HPC based computational platform for Višegrad dam seepage investigation and remediation

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Abstract: Water leakage under Višegrad dam was observed already in the first years of its exploitation. Further intensification of this phenomenon could have caused a variety of adverse effects, so it was necessary to repair leakage by incorporating granulated materials into underground cavities. However, the sealing of underground karst conduits is a very complex process, which requires continuous monitoring and control. In order to make the right decisions during the remediation, we have developed a software platform able to evaluate the effects of the implemented technological processes in near real-time and to help decision-makers in planning their future activities. The platform relies on numerical models of hydraulics and mass transport, which are used to calculate piezometric levels, flow rates, and tracer concentrations for an assumed system configuration and under given boundary conditions. The data obtained from the measurement system were periodically in an automated manner assimilated into numerical model in order to obtain the model states that best comply with the reality. To secure that simulation results are deployed in a reasonable timeframe, the platform is designed in the way that enables running all the calculations and data assimilation on a high-performance computing infrastructure.

INTRODUCTION

Since its construction, the dam of the hydropower plant Višegrad has recorded a water leakage through the karst terrain, which has continuously raised from 1.4 m^3/s in the year 1990 to 14.68 m^3/s in 2009. To reduce water and energy losses and to prevent further erosion or even collapse of the dam, an urgent remediation of the dam environment was required. In order to discover the unknown geometry of the karst conduits as the main pathways of water leakage, a number of various investigations and remediation actions were performed, as explained in [1]. Initial investigations, as well as continuous monitoring and directing of the remediation process, required usage of a sophisticated computational platform, capable of giving an *in silico* perspective to the problem on top of the in situ experimental investigations, but also of combining these two perspectives into an augmented and comprehensive picture of the problem.

In previous few decades a number of papers that deal with partial aspects of similar problems were published, but most of them are just suggestions for the application of specific techniques [2]. An overview of these documents show that several techniques have been used to obtain knowledge about karst development and leakage studies: (a) regional and dam site geological mapping [3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13], (b) boreholes and galleries [4, 6, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20], and (c) geophysical methods [5, 13, 18, 20, 21, 22]. However, to the best of authors knowledge, there are no publications about computational platforms that couple terrain investigations, in situ measurements, and computational model in a holistic, synergetic, and automated manner.

The main purpose of the computational platform for Višegrad dam seepage investigation and remediation was to provide an automated and continuous estimation of the spatial distribution of karst faults, their geometric parameters, and hydraulic properties before and during the remediation process, based on the measurements obtained by the installed monitoring system, as well as deterministic and empirical physical laws. During the remediation, investigations over the computational model were performed with the aim of gathering the information necessary in making decisions about optimal granulate injection. The model was developed as an assemblage of components for simulating phenomena that can otherwise be only particularly observed using the system for continuous monitoring or measured through periodical experiments (sinking upstream the dam, velocity of the flow at the downstream springs, sodium fluorescein dye tracing, sodium chloride tracing, tomography, etc.).

Based on the geological structure of the terrain and the hypothesis that erosion and water flow were predisposed by the spatial distribution of fault structures, an initial model topology containing all the possible water conduits was proposed. The proposed topology was represented by a set of nodes interconnected by conduits, creating a hypothetic network of the underground flows. As a basis of the mathematical model of underground flow we formed an 1D hydraulic model of the flow under pressure, subjected to boundary conditions in the form of upstream and downstream elevations (potentials). The input parameters of the model were cross-section areas and frictions in all conducting elements of the system, while the results were potentials, velocities, and flow rates at all nodes and conduits. Furthermore, as an extension to the hydraulic model, we formed a mathematical model of solution transport, which strongly relies on the results of the hydraulic model (velocities and flow rates). The outputs from this model are concentrations of the dissolved substance at the model nodes. Finally, coupling the hydraulic model and the model of solution transport we obtained an integral computational model of underground flow. The results obtained by the integral model now can be compared with the variables measured at the certain elements of the system, such as sinking velocity at the largest sinkhole, velocities at the downstream springs, piezometric levels, as well as the traveling times and concentrations of the tracers.

The difference between measured and calculated values are strong indicators how well the real system is described by the model. Varying the values of the conduit parameters (dimensions of karst cracks and frictions along the conduits), we obtain different model results, which less or more differ from measured ones. This way it is possible to search for the parameters that will give us a model that is a realistic picture of the underground network of fissures. Having in mind all the complexity of the considered models, it is clear that such a demanding iterative process cannot be effectively performed without the implementation of adequate algorithms. This problem can be considered as a mathematical optimization problem that searches for the dimensions and hydraulic properties of the conduits within the given network, that minimize the difference between calculated and measured values. Since the optimization problem is highly nonlinear and multi-objective, for the optimization purposes we employed genetic algorithm (GA), due to its inherent generality and robustness. The whole process of the simulation-based optimization using GA is implemented through a computational platform that automates the process of finding the most adequate model parameters using the principles and techniques of high-performance computing (HPC). Using the platform during the whole period of remediation, a series of simulations of granulate injection, transport, and deposition were ran periodically in an automated manner, giving the optimal parameters of the granulate mixture and speed of injection, regarding the sealing cracks in the most desirable way.

In the first section of this paper, we present the overall concept of the developed HPC platform for supporting decision making during the remediation of Višegrad dam. The second section gives the details about monitoring system and data acquisition, as well as the data about tracer experiments and the parameters of the injection process. In the third section, the governing equations and the implementation of the hydraulic and transport models are explained. The methodology, algorithms and HPC implementation of data assimilation are presented in the fourth section, followed by the description of the accompanying decision-making software tools and examples of the platform application. Finally, we give some concluding remarks and good practices for future dam remediations.

PLATFORM OVERVIEW

High-level concept of the HPC based computational platform for Višegrad dam seepage investigation and remediation is shown in Figure 1. The core component of the platform is Hydraulic model created according to the investigation about karst fissures topology. As precise geometric and hydraulic characteristics of the conduits are not known, they are initially assumed within the expected realistic ranges. After the hydraulic simulation on the assumed model configuration, the calculated flow rates are further used to run the Tracer transport model that results with tracer dynamics over time. Calculated piezometric levels, flow rates, and tracer concentrations are compared to measured values and used as indicators of the assumed configuration quality. These indicators are further used within Genetic algorithm as a driving factor in the evolution of the assumed system states to the system state that best describe the real state under the dam. In an iterative procedure, the GA creates better and better configuration assumptions, runs simulations, evaluates their fitness, and selects the best for the next generation. To take into account the effects of the granulated material injection on the Hydraulic model, the amount of the deposited material is calculated in each iteration of GA based on the previously calculated flow rates. Once the most adequate system configuration is obtained it is provided to the Remediation operators through a specially designed user application, enabling near real-time monitoring of the remediation process and conducting the appropriate actions.

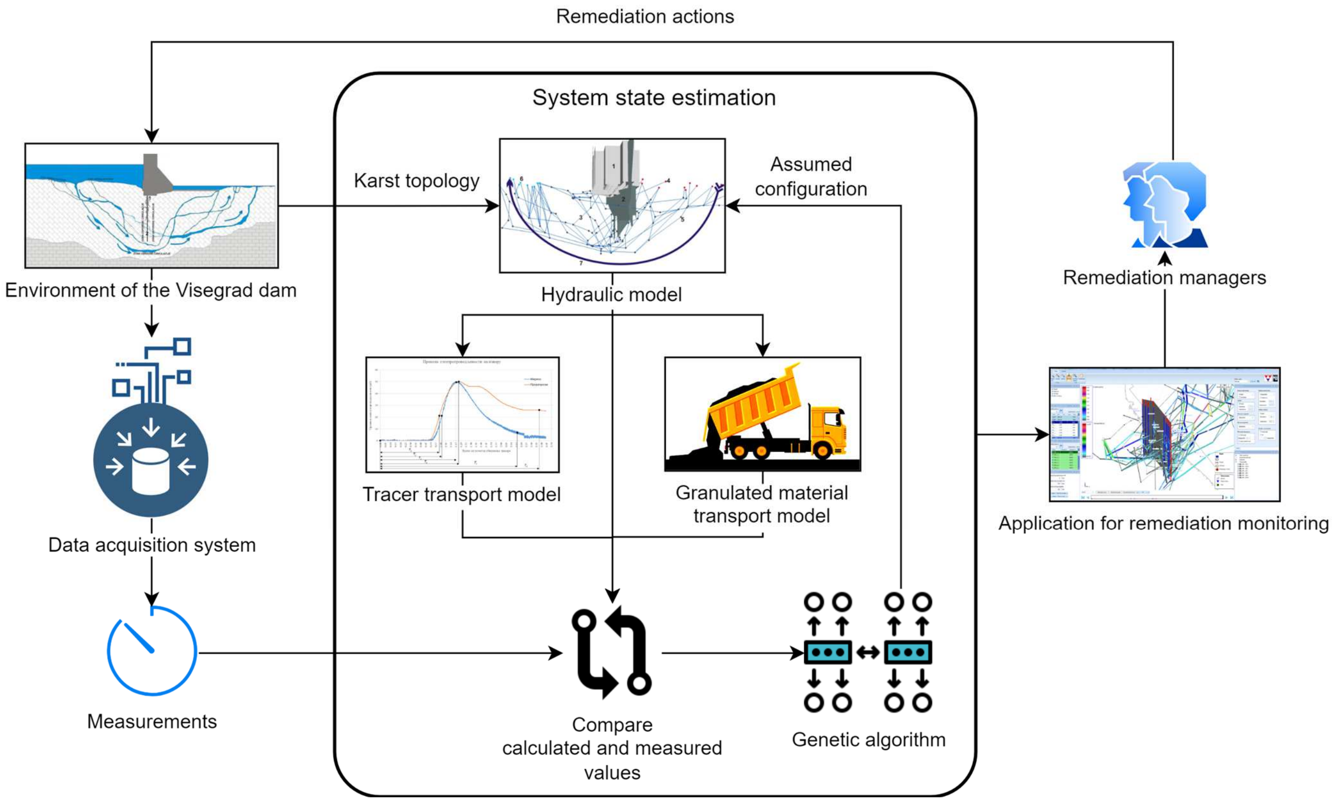


Figure 1. *Conceptual view of HPC based computational platform for Višegrad dam seepage investigation and remediation*

To provide continuous estimation of the system state within an acceptable timeframe, the platform is designed to run GA and all necessary calculations on high-performance computing infrastructure. The platform also incorporates data management system with automated quality control, so data for calculations is reliable and provided in near real-time. The Application for remediation monitoring is designed as a comprehensive 3D graphical application that provides all the indicators important for decision making in numerical, tabular, and graphical form.

Hydraulics

Having in mind the complexity of the seepage under the Višegrad dam, it is clear that it includes few different physical processes, which are strongly coupled and require holistic approach. The basic underlying process is fluid flow through the underground fractures made during millions of years of stone faulting and erosion. Assuming relatively large lengths of the conduits comparing to their transversal dimensions, we applied 1D hydraulic model, without the risk that some important hydraulic phenomena are neglected. On the other hand, big Reynolds numbers due to large cross-sections and flow rates imply turbulent flow regime. Solving turbulent flow equations was performed using Finite Element Method (FEM). Results from the simulation of the hydraulic model are piezometric levels at the characteristic points of the system, as well as the velocities and flow rates of the fluid within every single conduit.

Tracer transport

Since changes in boundary conditions are very slow compared to flow hydraulics, we perform stationary hydraulic calculations and do not consider the temporal dimension of the flow. Additional information about the velocities is obtained by the experiments using tracers injected into the key points of the systems. To simulate dynamics of the tracer through the system based on the results obtained from the hydraulic calculation, we developed an adequate computational model of solution transport. The result obtained from Finite Difference Method (FDM) simulation is the time course of tracer concentrations at key points of the underground network.

Granulated material transport and sedimentation

Remediation of the dam included injection of inert granulated material into the main sinkholes and a number of boreholes. The effects of the granulate injection on the piezometric levels and velocities were monitored using the installed monitoring equipment. However, for the purpose of determining the location and amount of the deposited material we had to develop a computational model of transport and sedimentation of granulated material. The model is based on calculation of critical velocities and tangent stresses for the deposition of the granulate within the sloped conduits, where the velocities and flow rates obtained by hydraulic simulations were used as inputs into the sedimentation model. For a given granulate dimension, critical velocities and tangential stresses are calculated for every single conduit, which are further used to calculate the probabilities of material deposition within every conduit. The calculation is repeated for all classes of granulate within a granulate mix, giving the amount of every class deposited during the considered time frame.

Since the sedimentation of the material within the conduits implies the change of conduit cross-section dimensions and friction, the hydraulics of the system is changed consequently. Therefore, every significant change induced by the sedimentation must be followed by new hydraulic calculation that will give an updated image of piezometric levels, velocities, and flow rates within the altered system. Having in mind that the updated velocities and flow rates have influence on the sedimentation calculation, it is clear that these two simulations (hydraulic and sedimentation) must be coupled and conducted simultaneously through an iterative process.

As shown in Figure 2, hydraulic calculation is performed at the beginning of every simulation time step, in order to obtain velocities and flow rates in conduits. Using the calculated velocities and the model of transportation and sedimentation, we calculate the rate of granulate deposition, and afterwards we calculate the changes of conduit dimensions and frictions. At the end of the step, the calculated hydraulic and sedimentation variables are written in output files, and the whole process is repeated for the next time step. The whole iterative procedure is repeated until the exceeding of the simulated time period or until the full sealing of the system.

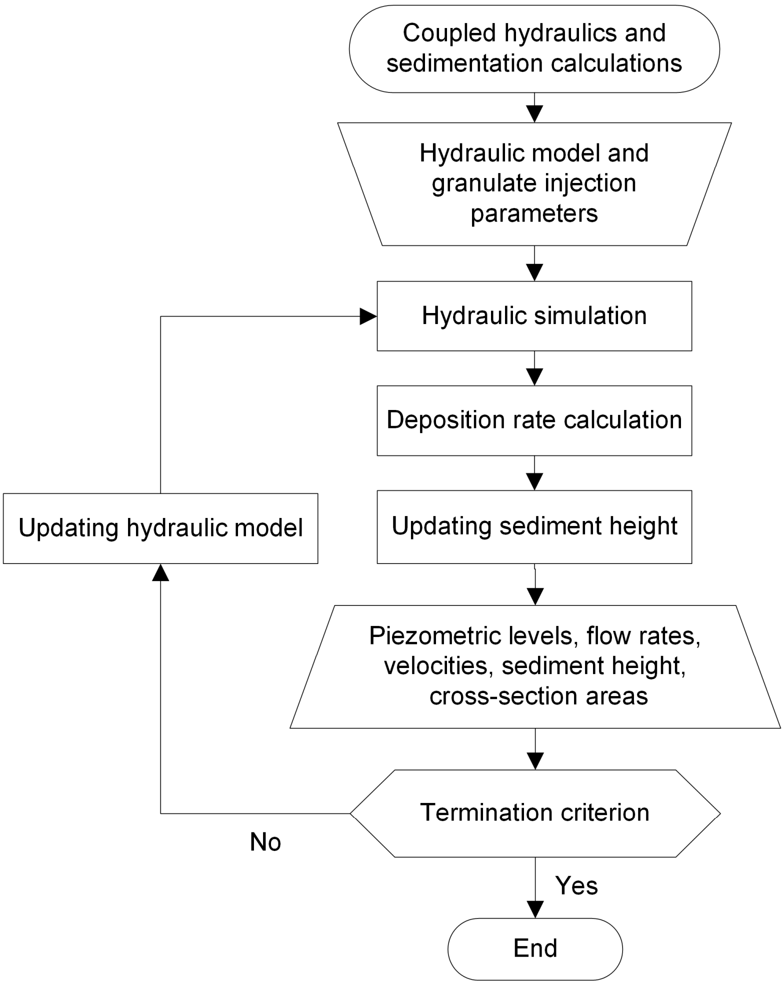


***Figure 2**. Algorithm of coupled hydraulics and sedimentation calculations*

Estimation of conduits' parameters

Before the beginning of the remediation, it was necessary to determine geometry and hydraulic parameters of the karst conduits through an estimation process relying on the measurements and the results of numerical models. Furthermore, during the remediation, dimensions and frictions of conduits are changed due to sedimentation of the injected granulated material, resulting in a series of different hydraulic system configurations. In order to compare piezometric levels and water velocities in the assumed and real system configuration for the same upstream and downstream levels, it is necessary to run the hydraulic simulation and to compare the results with the measurements. To assess the model compliance regarding the tracer dynamics, the calculation of tracer transport is conducted, and afterwards the calculated concentration time course is compared with the concentrations obtained by the experiment.

DATA MANAGEMENT

In order to provide reliable and timely data for calculations, a data management system has been established within the platform shown on Figure 1. The system is used for monitoring of variables relevant to the process of remediation, where most of measurements are automated, but some are performed manually. The system consists of acquisition server and central database server, which are equipped with specially designed services. It is hosted at server room at HPP Višegrad.

Data acquisition

The process of data acquisition is used to gather data form monitoring system, whether it is provided in file form (CSV, TXT, XLS, etc.), or it is entered manually by monitoring staff. It is based on widely adopted ETL process (Extract-Transform-Load), where information is extracted from original source, transformed into standard data model, and loaded into data store.

Automated readings from monitoring system on Višegrad dam include groundwater levels, headwater and tailwater levels, as well as water velocity and NaCl sensors at major karst system outlets (underwater springs). There are also several water level and NaCl sensors installed at upstream deep boreholes used for direct monitoring of levels in karst conduits under the dam.

Manual readings and inputs are made for weir flows, groundwater levels, wells' levels, and uplift pressures. Volumes of inert granulated and grouting materials are also monitored and acquired throughout remediation process. There are also manually acquired data on control measurements, borehole logs, salt tracing experiments, tomography experiments, etc.

Acquired data is stored locally at acquisition server, from where it is regularly transferred to central database server. All data on measurements is transformed in standard data model for time series, which is implemented in central database on a relational database system (Microsoft SQL Server). Other data is also stored at central database, together with metadata on measurements, investigations, and remediation processes. A special segment of central database is designed for configuration of computational model. This segment is crucial for real-time application of calculations because it contains data on updated state of computational model which is used for analysis and prognosis of effects of remediation works in decision support tools.

Data quality control

All acquired data is later used in calculations and optimizations to better understand the effects of remediation works. While acquired data itself may be readily available, in order to provide reliable input for calculations, it is essential that data is quality controlled. The goal of the process of quality control is to determine the level of reliability of each measured value against user-defined rules, which may take into account previous values of same variable, but also from a different one. Usually, the rule defines which values are considered acceptable based on characteristics of measuring equipment (e.g., measuring range), but also based on trend values (e.g., moving average), and values of other related variables (actual or averaged). The result of quality control process is data quality mark, which may be any value from interval 0-1, with 0 marking unreliable data, and 1 marking reliable data.

Data processing

Apart from serving raw data from database, central database server is capable of processing data upon request. This is accomplished through special data processing service which can be configured to provide engineering values based on raw data (e.g. water level obtained from frequency of vibrating wire in a piezometer). It is possible to define analytical formulas for data processing, as well as aggregation of values on time interval (minimum, maximum or average values). Special type of processing may be used for combining two or more time series from various measuring instruments into a single time series, where redundancy is of essence.

Data distribution

A specialized service is provided on central database server for data distribution to decision support tools and automated software components. User authentication is required to access data through this service, while user authorization rules define sets of data a user may access. A user or a software component issues a request for specific data to data distribution service, and the response is data from database or processed data, depending on the request. The request also defines acceptable quality threshold (usually 0.5), so that it may be applied in selecting data for the response, as well as in processing, especially in data aggregation. This way, only good quality data may be used for calculations, which is vital for estimation of effects of remediation works.

COMPUTATIONAL MODEL

In this section, we will give a detailed explanation of the platform underlying computational methods and their implementation in the form of the hydraulic numerical model, the model of tracer transport, and the model of granulated material transport.

Hydraulic modelling

Since the main part of the leakage under the Višegrad dam occurs through the faults, this physical problem is considered as a closed conduits flow, while the flow through porous media is neglected. Having relatively large dimensions of faults, as well as the fact that flow rates measured at some sinkholes reached up to 10 m^3/s, it was clear that we have to apply equations of turbulent flow due to very high Reynolds numbers. For calculations of turbulent flow through closed conduits we used Darcy-Weisbach equation [23], which give us relationship between flow rate Q and the difference between potentials (piezometric heads) φ at the ends of a conduit

$$\Delta\varphi = \bar{\lambda}\frac{L}{DA^2}\frac{1}{2g}Q^2 \tag{1}$$

where $\bar{\lambda}$ is Darcy-Weisbach friction factor, while L, A and D are length, cross-section area and equivalent diameter of the conduit. Notice that $\bar{\lambda}$ includes both the continuous losses along the conduit, λ, and the local losses, ξ. Since the conduits appear usually on the locations of planar faults, we assumed that they can be considered rectangular, so cross-section area and the perimeter of a conduit can be calculated as $A = ab$ and $O = 2(a + b)$, where a and b are width and height of the conduit. Having in mind high uncertainty of fault geometry, all the conduits were modeled as pipes of circular cross-section, where the diameter of each pipe is equal to the equivalent diameter of the corresponding conduit

$$D = 4R_h = 4\frac{A}{O} = \frac{2ab}{a+b} \tag{2}$$

Since the behavior of most of complex structures cannot be described in analytic form, to simulate the flow through a system of underground conduits we applied FEM. The basic idea behind FEM is that any physical field can be discretized into a number of subdomains called *finite elements*, connected by common nodes, where the relations between them are defined by physical laws, such as conservation of mass, conservation of energy, material constitutive relations, etc. These relations form a system of algebraic equations, which are solved using direct or iterative methods, giving the system configuration in a stationary state.

Equation (1) shows that head loss $\Delta\varphi$ is a quadratic function of flow rate Q, it must be subjected to certain modification to write it in a form that is suitable for solving a system of nonlinear equations. The equation (1) can be rewritten in the following form

$$k\sqrt{\Delta\varphi} = Q \tag{3}$$

where

$$k = \sqrt{2g\frac{4R_h A^2}{\bar{\lambda}L}} \tag{4}$$

Introducing the factor

$$\hat{\mathrm{k}} = \frac{\mathrm{k}}{\sqrt{\Delta\varphi}} \tag{5}$$

into equation (4) we obtain

$$\hat{\mathrm{k}}\Delta\varphi = \mathrm{Q} \tag{6}$$

so the equilibrium equation of the whole system can be written in matrix form as

$$\widehat{\mathbf{K}}\mathbf{\Phi} = \mathbf{Q}^{\mathbf{ext}} \tag{7}$$

where $\boldsymbol{Q}^{ext}$ represents the vector of inflows into the system at location of nodes. It should be noted that $\hat{k}$ is a function of head loss $\Delta\varphi$, thus consequently system matrix $\widehat{\boldsymbol{K}}$ is also a function of unknown nodal potentials $\boldsymbol{\Phi}$. To solve the system of nonlinear equations we used Newton-Raphson iterative method [24], where the following equations must be satisfied in each iteration

$$\begin{aligned} &\widehat{\mathbf{K}}^{(\mathrm{i}-1)}\Delta\mathbf{\Phi}^{(\mathrm{i})} = \mathrm{Q}^{\mathrm{ext}} - \mathbf{Q}^{(\mathrm{i}-1)} \\ &\mathbf{\Phi}^{(\mathrm{i})} = \mathbf{\Phi}^{(\mathrm{i}-1)} + \Delta\mathbf{\Phi}^{(\mathrm{i})} \end{aligned} \tag{8}$$

having

$$\mathbf{\Phi}^{(0)} = \mathbf{\Phi}_{\mathrm{lin}}; \qquad \mathbf{K}^{(\mathrm{i})} = \mathbf{K}\big(\mathbf{\Phi}^{(\mathrm{i})}\big); \qquad \mathbf{Q}^{(\mathrm{i})} = \mathbf{K}^{(\mathrm{i})}\mathbf{\Phi}^{(\mathrm{i})} \tag{9}$$

Through an iterative procedure, the vector of unbalanced nodal flow rates $\mathbf{Q}^{\mathrm{ext}} - \mathbf{Q}^{(i-1)}$ is corrected by the increment of nodal potentials $\Delta\boldsymbol{\Phi}^{(i)}$, until the unbalanced flow rates fall above prescribed tolerance. To secure fast convergence of Newton-Raphson method, we used potentials $\boldsymbol{\Phi}_{lin}$ obtained from the equivalent linear model as a first guess at the beginning of this iterative process.

Model of conduits and their parametrization

As explained in [1], in order to create a hypothetical network of karst conduits between sinkholes and the zone of springs, the 3D geological model is formed based on the known geological structure (Figure 3). The fault distribution in 3D was a result of systematic investigation of all accessible geological exploration objects (boreholes), their segmentation, as well as monitoring of the drilling process itself. Designing the network of the conduits is performed by logical connecting of most possible fault directions, using tectonics as a most influential factor in the initial phase of karst fissures forming.

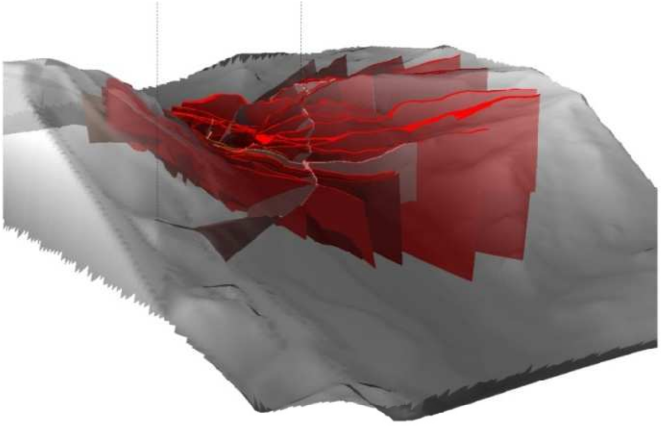


***Figure 3**. Reconstructing 3D model of tectonics for creation of karst conduit model*

Once all the karst elements were positioned in 3D space, we obtained a possible network of karst conduits, which was used as an initial topology for mathematical modeling of underground flow (Figure 4).

The assumed 3D network of karst conduits was a basis for all simulation, since it represents the set of finite elements with some unknown parameters that are obtained within the parameter estimation process. The approximate ranges of element geometric parameters were relatively precisely determined from the belonging of the element belonging to a certain fault structure.

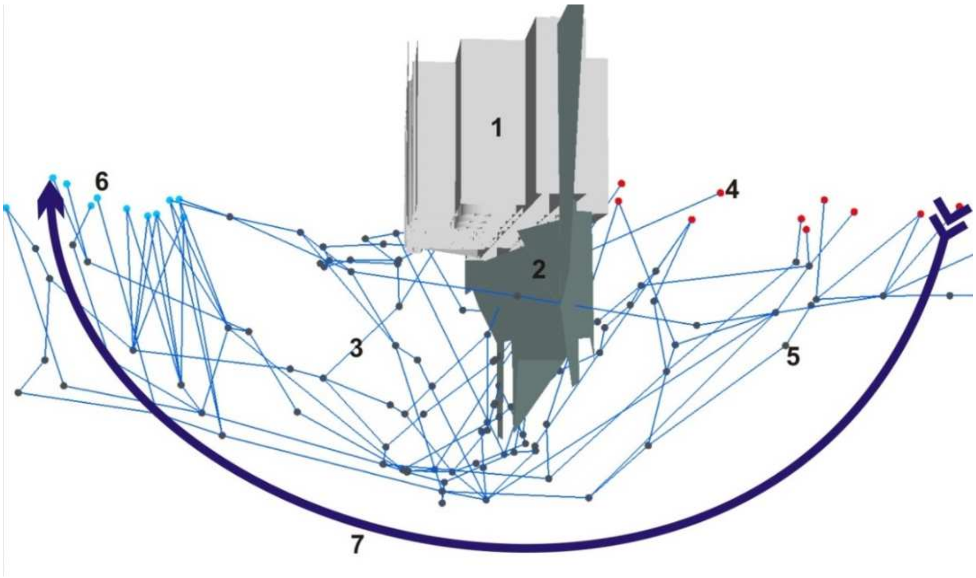


***Figure 4**. A possible network of karst conduits: 1. Dam, 2. Injection curtain, 3. Assumed direction of a karst conduit - edge, 4. External node - sinkhole, 5. Internal node – edge junction, 6. Zone of springs, 7. General direction of the flow below dam*

Boundary conditions

The external nodes of the finite element hydraulic model positioned upstream of the dam represent the main sinkholes. On the other hand, the downstream external nodes represent the downstream springs. Therefore, piezometric levels at the nodes representing sinkholes are considered equal to the upstream water level, while piezometric levels at the nodes representing the springs are equal to the downstream water level. In the operational usage of the hydraulic model, the measured upstream and downstream water levels were prescribed as Dirichlet boundary conditions at the corresponding external nodes of the model and are considered constant during the whole period of simulation (quasi-stationary).

The model of tracer transport

Once the flow rates for an assumed system geometry and given boundary conditions are obtained from hydraulic calculations, the dynamics of the tracer injected into certain points of the system can be calculated. On the other hand, dynamics of the tracer injection and tracer concentration time course are also obtained experimentally. Comparison between the calculated and measured tracer concentrations are an additional criterion that helps the parameter estimation algorithm to find the most probable system configuration.

Mass conservation equation for a dissolved matter can be written in the following form:

$$\frac{\partial \mathrm{C}}{\partial \mathrm{t}} = -\mathrm{V}\frac{\partial \mathrm{C}}{\partial \mathrm{x}} + \mathrm{D_L}\frac{\partial^2 \mathrm{C}}{\partial \mathrm{x}^2} \tag{10}$$

where C is the concentration of the dissolved matter, t time, x the longitudinal axis of the conduit, V the mean water velocity, and D_L longitudinal dispersion coefficient that includes all the factors that affect the tracer transport, such as molecular diffusion, turbulent dispersion, velocity variations, etc.

Laboratory experiments [25] have shown that dispersion coefficient is related to Raynolds number and proposed the following approximative relation:

$$\mathrm{D_L} = 3.6 \cdot 10^{-6}\ \ \mathrm{Re}^{0.764} \qquad \left[\frac{\mathrm{m}^3}{\mathrm{s}}\right] \tag{11}$$

where $Re = \frac{DV}{\nu}$, D is conduit diameter, and ν is kinematic viscosity coefficient.

For boundary conditions

$$\begin{aligned} &\mathrm{C}(\mathrm{x}, 0) = 0 \\ &\mathrm{C}(0, \mathrm{t}) = \mathrm{C_0}, \mathrm{t} \geq 0 \\ &\mathrm{C}(\infty, \mathrm{t}) = 0,\ \mathrm{t} \geq 0 \end{aligned} \tag{12}$$

Equation (10) have analytical solution in the form:

$$\frac{C(x,t)}{C_0} = \frac{1}{2}\left\{\operatorname{erfc}\left[\frac{x-Vt}{2\sqrt{D_L t}}\right] + \exp\left[\frac{Vx}{D_L}\right] \cdot \operatorname{erfc}\left[\frac{x+Vt}{2\sqrt{D_L t}}\right]\right\} \tag{13}$$

Since the analytical solution is inapplicable due to complex model geometry and boundary conditions, an equivalent numerical model for tracer transport was developed using finite volume method.

The model of the granulated material transport

The mixture of different fractions of the granulated material injected into the system are defined by the representative diameter d_i and the percentual contribution p_i for each fraction within the mixture.

The average shear stress on a conduit wall is calculated as:

$$\tau_0 = \rho V^2 \frac{\lambda}{8} \tag{14}$$

where ρ is water density (kg/m^3), and V is mean velocity (m/s).

Critical shear stress for a given grain diameter d_i is obtained as:

$$\tau_{cr,i} = 0.056 g(\rho_s - \rho) d_i \tag{15}$$

where $g = 9.81 m/s^2$, and $\rho_s = 2650 kg/m^3$.

Assuming normal distribution of critical shear stress, this value corresponds to a probability of 50% that the grain of diameter d_i will move. Due to the slope of the conduit and nonuniform mixture of the granulate, this value must be corrected by two factors:

$$K_1 = \cos\alpha\left(1 - \frac{\operatorname{tg}\alpha}{\operatorname{tg}\varphi_{i50}}\right)$$

$$K_2 = \left(\frac{d_{50}}{d_i}\right)^{1.2} \tag{16}$$

where α represents slope of the conduit, while ϕ_{i50} is the friction angle ≅ 35°. If the slope is larger or equal to the friction angle, the granulate is not deposited. Otherwise, the following calculation must be conducted.

The corrected value of the shear stress is calculated as:

$$\overline{\tau_{cr,i}} = \tau_{cr,i} \cdot K_1 \cdot K_2 \tag{17}$$

Having in mind stochastic nature of the process, a random variable is introduced:

$$X_i = \left(\frac{\overline{\tau_{cr,i}}}{\tau_0}\right) \tag{18}$$

The mean value of the random variable is $\overline{X_i} = 1$, while the standard deviation $\sigma_X = 0.57$ was taken from literature.

Probability of the grain deposition is defined by the probability density function:

$$F(X_i) = \frac{1}{\sigma_X\sqrt{2\pi}}\int_{-\infty}^{X} \exp\left(-\frac{(y-\overline{X})^2}{2\sigma_X^2}\right) dy \tag{19}$$

so $F(X) \cdot 100\%$ of grains from d_i class will be deposited, while $(1 - F(X)) \cdot 100\%$ will be carried to next conduit.

In the case when the slope of the conduit is negative (downstream end of the conduit is higher than the upstream end), it is better to use critical velocity as a deposition criterion:

$$U_{cr} = 0.85\sqrt{2g\Delta D_z \cos(\vartheta)} \tag{20}$$

where D_z is the grain diameter, ϑ is the conduit slope, and $\Delta = (\rho_z - 1000)/1000$ relative grain density comparing to water density. Here, we also introduce a random variable:

$$X_i = \left(\frac{U_{cr}}{U(y = D_{zi}/2)}\right) \tag{21}$$

with $\overline{X_i} = 1$ and $\sigma_X = 0.57$, and use it to calculate the percentage of the deposited granulate.

This calculation is repeated for each class of the granulated material within the mixture, fiving the total amount of the deposited material. As described in Figure 2, calculation of the deposited material is performed in each time step of the hydraulic simulation, giving the change of the conduits' diameters and frictions due to deposition. For an assumed roughness of the conduit walls κ, the continuous longitudinal hydraulic losses are calculated as:

$$\lambda = \left(\frac{1}{2\log(3.7D/\kappa)}\right)^2 \tag{22}$$

Based on the total hydraulic losses $\bar{\lambda}$ and the continuous longitudinal losses λ, local hydraulic losses are calculated as:

$$\sum\xi = \left(\bar{\lambda} - \lambda\right)\frac{L}{D} \tag{23}$$

If we assume that the granulate is smeared along all the conduit, only the longitudinal losses λ are affected, thus new total losses are calculated as:

$$\bar{\lambda}_{\text{novo}}\frac{L}{D} = \lambda_{\text{novo}}\frac{L}{D} + \sum\xi \tag{24}$$

This change in the model configuration requires new hydraulic calculation to obtain the altered hydraulic picture (piezometric levels and velocities within the partially congested conduits), which in turn alters further deposition, implying an iterative hydraulics-deposition calculation, as shown in Figure 2.

DATA ASSIMILATION

Compliance of an assumed system configuration and the corresponding hydraulic model with the real state of the underground network of fissures is determined by the following indicators:

- Matching between the calculated piezometric levels and the measured ones;
- Matching between the calculated water velocities and the measured ones;
- Matching between the calculated tracer dynamics and the measured concentration time course.

Unknown parameters of each configuration (equivalent diameters and frictions of conduits) are determined using genetic algorithm (GA), where the quality of a particular configuration is determined by the matching of calculated piezometric levels, velocities, and tracer dynamics with the measured values for the same boundary conditions (upstream and downstream water levels).

However, such an approach would lead to a series of independently estimated configurations, neglecting the fact that every configuration is a result of the sedimentation in previous ones. Therefore, the difference between the volumes of two subsequent configurations must be in proportion to the amount of the material injected during the time span between these configurations. On the other hand, frictions of conduits must change in function of the deposited material in a consisted manner. To meet these requirements, the matching between subsequent configurations in terms of the deposited material is introduced as an additional indicator of the model compliance (morphological indicator).

Methodology

Unknown parameters of the system are determined by the implementation of the following methodology:

- Parameter estimation is performed using GA for multiobjective optimization (MOGA), where every individual within the population represents a different set of possible parameter values.
- Since the parameters in different system configurations are causally related, the estimation is done simultaneously for several typical configurations: the initial configuration and few configurations after some significant events.
- In the initial configuration parameters of all the elements of the systems are considered unknown. For all the latter configurations only the parameters of the elements where deposition of the granulates is expected are declared as unknown.
- As a key part of the evaluation of an individual within the GA, the similarity of each configuration with the reality is determined by calculation of the indicators as explained before.
- Every single individual within the GA is evaluated in the following way:
    - Hydraulics and tracer transport in the initial configuration are simulated using the set of parameters defined by the individual, and the fitness of the individual is determined according to the first three

  indicators. The morphological indicator is not taken into account since there is no material injection in the initial configuration.
  - The calculations for the subsequent configurations are performed with the parameters defined by the individual. However, the radiuses of elements are changed from configuration to configuration according to the calculated material deposition. In case of a radius reduction, the change of local hydraulic resistance within that conduit is calculated as well.
  - After the separate evaluation of each configuration, the evaluation regarding the morphological criterion is performed.
  - Once all the calculations are done, the parameter set represented by the individual is evaluated according to four criteria, which is further used for the selection of fittest individuals within GA.
- As a result of the parameter estimation using MOGA we obtain Pareto front defined by the four marks for every individual within population. Based on the expert judgement about the importance of each of the criteria, one solution from the front is chosen as a most probable set of unknown parameters.

Evolutionary algorithms

As mentioned before, the estimation of the unknown parameters of the underground conduits is performed using multiobjective GA (Figure 5).

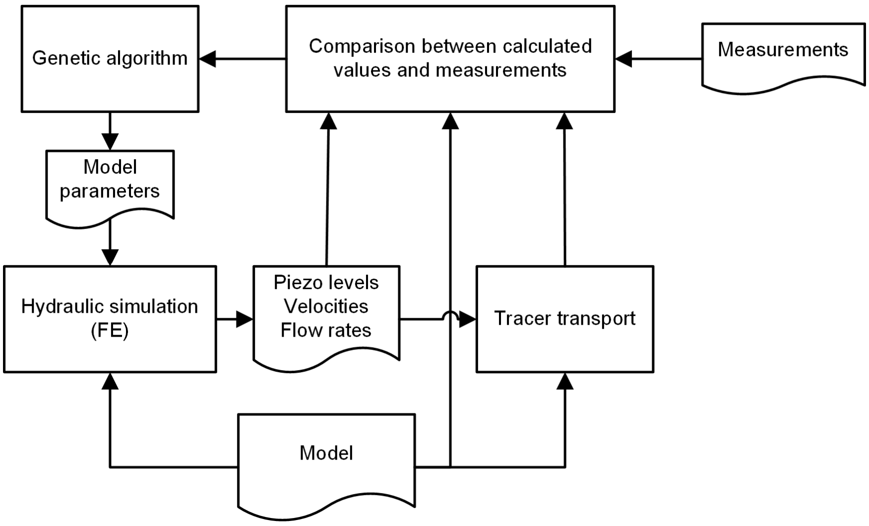


***Figure 5**. Schematic view of the parameter estimation process*

The process of the parameter estimations begins with the creation of the initial generation of parameter sets (individuals). Based on the parameters defined by each individual, simulation of the hydraulic model is performed, resulting with piezometric levels and flow rates. Using the calculated flow rates, tracer transport is also calculated. Once the hydraulics and tracer dynamics are known, they are compared to the measured values, giving the quality of the considered parameter set (the individual fitness). Based on the evaluation of all individuals, GA choses best solutions to be further subjected to processes of selection, cross-over and mutation, resulting in a new generation of individuals. Afterwards the described process is repeated in an iterative manner until reaching the acceptable matching between the calculated results and the measured values, when the parameters are adopted as the most probable.

HPC implementation

Genetic algorithms have proven themselves as robust and powerful mechanisms when it comes to solving complex real-world optimization problems. However, GA is characterized by a large number of individual evaluations, which in case of complex systems may require running simulations that will provide results necessary to assess the fitness of each individual. These simulations are usually time-consuming, making the fitness evaluation a bottleneck of the optimization algorithm. In the case of Višegrad dam, running all the mentioned simulations necessary to evaluate the quality of a single individual takes few minutes. Consequently, the whole parameter estimation process, that require evaluation of hundreds of individuals through tens of generations, would last for days or even months, which was not acceptable in the case when decisions about remediation actions had to be made on daily basis.

In order to provide speedup of the execution of the algorithm and to reduce the optimization duration to a reasonable timeframe, we have developed WoBinGO [26], a software framework for solving optimization problems over heterogeneous resources, including HPC clusters and Globus-based Grids. The framework was designed to meet the following goals: (1) speeding up the optimization process by parallelization of GA over the Grid; (2) relieving the researcher burden of obtaining Grid resources and dealing with various Grid middlewares; (3) enabling fast allocation of Grid jobs to avoid waiting until requests for computing resources are processed by Grid middleware; (4) providing flexible allocation of worker jobs in accordance with the dynamics of the users' requests, thus avoiding the unnecessary reservation of computing resources. It uses a master–slave parallelization model and allows parallel evaluation of a population in GA.

This framework incorporates the Work Binder (WB) [27] which provides almost instant access to Grid resources and interactivity for client applications. Integration of WB into the framework enables the programmer to focus solely on the optimization problem without having to worry about specific details of Grid computing. Additionally, WB increases the utilization of the Grid infrastructure by offering automated elasticity in its occupancy, based on present and recent client behaviour. With the master–slave parallelization model and WB, evaluation of individuals is separated from the rest of the algorithm and performed on Grid computing elements (CEs).

The basic structure of the framework is illustrated in Figure 6. The framework consists of the optimization master and the distributed evaluation system based on WB. The distributed evaluation system is composed of the evaluation pool and the WB subsystem. The master executes the main evolutionary loop and the distributed evaluation system takes care of the Grid execution of the evaluation processes. It should be noted that the evaluation pool is NOT the same entity as the pool of ready jobs created and maintained by WB itself.

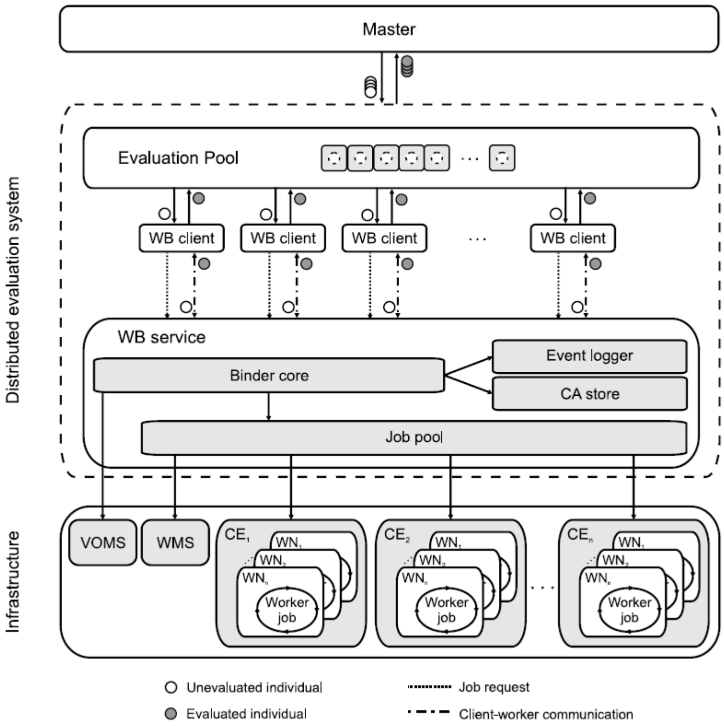


***Figure 6**. Structure of WoBinGO framework*

The master performs the main evolutionary loop to the point when a generation has to be evaluated. At that moment, the master sends all individuals in a generation to the evaluation pool. After all individuals from a generation have been evaluated, and assigned with an objective function value, the master proceeds with the rest of the evolutionary algorithm until the stopping criteria is reached.

The evaluation pool acts as an intermediate layer between the master and the WB service. It provides asynchronous parallel evaluation of individuals from a generation. Each time a generation has to be evaluated, the evaluation pool receives individuals from the master and enqueues them. The evaluation pool invokes the WB client for each of the queued individuals. When an individual is evaluated, the evaluation pool receives the result back from a WB client and then assigns objective function value to the corresponding individual.

The WB environment consists of software components distributed in three tiers: the client, the worker, and WB service. The purpose of the WB service is to maintain the pool of ready worker jobs on the Grid and to bind them with clients that request evaluation. It submits jobs to the Grid CEs in order to load enough worker jobs in the pool for incoming requests. The client establishes a connection to the WB service and requests a worker. As soon as the client and worker are successfully coupled, the WB service acts as a proxy that relays traffic between them. For the purpose of distributed evaluation, the client sends an individual to a worker which computes fitness value and sends it back through WBproxy. After completing the evaluation, the worker reconnects to the WB service asking for more work within job time limits determined by WB configuration. The job lifetime cannot exceed the limit specified by the local Grid site administrator, obtained using MDS.

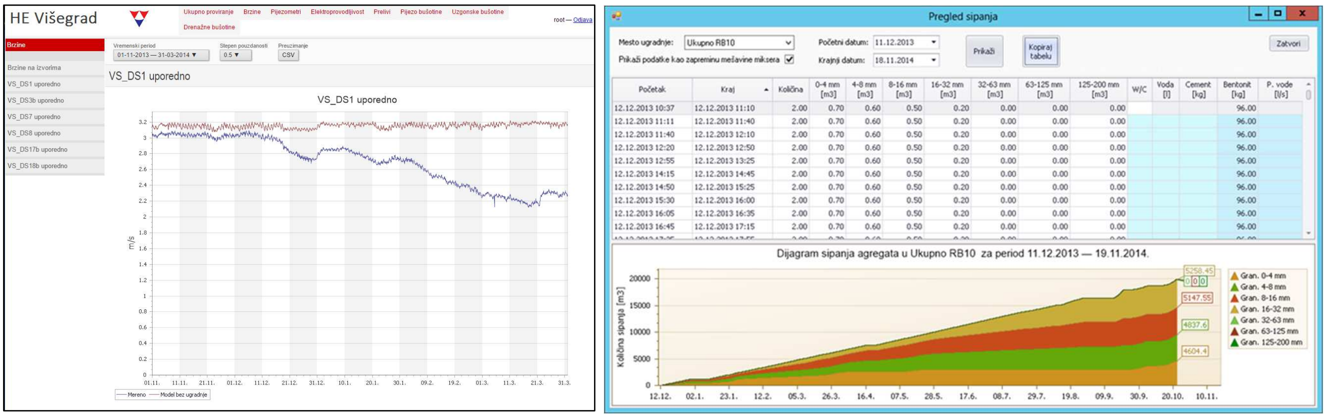
DECISION SUPPORT TOOLS

Investigation and remediation of Višegrad dam seepage presented various challenges that required prompt response from decision makers to successfully define and coordinate further actions. That is why specially designed decision support tools were made, so that decision makers were enabled to make informed decisions and analyze outcomes of their actions. One tool is specifically designed for real-time tracking of remediation works, while the other is designed for analysis and planning. Both tools rely on computations performed on mathematical models that are part of HPC platform, as well as measured data and metadata.

Application for real-time tracking of remediation

This tool is designed for decision support in real-time, and therefore it is mainly focused on recent measurements, but it also provides insight into calculation results. Apart from the fact that recent values of measured variables may be used for assessment of effects of remediation works, this tool also provides values from continuous calculation performed on HPC platform. The goal of remediation is to minimize seepage under the dam by injecting both inert and grouting material into karst conduits, therefore reducing effective cross-section of conduits and their hydraulic conductivity. Before remediation process began, an estimation of model parameters had been carried out, and an initial model configuration had been stored in central database. During the remediation process, a continuous automated calculation was performed using initial model, with the current boundary conditions. This way, reference values have been provided, which correspond to seepage unaffected by remediation works. These reference values are then compared against currently measured values, thus giving insight into the effects of remediation on seepage under the dam. As shown on Figure 7, reference water velocity at spring DS1 (red line) is relatively constant, as opposed to measured water velocity (blue line), which is reducing considerably, as remediation works are performed over time.

The tool also provides 2D and 3D visualizations of measurements and model results and configurations, along with other data from central database: injection logs, both for inert granulated material, and for grouting material, tomography charts, etc. Injection logs can be listed individually or interpreted through data processing as total volume over time (Figure 7). Logs are detailed and users may view volume of injected material per batch, and volume for each granulation, as well as borehole and depth where material has been injected.



Vremenski period: 01-11-2013 — 31-03-2014
Stepen pouzdanosti: 0.5
Preuzimanje: CSV

Mesto ugradnje: Ukupno RB10
Prikaži podatke kao zapreminu mešavine miksera ☑
Početni datum: 11.12.2013
Krajnji datum: 18.11.2014

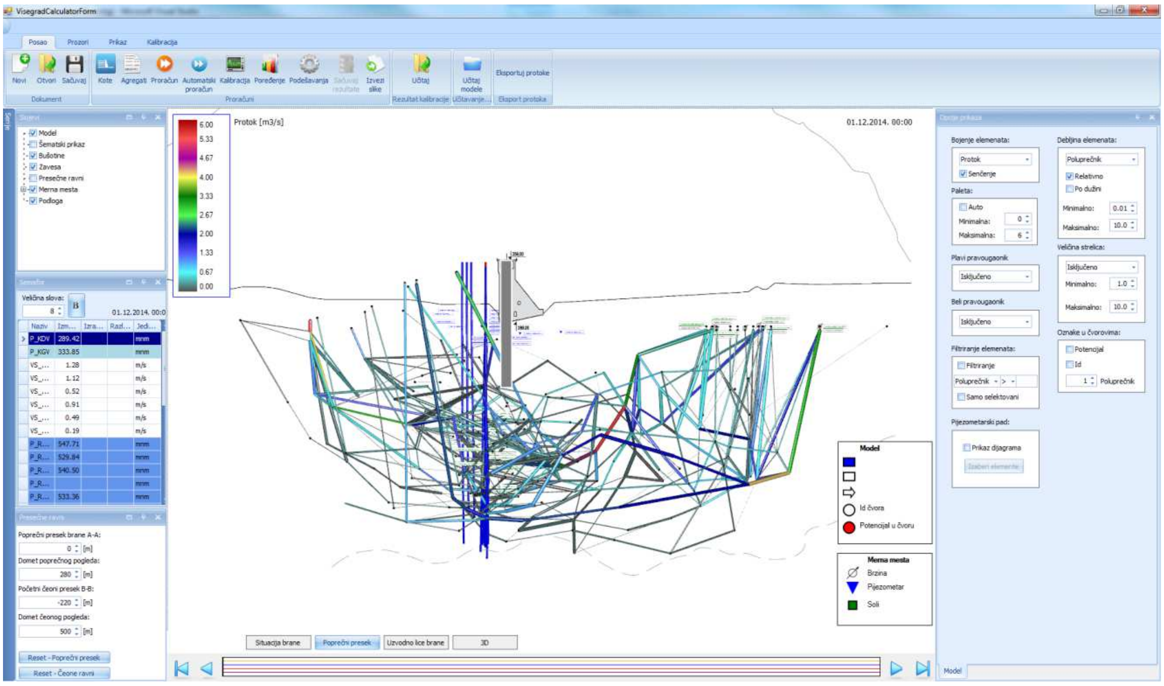
Početak	Kraj	Količina	0-4 mm [m3]	4-8 mm [m3]	8-16 mm [m3]	16-32 mm [m3]	32-63 mm [m3]	63-125 mm [m3]	125-200 mm [m3]	W/C	Voda [l]	Cement [kg]	Bentonit [kg]	P. vode [l/s]
12.12.2013 10:37	12.12.2013 11:10	2.00	0.70	0.60	0.50	0.20	0.00	0.00	0.00				96.00	
12.12.2013 11:11	12.12.2013 11:40	2.00	0.70	0.60	0.50	0.20	0.00	0.00	0.00				96.00	
12.12.2013 11:40	12.12.2013 12:10	2.00	0.70	0.60	0.50	0.20	0.00	0.00	0.00				96.00	
12.12.2013 12:20	12.12.2013 12:50	2.00	0.70	0.60	0.50	0.20	0.00	0.00	0.00				96.00	
12.12.2013 12:55	12.12.2013 13:25	2.00	0.70	0.60	0.50	0.20	0.00	0.00	0.00				96.00	
12.12.2013 14:15	12.12.2013 14:45	2.00	0.70	0.60	0.50	0.20	0.00	0.00	0.00				96.00	
12.12.2013 14:50	12.12.2013 15:25	2.00	0.70	0.60	0.50	0.20	0.00	0.00	0.00				96.00	
12.12.2013 15:30	12.12.2013 16:00	2.00	0.70	0.60	0.50	0.20	0.00	0.00	0.00				96.00	
12.12.2013 16:05	12.12.2013 16:35	2.00	0.70	0.60	0.50	0.20	0.00	0.00	0.00				96.00	
12.12.2013 16:45	12.12.2013 17:15	2.00	0.70	0.60	0.50	0.20	0.00	0.00	0.00				96.00	

***Figure** 7. Real-time tracking of effects of remediation on water velocity at springs (left) and real-time tracking of volume of inert material injected into a borehole (right)*

Application for analysis and planning

Throughout the remediation works, various scenarios of inert material injection have been regularly simulated. Based on analysis, optimal parameters of injection process have been defined, and then used for planning.

Application for analysis and planning have been used for decision support in daily and weekly planning. An updated state of hydraulic model has been used for simulation of inert material injection, while boundary conditions have been retrieved from headwater and tailwater level measurements. The rate and location of injection were also user-defined, while ratio of various grain sizes was also subject of analysis. The results of simulation were flow rates and velocities in conduits, piezometric heads, as well as changes in volumes of conduits due to deposition of inert material. This way, it was possible to assess the effects of injection or grouting and define plans for further work, usually for up to 7 days. Figure 8 shows 3D representation of conduits with effective diameters and resulting flows represented by colour scale.



☑ Model
☐ Šematski prikaz
☑ Bušotine
☑ Zavesa
☐ Presečne ravni
☑ Merna mesta
☑ Podloga

Veličina slova: 8

01.12.2014. 00:0

Naziv	Izm...	Izra...	Razl...	Jedi...
P_KDV	289.42			mnm
P_KGV	333.85			mnm
VS_...	1.28			m/s
VS_...	1.12			m/s
VS_...	0.52			m/s
VS_...	0.91			m/s
VS_...	0.49			m/s
VS_...	0.19			m/s
P_R...	547.71			mnm
P_R...	529.84			mnm
P_R...	540.50			mnm
P_R...				mnm
P_R...	533.36			mnm

Poprečni presek brane A-A: 0 [m]
Domet poprečnog pogleda: 280 [m]
Početni čeoni presek B-B: -220 [m]
Domet čeonog pogleda: 500 [m]

Bojenje elemenata: Protok
☑ Senčenje
Paleta:
☐ Auto
Minimalna: 0
Maksimalna: 6
Plavi pravougaonik: Isključeno
Beli pravougaonik: Isključeno
Filtriranje elemenata:
☐ Filtriranje
Poluprečnik >
☐ Samo selektovani
Pijezometarski pad:
☐ Prikaz dijagrama
Izaberi elemente

Debljina elemenata: Poluprečnik
☑ Relativno
☐ Po dužini
Minimalno: 0.01
Maksimalno: 10.0
Veličina strelica: Isključeno
Minimalno: 1.0
Maksimalno: 10.0
Oznake u čvorovima:
☐ Potencijal
☐ Id
1 Poluprečnik

***Figure 8**. A 3D view of karst conduits visualized in application for analysis and planning*

EXAMPLES OF PLATFORM APPLICATION

The platform has been used mainly for tracking the effects of remediation works on seepage, since the model could provide estimation of total seepage given the amounts of injected material over time. An example of such an estimation is given on Fig. 9, at final stage of remediation.

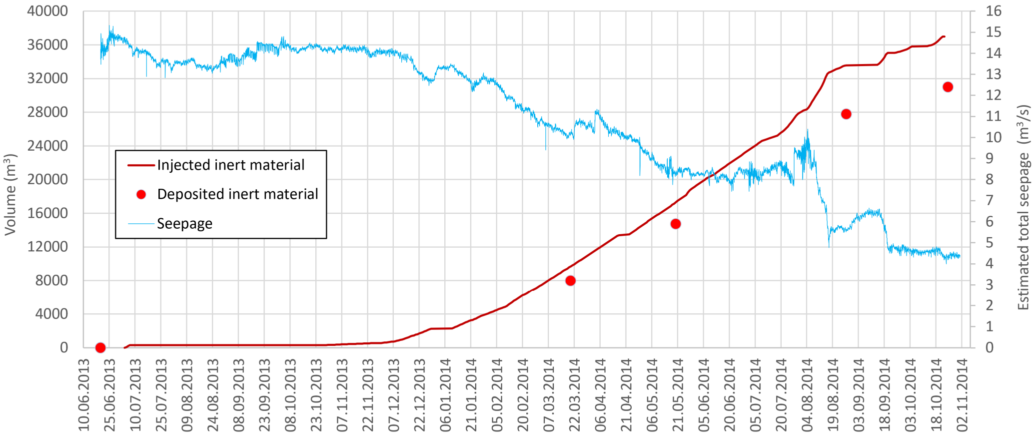


***Figure 9**. Inert material volumes and estimated total seepage over the course of remediation works*

However, at certain points, important decisions were made based on simulation results that significantly impacted the course of further actions. One example was the decision not to abandon injection through the largest sinkhole, although the injection has already been stalling for some time. At that point, the most recent plans defined the depth and mixture for injection of inert material, but the effects were not satisfying. Various alternate scenarios have been assessed using decision support tools to overcome this problem, and several possible solutions were found. The most viable option was chosen, having in mind the existing locations for injection and available equipment on site. Figure 10 shows comparison of flows in karst conduits before and after inert material injection and deposition.

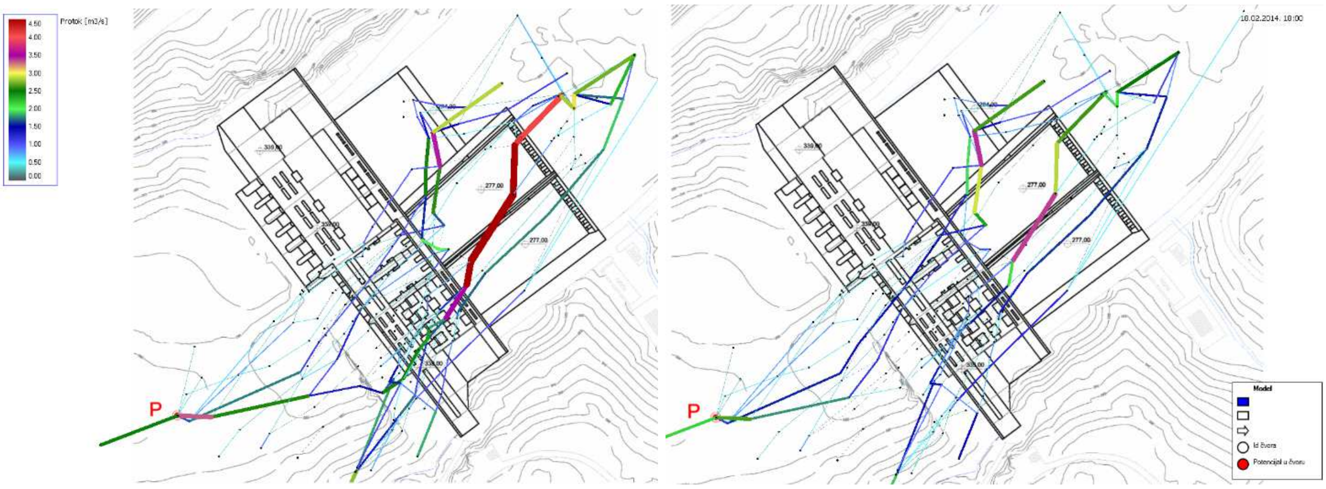


***Figure 10**. Initial flows through conduits (left) and assessed flow after inert material deposition (right)*

It was shown that it is justified to continue injection of inert material into largest sinkhole, which eventually proved to be correct decision, since 10,000 m³ of material was later spent at that location.

In total, almost 37,000 m³ of inert granulated material was used, of which up to 30,000 m³ was deposited within conduits, and the seepage has been significantly reduced. The grouting injection was performed at the end, to consolidate deposited material and make the effects of remediation permanent.

CONCLUSION

In this paper we presented the high-performance computing platform for decision support during the remediation of the Višegrad dam. The core components of the platform are numerical models of hydraulics, tracer transport, and granulated material transport and sedimentation. Since some of the hydraulic model parameters were known approximately within the ranges obtained by geological research, the main part of the platform was the algorithm for parameter estimation based on genetic algorithm. The algorithm is capable to determine the geometric and hydraulic parameters of the assumed karst conduits, so the results of the simulations best match the *in situ* measurements, resulting with a model configuration that represents a genuine image of the underground network of fissures. Thanks to the implemented parallelization strategy, the calculations were run on a distributed computing environment, enabling parameter estimation within the acceptable time frame, and decision support on daily basis.

The platform fulfilled all the requirements defined before and during the remediation, and enabled monitoring the effects of granulated material injection in near real-time, but also the predictions of the hypothetic injection scenarios during the remediation planning. Reliability of the results was on the satisfactory level, which was proven by comparison of the predicted changes of key variables and their measured values.

Having in mind that the platform is developed as a modular software-hardware system, the inherent robustness of the applied algorithms, and the efficiency of the parallelization strategy, the platform can be easily adapted and transformed into a very powerful decision support system for similar projects. Possible directions for improvements of the platform could be implementation of modern HPC techniques, Cloud technologies, and eventually AI methods that could help in modeling weakly defined physical processes.

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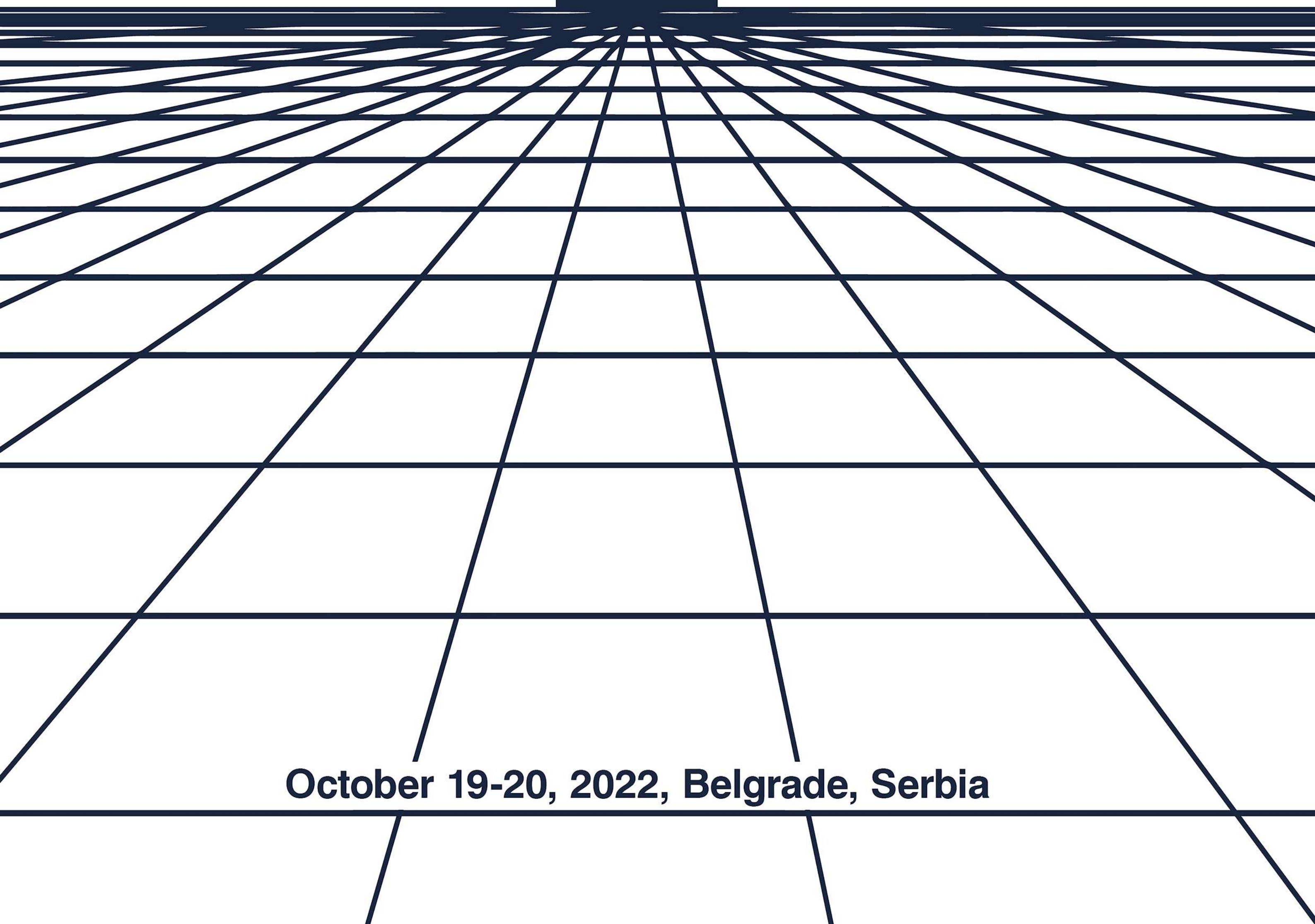

October 19-20, 2022, Belgrade, Serbia

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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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