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Comparison of temperature and displacements of a gravity section and a buttress section illustrated with the example of concrete dam in Rożnów

Porównanie termiki i przemieszczeń sekcji ciężkiej i półciężkiej na przykładzie zapory betonowej w Rożnowie

Abstract
This paper presents the results and the process of numerical analysis of a selected section of the concrete dam in Rożnów. The calculations were carried out for two different variants: the gravity section and the buttress section. The effects of the geometry on the temperature distribution inside the section, and the effect of the temperature on displacements, were examined.
Keywords: numerical modelling, concrete dam, thermal analysis

Streszczenie
W artykule przedstawiono wyniki i proces analizy numerycznej dla wybranej sekcji zapory betonowej w Rożnowie. Obliczenia przeprowadzono dla dwóch różnych wariantów, dla sekcji ciężkiej i półciężkiej, sprawdzając wpływ geometrii na warunki temperaturowe, rozkład temperatury wewnątrz sekcji oraz ich wpływ na przemieszczenia.
Słowa kluczowe: modelowanie numeryczne, zapora betonowa, analiza termiki

1. Introduction

The concrete gravity dam in Rożnów was erected on the 80th kilometer of the Dunajec River, in a place where the river considerably changes its course, taking the shape of the so-called Rożnów Serpentine. The process of construction began in 1935 and finished in 1941, when filling the reservoir initiated. The Dam consists of 44 sections, seven of which are spillway sections and another five sections form the power station containing Kaplan hydroelectric sets and machine hall. The sections are 15 m wide, except for sections containing turbines (17 m wide) and sections near the left abutment (5 and 7.5 m wide). According to [1], the structure has been classified as a category I dam.

The structure is located on the Carpathian flysch. In the subsoil, there are sandstone layers with interlayers of shale. Sandstone nearby the location of the Dam is strongly cracked. In the initial project prepared by Professor Zbigniew Zmigrodzki from the Warsaw University of Technology, it was assumed to build straight axis buttress dam, consisting of T-shaped sections and U-shaped sections containing a power station. However, as ground works progressed and further geological researches of the subsoil were continued, four detachment faults were discovered and the project was changed. It was decided to curve the axis of the Dam near the left abutment and to alter the buttress sections to gravity sections.

To prevent water outflow from the reservoir, the ground was improved with two grouting screens reaching 30 m below the foundation of the Dam. By dint of this solution, subsoil rock was strengthened. Moreover, after finishing concrete works, subsidences were reduced.

2. Preparing of the numerical model

The subject of numerical modelling was the 18th section of the Dam. It is the highest of the typical sections. It is located in central part of the Dam, near to the so-called Rożnów Peninsula and borders on sections containing a hydroelectric power station. The calculations were carried out for the following variants: already built gravity section and initially designed buttress section. In addition, two different variants of concrete were considered: it was assumed to be an elastic substance in the first one and viscous-elastic in the other one, in which creep and relaxation were taken into account.

The first stage of the analysis was establishing the proper geometry of the model. The geometry of the gravity section was drawn on the basis of available archival materials. The final shape was verified by comparing it with laser scanning measurements [2]. The geometry of the buttress section was established according to the available publications containing initial project sketches. The geological layer system in the subsoil was simulated on the basis of archival studies, the data from articles concerning the foundation of the water power station [3] as well as the project of grout curtain elaborated by the Polish Geological Institute.

The system of geological layers in the subsoil is presented in Fig. 1. The models of the gravity section and the buttress section, along with classification of material properties, are presented in Fig. 2 and 3.

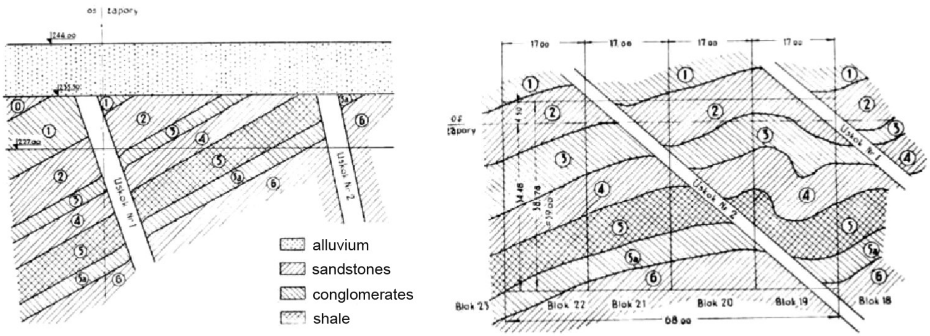

Fig. 1. The system of the geological layers near the 18th section of the Dam [3]

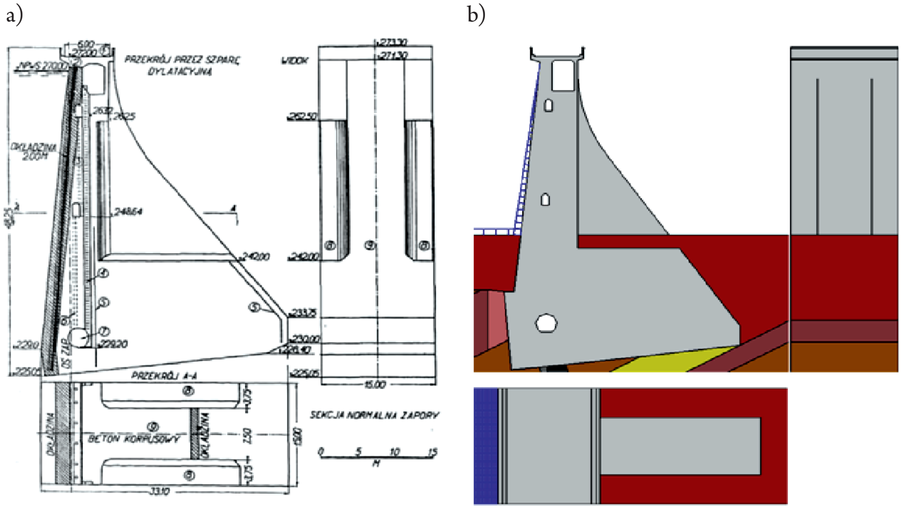

Fig. 2. The geometry of the buttress section: a) sketch [4], b) model generated by Z-Soil software [5]

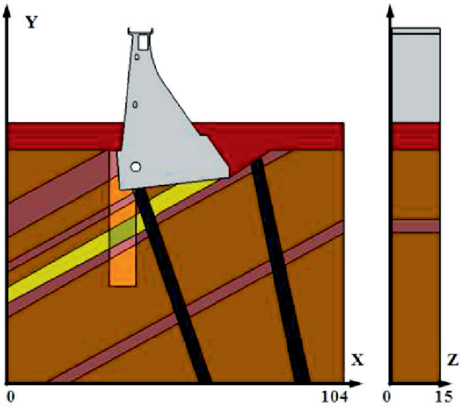

Fig. 3. The geometry and dimensions of the gravity section [5]

Values of the material properties used in calculations were assumed on the basis of researches carried out during the construction process of the Dam, as well as literature and standard data. Properties used in thermal analysis are given in Table 1 and properties used in calculations of displacements and stresses are shown in Table 2.

Table 1. Material properties used in thermal analysis [5]

No	Name	Symbol	Thermal conductivity	Volumetric thermal capacity	Thermal dilatancy
			[kN/d/C]	[kN/m²/C]	[1/C · 10⁻⁵]
1	Concrete	1	112.32	2058.00	1.13
2	Alluvium	2	121.00	1428.00	1
3	Sandstone I	3	232.40	2050.70	1
4	Sandstone II	4	232.40	2050.70	1
5	Conglomerate I	5	232.40	2059.02	1
6	Conglomerate II	6	232.40	2059.02	1
7	Shales I	7	99.36	2302.50	1
8	Shales II	8	99.36	2302.50	1
9	Discontinuity spacing I		232.40	2050.70	1
10	Discontinuity spacing II	10	232.40	2050.70	1

Table 2. Material properties used in mechanical analysis [5]

No	Name	Dead weight	Young's modulus	Poisson's ratio	Hydraulic conductivity
		[kN/m³]	[kPa]	[–]	[m/d]
1	Concrete	24.5	40 000 000	0.2459	$1 \cdot 10^{-9}$
2	Alluvium	17.0	80 000	0.20	10
3	Sandstone I	24.5	590 000	0.25	$4 \cdot 10^{-5}$
4	Sandstone II	24.5	590 000	0.25	$1 \cdot 10^{-9}$

5	Conglomerate I	24.6	330 000	0.25	$3 \cdot 10^{-6}$
6	Conglomerate II	24.6	330 000	0.25	$1 \cdot 10^{-9}$
7	Shales I	25.0	39 000	0.20	$9 \cdot 10^{-8}$
8	Shales II	25.0	39 000	0.20	$1 \cdot 10^{-9}$
9	Discontinuity spacing I	24.5	413000	0.25	10
10	Discontinuity spacing II	24.5	413000	0.25	$1 \cdot 10^{-9}$

To describe the creep of concrete, creep function of exponential type was assumed:

$$C(t,\tau) = A \cdot \left(1 - e^{-\frac{1}{B}(t-\tau)}\right) \tag{1}$$

Parameter A (the creep coefficient) is described by the following formula: $A = \frac{\phi}{E}$. The ϕ coefficient was estimated according to PN-EN-1992-1 Polish Standard. For humidity of RH = 80% (on the outside), dimensions of the element as at mid-height of the Dam, time of load imposing $t_0 = 365$ d and concrete strength C30/37 the result was $\phi = 1$. Thus, it was designated that $A = 2.5 \cdot 10^{-8}$ [1/kPa]. For parameter B, time of retardation was assumed to be 33.3 d [6].

3. Thermal analysis

3.1. Boundary conditions

The problem of thermal (variable in time) was solved as the first one. Determined temperature fields and their changes in annual cycle of atmospheric conditions were implemented into the mechanical analysis as a load. For that purpose, the Fourier equation was solved:

$$(\lambda T_{,i})_{,i} + \frac{\partial H}{\partial t} = c^* \frac{\partial T}{\partial t} \quad \text{w } \Omega \tag{2}$$

where:
T – temperature [°C],
t – time [d],
λ – thermal conductivity [kN/d/C],
c^* – volumetric thermal capacity [kN/m²/C],
H – source of the heat [kN/m²].

Boundary conditions of three types were used in the analysis:

1) Boundary conditions of the first type consist in applying a known temperature to the surface. Boundary conditions of that type were applied to the upstream face and

to the surface of the reservoir bottom, where concrete and subsoil are in permanent contact with water, as well as around the model, where constant temperature of the ground (9°C) was applied on the boundaries;

2) Boundary conditions of the second type – convection.

$$-h\left(T-T_e\right)=\lambda\frac{\partial T}{\partial n} \tag{3}$$

where:

T_e – temperature of the surroundings [°C],

h – convection coefficient, based on PN-91/B-02020 Polish Standard h = 23 [W/m/K].

That boundary condition was applied to surfaces, which remain in contact with external air, this is: to the downstream face, to the upstream face above water surface and to the crest of the Dam. In case of the buttress dam, it was also applied to the lateral surfaces.

3) Boundary condition of third type – adiabatic:

$$0=\lambda\frac{\partial T}{\partial n} \tag{4}$$

That condition was applied to surfaces, where the heat flow induced by air movement is inconsiderable. The condition was applied to the lateral surfaces of the model, which are perpendicular to the axis of the Dam, to revision galleries and to external surfaces, where other boundary conditions were not applied.

Surfaces, to which boundary conditions were applied, are presented in the Fig. 4.

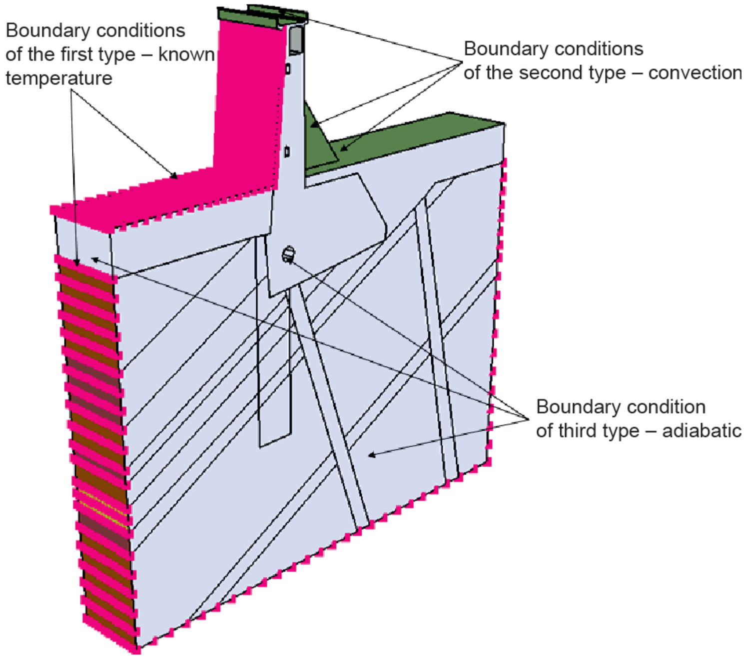

Fig. 4. Boundary conditions used in thermal analysis [5]

Calculations were conducted for a variable water level. The character of air and water temperature changes is sinuous and is described by the following formula:

$$T(t)=T_{sr}\left(1-\frac{\Delta T}{T_{sr}}\cdot\cos\left(\frac{2\pi}{365}t\right)\right)\ [^{\circ}C] \tag{5}$$

where:
$T(t)$ – temperature at a given instant of time t[°C],
T_{sr} – average temperature [°C],
Δt – temperature amplitude [°C].

Water temperature in the reservoir was assumed on the basis of thermal characteristics of the Rożnów Lake. Temperature distribution according to the depth is presented in Fig. 5. Temperature was implemented into the model in 5 points at every 5 m in depth. Temperature between them was linearly interpolated. The data used in calculations of temperature are given in Table 3 and in Fig. 6.

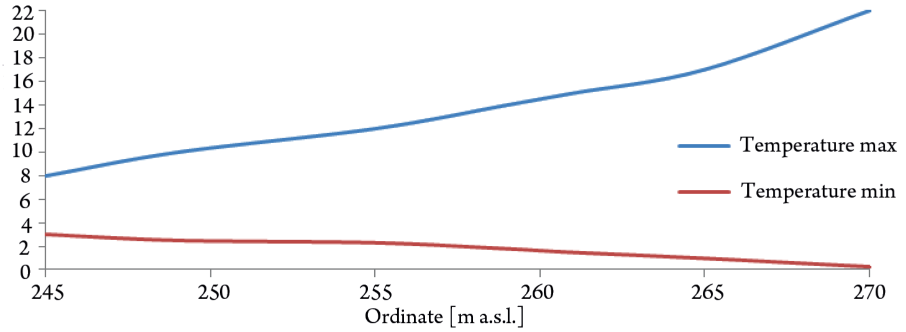

Fig. 5. Water temperature in the Rożnów Lake

Table 3. Data used in thermal analysis

	Symbol on Fig. 6	T_{max} [°C]	T_{min} [°C]	ΔT [°C]	T_{sr} [°C]
Air temperature	(dark green line)	24	–6	30	9
Water temperature 245 m.a.s.l.	(blue line)	8	3	5	5.5
Water temperature 250 m.a.s.l.	(teal line)	10.5	2.5	8	6.5
Water temperature 255 m.a.s.l.	(light green line)	12	2.3	9.7	7.15
Water temperature 265 m a.s.l.	(light blue line)	17	1	16	9
Water temperature 270 m.a.s.l.	(orange line)	22	0.3	21.7	11.15

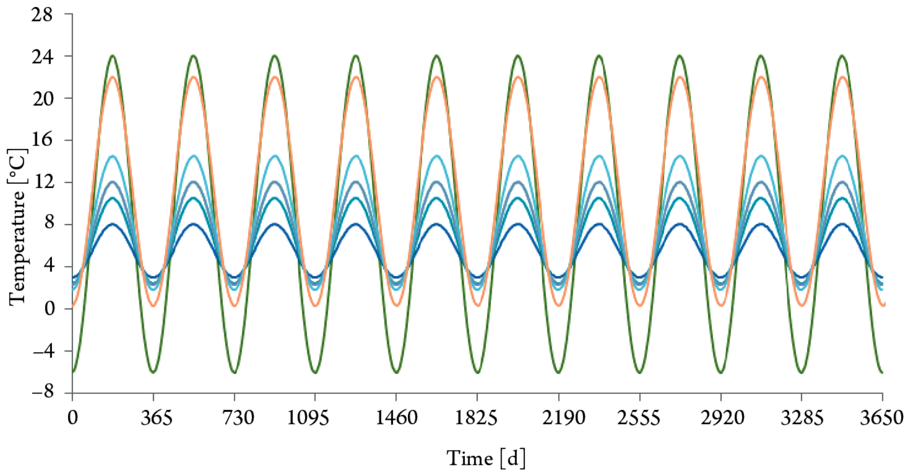

Fig. 6. Functions describing annual changes of water temperature

3.2. Results of thermal calculations

Analysis was carried out for 10 calculation series. Each of the series was 365 days long. A step of 5 days was set. Taking into account the transient character of the phenomena, the time of calculation must have been established. The differences between successive calculation series of identical boundary conditions are shown on Fig. 7. As can be noticed, the temperature in the model is stabilizing during initial cycles. The temperature difference exceeded 5°C after the first series. The difference between the consecutive cycles was decreasing more and more and was less than 0.5°C between series 5 and 4.

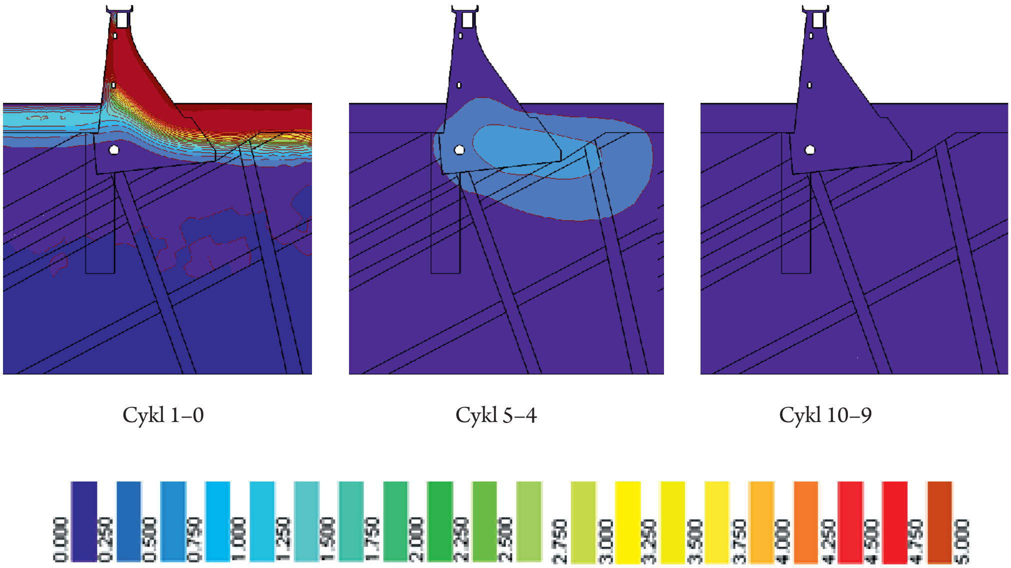

Fig. 7. Changes of temperature in consecutive calculating cycles

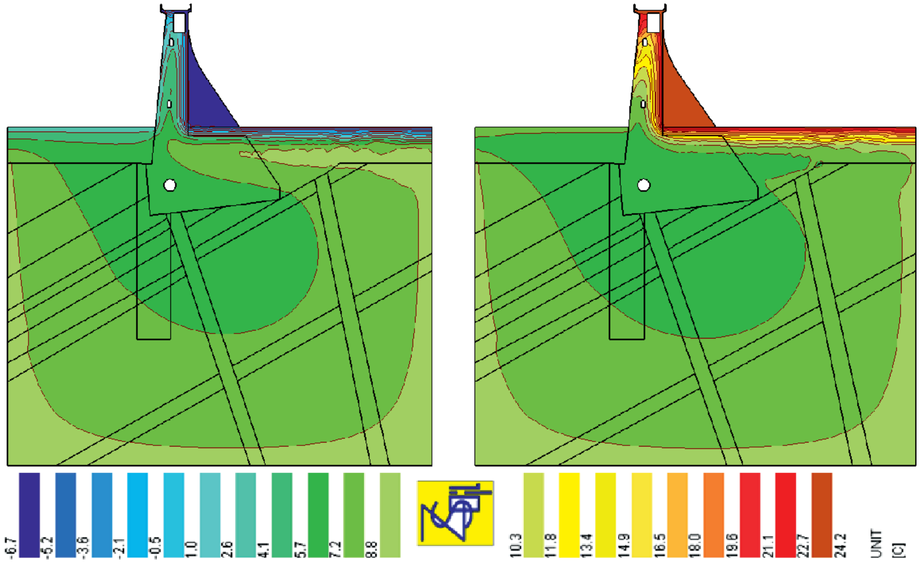

Fig. 8. Temperature distribution in the buttress section in summer and in winter

The temperature distribution inside the Dam and in the subsoil in the summer and in the winter is presented in Fig. 8. As can be seen, only near-surface layers of concrete and subsoil are susceptible to changes. Inside the structure, the temperature is constant and does not depend on weather conditions throughout the year. The temperature difference between the body of the dam and concrete surface layers induces thermal stresses. The exact temperature course throughout the year at selected points is shown in Fig. 9 and 10.

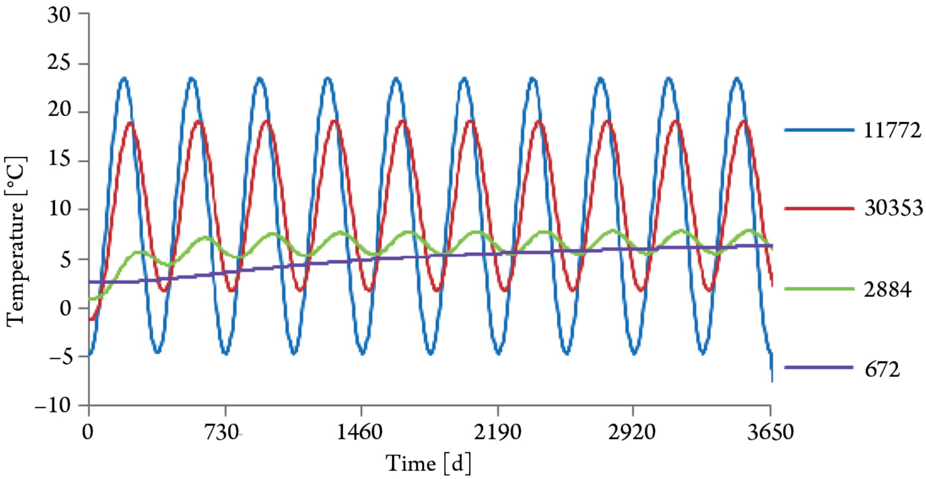

Fig. 9. Temperature changes in time at selected points of the buttress section

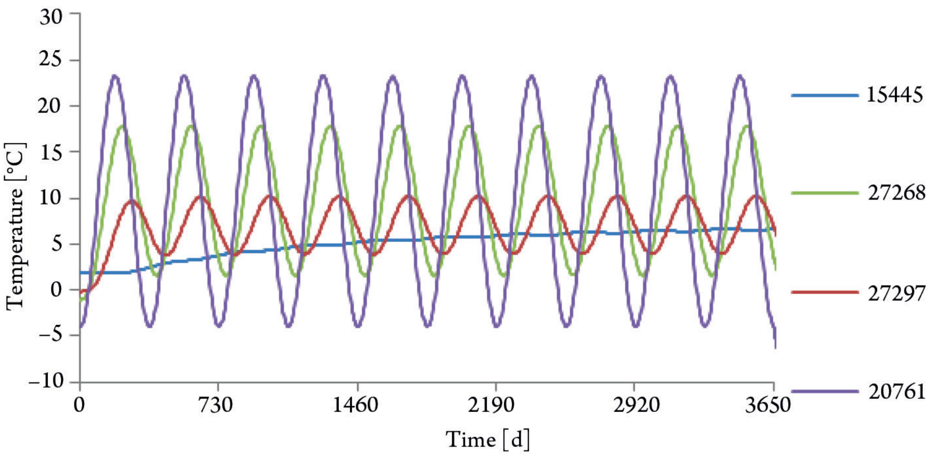

Fig. 10. Temperature changes in time at selected points of the gravity section

As the charts show, the near-surface layers of concrete react to temperature changes most quickly (points 11772 and 15445). The temperature increase in time at points located inside the Dam is slow. With time, increases diminish more and more. From the moment of stabilization of conditions, results of thermal analysis can be used for loading the mechanical model. The other points located inside the dam react with some delay. The highest temperature at points 30353 and 27268 occurs about 20 days later than at points situated on the surface, whereas at points in the second revision gallery (points 27297 and 2884), the delay is about 50 days. The inside of the buttress section heats up more quickly than the inside of the gravity section. The temperature in the buttress section is higher than in the gravity section during the summer and vice versa during the winter.

4. Analysis of displacements

4.1. Boundary conditions

The model used in the calculations of displacements was loaded with upstream and downstream (groundwater) water pressure. Upstream water level at 270 m.a.s.l. was assumed to be constant in time. Downstream water level ordinate was assumed to be 237.7 m.a.s.l. Moreover, hinged supports (applied to underneath of the model) and movable supports (allowing the subsoil and the structure to subside; they were applied to external vertical surfaces of the model) were used as boundary conditions.

Values of displacements obtained for elastic and viscous – elastic model were identical. During the summer, in the case of the buttress section as well as the gravity section, the crest of the Dam leans towards the upstream water, whereas during the winter, it leans towards the downstream water. Values obtained for the buttress section are almost two times higher.

Points localized inside the section do not displace. Results for selected points of the gravity section are presented in Fig. 12 and 13 and in Fig. 14 and 15 for the buttress section. (The points are located as in Fig. 10)

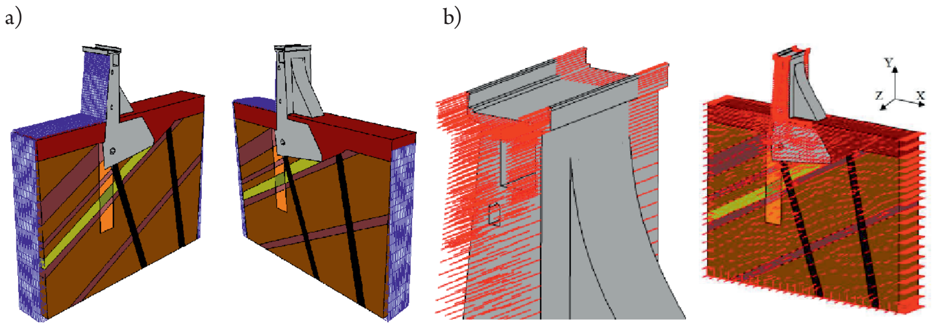

Fig. 11. Boundary conditions used in analysis of displacements [5]: a) Upstream and downstream water level, b) Supporting of the model

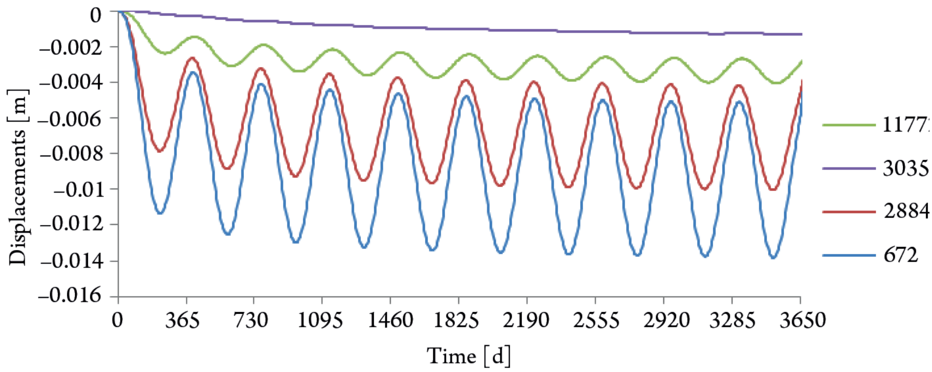

Fig. 12. Horizontal displacements of the points in the gravity section

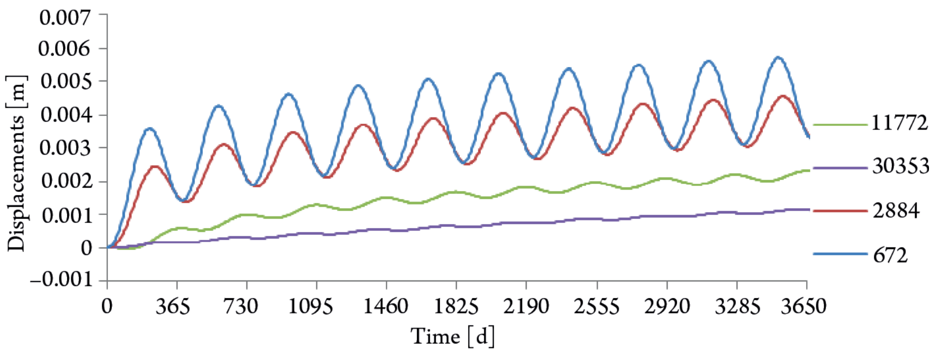

Fig. 13. Vertical displacements of the points in the gravity section

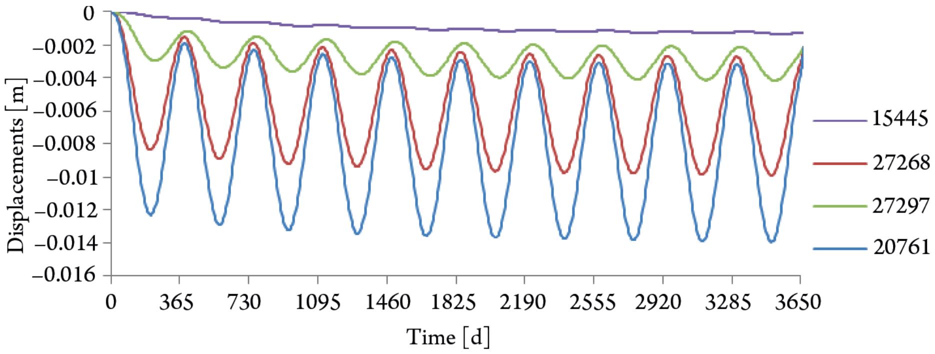

Fig. 14. Horizontal displacements of the points in the buttress section

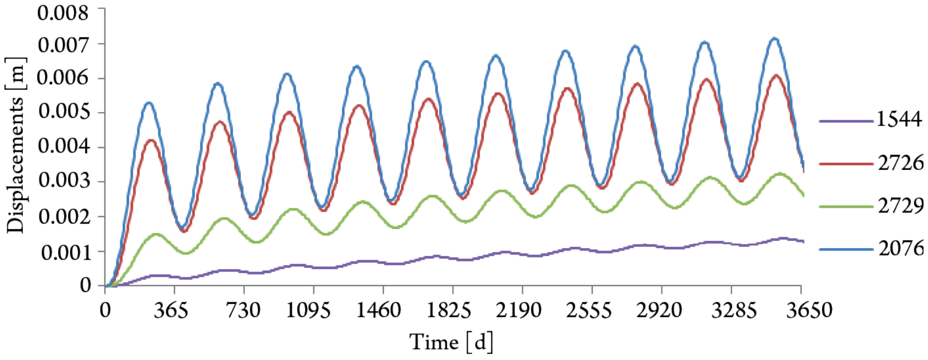

Fig. 15. Vertical displacements of the points in the buttress section

On the basis of the charts, it can be noticed that the increase of displacements is changing in time and it is diminishing in the subsequent years. Points located on the crest of the Dam are susceptible to the most significant displacements. The charts of displacements are of the same type as charts of temperature. In addition, it can be seen that points located near the concrete surface layers react to temperature changes much more quickly than points located deeper inside the section. The difference of horizontal displacement values between the summer and the winter is about 13 mm for the buttress section and about 7 mm for the gravity section.

5. Final conclusions

Temperature in the subsoil and in the inside of the gravity section and the buttress section is constant throughout the year. Near-surface layers are most susceptible to temperature changes. The difference between temperature of the inside of the Dam and external temperature is caused by displacements. The differences in temperature distribution of the gravity section and the buttress section are caused by differences of the geometry of the sections. The displacement values obtained for the buttress section are more significant than the ones obtained for the gravity section. The displacements obtained for elastic and viscous-elastic model were identical. The Dam leans towards the upstream water in the summer and towards the downstream water in the winter. It is essential to take into account the effect of temperature changes on the values of displacements, while analyzing the monitoring of displacements in massive concrete hydrotechnical structures.

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