A METHOD OF DETERMINING PARAMETERS OF BOFANG MODEL ON THE EXAMPLE OF "BILECA" RESERVOIR

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Summary: *In this research paper, measurement data of air and water temperatures and water levels for "Bileca" reservoir for a period between 1967. and 2017. are presented. Based on the averaged measurement data values, an analytical expressions for amplitude of periodic temperature variation of "Bileca" reservoir are derived and an average annual temperature, as a function of the observed depth, is obtained, based on Bofang model. The obtained results allow thermal stress analysis, which represents an important factor for stability and safety monitoring of dams.*

Key words: *temperature field, Bofang model, measurement.*

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1. INTRODUCTION

Monitoring and collecting of measurement data during operation of dams is a very important segment which is related to design, construction and functionality of these objects. Verification of the adopted assumptions by measurements and analyses of results obtained on a large number of dams have general scientific significance and necessarily lead to further development of methodology of design and construction of large dams.
Measurement of water, air and concrete temperatures is an important part of the process of technical monitoring of large dams. Using these measurements, it is possible to obtain state of thermal stress, which is of great importance for the assessment of stability and safety of these structures. A great number of research papers devoted to this subject is available in literature [1], [2], [3], [4]. In this paper, the temperature of the water of "Bileca" reservoir is determined according to Bofang model [1], based on measurements of water temperatures at "Grancarevo" dam.

2. "BILECA" RESERVOIR AND "GRANCAREVO" DAM

"Grancarevo" dam (Figure 1.) was built about 50 years ago as the first step in the row of the hydropower system on river Trebisnjica. It is located 18.0 km downstream of the river’s source and 17.0 km upstream of the city of Trebinje.

Figure 1. Hydroelectric power station "Trebinje 1", "Grancarevo" dam

Hydropower plant is situated close to the dam and its main constituent objects are (Figure 2):

- doubly-curved arch dam with perimeter joint which separates the symmetrical internal part of the dam from the rest of the structure,
- open channel spillway for surplus water evacuation, controlled by radial gates, which is located at the left flank of the dam and which is designed to 1000-year flood Q=874.0 m^3/s (2 bays 15.0 m wide),
- three penstocks, which run through the dam, 4.0 m in diameter, length of 58.0 m, with installed capacity of 3×70.0 m^3/s,

- two bottom outlets, which also run through the dam, with diameter of 2.50 m each, length of 94.0 m and 100.0 m for the left and the right one, respectively, discharge capacity of Q=132.0 m^3/s and Q=134.0 m^3/s,
- the machine house with three generators 3x60.0 MW situated near the dam (downstream),
- tailrace canal, formed by deepening of the existing riverbed of river Trebisnjica.

The dam is doubly-curved arch made of concrete, height above the lowest foundation is 123.0 m, length of the crest is 439.0 m. The lowest foundation level is at 280.0 m a.s.l. and the elevation of the crest is at 403.0 m a.s.l. The thickness ranges from 26.91 m at the bottom to 4.60 m at the top. The concrete for the dam was placed in 31 elements (blocks) with total volume of 377 000.0 m^3, with contraction joints between them which were injected upon the casting of concrete. This way, the constituent parts of the dam were made to act as an integral concrete structure. The dam is designed with a perimeter joint which roughly follows the shape of the terrain and separates the foundation from the symmetrical mass of the dam.

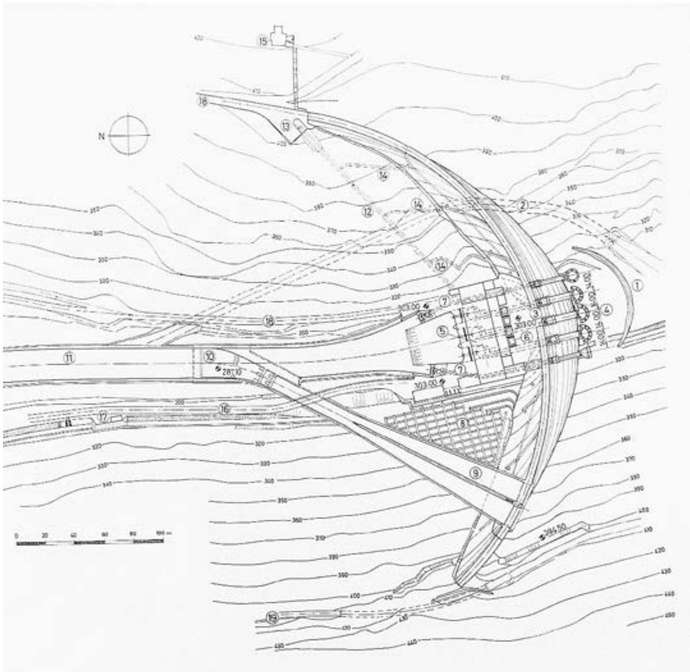

Figure 2. Ground plan of "Grancarevo" dam: 1. Cofferdam 2. Diversion tunnel 3. Dam 4. Intake structures 5. Machine house 6. Switchyard 7. Bottom outlets 8. Reinforcement of the left batter 9. Spillway 10. Stilling basin 11. Tailrace canal 12. Funicular 13. Funicular operating house 14. Access to inspection galleries 15. Measurements registration room 16. Access road to machine room 17. Porter's lodge 18. Access road to dam crest 19. Railway line Trebinje - Bileca

Three penstocks, inclined at 15.0˚ angle, made of steel sheeting, positioned 15.0 m apart, penetrate the mass of the dam.

"Grancarevo" dam is doubly-curved arch dam with vertical curvature more pronounced than the horizontal one. The vertical curvature is defined by the radius R=185.48 m. The arches in horizontal sections are also of circular shape, with one center point for the exterior and three centers for the interior face. This way, slight widening of the arches at the interior face is achieved.

The main features of "Bileca" reservoir are as follows:

- gross capacity of reservoir: 1278.0×10^6 m^3,
- active capacity: 1114.0×10^6 m^3,
- mean annual inflow: 71.0 m^3/s,
- storage energy value: 1010.70 GWh,
- elevation of maximum water level: 401.31 m a.s.l,
- elevation of normal water level: 400.0 m a.s.l,
- elevation of minimum working level: 348.0 m a.s.l,

3. REVIEW OF MEASURED DATA OF SERIES OF AIR AND WATER TEMPERATURES AND RESERVOIR WATER LEVELS

The air and water temperature measurements, used in this research, are collected in the vicinity of "Grancarevo" and in "Bileca" reservoir respectively. These data were obtained during the period from 1967. to 2017.

Figure 3. Weather station with air thermometer

The air temperature data (Figure 4.) were obtained by measurement with mercury air thermometer which is a part of the weather station (Figure 3.), located near the dam at the right riverbank. Data are presented as mean daily values, shown in the diagram below.

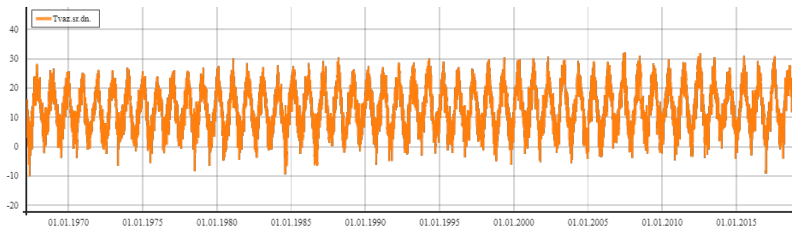

Figure 4. Mean daily values of air temperature

Time series of water temperatures (Figures 6. and 7.) were obtained by measurement with water thermometers, located at the downstream face of the dam at elevations of 370.0 m a.s.l. – sensor 1 and 330 m a.s.l. – sensor 2 (Figure 5.). Data were collected once every two weeks until the end of year 2000, from the beginning of 2001. data was collected daily.

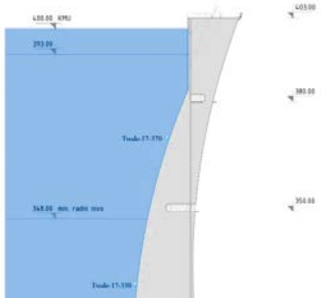

Figure 5. Position of water thermometers in the upper part of the cross-section of the dam

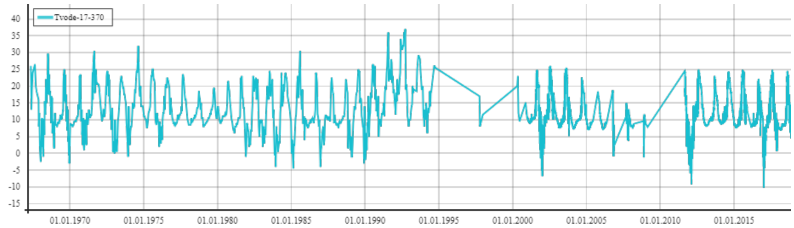

Figure 6. Water temperature at 370.0 m a.s.l. (sensor 1)

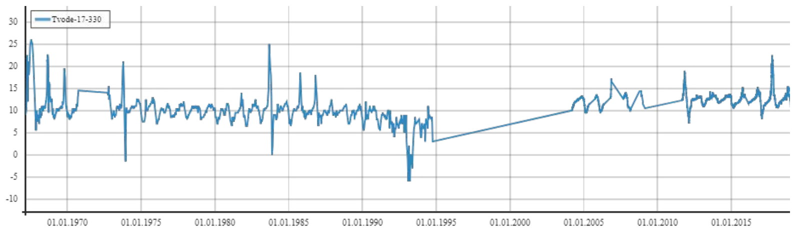

Figure 7. Water temperature at 330.0 m a.s.l. (sensor 2)

Time series of water levels (Figure 9.), obtained by measurement using staff gauges which are located at the right bank next to the dam (Figure 8.), are presented as mean daily values. The reading from staff gauges started in 11.11.1967. One day before that, the reservoir filling commenced.

The above diagrams include all data which were collected from the beginning of the reservoir filling. For the purpose of forming a model of water temperature distribution in accordance to Bofang model, a quality control of the data was conducted. All of the temperature values obtained when the reservoir water level was below the level of the sensors were removed (in this situation, the sensor measured air temperature). However, presented measured data have flaws in terms of missing values for certain time periods of few years. Moreover, unjustifiably high values of water temperatures were occasionally observed, especially in the shallower parts of the reservoir. The fact that intake structures are located at the bottom of the reservoir and that they influence the values read from the sensors should be borne in mind. This has an impact on evaluation of the temperature field in the reservoir according to Bofang model.

Figure 8. Staff gauges

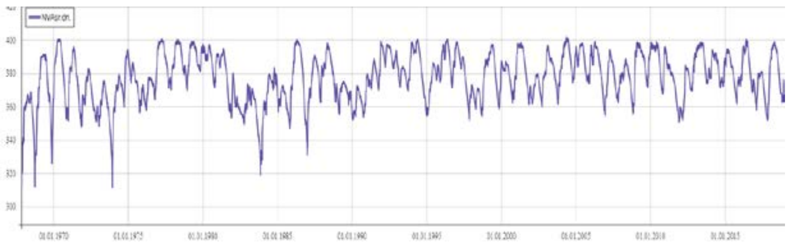

Figure 9. Reservoir water level

Taking into consideration the aforementioned facts and restrictions, the water temperature distribution model in the reservoir according to Bofang, which is presented in the following chapter, will certainly have some deviations with respect to the ideal model.

4. THE ASSESSMENT OF PARAMETERS OF BOFANG MODEL

Annual variation of the reservoir water temperature field $T(y,\tau)$, modeled in accordance to Bofang model, is a function of time τ and depth y of the observed point, where τ is expressed in months and y in meters, and it has the following form [1]:

$$T(y,\tau) = c + (T_S - c)e^{-\alpha y} + A_0 e^{-\beta y} cos[\,\omega(\tau - \tau_0 - \varepsilon(y)]. \quad (1)$$

The parameters in the equation above have the following meaning:

- ω – angular frequency for a time period of 12 months; it is defined by the equation:

$$\omega = \frac{2\pi}{12\text{months}} = \frac{\pi}{6}\frac{\text{rad}}{\text{months}},$$

- τ_0 – time of the maximum mean air temperature in the near surrounding of the dam, expressed in months,
- $\varepsilon(y)$ – time dilation of water temperature as a function of depth; it can be obtained from the following equation:

$$\varepsilon(y) = 2.15 - 1.3e^{-0.085y} \text{ [months]},$$

- A_0 – maximum amplitude of water temperature variation $[°C]$,
- α, β – factors which account for exponential decrease of temperature with the increase of depth $[\frac{1}{m}]$,
- c – mean water temperature deep below the surface $[°C]$,
- T_S – mean water temperature at the surface of reservoir$[°C]$.

Unknown parameters to be determined from the measured air and water temperatures over the course of many years are τ_0, A_0, α, β, c и $T_S - c$. These values shall be obtained in a manner which leads to the minimum deviation of the measured water temperatures from the Bofang model. Regarding the fact that the reservoir water level is changing over time as a result of normal operation of the dam and hydrologic conditions, the depths of water temperature sensors, which are fixed to the dam, are changing. The mean depths of temperature sensors during the measurement are labeled y_1 and y_2 and these values, based on the known positions and mean value of the reservoir water level are:

$$y_1 = 11.50\, m,$$
$$y_2 = 51.50\, m.$$

Based on the properties of function $T(y,\tau)$ it can be concluded that the maximum values of water temperature at the depth y occur when the following condition is fulfilled:

$$cos[\,\omega(\tau - \tau_0 - \varepsilon(y)] = 1, \tag{2}$$

that is, in the moments:

$$\tau_1 = \tau_0 + \varepsilon(y_1) \text{ and } \tau_2 = \tau_0 + \varepsilon(y_2),$$

and at the mean depths of sensors, y_1 and y_2 amount to:

$$T_{1max} = T(y_1, \tau_1) = c + (T_s - c)e^{-\alpha y_1} + A_0 e^{-\beta y_1}, \tag{3}$$
$$T_{2max} = T(y_2, \tau_2) = c + (T_s - c)e^{-\alpha y_2} + A_0 e^{-\beta y_2}. \tag{4}$$

At the beginning of the measurement, when $\tau = 0$, these temperatures are as follows:

$$T_{10} = T(y_1, \tau = 0) = c + (T_S - c)e^{-\alpha y_1} + A_0 e^{-\beta y_1} cos[\,\omega(\tau_0 + \varepsilon(y_1)], \tag{5}$$
$$T_{20} = T(y_2, \tau = 0) = c + (T_S - c)e^{-\alpha y_2} + A_0 e^{-\beta y_2} cos[\,\omega(\tau_0 + \varepsilon(y_2)]. \tag{6}$$

By forming the ratio of temperature differences, we arrive at the formula for analytical definition of parameters A_0и β:

$$\frac{T_{1max}-T_{10}}{T_{2max}-T_{20}}=\frac{A_0 e^{-\beta y_1}(1-cos[\omega(\tau_0+\varepsilon(y_1))])}{A_0 e^{-\beta y_2}(1-cos[\omega(\tau_0+\varepsilon(y_2)])}=\left(\frac{sin[\omega(\tau_0+\varepsilon(y_1))/2]}{sin[\omega(\tau_0+\varepsilon(y_2))/2]}\right)^2 e^{-\beta(y_1-y_2)}, \quad (7)$$

$$\beta=\frac{1}{y_1-y_2}\ell n\frac{(T_{2max}-T_{20})\,sin^2[\omega(\tau_0+\varepsilon(y_1))/2]}{(T_{1max}-T_{10})\,sin^2[\omega(\tau_0+\varepsilon(y_2))/2]}, \quad (8)$$

$$A_0=\frac{(T_{1max}-T_{10})e^{\beta y_1}}{2\,sin^2[\omega(\tau_0+\varepsilon(y_1))/2]}. \quad (9)$$

The parameters c и T_S-c can be obtained from the following equations, based on equations (5) и (6):

$$T_{10}-A_0e^{-\beta y_1}cos[\,\omega(\tau_0+\varepsilon(y_1)]=c+(T_S-c)e^{-\alpha y_1},$$
$$T_{20}-A_0e^{-\beta y_2}cos[\,\omega(\tau_0+\varepsilon(y_2)]=c+(T_S-c)e^{-\alpha y_2}.$$

By subtracting these parameters, we find the following expressions:

$$T_S-c=\frac{T_{10}-T_{20}+A_0\{e^{-\beta y_2}cos[\omega(\tau_0+\varepsilon(y_2)]-e^{-\beta y_1}cos[\omega(\tau_0+\varepsilon(y_1)]\}}{e^{-\alpha y_1}-e^{-\alpha y_2}}, \quad (10)$$

$$c=T_{10}-A_0e^{-\beta y_1}cos[\,\omega(\tau_0+\varepsilon(y_1)]-(T_S-c)e^{-\alpha y_1}. \quad (11)$$

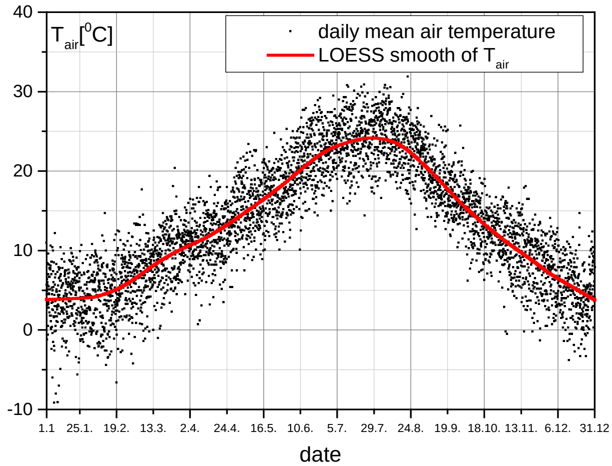

Figure 10. Measured air temperatures shown for a time period of 1 year and a curve which represents average temperatures (red line)

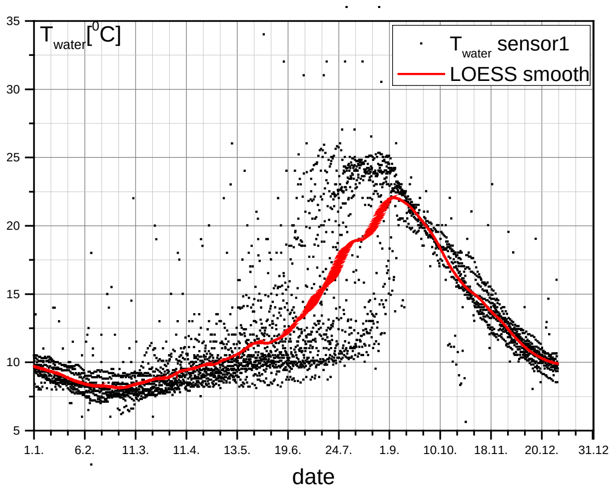

Figure 11. Measured water temperatures shown for a time period of 1 year – sensor 1 (370.0 m a.s.l.) and a curve which represents average temperatures (red line)

In Figure 10. all of the measured air temperatures are shown graphically (see Figure 4.), reduced to a period of 1 year. Mean air temperature and its maximum in the moment τ_0 in the year are determined by smoothing the measured temperatures by using LOESS methods (Locally Estimated Scatterplot Smoothing); the obtained curve is shown in Figure 10. (red line). In Figures 11. and 12. the measured values of the reservoir water temperatures, obtained by reading from the sensors 1 and 2 during the entire measuring period (1967. – 2017.) are shown for a time interval of 1 year. Utilizing the same smoothing method, average temperature curves are obtained and they are shown as red curved lines on the diagrams. These curves were used to obtain the parameters T_{1max}, T_{10}, T_{2max} and T_{20}, which represent the maximums of the curves, as well as temperature values for the 1st of January. The values of the parameters obtained from the previously defined diagrams are as follows:

- Figure 10: $\tau_0 = 7.87\ months$ for date 27.07,
- Figure 11: $T_{1max} = 22.0\ °C$, $T_{10} = 9.70\ °C$,
- Figure 12: $T_{2max} = 14.50\ °C$, $T_{20} = 11.40\ °C$.

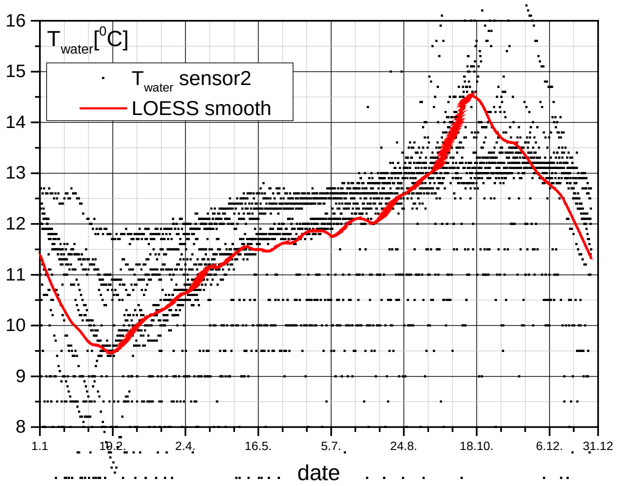

Figure 12. Measured water temperatures shown for a time period of 1 year – sensor 2 (330.0 m a.s.l.) and the corresponding average temperature curve (red line)

For the value of α the usual value of $\alpha = 0.04\ \frac{1}{\mathrm{m}}$ was adopted. This value is reccomended by the literature [1]. The numerical values of the rest of the parameters of Bofang model, obtained by numerical calculations, are:

$$A_0 = 12.7069\ °C, \beta = 0.025\ \frac{1}{\mathrm{m}}\ , T_S - c = 33.3878\ °C, c = -16.0286\ °C.$$

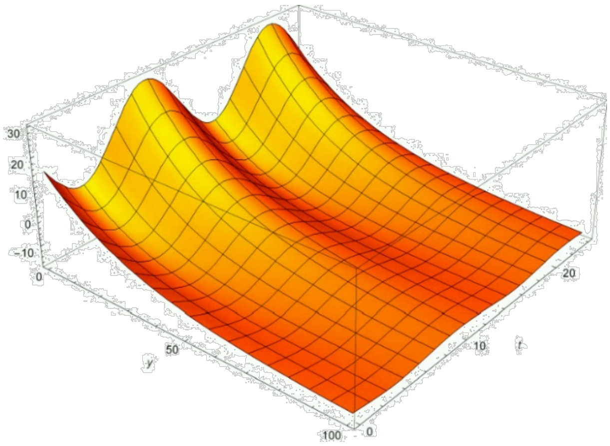

Figure 13. 3D view of Bofang model of water temperature distribution as a function of depth and time for a 2-year period for "Bileca" reservoir. The depth y is expressed in meters, the time t in months and the water temperature in [^{0}C]

By substituting the aforementioned parameters in equation (1), the final form of the defined model is obtained:

$$T(y,\tau) = -16.0286 + 33.3878e^{-0.04y} + 12.7069e^{-0.0250y}\, cos[\frac{\pi}{6}(\tau - 10.02 + 1.3e^{-0.085y1}].$$

3D graphic representation of the temperature model is shown in Figure 13.

5. CONCLUSION

In this research paper, water and air temperature and water level measurement data are presented for "Bileca" reservoir. Measurements are used in order to obtain the parameters of Bofang model which represents the reservoir water temperature change as a function of depth and time. The obtained model can be used as an input value in calculation of thermal stresses and safety analysis of the dam.

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ЈЕДНА МЕТОДА ОДРЕЂИВАЊА ПАРАМЕТАРА БОФАНГОВОГ МОДЕЛА НА ПРИМЕРУ АКУМУЛАЦИЈЕ "БИЛЕЋА"

Резиме: *У раду су приказани подаци мерења температуре ваздуха, воде и нивоа воде у акумулацији "Билећа" у периоду од 1967. до 2017. године. На основу усредњених измерених температура изведени су аналитички изрази за амлитуду периодичне веријације температуре акумулације и одређена средња годишња температура у функцији посматране дубине који се засновају на Бофанговом моделу. Добијени резултати омогућавају анализу термичког напрезања, што представља важан фактор праћења стабилности и сигурности брана.*

Кључне речи: *температурно поље, Бофангов модел, мерења.*