$

$$h_t(x) = 0 \quad t = 1,2,\ldots,T \tag{5}$$

$$x_i^D \le x_i \le x_i^G \quad i = 1,2,\ldots,n \tag{6}$$

Solving the optimization problem involves finding an n - dimensional vector $x = \vec{x} = (x_1^*, x_2^*, \ldots, x_n^*)$ that satisfies conditions (4), (5) and (6) and optimizes S objective functions (criteria) $K_1, K_2, \ldots, K_S$. The condition defined by Eq. (1) represents the search area for values that are the coordinates of the vector $\vec{x}$ (the coordinates of the vector are the parameters that are the subject of optimization). Both J inequalities and T equalities determine the solution of the problem (combination of parameters). The functions $g_j(x)$ and $h_t(x)$ are called constraint functions, and they define the admissible search area.

Given the fact that the determination of parameter values is a systematic search for the best (optimal) value of a set of parameters, the steps to be taken must be defined. The first step is to determine the parameters significant for optimization from the broadest set of parameters. The set of parameters specified through the optimization process is determined based on the results of the parameter sensitivity analysis. Based on the sensitivity analysis results, the parameters that will be the subject of the search in the optimization algorithm are defined. After defining a set of parameters, search areas for the parameters in the optimization algorithm are defined.

Computations using the FEM model, comparison of computation results with test and measurement results, and evaluation of criterion values are repeated until the minimum criterion value is reached. Numerical simulations are performed each time with a new combination of parameters. Criterion functions are often defined as the mean value of the sum of deviations or squared deviations between the computation and measurement results. If there is one criterion function, then the optimization is single-criteria, and the solution that minimizes the proposed criterion is sought.

When applying two or more criteria (multi-criteria optimization), there is a set of compromise solutions called the Pareto front [27]. The set of Pareto optimal solutions contains solutions that are superior to all other solutions from the search space for each criterion but inferior to other criteria in comparison to other solutions from this set. The optimal solution is chosen based on a set of compromise solutions, considering all the criteria.

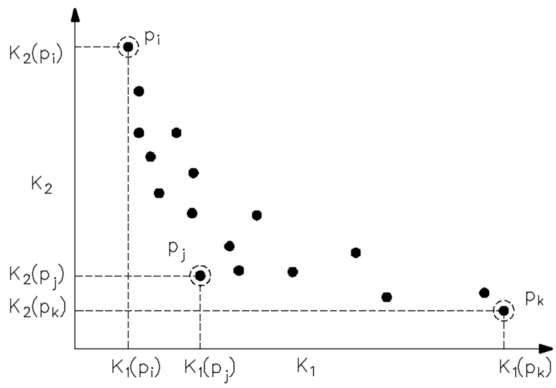


Figure 13. *Pareto front of optimal solutions [24]*

From the Pareto front (Figure 13), three solutions (p_i, p_j, and p_k) were chosen. All three solutions represent optimal compromise solution according to both criteria (K_1 and K_2). If the decision-maker chooses solution p_i, they will encounter the situation where this optimal solution, according to criterion K_1, is superior to criterion K_2. If the decision-maker chooses solution p_k, they will have a situation where this optimal solution, according to criterion K_2, is superior to criterion K_1. In the case of choosing solution p_j, both criteria are mutually balanced.

Limitations of the application of the general algorithm for determining parameter values

The general algorithm for determining parameter values cannot be fully applied in the case of estimating the parameters of the stress-deformation processes because specific parameters of the stress-deformation processes cannot be determined based on the observation results at the dam. Various stress-deformation quantities are measured through a technical monitoring system: displacements, deformations, slopes, and stresses. With the help of these quantities, the state of the stress-deformation quantities cannot be fully determined because the quantities observed are primarily seasonal, and based on them, the normal behavior of the dam can be determined, which is most often in the elastic domain of behavior. To analyze the behavior of the dam in the context of damage and fracture in the concrete or rock mass, it is necessary to know the parameters of the constitutive model of the material that defines the behavior of the material in the domain of plastic deformations and fracture, as well as behavior after cracking. Dams, fortunately, are not in the domain of failure, so such a condition cannot even be observed, but they can often be found in a state of damage to the concrete structure and rock mass in the sense that there are cracks and fissures. Various other alternative approaches are used to evaluate and estimate the values of the parameters that define the state of concrete and rock mass in the area of plastic deformation and fracture.

The failure state can be estimated based on rock mass. This refers primarily to the results of in situ tests in the rock mass (for example, large-scale shear tests). In addition, various other supplementary methods can be used based on categorizing concrete and rock mass (mapping of various phenomena), geophysical tests, and appropriate correlations between various variables (for example, between the results of mapping and the results of in situ tests). Here it is essential to emphasize that the scale effect strongly influences the mechanical properties of the rock mass. That is, the values of the resistance of the rock mass decrease with the increase of the scale value in the rock mass. Likewise, the effect of scale is present in concrete due to various cracks, so the results of, for example, laboratory tests on concrete samples cannot be directly copied to the dam's concrete. For instance, in the research [28], it is stated that the compressive strengths of small and large concrete samples are the same and that the tensile strength ratio of small and large samples is 0.6 to 0.7, even 0.5 up to 0.6.

Dam safety assessment

Dam safety assessment represents the most complex type of analysis where, in addition to the application of appropriate computation analysis based on the application of the FEM model, appropriate norms and criteria are used to assess whether the dam or part of the dam has satisfactory safety. As for the FEM model, parameters, and computational state of the dam, it can be said that it is established in accordance with the actual behavior of the dam. Difficulties during safety assessment occur in applying appropriate criteria based on which it is determined whether and to what extent the entire dam-rock mass system or a part of the system is safe because the relevant legislation defines no clear criteria.

The usual practice for designing and analyzing dam safety has often been applying appropriate approaches and recommendations from different countries and professional associations (ICOLD, USBR, FERC, etc.). In the Republic of Srpska, where the Grančarevo Dam is located, the old Yugoslav regulations are still in use. Still, new rules for building structures are being developed based on the application of Eurocode standards. The Eurocode does not have explicit dam provisions but implicitly provides guidelines for defining criteria for analyzing load-bearing capacity and usability of structures that can be applied to any structure. In the main book of the Eurocode - EN 1990 [29], the main principles, guidelines, and instructions for design have been established. Among other things, it presents the principles of structure reliability, durability, and quality control. In this regard, and bearing in mind that in engineering practice, the reliability method for assessing the safety of structures is increasingly present [30-32], the application of the Eurocode guidelines is justified for the analysis of the safety of dams.

CURRENT STATE OF GRANČAREVO DAM

The current state of thermal processes

Based on the FEM model of the dam, thermal computations, and specific parameter values, the thermal field in the concrete construction of the dam was estimated. The thermal state of the dam is estimated so that there are minimal deviations between the computed values of the temperatures at the places where the concrete temperatures are observed. Figures 14 and 15 show the comparative results of computations on FEM models and measurements on certain thermometers on the upstream face of the dam, in the body of the dam, and on the downstream face of the dam for a certain period. It can be concluded that significantly good matches were obtained between the measurement and computation results.

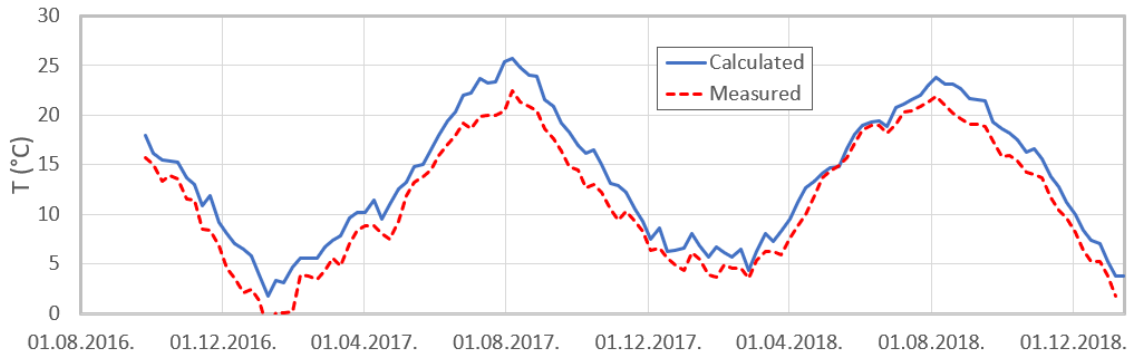


Figure 14. *Comparison of measured and computed values of concrete temperature on the embedded extensometer EH-25U at the level of 398 masl (downstream face of the dam)*

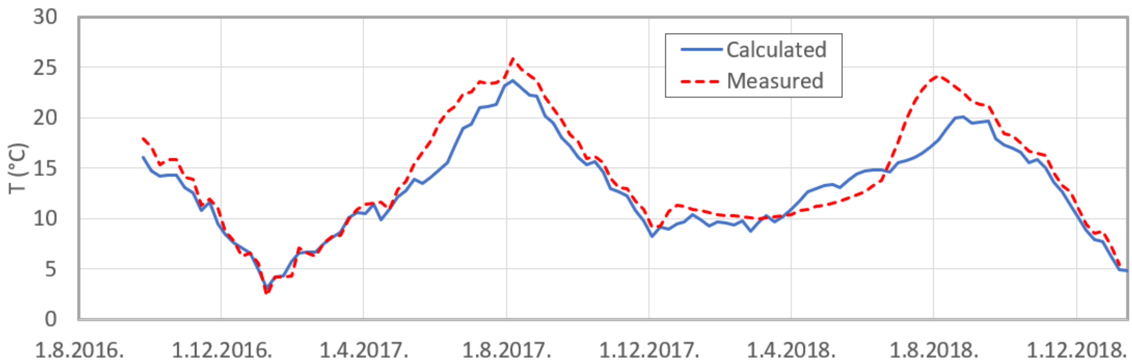


Figure 15. *Comparison of measured and computed concrete temperature values on the F22-23 fleximeter (dam body)*

For selected dates corresponding to the end of summer (summer thermal conditions), the thermal fields on the dam's downstream face and through the central cantilever are shown in Figure 16.

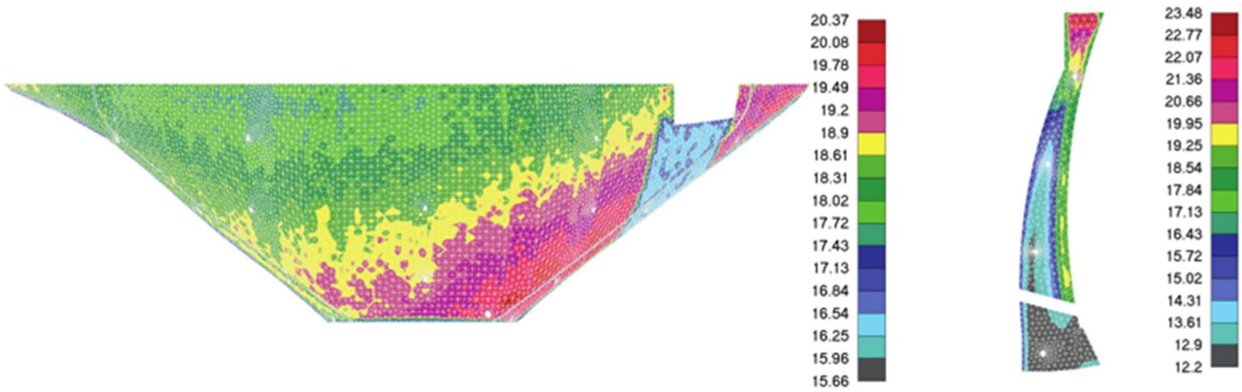


Figure 16. *Thermal field on the upstream face of the dam and in the section through the central cantilever for summer thermal conditions*

The current state of filtration processes

By applying FEM models for specific optimal values of the parameters of filtration processes, the state of the filtration processes on the concrete structure of the dam and in the surrounding rock mass was estimated. The current state of filtration processes was analyzed for 2019-2020 (4 situations were considered). For the considered dates, the measurement values at the measuring points of the piezometers and the places where the flows are observed were selected. Water tables and flows are calculated in the optimization process for selected parameter values for the same measuring points, which enter into the calculation of the criterion function and concrete tests. The optimization of filtration process parameters was carried out as a two-criteria. The first criterion refers to the minimization of deviations between the results of measurements and calculations for flows at drainage boreholes and the Parshall flume. The second criterion refers to the minimization of deviations between the results of calculations and measurements on piezometers.

The estimation of the state was determined based on the values of 27 parameters and for the given filtration boundary conditions. For the adopted values of the estimated parameters of the filtration processes, a comparative presentation of the computed values and the measured values (water tables at the locations of piezometer measuring points) is given for the corresponding calculation situations that correspond to the realistically observed ones (Figure 17). Figure 18 shows the water height field in a section through the central cantilever. The obtained mean deviation of the calculated values of the water table from the measured values of the water table for the piezometers used and for all calculation situations is 4.2 m. Considering the complex karst terrain where not all phenomena can be covered by full discretization in the FEM model, it can be said that the computation results are in agreement with the measurement results and that satisfactory deviations were obtained, so the estimated state of the filtration processes can be considered quite acceptable.

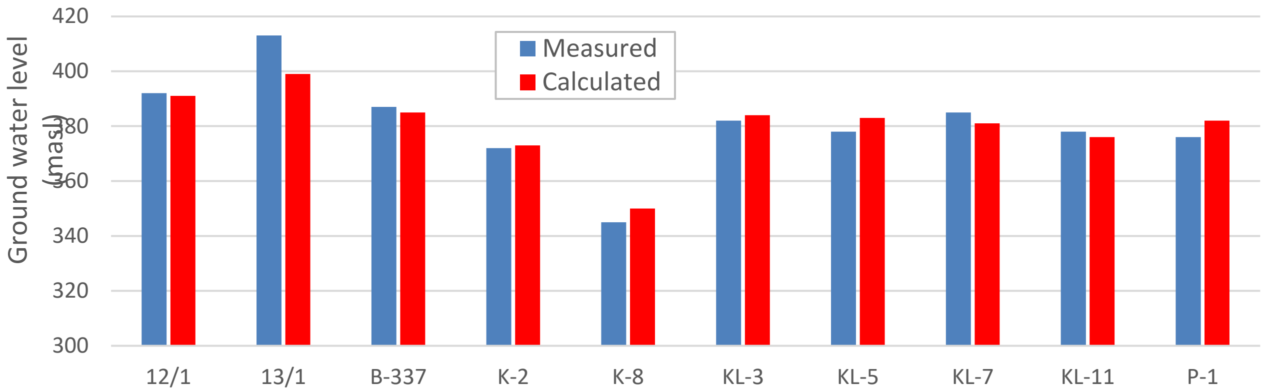


Figure 17. *The water level in the terrain - profile I, downstream from the grout curtain (example of a comparison between measurement results and computation results)*

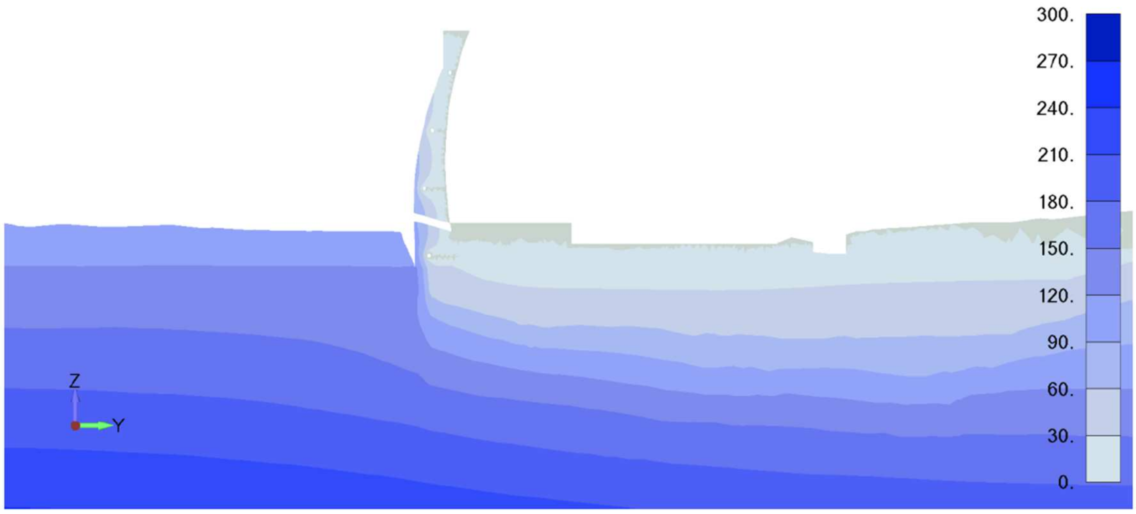


Figure 18. *Water level height – cross-section through the center cantilever*

The current state of stress-deformation processes

Stress-deformation processes are the most complex for dam analysis because they require knowledge of many parameters used to describe the mechanical behavior of rock mass and concrete, bearing in mind the interaction with thermal and filtration computations.

The current state of stress-deformation processes at the Grančarevo Dam was determined by applying the FEM model and the parameters of the mechanical behavior of the rock mass and concrete, for which the best matches between the measurement results and the computation results were obtained.

To define the number of parameters that need to be determined, it is essential to define sufficient heterogeneity in the FEM model to satisfactorily consider all the specificities related to the dam structure and rock mass. In terms of heterogeneity, the simplest thing is for the entire concrete structure to be the concrete same quasi-homogeneous zone, meaning that it has the same mechanical properties throughout the structure. This is undoubtedly a very simplified approximation, which is not accurate at all, considering the cracking of the concrete on the dam in different zones. This led to the need for a more detailed discretization of quasi-homogeneous zones, and the assumption was introduced that each concrete zone in the FEM model should be treated as a separate quasi-homogeneous zone (91 quasi-homogeneous zones in total). This division of concrete into zones enables a better simulation of stress-deformation processes and damage detection in the dam's concrete structure. The rock mass is divided into three quasi-homogenous zones based on available basic data. For each considered material zone, it is necessary to determine the values of 16 parameters of the damage plasticity model [21-24], which means that a total of 94x16=1504 parameters of mechanical behavior need to be determined.

The algorithm for determining the value of parameters cannot determine all parameters based on the results of technical monitoring. Other approaches have been used to define the failure parameters and the parameters that define the state after failure and the plastic deformation capacity.

The current state of the elastic characteristics of the Grančarevo dam is estimated for 2019-2020. Knowing the distribution of elastic characteristics on the dam, the current state of dam damage was determined.

Four calculation situations from the considered period were selected for which values of the appropriate measurements were selected, which were then used to determine the dam's damage state. The measurement results are relative in time and space; for example, the displacement of the dam crest is observed in time in relation to the zero state when the first measurement was made, and the displacement of the dam crest is given with regard to the base point. This means that the calculation results must be adjusted to the measurement results to make comparisons. Two calculations for different dates and the corresponding measurement results for the observed dates must always be analyzed. The analysis procedure within the Grančarevo Dam safety management system is automated within the central computation server so that at the observation points in the FEM model, the appropriate sizes are calculated, which are then transformed into the monitoring system, and comparisons and computations of deviations are made.

From the measurement results, relative displacements, inclinations, displacements at the dam's crest, and expansions in the dam body are used to estimate the condition. Certain types of measurements, such as dilatation measurements in the rock mass, were not used to estimate the state of damage due to the low reliability of those measurement results. Figure 19 shows the estimated damage state for each quasi-homogeneous zone of the dam's concrete structure, and Figure 20 shows the estimated values of the modulus of elasticity. For the calculated damage values, comparisons are given between the measurement results and the calculation results for individual measurements (Figures 21-23).

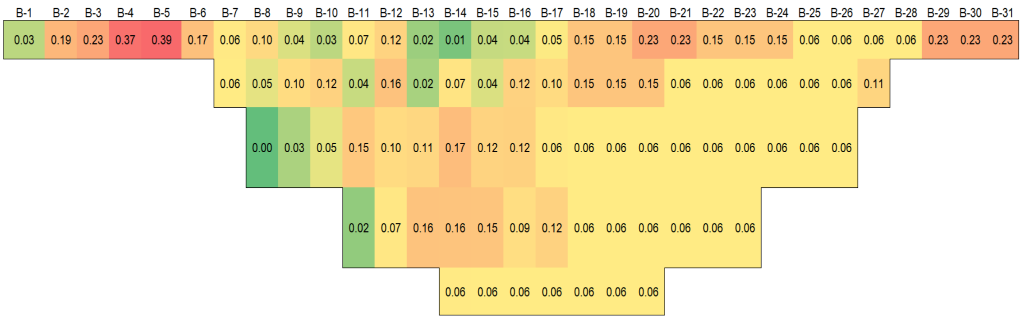


Figure 19. *Estimated values of the state of damage in the dam's concrete, the downstream face of the dam*

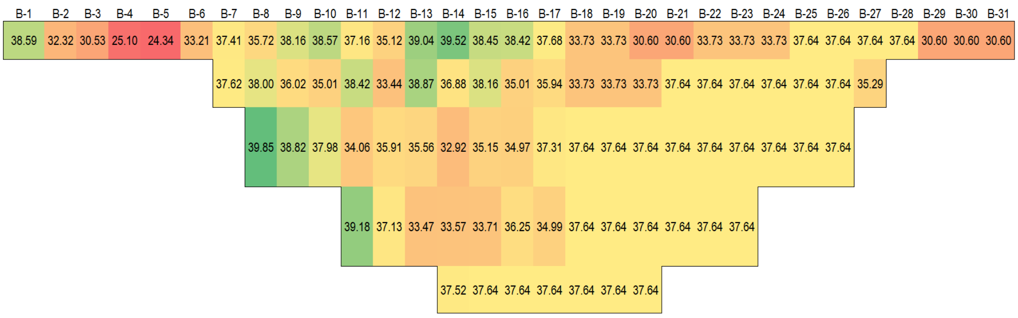


Figure 20. *Estimated values of the modulus of elasticity, downstream face of the dam (GPa)*

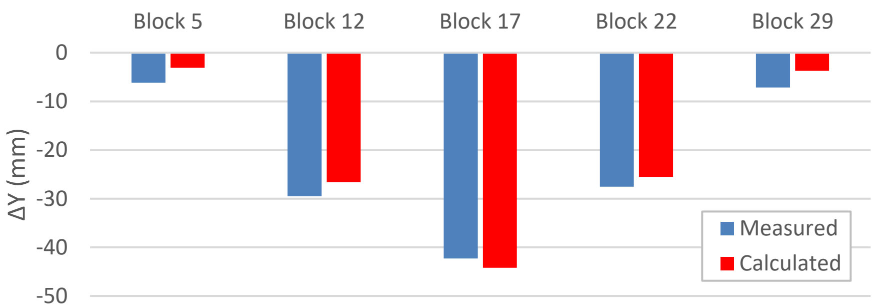


Figure 21. *Displacement of points on the crown of the dam (measured by the alignment method)*

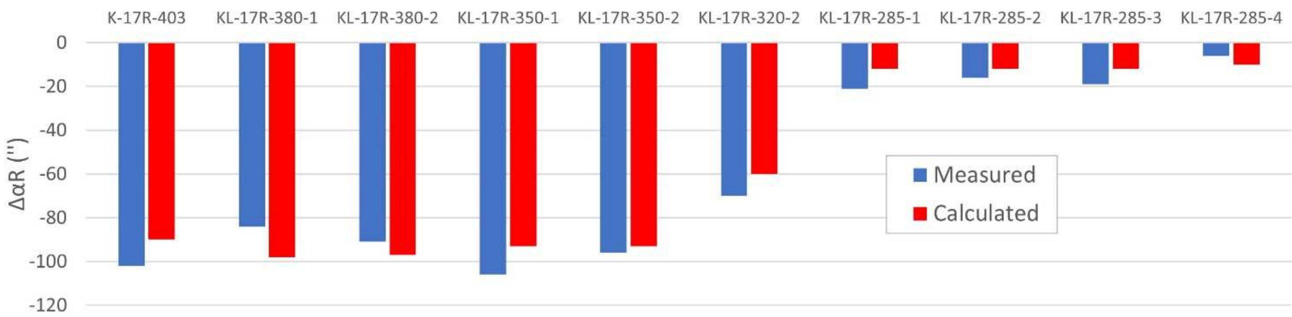


Figure 22. *Example of a comparison of measured and computed values for certain clinometers*

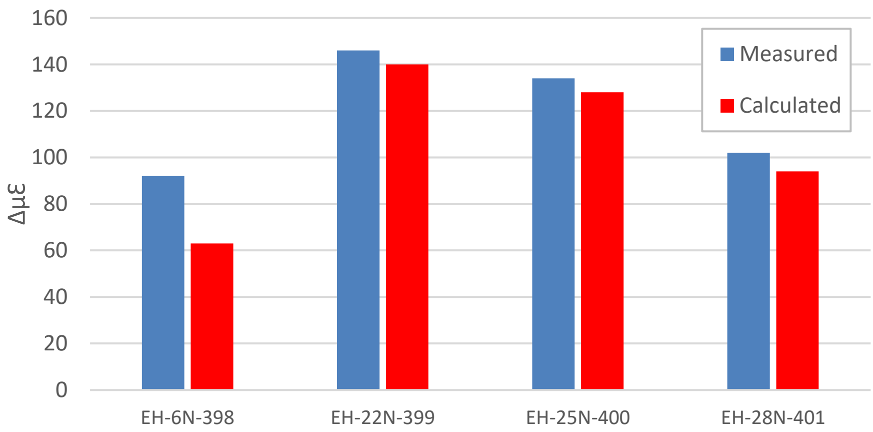


Figure 23. *Example of a comparison of measured and computed values for measurements on extensometers in the concrete*

The most extensive damage to the dam was found on the right flank in blocks 1 to 5, specifically in blocks 4 and 5. Figure 24 (left) shows the distance from the fracture condition in blocks 1 to 5, and Figure 24 (right) shows the state of degradation.

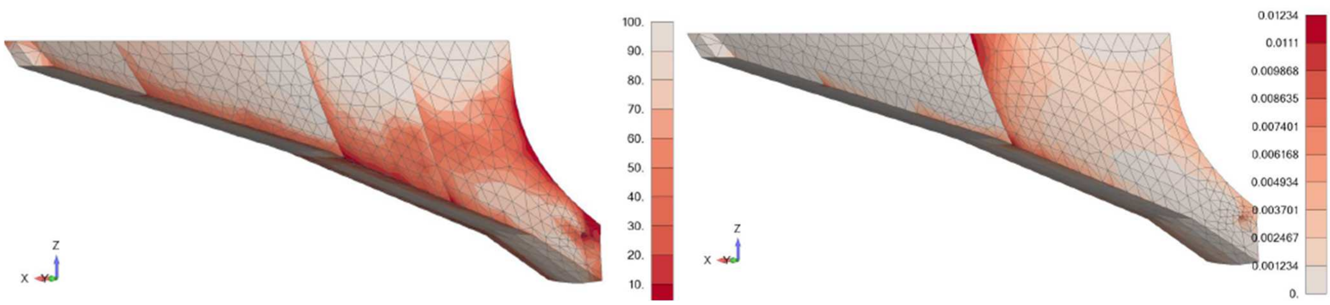


Figure 24. *Distance from failure condition (left); Degradation (right)*

To determine the state of safety of the dam, it is necessary to know the parameters that cannot be determined based on observations. These parameters were determined based on available data on in-situ tests in the rock mass from the time of construction, based on mapping results of concrete cracking, literature correlations between cracking and other mechanical properties, and literature recommendations for specific parameters. Based on damage estimation, it was determined that the smallest distance from the fracture condition in blocks 4 and 5 (Figure 24-left) is consequently the most significant degradation in the concrete material in blocks 4 and 5 (Figure 24-right). In connection with this, the safety aspects of the dam for the right flank, which has the highest degree of damage, were also analyzed.

By applying the appropriate criteria based on the Eurocode norms and USBR recommendations, it is concluded that the level of safety of the dam on the right flank is lower than the accepted values given by these norms. On this basis, it can be said that the right side of the dam is in a state of unsatisfactory safety. Accordingly, appropriate preventive remediation measures should be taken to bring the flank to a satisfactory state of safety.

CONCLUSION

Arch dams are structures that have very complex behavior, and from the point of view of modeling and assessing state and safety, they represent enormous challenges. Safety management of dams in general and arch dams is treated differently worldwide. Other countries have different guidelines, recommendations, and legal frameworks, according to which the state and safety of dams are analyzed.

This paper presents the concept of safety management of the Grančarevo Dam and the software-hardware structure to support safety management. By applying the concept of safety management, dam condition analyses were performed for various processes: thermal, filtration, and stress-deformation. Suitable matches between the computed and measured concrete temperatures were obtained as temperature fields in the concrete, which agree with the thermal behavior of the dam.

Based on the performed analysis of the filtration processes, it can be said that satisfactory computation results were obtained for the adopted parameters and that there are suitable matches between the computation results and the measurement results, especially bearing in mind that these are complex conditions, karst terrain, and a limited pool of flow measurement data, both on the wells and the Parshall flume, as well as insufficient reliability of the position of individual measuring points, etc. Additionally, it can be said that a satisfactory view of the estimated state of the water table in the terrain and the foundation joint has been obtained, which is an essential prerequisite for further analyses, primarily for stress-deformation analyses that depend on filtration forces. In other words, based on the measurement results and computation results, no phenomena were observed that would indicate a significant disturbance in the filtration condition of the dam and the surrounding terrain.

As a result of the damage estimation in the dam, it was found that the damage in the dam ranges from 0 to 0.39, and the corresponding modulus of elasticity ranges from 24.3 GPa to 39.5 GPa. The damage results show that the greatest damage was noted on blocks 4 and 5, per the actual situation on the ground, which was the dam's thermal behavior determined through the investigative work conducted by the Jaroslav Černi Water Institute in 2019, where a significant degree of concrete cracking was determined.

The state of cracking negatively affects the safety of the right flank of the dam and generally negatively affects the entire structure. It was determined that the right side of the dam was not sufficiently safe. Thus, it is necessary to take appropriate remediation measures to bring the right flank to a state of satisfactory safety. In connection with the remediation of the right flank, the Jaroslav Černi Water Institute has developed a Remediation Project, which involves strengthening the right side of the dam by adding concrete downstream and upstream and prestressing the new and old concrete with anchors to bring the structure to a state of satisfactory safety.

It is recommended for the company that manages the dam and the reservoir to begin activities on the implementation of remediation works as soon as possible to bring the dam to a state of satisfactory safety and thereby prevent possible catastrophic consequences that would lead to a potential failure in the right flank.

It is recommended to continue all activities in the further development and use of the Dam Safety Management System to determine the causes of the cracks in the right flank and take any additional measures to achieve complete safety of the right side of the dam.

Considering that the knowledge about the characteristics and structure of the rock mass is very scarce, and the safety of the dam depends on it the most, it is necessary to carry out appropriate investigations of the rock mass in the coming period based on which a better insight into the arrangement and structure of certain quasi-homogeneous zones of the rock mass would be gained and based on which the mechanical properties of the rock mass necessary for the calculation of the safety of the dam would be more reliably assessed.

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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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