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КНИГА НА ТРУДОВИ PROCEEDINGS

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ДРУШТВО НА ГРАДЕЖНИ КОНСТРУКТОРИ НА МАКЕДОНИЈА

MASE

MACEDONIAN ASSOCIATION OF STRUCTURAL ENGINEERS

19 МЕЃУНАРОДЕН СИМПОЗИУМ
INTERNATIONAL SYMPOSIUM

ОХРИД, С. МАКЕДОНИЈА
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ЗБОРНИК НА ТРУДОВИ
19ТИ МЕЃУНАРОДЕН СИМПОЗИУМ НА ДГКМ

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NUMERICAL ANALYSIS OF CONCRETE ARCH DAM AT STATIC LOADING – A CASE STUDY

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ABSTRACT

The behavior of an arch dam and assessment of its structural stability during service period is of paramount importance for such structures. The numerical analysis should be carried out according to monitoring data and records thus creating loading scenarios to assess the dam behavior and specify limit values for the stresses and displacements of the dam. By such specification is obtained a range for the regular behavior of the dam. In the paper is presented the specified approach and the output results from numerical experiment of an arch dam, by application of the Finite Element Method, carried out for three loading scenarios, generated from monitoring data and records of the dam.

Keywords: arch dam, numerical analysis, SOFiSTiK, static behavior.

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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 [1 ,2]. 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.

Static stability of concrete dams is confirmed with analysis (research) of the response of the structure (dam) under action of static loads [3, 4, 5 ,6]. In this paper are systemized acknowledgments from the linear and nonlinear static numerical analysis of concrete arch dam, obtained with application of numerical methods, based on Finite Element Method, with the code SOFiSTiK. Namely, here below will be illustrated output data from the numerical experiment for analysis of the behavior of an arch dam, located in France. The aim of the task is to assess the dam behavior, focusing on the displacements and stresses in the dam body.

2. CASE STUDY

The analyzed dam is located in France, and itt 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 and base thickness 2m and 6m respectively.

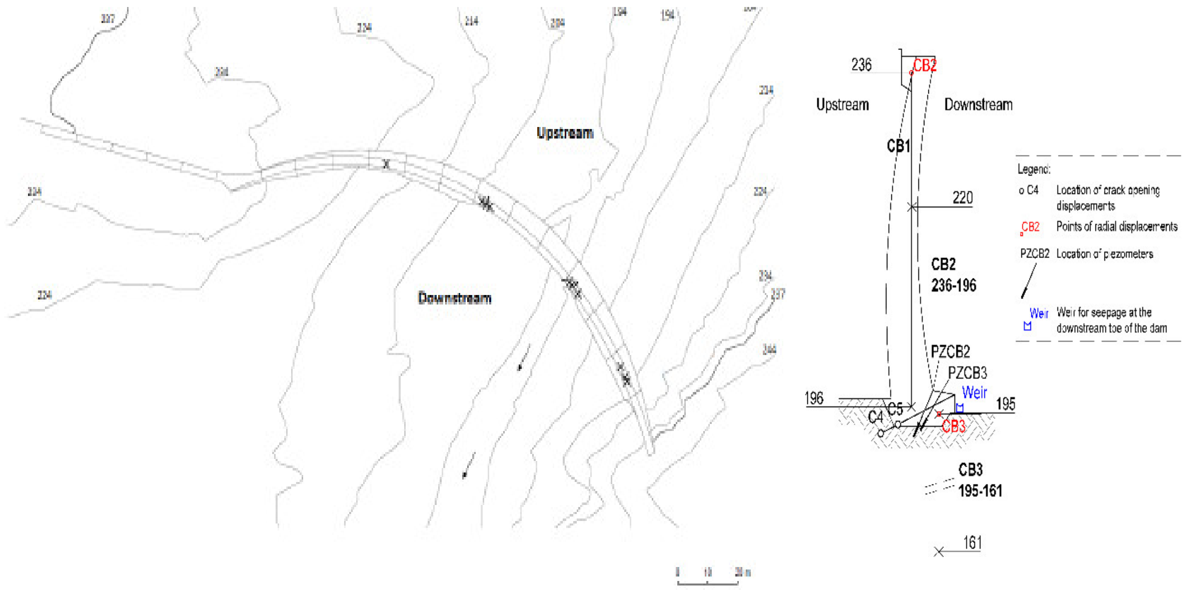

Fig. 1. Layout of the dam (left) and central block section with monitoring instruments (right).

3. NUMERICAL MODEL OF THE DAM

The numerical analysis of Dam EDF is created by application of the program SOFiSTiK, produced in Munich, Germany. The program is based on finite element method and has 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 own library contains and various standards and constitutive laws (linear and non-linear) for analysis of the structures.

The numerical experiment includes following steps, typical for this type of analysis: (1) choice of material properties and constitutive laws (concrete and rock); (2) discretization of the dam and the rock foundation and (3) simulation of the dam behavior for the typical loading states.

1.1. Material properties

The linear material properties for the dam body (concrete) and the foundation (rock) are systematized in Table 1. The specified parameters are adopted according to specified data [7] as well and previous carried out analysis and reference literature [8, 9 10, 11, 12].

Table 1. Material parameters.

Parameter		dam body (concrete)	rock	Comment
γ_{spec}	kN/m^3	24.0	27.0	Unite weight
k_s	m/s		2e-05	Permeability coefficient
ν		0.350	0.450	Poisson coefficient
Alpha	1/C°	7.0E-06		Thermal expansion coefficient
E	GPa	22	3	Young's modulus of elasticity

Additionally, for carrying out of non-linear analysis of the dam is applied non-linear constitutive law for concrete based on elasto-plastic material law Lade with non-associated flow rule from SOFiSTiK library of materials (Table 2) [8, 9]. The formulation of the yield condition and plastic potential using stress invariants is according to equations (1) and (2):

$$f = I_1^3 - \left[27 + \eta_1 \left(\frac{p_a}{I_1}\right)^m\right] I_3 \leq 0 \tag{1}$$

$$g = I_1^3 - \left[27 + \eta_2 \left(\frac{p_a}{I_1}\right)^m\right] I_3 \tag{2}$$

whereas:

pa – atmospheric air pressure (103.32 KPa)
I_1 and I_3 - 1st and 2nd stress invariant for magnitudes of the uniaxial tensile (f_t) and compressive strength (f_c) according to equations (3) and (4)

$$I_1=-(\sigma_1-P_3)-(\sigma_2-P_3)-(\sigma_3-P_3) \tag{3}$$

$$I_3=-(\sigma_1-P_3)\cdot(\sigma_2-P_3)\cdot(\sigma_3-P_3) \tag{4}$$

By rewriting the yield function in order to specify parameter η_1 eq. (5) is derived:

$$\eta_1 = \left(\frac{I_1^3}{I_3} - 27\right)\left(\frac{|I_1|}{P_a}\right)^m \tag{5}$$

By specification of parameter for compressive strength f_c the model can optionally be extended by a spherical cap (in principal stress space) thus limiting the volumetric compressive stresses to a maximum possible value.

Table 2. Non-linear material parameters for concrete.

Parameter	Dimension	Dam body (concrete)	Comment
η_1		88162	Yield function
m		1	Parameter for curvature of the yield surface towards the hydrostatic axis
f_t	kN/m^2	2900	Uniaxial tensile strength
η_2		8816	Parameter for flow rule
f_c	kN/m^2	33333	Compressive strength
ε_{tu}	‰	2	Tensile failure strain

The plastification zones according to the specified parameters are determined by the value of the plastification number, eq. (6):

$$p=\sigma_{lin}/\sigma_{nonlin}-1 \tag{6}$$

whereas:
p – plastification number
σ_{lin} – concrete stress computed linearly from the strain,
σ_{nonlin} – non-linear stress.

1.2. Discretization of dam body and foundation by finite elements

Numerical analysis of the arch is carried out by spatial (3D) model, where the dam body and the foundation are modeled with volume 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 are applied finite element type bric (trilinear hexahedron), by 4 nodes and kinematic constraints at the interface dam-rock foundation. Namely, the model is composed of dam body and rock foundation with constraints at the interface dam-foundation. The spatial (3D) model has geometrical boundaries, limited to horizontal and vertical plane. In these planes are defined the boundary condition of the model (Fig. 2). The curvature plane in the lowest zone of the model is adopted as non-deformable boundary condition (fixed displacements in XYZ direction), vertical planes perpendicular on X-axis are boundary condition by applying fixed (zero) displacements in X-direction and vertical planes perpendicular on Y-axis are boundary condition by applying fixed (zero) displacements in Y-direction. The discretization is conveyed by including zones of various materials in the model – concrete and rock foundation. The dam is modeled as monolithic structure.

SOFiSTiK

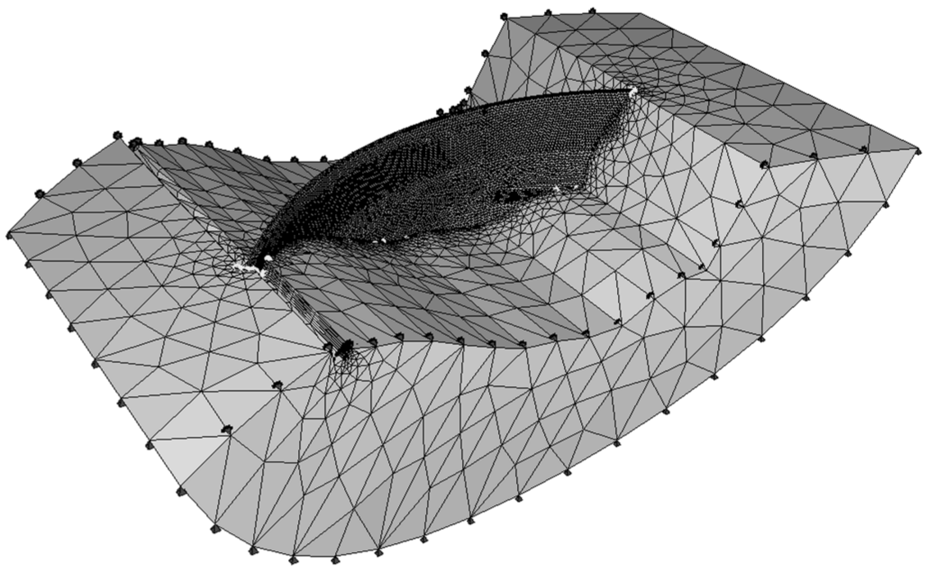

Fig. 2. View of the numerical model, discretized with total of 186583 elements and 39419 nodes.

1.3. Dam loading scenarios for calibration and prognosis stage

The dam loading is applied according to registered data for the water level in the reservoir and air temperature for period of 12 years. The numerical analysis is carried out by coupled thermo-mechanical model for analysis of the dam behavior. The thermal effect of the dam is simulated by applying temperature loading of the dam body according to air temperature time series as uniform distribution within the volume (bric) elements. The assumption is that the temperature loading in the dam body is uniformly distributed and approximately in range of the air temperature. The temperature effect is coupled with the hydrostatic loading in accordance with the specified water levels from the reservoir. The hydrostatic loading is applied at upstream face of the dam as spatial load in accordance with the water levels in the reservoir. The analysis is carried out by combined choice of extreme (highest) values for the air temperature and water levels in the reservoir thus adopted total of three loading scenarios (Fig. 3, red lines). On Fig. 3 are displayed measured data for water levels in the reservoir and temperature. According to the measured data values are specified three loading scenarios (Fig. 3, red lines) such as: LS51 - high water level (234.5 masl) with low temperature; LS52 - low water level (194.5 masl) with high temperature and LS53 - high water level (234.5 masl) with high temperature (20 °C), thus obtaining a representative loading scenarios for specification of limit values for the displacements and stresses in the dam body in order to assess the range of the conventional dam behavior.

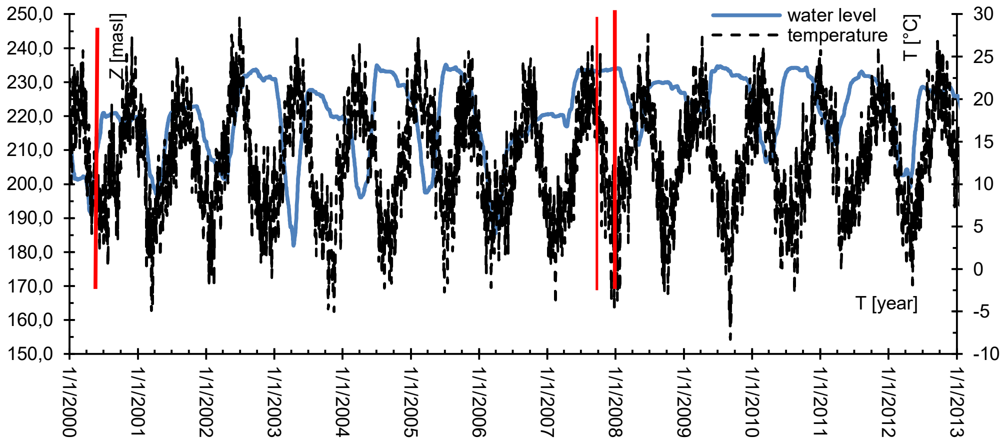

Fig. 3. Measured data for water level in the reservoir and air temperature.

4. OUTPUT RESULTS

The dam behaviour is assessed upon values and distribution of the displacements and stresses in the dam body. On Fig. 4 are displayed calculated radial (horizontal in upstream-downstream direction) and vertical displacements in the dam body for LS51. The radial displacements are dominantly in downstream direction due to the hydrostatic load, with maximal value of 25.4 mm approximately at intermediate zone of the dam crest, while in section towards the right bank there is occurrence of displacements in upstream direction, value of 7.6 mm. The vertical displacements are directed towards the gravity (settlements), with maximal value of 17.6 mm at interface zone dam-foundation in the right bank, approximately at 80% of the dam height. On Fig. 5 are displayed calculated principal stresses in the dam body for LS51. The principal stresses σ_1 are dominantly in compression, maximal value of 8.4 MPa, at interface zone dam crest-foundation in the left bank. The principal stresses σ_3 are dominantly in tension, maximal value of 1.3 MPa, at interface zone dam-foundation in the left bank, approximately at 80% of dam height.

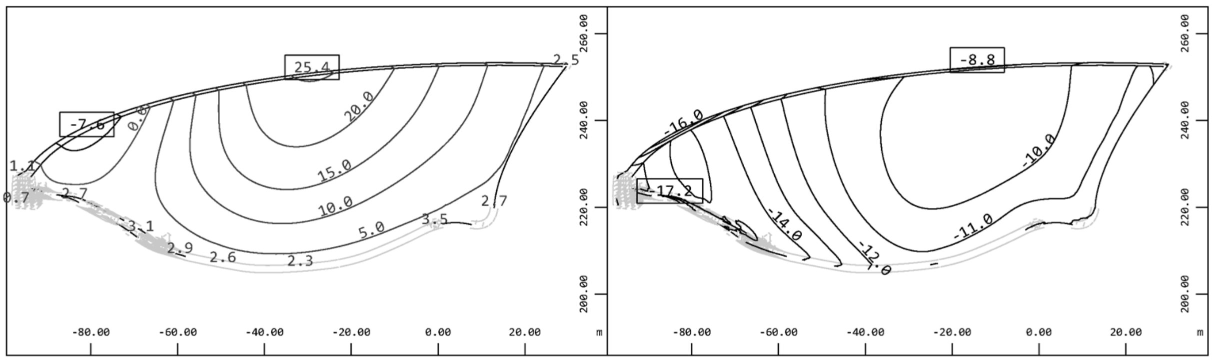

Fig. 4. Display of radial (left) and vertical (right) displacements in the dam body for LS51.

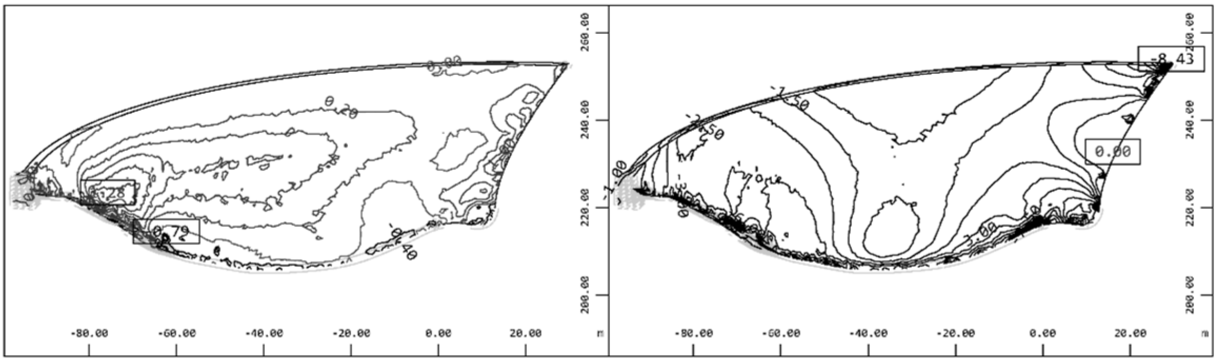

Fig. 5. Display of principal stresses σ_3 (left) and σ_1 (right) in the dam body for LS51.

On Fig. 6 are displayed calculated radial and vertical displacements in the dam body for LS52. The radial displacements are dominantly in upstream direction, maximal value of 25.4 mm approximately at intermediate zone of the dam crest, due to the temperature effect. The vertical displacements are directed towards the gravity (settlements), with maximal value of 15.8 mm at interface zone dam-foundation in the right bank, approximately at 80% of the dam height, similar as previous loading scenario LS51. On Fig. 7 are displayed calculated principal stresses in the dam body for LS52. The principal stresses σ_1 are dominantly in compression, maximal value of 8 MPa, at interface zone dam crest-foundation in the left bank. The principal stresses σ_3 are dominantly in tension, maximal value of 1.2 MPa, at interface zone dam-foundation in the left bank, approximately at 40% of dam height.

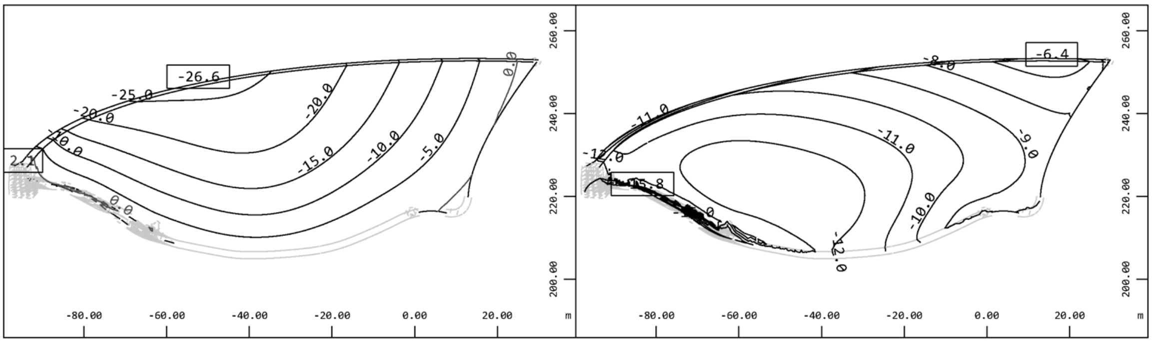

Fig. 6. Display of radial (left) and vertical (right) displacements in the dam body for LS52.

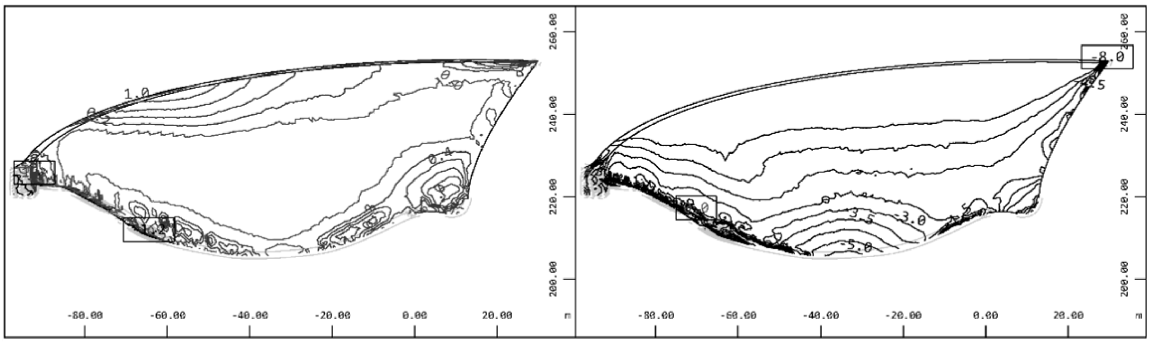

Fig. 7. Display of principal stresses σ_3 (left) and σ_1 (right) in the dam body for LS52.

On Fig. 8 are displayed calculated radial and vertical displacements in the dam body for LS53. The radial displacements are dominantly in upstream direction, maximal value of 8.4 mm approximately at intermediate zone of the dam crest, while in section towards the right bank there is occurrence of displacements in upstream direction, value of 19.3 mm. The vertical displacements are directed towards the gravity (settlements), with maximal value of 16.8 mm at interface zone dam-foundation in the right bank, approximately at 80% of the dam height.

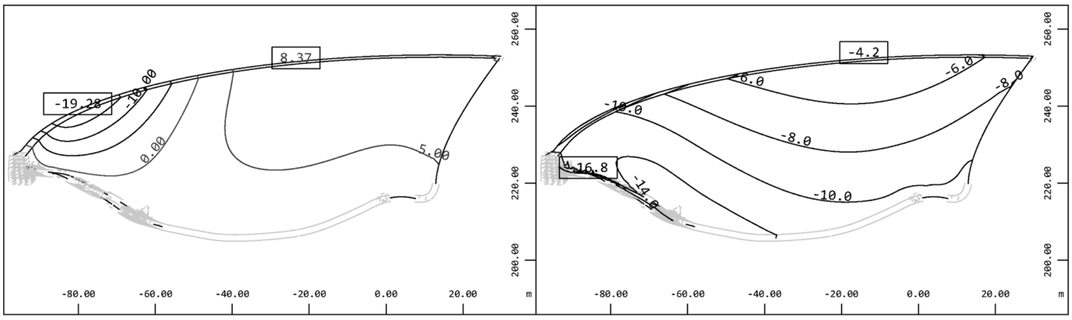

Fig. 8. Display of radial (left) and vertical (right) displacements in the dam body for LS53.

On Fig. 9 are displayed calculated principal stresses in the dam body for LS51. The principal stresses σ_1 are dominantly in compression, maximal value of 18 MPa, at interface zone dam crest-foundation in the left bank. The principal stresses σ_3 are dominantly in tension, maximal value of 1.7 MPa, at interface zone dam-foundation in the left bank, approximately at 80% of dam height. One reason for such higher value can be the modeling of the interface zone dam-foundation by kinematic constraints, as support conditions which can be defined in relation to another node (reference node). Such coupling conditions describe infinitely stiff elements and special boundary conditions, which are numerically stable. They are commonly used for the formulation of boundary conditions for plates and shells and the modeling of very stiff structural parts. Further step is to model the contact zone dam-foundation by interface elements (spring elements) with non-linear constitutive law in order to simulate more realistic behavior of the contact zone.

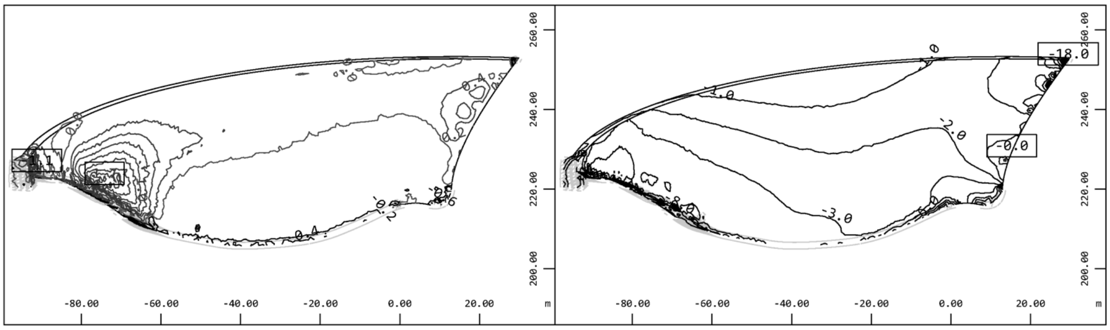

Fig. 9. Display of principal stresses σ_1 (left) and σ_3 (right) in the dam body for LS53.

5. CONCLUSIONS

The behavior of the dam during service period for various water levels in the reservoir and temperature effect, obtained from monitoring data, was simulated by application of the Finite Element Method with spatial (3D) numerical model. The numerical analysis was carried out by applying coupled thermo-mechanical analysis of the dam at static loading. The analysis of the behavior of the dam carried out for three loading scenarios. From the carried out numerical experiment of simulation for prediction of the behavior of the dam EDF, following main conclusions and recommendations are derived:

1) In case of loading scenario LS51 (high water level and low temperature) there is occurrence of maximal radial displacements in downstream direction of 25.4 mm approximately at intermediate zone of the dam crest and vertical displacements in gravity direction of 17.2 mm at interface zone dam-foundation in the right bank, approximately at 80% of the dam height. Regarding the stresses, there is occurrence of principal compression stresses and tension stresses with maximal values of 8.4 MPa (interface zone dam crest-foundation in the left bank) and 1.3 MPa (interface zone dam-foundation in the left bank, approximately at 80% of dam height) respectively.

2) In case of loading scenario LS52 (low water level and high temperature) there is occurrence of maximal radial displacements in upstream direction of 26.6 mm approximately at intermediate zone of the dam crest and vertical displacements in gravity direction of 15.8 mm at interface zone dam-foundation in the right bank, approximately at 80% of the dam height. Regarding the stresses, there is occurrence of principal compression stresses and tension stresses with maximal values of 8 MPa

(interface zone dam crest-foundation in the left bank) and 1.2 MPa (interface zone dam-foundation in the left bank, approximately at 40% of dam height) respectively.

3) In case of loading scenario LS53 (high water level and high temperature) there is occurrence of maximal radial displacements in section towards the right bank at 20% of the crest length in upstream direction, value of 19.3 mm and vertical displacements in gravity direction of 16.8 mm at interface zone dam-foundation in the right bank, approximately at 80% of the dam height. Regarding the stresses, there is occurrence of principal compression stresses and tension stresses with maximal values of 18 MPa (case of local stress concentration in the interface zone dam crest-foundation in the left bank due to the dam) and 1.7 MPa (interface zone dam-foundation in the left bank, approximately at 80% of dam height) respectively.
4) The calculated displacements regarding the distribution and values are mainly in correlation with the water level and temperature effect for LS51 and LS52 thus obtaining the limit values range of radial (-26.6÷25.4) mm and vertical displacements (up to 17 mm) in which a regular behavior of the arch dam can be assumed.
5) The calculated stresses for all three loading scenarios has a similar distribution and varying values. In the dominant part of the dam body the obtained principal stresses are creating also a range of limit values for regular behavior of the dam (principal compressive stresses 8.5 MPa and principal tension stresses 1.7 MPa) with exception of local stress concentration in the interface dam-foundation in the left bank in case of LS53.
6) It is required modeling of the contact zone dam-foundation by interface elements in order to obtain more realistic simulation of the behavior of such zone.
7) It is required to calibrate the calculated values with measured data and records in order to obtain integral data for the arch dam behavior and to verify the obtained limit values for the displacements and the stresses.

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