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Engineering problems in soft rocks

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ENGINEERING PROBLEMS IN SOFT ROCKS

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Петтиот симпозиум на Друштвото за геотехника на Македонија (ДГМ), Специјализирана конференција на Меѓународното друштво за механика на карпи и инженерство во карпи (ISRM) и Втора конференција на регионалните геотехнички друштва, е организирана од ДГМ, под покровителство на ISRM и поддржано од Меѓународното друштво за механика на почви и геотехничко инженерство (ISSMGE).

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Calibration Analysis Of Seepage Flow At Arch Dam Foundation – A Case Study

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ABSTRACT

The assessment of the structural stability and the behavior of the dam during construction and service period is of vital importance. In the paper are presented acknowledgments from the calibration analysis of the seepage process in the foundation of an concrete arch dam, by application of numerical methods, based on Finite Element Method (FEM), with applied code SOFiSTiK. The aim of the task is to assess and predict the seepage process, that includes calibration (based on monitoring data) and prognosis stage (short-term and long-term) focusing on variable such as seepage flow. Seepage analysis in time domain was carried out the for calibration and prognosis stage. The key conclusion from the numerical experiment is that obtained seepage flow values within the calibration stage are matching good with the measured data, that allows to predict the future seepage flow data and to assess the state of the foundation and permissible boundary values.

KEYWORDS

Seepage flow; FEM; Rock foundation, Calibration Process; Prediction.

1. INTRODUCTION

The dams, having in consideration their importance, dimensions, complexity of the problems that should be solved during the process of designing and construction along with the environmental impact are lined up in the most complex engineering structures (Tanchev, 2014; Novak & all., 2007). The assessment of the structural stability and the behavior of the dam during construction, at full reservoir and during the service period is of paramount importance for such structures.

The dams should satisfy several types of safety such as: hydrologic, hydraulic, structural (static and dynamic) and seepage safety. Seepage stability of the foundation beneath the dams is confirmed with analysis (research) of the response of the medium under action of hydraulic head (Petkovski and Tanchev, 2004; Petkovski et all, 2009, Petkovski et all, 2021). According to the advanced approach for structural analysis of dam, the analysis is carried out by unique and full numerical model of coupled mechanical and hydraulic response of the structure/medium that enables to track and assess the construction chronology and dam service period (ICOLD, 1994.a). In such a way, beside the mechanical and hydraulic parameters of the materials, time coordinate is included also in the analysis of the dam behavior (Petkovski L., Tančev L., Mitovski S., 2007.).

In this paper are systemized acknowledgments from the seepage analysis in the rock foundation of an concrete arch dam, obtained with application of numerical methods, based on Finite Element Method, with the code SOFiSTiK. Here below will be illustrated output data from the numerical experiment for calibration and prediction seepage process in the rock foundation of an arch dam, located in France. The aim of the task is to predict the dam foundation behavior, that includes calibration (based on monitoring data) and prognosis stage (short-term and long-term) focusing on variable such as seepage flow (measured in weir downstream of the dam).

2. CASE STUDY

The analyzed dam is located in southern France, constructed in period 1957-1960. It is a case of double curvature arch dam, with asymmetric shape due to the valley formation (Fig. 1). The dam foundation is laminated metamorphic slate with high compressive strength, with present anisotropy in the left bank. The dam height above the foundation si H=45 m, with crest thickness of 2 m and base thickness of 6 m.

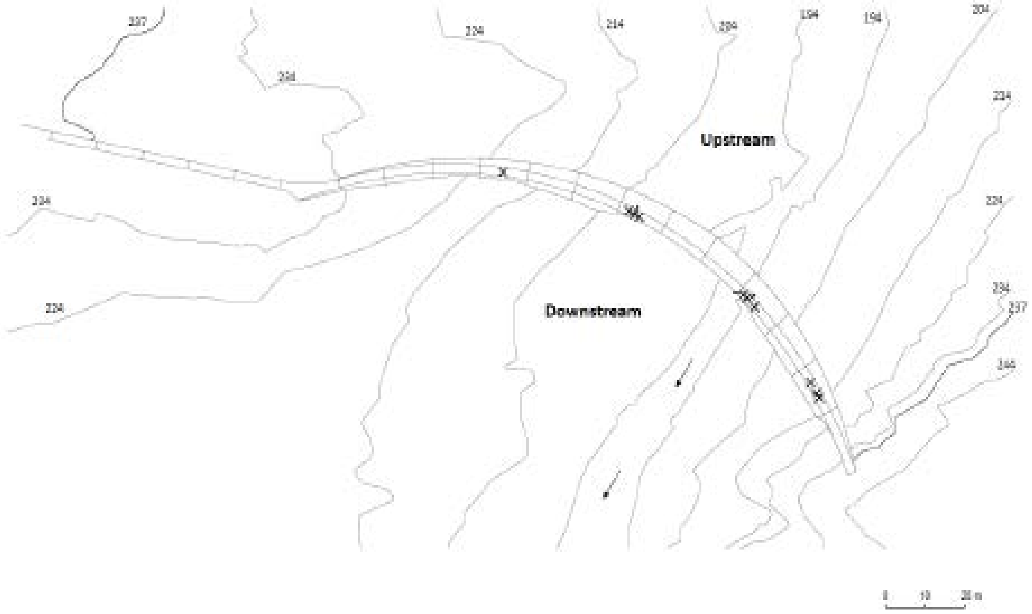

Figure 1. Layout of the dam.

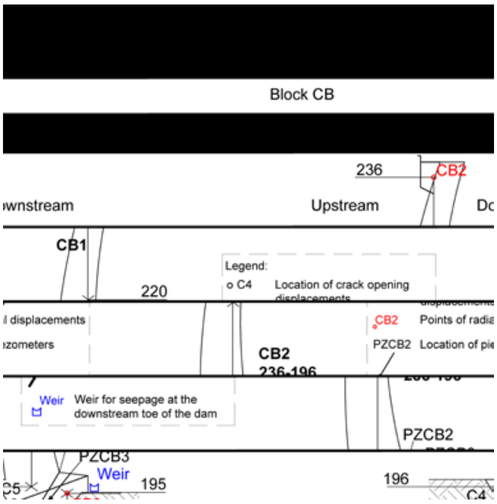

Figure 2. Central block section with display of monitoring instruments (right).

3. NUMERICAL MODEL OF THE DAM

The numerical analysis of Dam EDF is carried out by application of program SOFiSTiK, produced in Munich, Germany. The program offers many possibilities for complex modeling of the structures and simulation of their behavior. It also has possibility in the analysis to include certain specific phenomena, important for realistic simulation of dam's behavior, such as: discretization of the dam and foundation taking into account the irregular and complex geometry of the structure, simulation of stage construction, simulation of contact behavior by applying interface elements and etc. in order to assess the dam behavior and evaluate its stability. The program SOFiSTiK in its library contains and various standards and constitutive laws (linear and non-linear) for structures analysis. By applying module HYDRA from SOFiSTiK there is possibility to analyze potential flows such as the seepage flow.

The numerical experiment includes following steps, typical for this type of analysis: (1) choice of material properties; (2) discretization of the seepage medium (rock foundation) and (3) simulation of the foundation behavior for various levels in accordance with the measured water levels in the reservoir.

1.1. Material hydraulic properties

The mechanical material properties for the dam body (concrete) and the foundation (rock) are systematized in Table 1. The specified parameters are adopted according to Theme A formulation (Malm & all, 2021) as well and previous carried out analysis and reference literature (SOFiSTiK, 2022; EC 2, 1992; Mitovski, 2015, USBR, 1977).

Table 1. Material parameters.

Zone		dam body (concrete)	rock	Comment
γ_{spec}	kN/m^3	24.0	27.0	Unit weight
k_s	m/s		2.0e-05	Permeability coefficient
ν		0.350	0.450	Poisson coefficient
E	GPa	22	3	Young's modulus of elasticity

However, the hydraulic properties for the material in the rock foundation were not available. So, the first step is to calibrate the value for the permeability coefficient k in accordance with the seepage values from the monitoring process for homogeneous rock foundation. The estimated permeability coefficient for laminated metamorphic slate ranges in interval $k=(10^{-7}\div10^{-9})$m/s [Lianyang, 2016, Fell et all, 2015]. The permeability coefficient additionally is calibrated by the value of the full seepage flow directly below the dam, specified as measured values in weir at gallery located at the downstream toe of the dam. So, according to the available measuring data for water level at 232.0 m the average registered seepage flow is 8 l/min. From the registered reservoir water levels and seepage flow it can be noticed general correlation, however in some periods there is discrepancy in the measured values that could be indication that the seepage flow is caused by additional influences then the seepage process in the rock foundation. The seepage analysis was carried out for H=232.0 m as upstream boundary condition and H=0 m as downstream boundary condition, by applying Darcy flow rule adopting the rock foundation as heterogeneous flow medium, composed of rock material (laminated metamorphic slate) and two sections (vertical and inclined) of grout curtain, by assumed permeability coefficient in first iteration $k_r=1\times10^{-7}$ m/s for the rock zone. The calibration calculations are displayed in Table 1.

By the initial calibration calculation of the permeability coefficient for homogeneous rock foundation was obtained value of $k=2.89\times10^{-8}$ m/s, applied in the calculation for the full calibration and prognosis analysis of the piezometric levels and seepage. Due to the grout curtain in the rock foundation (heterogeneous zone), additional calibration were carried out, in order to match the measured seepage flow Qm=8 l/min and thus obtaining value of permeability coefficient for the rock foundation $k_{rf}=12.5\times10^{-8}$ m/s and permeability coefficient for the grout curtain $k_{gc}=2.5\times10^{-8}$ m/s, used as input parameters for the seepage calibration and prognosis stage.

Table 1. Calculation for calibration of permeability coefficient.

no.	Title	dimension	mark	value
1	Hydraulic head	[m]	H	232
2	Assumed permeability coefficient for rock foundation	m/s	k'	1.00E-07
3	Calculated specific seepage flow in the foundation	l/s/m	qo'	2.15E-03
4	Calculated specific seepage flow in the foundation	m3/s/m	qo'	2.15E-06
5	Average width of the dam site, assumed by longitudinal section per axis of the dam	m	B	150
6	Calculated seepage flow in foundation	m3/s	Qo'	3.23E-04
7	Calculated seepage flow in foundation	l/s	Qo'	0.32
8	Measured seepage flow at dam site (abutments, dam and foundation)	l/s	Qsum	0.13
9	Assumed coefficient for seepage flow share in foundation		c	0.7
10	Seepage flow in foundation	l/s	Qo	0.09
11	Seepage flow in foundation	m3/s	Qo	9.34E-05
12	Specific seepage in the foundation	m3/s/m	qo	6.22E-07
13	Ratio of measured and calculated seepage		qo/qo'	0.29
14	Calibrated permeability coefficient for rock foundation	m/s	k	**2.89E-08**

1.2. Discretization of dam body and foundation by finite elements

Numerical analysis of seepage flow in the foundation of the arch dam is carried out by plane (2D) model, where foundation with included grout curtain is modeled with plane elements. A powerful and reliable finite element should be applied in case where an analysis of structure with complex geometry and behavior is required, having in consideration that the correctly calculated deformations and stresses are of primary significance for assessment of the dam stability. In this case, for discretization of the dam body and the rock foundation is applied quadrilateral finite element, by 4 nodes. Namely, the model is composed of the rock foundation with included zone of grout curtain. The plane (2D) model has geometrical boundaries, limited to horizontal and vertical plane (Fig. 3), adopted according to the specified data [Malm & all, 2021]. The discretization is conveyed by including zones of various hydraulic parameters in the model – rock foundation and grout curtain, approximately modelling the rock foundation per 75m upstream and downstream of the dam.

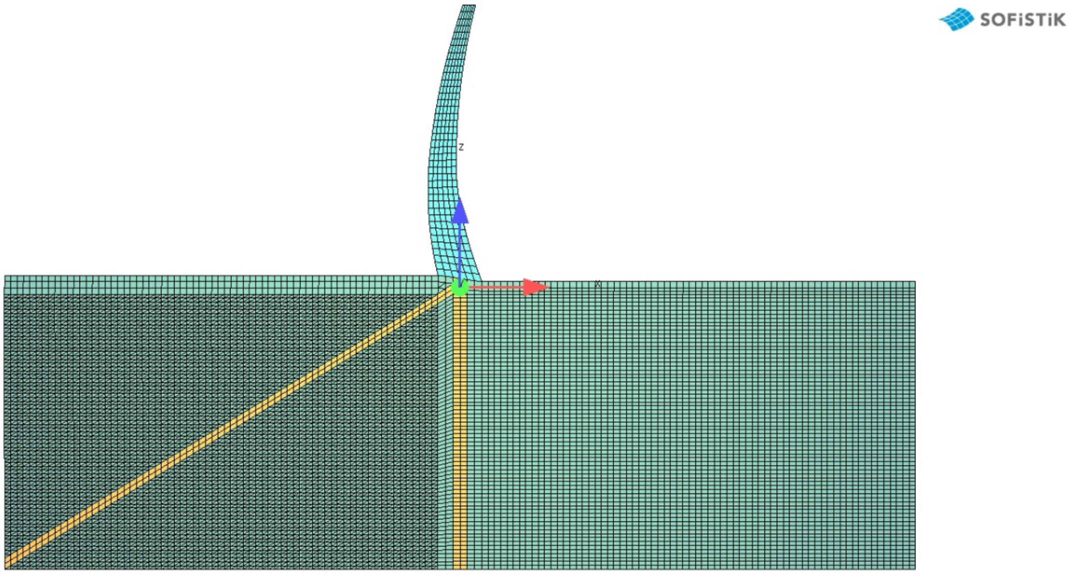

Figure 3. View of the plane numerical model, material distribution and FEM, discretized with total of 15511 elements and 11252 nodes.

1.3. Analyzed scenarios for calibration and prognosis stage

The hydraulic loading of the dam is directly correlated with the seepage calibration and prognosis stage for the dam behavior. Therefore, the numerical analysis is carried out by hydraulic (seepage) model for analysis of the dam foundation behavior for both calibration and prediction stage. More precisely, the calibration process for seepage analysis is carried out by modelling the foundation medium with grout curtain (vertical and inclined section in upstream direction) below the central block of the dam including running of load cases for full timeline period 2000-2012, and subsequent comparison of the measured and calculated seepage flow quantities. Similar approach for the seepage analysis is applied and for prognosis stage, by running of full time steps for the time series within the short-term and the long-term period from Januari,2013 to December,2017.

4. MATHEMATICAL MODEL FOR SEEPAGE ANALYSIS

In general, purpose of the hydrodynamic analysis of the dam and the foundation is to determine: (a) pore pressure, that is to be compared with registered pore pressure values from monitoring process, (b) seepage flow, also to be compared with registered seepage flow values from monitoring process and (c) hydraulic gradients, for assessment of the seepage safety of the dam and the foundation. The seepage analysis is carried out for the central cross section of the dam on rock foundation, by including the grout curtain. The research has been conveyed for stationary seepage flow, at variation of the water level in the reservoir and maintenance of constant boundary hydrodynamic conditions, by application of the module HYDRA from code SOFiSTiK.

For seepage analysis for the Case Study is applied Finite Element Method (FEM). It is a case of powerful mathematical tool, based on approximation of the continua problems (Zienkiewicz O.C., 1975.), where as: (a) the continua is discretized in finite number of elements, whose behavior is specified by finite number of parameters, and (b) the solution for the full system, as composure of its elements, tracks the same rules applied in the discretized task. By application of the FEM for hydrodynamic analysis in porous media (Connor and Brebbia, 1980; SEEP/W, 2003; SOFiSTiK Hydra 2022), a plane (2D) and spatial (3D) stationary and non-stationary seepage flow of ground water in saturated and non-saturated domain can be treated. The basic assumption for the seepage analysis is formalization of the dependence between the pore pressure P_w [kPa] and water content, expressed by coefficient Θ – volumetric content of water (Eq. 1):

$$\Theta = V_w / V \quad (1)$$

where as: V_w = water content and V = total volume of the porous medium.

In the seepage analysis, owing to the flow low velocity the kinematic component of the hydraulic head is disregarded, so the total (potential) head H [m] is calculated by Bernoulli equation (Eq. 2):

$$H = P_w / \gamma_w + y \quad (2)$$

where: γ_w = 9.807 kN/m^3, volume weight of water and y = elevation head (distance over chosen plane).

The flow, in saturated or non-saturated medium is represented by Darcy's law (Eq. 3-4):

$$q= A\,k\,i \quad (3)$$

$$v = k\,i \quad (4)$$

where: q = flow quantity [m3/s], v = flow velocity [m/s], k = permeability coefficient [m/s], i = hydraulic gradient and A – area of cross section through which the flow is performed.

The basic differential equation for description of the flow in porous medium is partial differential equation, expressed by head (potential) function (Eq. 5):

$$\frac{\partial}{\partial x}\left(k_x \frac{\partial H}{\partial x}\right) + \frac{\partial}{\partial y}\left(k_y \frac{\partial H}{\partial y}\right) + Q = \frac{\partial \theta}{\partial t} \quad (5)$$

where as: H = total (potential) head, k_x = permeability coefficient in horizontal direction, k_y = permeability coefficient in vertical direction, Q = applied boundary flow and t = time component. In stationary regime, the quantity of porous water entering and exiting in the elementary volume is not compressible in time domain, so the value of the right side if the differential equation has "zero" value, apropos $\partial\Theta/\partial t = 0$.

5. CALIBRATION PROCESS FOR SEEPAGE TIME SERIES

The calibration process includes seepage analysis for timeline 2000-2012. The obtained equipotential lines, pore pressure distribution (as water table expressed in meters) and contour lines of flow quantities in the rock foundation for water level in the reservoir H=232.0 m are displayed on Fig. 4-6. The calculated seepage flow for reservoir water level at 232.0 masl is Qc=9.5 l/min, that is approximately matching the measured seepage flow of Qm=8 l/min, thus enabling calibration of permeability coefficients for the rock foundation and the grout curtain. The obtained equipotential lines and pore pressure values are in accordance with expected values for such seepage medium and hydraulic head.

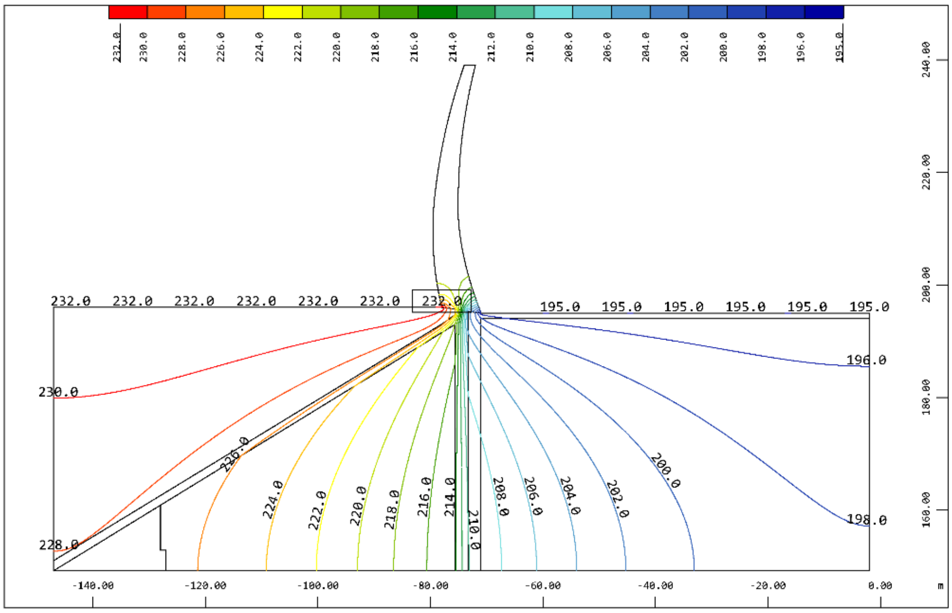

Figure 4. Equipotential lines in the foundation medium for water level H=232.0 m.

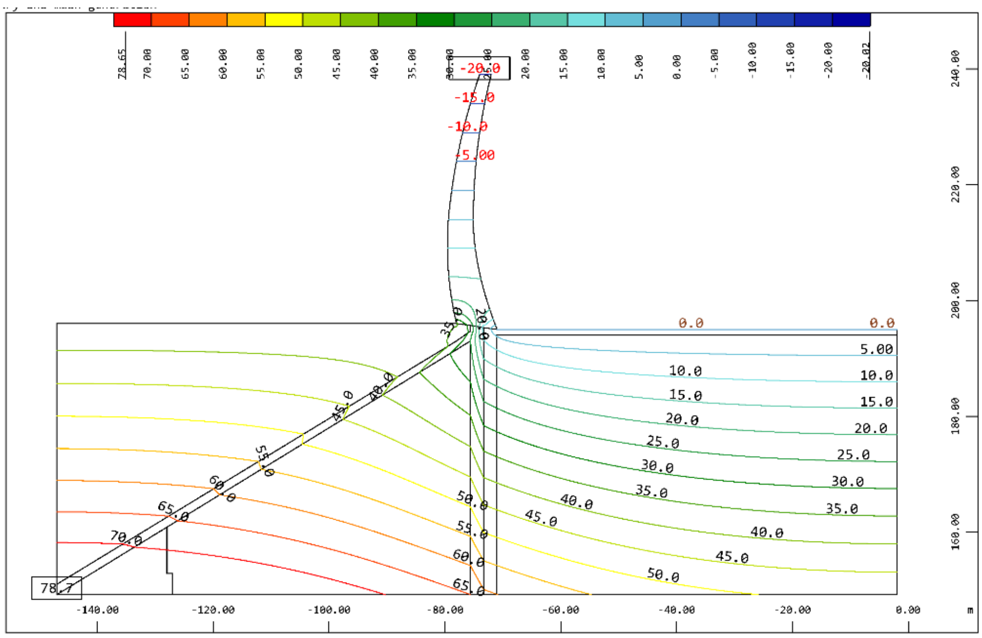

Figure 5. Pore pressure distribution in foundation medium as water table [m] for water level H=232.0 m.

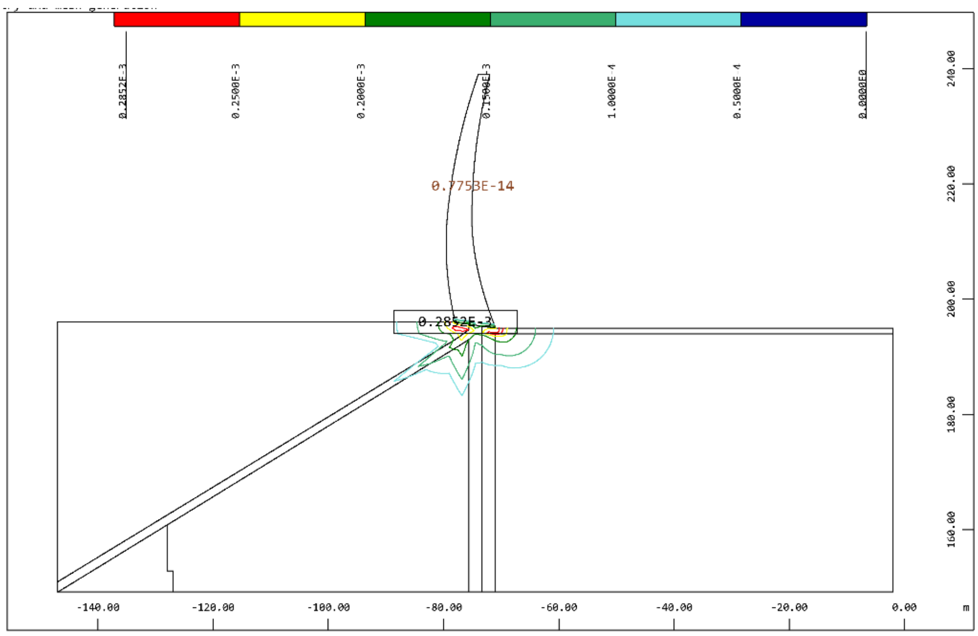

Figure 6. Contour lines of specific seepage flow in foundation medium [l/s/m’] for water level H=232.0 m.

By comparison of the calculated and measure seepage values (Fig. 7) it can be noticed good matching of the registered and calculated seepage flow data regarding the distribution and the quantities. Also, there is good matching apropos correlation of the registered reservoir water levels (Fig. 8) and registered and calculated seepage flow (Fig. 7). The measured peak values of the seepage flow occur are approximately at normal water level so this may be indication for additional leakage occurrences that affect the seepage process. The measured seepage flow varies in interval (0.01 ÷ 26.5) l/min, while the calculated values in interval (0.001 ÷ 18) l/min. However, the occurred peak values of the seepage flow (especially in 2009) required additional explanation and research due to the very high values at approximately constant water level in the reservoir. Namely, they could occur due to another reason such as seepage zone in the dam or zones in the rock foundation that have higher permeability than the presumed. Additional calibration should include modelling of eventual more permeable zones in the rock foundation and more precise calibration of the permeability coefficient of the grout curtain. Namely, the obtained value of the permeability coefficient of the grout curtain of $k_{gc}=2.5\times10^{-8}$ m/s is higher than the minimal prescribed value of 1 Lugeon for grout curtain beneath the dam body and further research of such value would result in improved calibration.

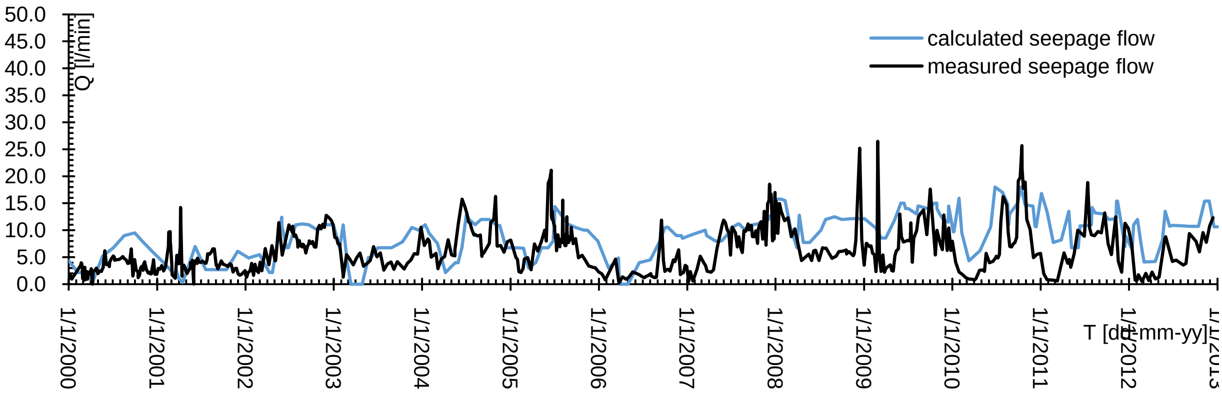

Figure 7. Display of measured and calculated seepage flow time series at the weir for period 2000-2012.

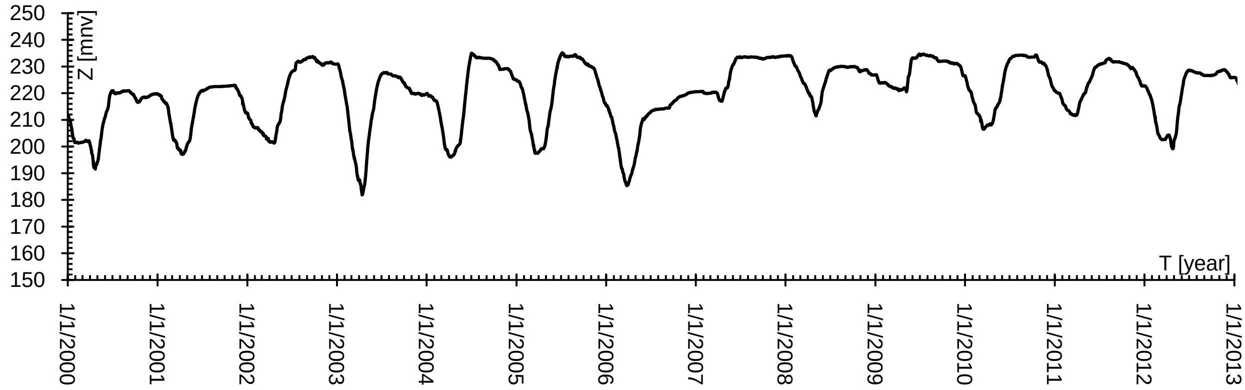

Figure 8. Display of registered reservoir water levels for period 2000-2012.

6. PREDICTION (PROGNOSIS) PROCESS OF SEEPAGE TIME SERIES

The calculated seepage flows for the short-term and long term prognosis (Fig. 10), as expected, are varying in correlation with the water level in the reservoir (Fig. 11). The maximal calculated values for the seepage flow is 15.5 l/min.

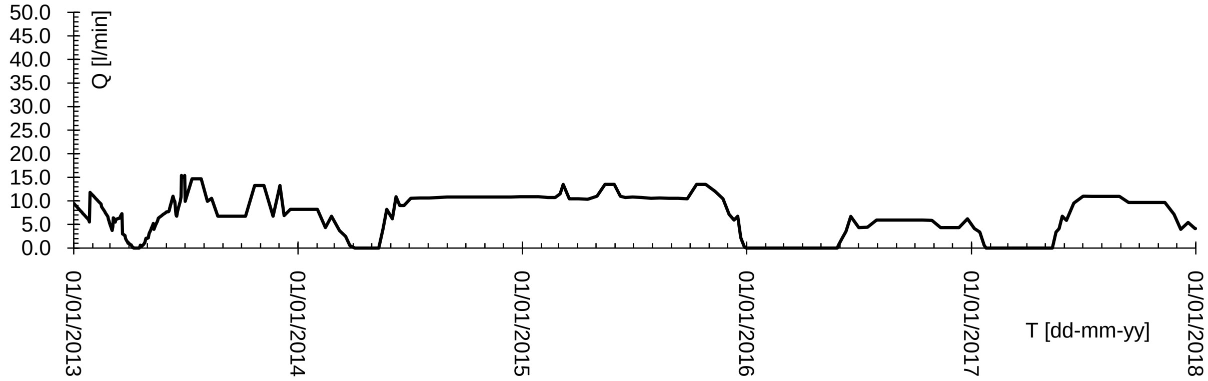

Figure 11. Calculated prognosis time series of seepage flow for period 2013-2017.

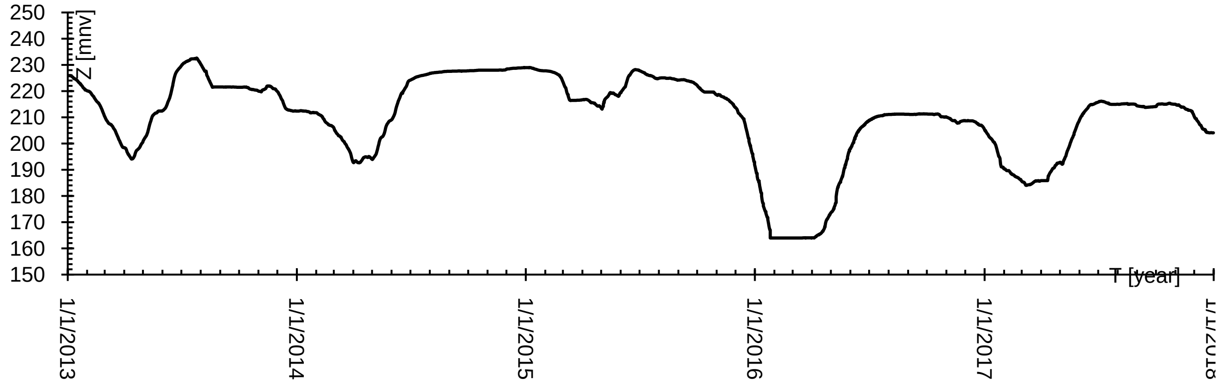

Figure 10. Registered reservoir water levels for period 2013-2017 .

7. CONCLUSIONS

The behavior of the rock foundation beneath an arch dam in case of seepage during the service period for variation of the water levels in the reservoir was simulated by application of the Finite Element Method with plane (2D) numerical model. The numerical analysis of the was carried out by taking in consideration the specified data for the numerical model, variations of the reservoir water level and calibrated permeability coefficients for rock foundation and grout curtain, by applying stationary state of seepage flow. The loading scenarios for analysis of the seepage process and calculation of the required variables were in full by reproducing the available time series.

The prediction of the seepage process for the rock foundation beneath the dam was analyzed in two stages – calibration and prognosis stage. From the carried out numerical experiment of simulation for analysis and prediction of the seepage process in the dam foundation, following main conclusions and recommendations are derived:

(1) The permeability coefficients for the rock foundation and the grout curtain were determined by calibration for reservoir water level H=232.0 m and corresponding average seepage flow Qm= 8 l/min, thus obtaining values for the rock foundation $k_{rf}=12.5\times10^{-8}$ m/s and for grout curtain $k_{gc}=2.5\times10^{-8}$ m/s.

(2) The obtained equipotential lines and pore pressure values are in accordance with expected values for such heterogeneous seepage medium (rock foundation and grout curtain) and corresponding hydraulic head (registered reservoir water levels).

(3) The calibration process of the measured and calculated seepage flow provided good matching of the data regarding the distribution and the values for calibration stage. Namely, measured seepage flow varies in interval (0.01 ÷ 26.5) l/min, while the calculated values in interval (0.001 ÷ 18) l/min, that is not influencing the water balance of the reservoir significantly.

(4) The calibrated value of the permeability coefficient of the grout curtain of $k_{gc}=2.5\times10^{-8}$ m/s is higher than the minimal prescribed value of 1 Lugeon for case of grout curtain beneath the dam body and approximately five times greater than the permeability coefficient of the rock foundation.

(5) The calculated seepage flows for the calibration and for prognosis (short-term and long term) stage are varying in correlation with the water level in the reservoir.

(6) According to the measured and calculated values for the seepage flow in the rock foundation beneath the arch dam is specified value interval (greater calculated/measured value), and further monitoring and comparation is required in order to track such occurrence and the overall behavior of the rock foundation from aspect of seepage safety.

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