STATIC ANALYSIS OF GRATCHE ARCH DAM – A CASE STUDY

Borjana BOGATINOSKA[1], Frosina PANOVSKA[1], Ana GRUPCHEVA[1], Stefanija IVANOVSKA[1], Dimitar KONDINSKI[1], Stevcho MITOVSKI[2], Ljupcho PETKOVSKI[3]

ABSTRACT

The advantages of building a curved (arch) dam were appreciated as early as Roman times (dam Kebar in Qom Providence, Iran, build in approx. 1300 AD). Arch dams act as an arch, accepting the loading from the upstream side and transferring it to the banks apropos the rock foundation. Dam sites, considered as favorable for arch dams, are to be composed of sound rock.

Several safety requirements are to be fulfilled in order to ensure the stability of all dam types, such as: functional (degree of satisfaction of the users' objectives), economic (ratio of cost/benefit), hydrological (acceptable risks for flood evacuation), hydraulic (conduits capacity), seepage (intensity of hydrodynamic process) and structural (dam's behavior at static and dynamic loads).

In the paper are given main findings regarding the stress-deformation state for static loads from the case study of Gratche arch dam, build on river Kochanska in 1959, in nearby of Kochani Municipality, Republic of Macedonia, with structural height of 43 m. The numerical analysis is conveyed with application of the code SOFiSTiK, based on the finite element method.

Keywords: Arch dam, static analysis, finite element method, SOFiSTiK.

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 [Novak et al., 2007; Tančev, 2013]. The number of constructed large dams in the world in specific periods is presented in Fig. 1. The ICOLD Register of dams lists around 45,000 dams higher than 15 m. According to the rapid population increase, foreseen to reach 10 billion inhabitants by the end of the century, more dams will have to be built in order various water demands to be satisfied.

Republic of Macedonia is located in the central part of the Balkan Peninsula, covering area of 25,713 km^2 with a population of about 2 million inhabitants. The rivers in Republic of Macedonia belong to three main river basins: (a) The Aegean basin, in which they flow out through the rivers Vardar and Strumica; (b) The Adriatic basin, to which they are taken away through the river Crn Drim (Black Drim); and, (c) The Black Sea basin, through the river Binachka Morava, which extends over a quite insignificant part. The biggest is the catchments basin of the River Vardar, which extends to some

[1] Student, Faculty of Civil Engineering, Ss Cyril and Methodius, Skopje, Republic of Macedonia, e-mail: borjana95@gmail.com
[2] Assistant Professor, Faculty of Civil Engineering, Ss Cyril and Methodius, Skopje, Republic of Macedonia, e-mail: smitovski@gf.ukim,edu,mk
[3] Full Professor, Faculty of Civil Engineering, Ss Cyril and Methodius, Skopje, Republic of Macedonia, e-mail: petkovski@gf.ukim.edu.mk

20,525 km^2 or 80% of the territory of the Republic of Macedonia. Total available surface water resources in the Republic of Macedonia are assessed as about 3,300 m^3 per capita annually.

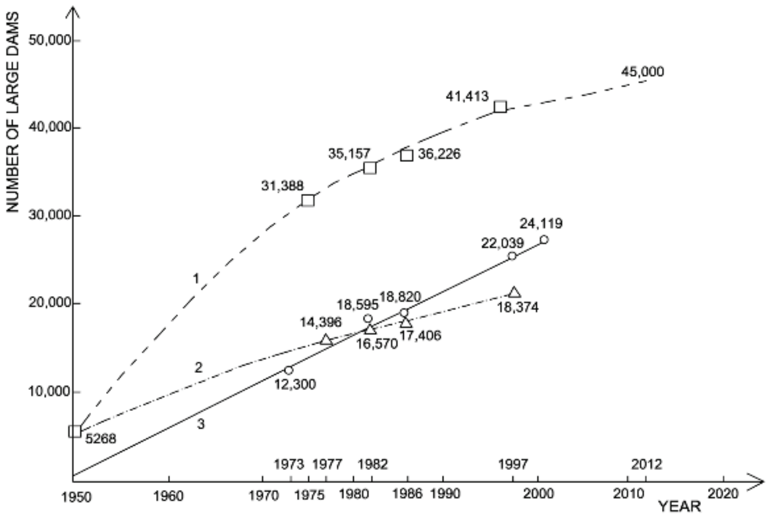

Fig. 1. Total number of constructed dam in the world [Jiazheng & Jing, 2000]. (1) Total number of dams in the world; (2) Number of large dams in the world except China; (3) Number of large dams in China.

The dam construction in Macedonia dates from 1938 when the Matka arch dam was constructed, located on the River Treska, in vicinity of Skopje, still in service. Up to now are constructed 27 large dams [Tančev et al., 2013]. Different types of dams are represented, having in consideration the various geological, topographical and hydrological conditions, among which 18 are embankment dams, 8 concrete arch dams and 1 concrete multiple arch dam. Latest constructed dam is St. Petka double curved arch dam, in nearby of Skopje, as final part of the cascade system on river Treska, along with dams St. Andrea and Kozyak, commissioned in August, 2012.

The assessment of the stability and the behaviour of dams during construction at full reservoir and during service period is of vital importance. The paper deals with numerical three-dimensional analysis of Gratche dam, performed with application of the program package SOFiSTiK.

GRATCHE DAM

During the period 1958/59 Gratche dam, was constructed in order to create reservoir purposed for irrigation of the rice fields in Kochansko Pole and for water supply of the industry in the city of Kochani. The dam has been constructed on Kochanska River, which flows through a canyon with very steep banks. The foundation is composed of crystal schists, decomposed at the surface in a zone of several meters. The height of the dam above the ground amounts to 29 m, while, above the highest point of the foundation is 43 m [Tanchev, 2014; YUCOLD, 1970]. On Fig. 1 is displayed the dam layout, where we can notice the steep banks and the relatively wide riverbed of the Kochanska River. The dam creates storage space of 2.4 million m^3. The first filling of the dam commenced in November, 1959, while the dam was commissioned in June, 1960. The dam is still in service, and without non-regular occurrences that can endanger its safety (cracks, increased leakage etc.).

In the horizontal sections of the dam the thickness is constant. The upstream face of the dam is vertical (Fig. 2). The radius of curvature of the horizontal arches varies very little – from 64.35 to 50.75 m, so that it can be considered constant. The central angle ranges within the limits from 136° to 96°. In the dam's body there have been incorporated 12,000 m^3 of concrete, with an average reinforcement of 40 kg reinforcing steel per 1 m^3 of concrete.

On Fig. 2, the part which is above the ground (1) is a thin reinforced concrete structure in the river bed, founded above a massive concrete block (2) connects the thick layer of river sediment (3). At the crest the dam is 150 m long and 1.0 m thick. Going downwards, the thickness increases and, near the concrete block amounts to 3.45 m. The massive concrete block in the foundation is 6.45 m wide and 14 m deep. It plays the role of a plug through the deposited sediment material, while at the same time serving also as a foundation of the dam. The spillway is completely separated from the dam's body and consists of four spillway spans, each 7 m wide. The overflow capacity is 120 m^3/s. The bottom outlet works accommodated in the central part of the dam has been provided with two gates, located in a small structure, immediately downstream of the dam. The pipe of the bottom outlet has a diameter of 1000 mm.

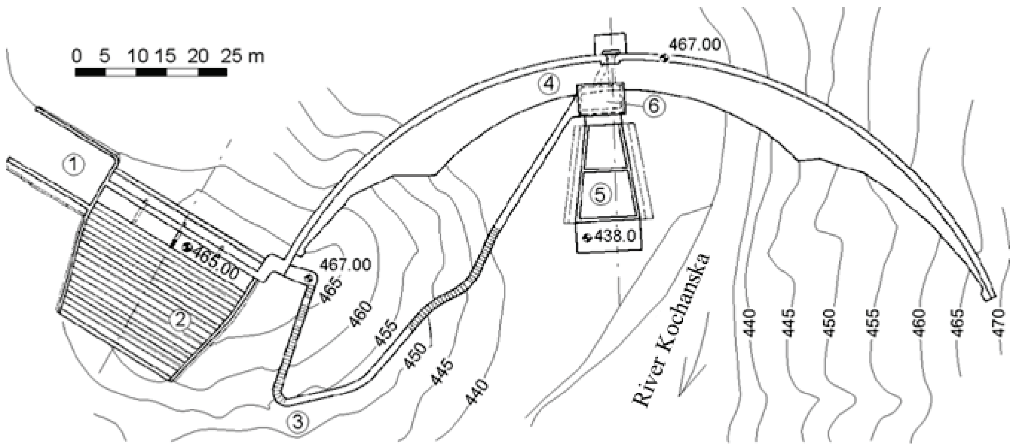

Fig. 2. Gratche dam, layout. (1) Plateau; (2) spillway; (3) roadway; (4) the dam's body; (5) stilling basin at the bottom outlet; (6) gate chamber at the bottom outlet.

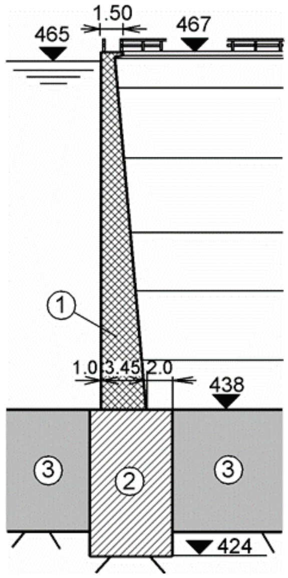

Fig. 2. Gratche dam, cross-section.

NUMERICAL MODEL

The static analysis of Gratche dam is conveyed with application of the program package SOFiSTiK, based on the finite element method. In order to perform the numerical analysis following steps are undertaken: (1) choice of material parameters – constitutional laws (one of the most complex tasks during the analysis), (2) adoption of dam geometry and (3) simulation of the typical dam loading stages (empty and full reservoir).

The constitutional law for the concrete in the dam body and foundation is adopted according to EC 2, concrete grade CG 30 [Eurocode, 1992; ICOLD, 2009], directly applied form the material library of the code SOFiSTiK. On Fig. 2 are specified main input date for concrete.

Fig. 2. Input date for concrete, according to EC 2.

Parameter	Mark	Value	Unit
Density	γ	24.00	kg/m^3
Temperature coefficient	α	$1.00*10^{-5}$	
Elastic modulus	E	32837	MPa
Poisson ratio	ν	0.20	

The rock foundation is simulated as massless zone, by applying linear elastic constitutive law due to the fact that the rock foundation state is simulated only as initial stage in the model and the deformations in that zone are irrelevant for the dam behaviour. The input parameters for the rock foundation are modulus of elasticity E=10,000 MPa and Poissons's ratio ν=0.25, adopted according to reference [YUCOLD, 1970; Jovanovski et all, 2012].

The numerical model is composed of the dam body, concrete foundation and rock foundation. The dam body is limited by the dam site shape, and rock foundation, with length of 60.0 m upstream and 100.0 m downstream of the dam's central cantilever [ICOLD, 1987], while the rock foundation under the concrete foundation in the river bed is adopted at depth of 45.0 m (Fig .3). The rock foundation in the left and the right bank is adopted at length of 50.0 m on both sides of the dam crest. By such parameters is defined the non-deformable limit boundary condition. The discretization is conducted by capturing zones with different materials – concrete (dam body and foundation) and rock zone in groups. The dam's thickness is divided in 3 layers (groups).

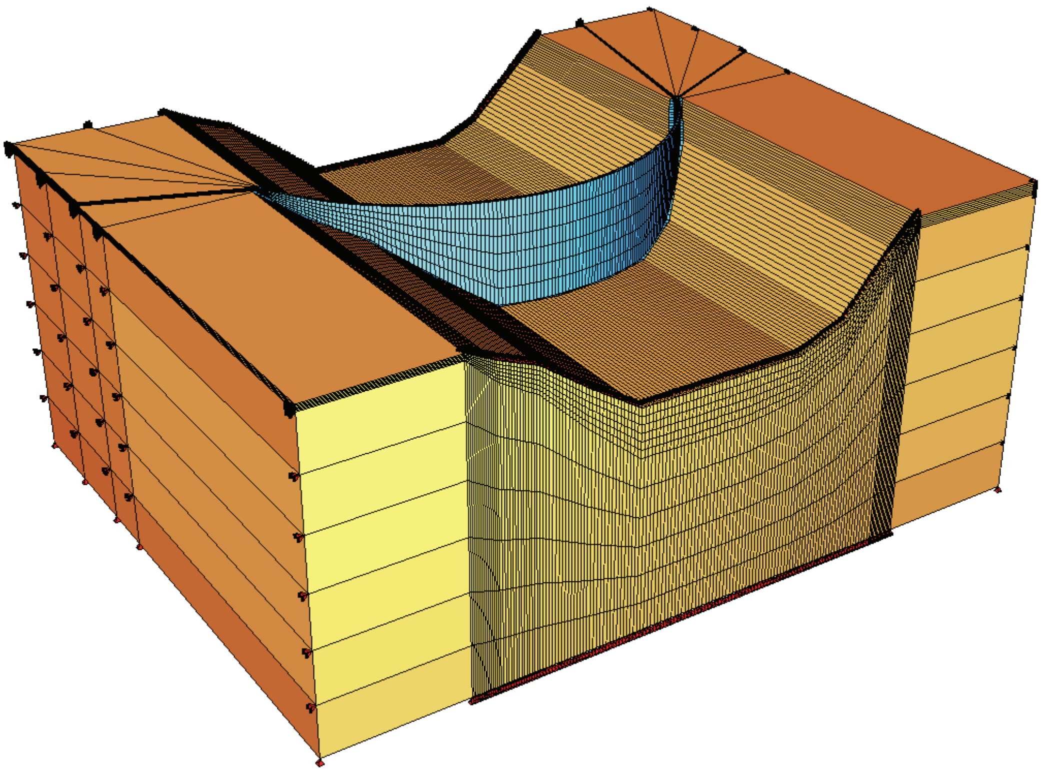

Fig. 3. Gratche dam model, spatial view from upstream side, number of elements E=6791.

The dam analysis includes simulation of state at full reservoir in case of low (winter period) and high temperatures (summer period). In case of Gratche dam there are no installed devices for temperature measurement within the dam body. Therefore, the temperature load (Fig. 4) is adopted in accordance with data from literature [ICOLD, 1987], as well and from previously performed analysis of such dams [Kokalanov et all, 2007; Mitovski, 2015]. Namely, the dam is divided in three groups along its thickness in order to apply various input values for the temperature, according to simulated loading stage (winter or summer period). The hydrostatic pressure on the dam is taken up to normal water elevation of 465.0 masl (Fig. 5).

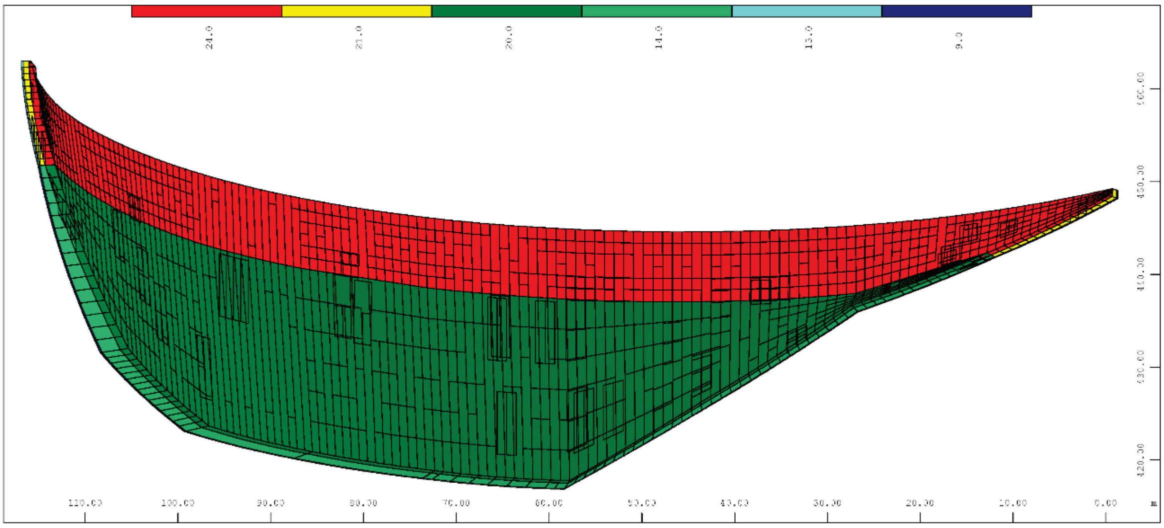

Fig. 4. Temperature load applied for summer period, T=9-24 °C.

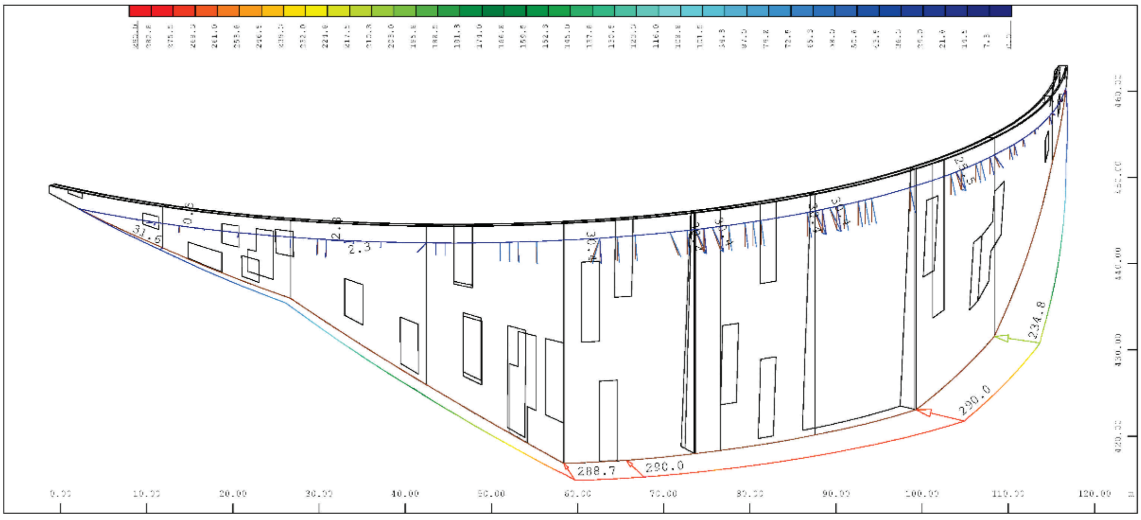

Fig. 5. Water load applied on dam body (full reservoir).

OUTPUT RESULTS

The dam state is assessed by analysis of the values and distribution of the displacements in the dam's body. The contour lines of the horizontal displacements (X-direction, „-“denotes displacement in downstream direction) for case at full reservoir and winter period are displayed in Fig. 6. The dam mainly deforms in downstream direction having in consideration that both temperature and hydrostatic load are acting in such direction. So, the maximal displacement occurs directly below the central at zone of the dam crest, approximately at 70% of the dam height, value of 7.0 mm. The contour lines of the horizontal displacements for case at full reservoir and summer period are displayed in Fig. 7. In this case the dam mainly deforms in upstream direction having in consideration that temperature load is dominant in case of thin arch dam. In this case the maximal displacement occurs along great section of the dam crest, approximately on section of 1/3 of the crest length, value of 17.0 mm. In the central point of the dam crest the displacement is approximately 15 mm.

The isolines of the horizontal displacements (Y-direction, „-“denotes displacement towards the left bank) for winter period and full reservoir are displayed on Fig. 8. The maximal displacements occurs in the dam crest in vicinity of the right bank, with value of almost 3.0 mm. We can notice that there is analogue distribution in case of simulation of summer period (Fig. 9). Namely, the maximal displacements occurs on the same location, with somewhat increased value of 11.0 mm.

The distribution of the vertical displacements („-“denotes displacement in in gravity direction) for case at full reservoir and winter period are displayed in Fig. 10. The maximal displacement occurs at dam crest, approximately on ½ of dam’s crest length, value of 1.0 mm. The distribution of the vertical displacements at full reservoir and summer period are displayed on Fig. 11. Also, similar as previous case, the temperature load causes displacements in opposite direction of the gravity apropos rising occurs. The maximal value of the displacements is 5.3 mm, located in the central part of the dam’s crest.

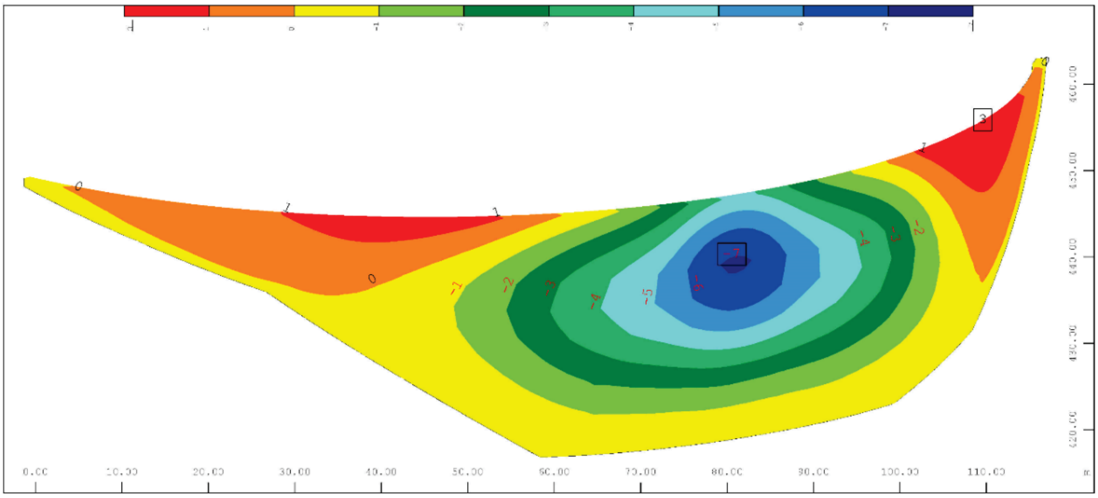

Fig. 6. Contour lines of summary horizontal displacements (X direction) at full reservoir and winter period.

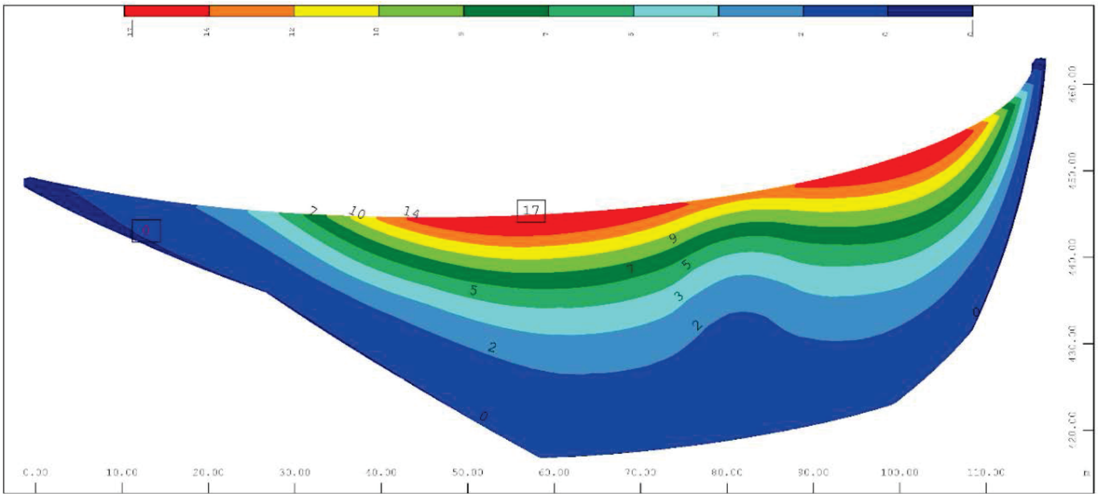

Fig. 7. Contour lines of summary horizontal displacements (X direction) at full reservoir and summer period.

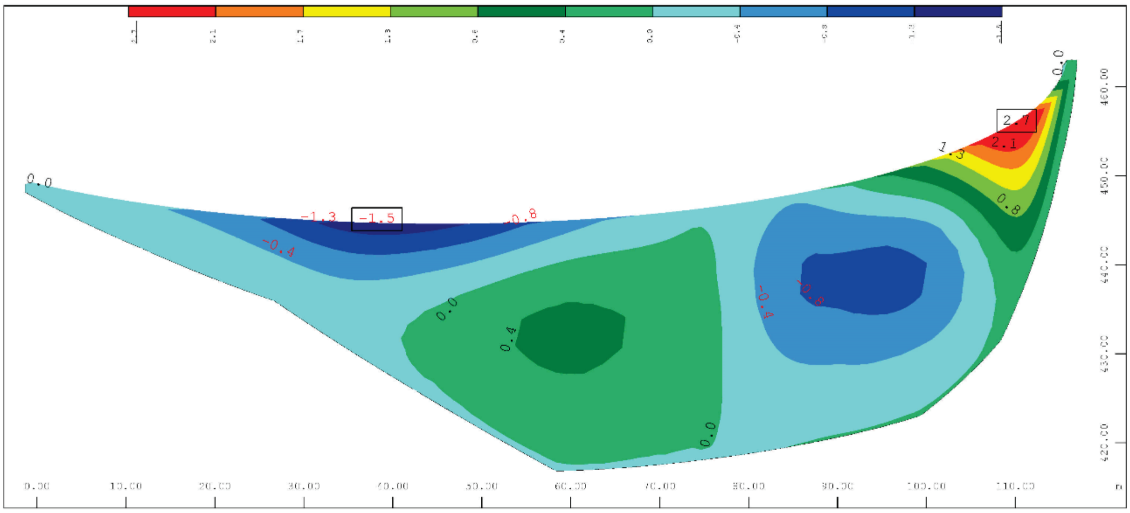

Fig. 8. Contour lines of summary horizontal displacements (X direction) at full reservoir and winter period.

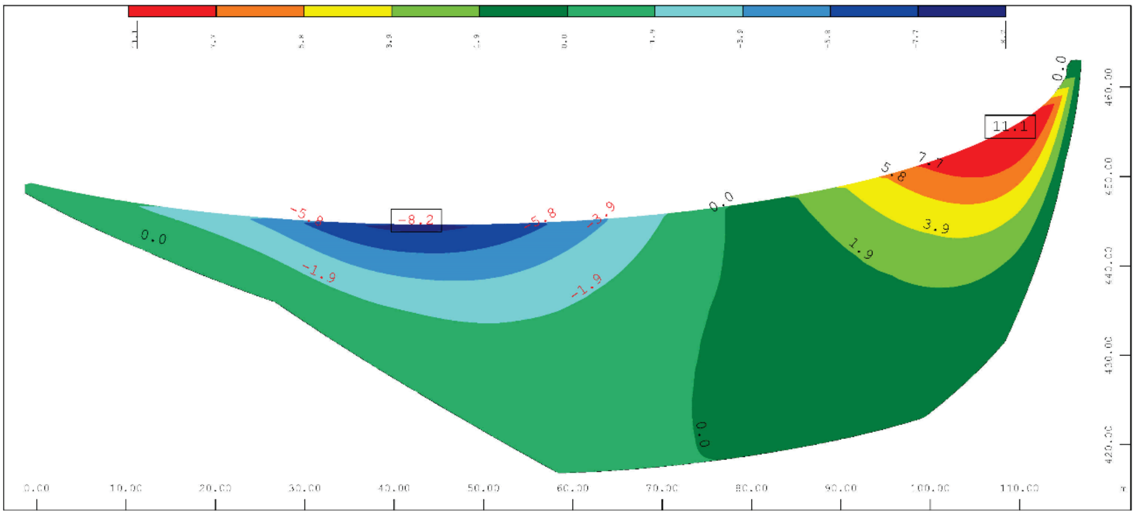

Fig. 9. Contour lines of summary horizontal displacements (X direction) at full reservoir and summer period.

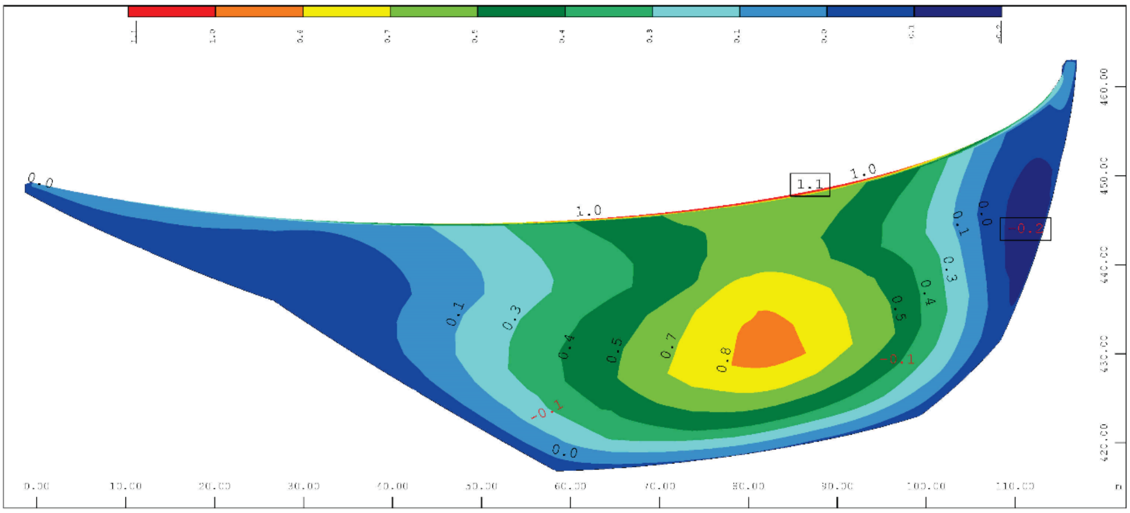

Fig. 10. Contour lines of summery vertical displacements at full reservoir and winter period.

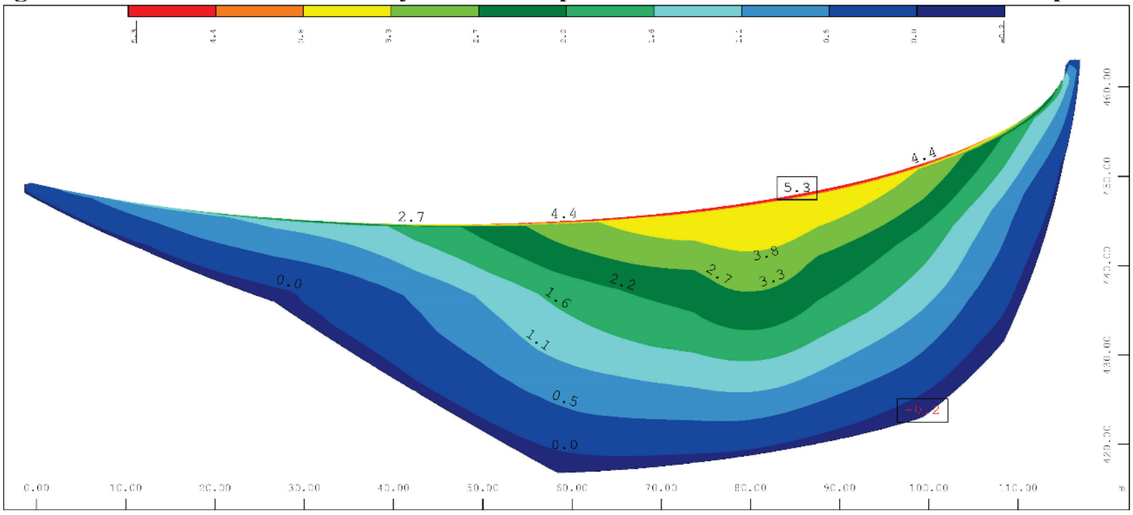

Fig. 11. Contour lines of summary vertical displacements at full reservoir and summer period.

On Fig. 12 are displayed main principal stresses for full reservoir state and temperatures for summer period. The stresses are in full compressive, reaching maximal value of 15.0 MPa at the right bank, at contact zone of the dam and the rock foundation.

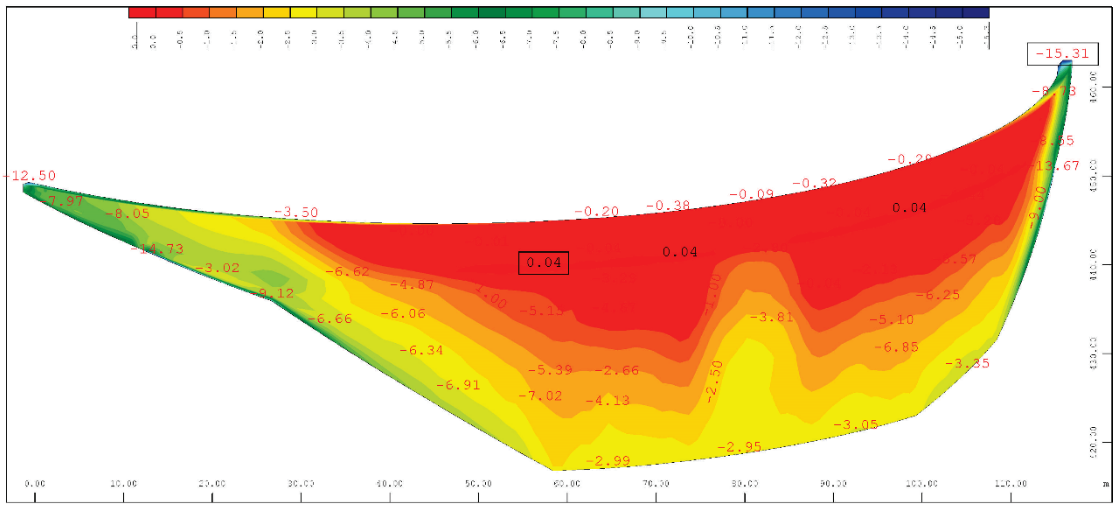

Fig. 12. Main principal stresses in the dam's body at full reservoir and summer period.

MONITORING DATA COMPARISON

The technical monitoring of the dams should fulfil two objectives: (1) to verify the conducted numerical analyses of the dam and to follow the dam behaviour in the service period, in order to detect eventual non-regular occurrences in the dam and the foundation, that could endanger the dam safety and (2) taking of timely and appropriate restoration measures. The concept of the technical monitoring system regarding the number of instruments, location, reading frequency etc. is primarily determined in dependence of the dam type and importance.

On Gratche dam is installed geodetic survey system for monitoring. Namely, by method of levelling is executed monitoring of the horizontal displacements of the central point (benchmark) of the dam crest during one year by total of 10 measurements. The partial measured displacements (compared to the “zero” measurement) of the specified benchmark point for 2017 are displayed on Fig. 13 [Elaborate, 2017] apropos the absolute displacement is approximately 25 mm. The water level in 2017 was varying between minimum elevation of 461.0 masl to maximum elevation of 465.0 masl, so we can take in to account that mainly the water level in the reservoir was at state of full reservoir. Also, on Fig. 13 are displayed the calculated horizontal displacements of the benchmark point, obtained with the numerical analysis, varying from winter period to summer period (the displacement curve is constructed by four points, simulating four periods within one year by additional simulation of two dam stages – for spring and autumn period, by varying input date for temperature). By comparation of the displacement curves we can conclude that there is good matching of the measured and calculated values for the displacements of benchmark point at dam crest for both – values and pattern.

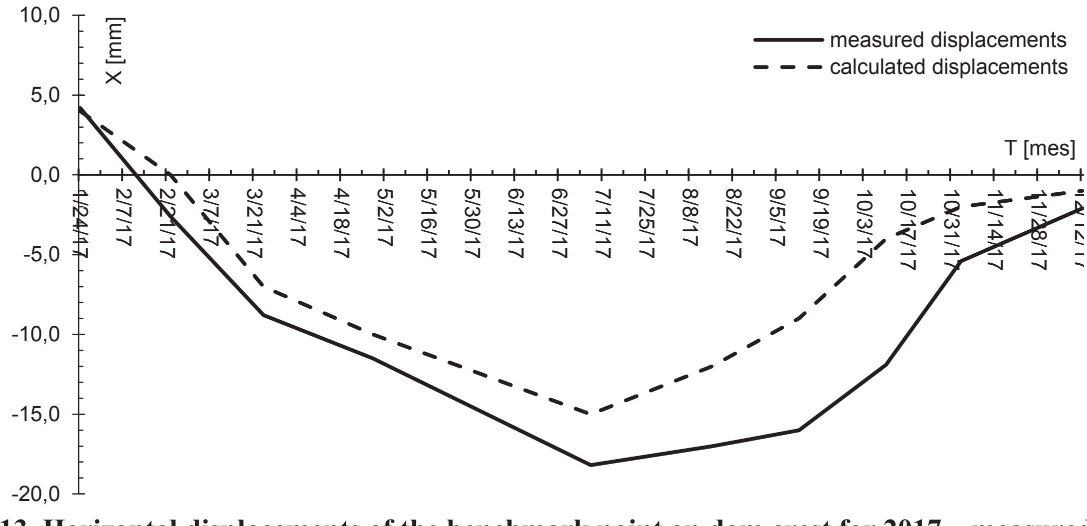

Fig. 13. Horizontal displacements of the benchmark point on dam crest for 2017 – measured and calculated values.

CONCLUSIONS

The prediction of the dam’s behaviour during construction and service period is essential for ensuring and providing interval data for displacements and stresses, purposed for assessment of the dam stability within its life span. The dam behaviour is assessed by comparation of the measured and calculated date.

Maximum allowable stresses for usual loading state of the dam (self weight, temperature and hydrostatic pressure) should be less than 1/2 of specified compression strength and according to the maximal calculated value of the principal stresses of around 15.0 MPa, such criteria is met. Namely, up to now there are no registered crack occurrences in the dam body.

The comparison of the calculated and measured horizontal displacements was undertaken. Namely, the deformation pattern and displacements values for both calculated and measured values shows good matching, analysed for period from winter to summer temperatures at full reservoir state. The comparison analysis gives valuable findings for the dam behaviour, and it serves as base for calibration process of the numerical model and installed monitoring instruments.

The obtained value for the displacements and stresses are in region of expected for arch dam with such dimensions, so we can conclude that the dam is stabile at action of static loads.

REFERENCES

Elaborate for analysis and assessment of the stability and functionality of dam Gratche with appurtenant structures and stability of the terrain around the dam and the reservoir for 2017, 2017. University Ss Cyril and Methodius, Civil Engineering Faculty – Skopje.

EUROCODE 2, 1992. “Design of concrete structures, European Committee for Standardization”.

ICOLD Bulletin 145, 2009. “The physical properties of hardened conventional concrete in dams”.

ICOLD Bulletin 30a, 1987. “Finite element methods in design and analysis of dams”.

Jiazheng, P. & Jing, H. 2000. “Large Dams in China. A Fifty – Year Review”. Beijing: China Water Power Press.

Jovanovski M., Gapkovski N., Pesevski I., Abolmasov B., 2012. “Engineering Geology”, University Ss Cyril and Methodius, Civil Engineering Faculty – Skopje, Republic of Macedonia.

Kokalanov G., Tančev L., Mitovski S., 2007. “Analysis of the elastic behavior of La Acena arch – gravity dam” Ninth International Benchmark Workshop on Numerical Analysis of Dams, Proceedings, St. Petersburg, Rusia.

Mitovski S., 2015. „Static analysis of concrete dams by modeling of the structural joints“, PhD thesis, Ss Cyril and Methodius University, Civil Engineering Faculty – Skopje.

Novak P. et all, 2007. “Hydraulic structures”, Taylor & Francis Group, London.

Tanchev L., 2014. “Dams and appurtenant hydraulic structures”, Second edition, A.A. Balkema Publ., CRC press, Taylor & Francis Group plc, London, UK

Tanchev, L., Petkovski L., Mitovski S., 2013. “Dam engineering in Republic of Macedonia: Recent practice and plans” International Symposium Dam engineering in Southeast and Middle Europe, Recent experience and future outlooks, Ljubljana, Slovenia

Yugoslav National Committee on Large Dams (YUCOLD), 1970. “Dams of Macedonia”.