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WATER WARMING IN HYDROPOWER HEADRACE TUNNELS

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Abstract

The research refers to finding a way to quantify water heating when going through underground adductions. At first sight, in winter, the cold water from the rivers passing through an underground gallery should warm up. There are no approaches to the problem in the technical literature. All theoretical approaches to natural phenomena are approximate. The number of unknowns is always higher than the number of equations we can write. In order to quantify the phenomenon, we make simplifications. It was used an existing calculation model of the heat transfer between the rock massif and the water that transits it. The results obtained by calculation were confirmed by measurements at operating hydropower plants. The contribution of this research is the identification and validation of the calculation model of the heat transfer between the rock massif and the water from the adductions.

Key words: headrace tunnel, heat transfer; hydropower, ice jam melting

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1. Introduction

The research aims to find a calculation model for heat transfer for water heating when passing through an underground gallery. Once the heat transfer is quantified, what do we do with the heated water? In fact, the research was initiated by the need to somehow melt the ice jams on the rivers. The way in which heated water melts ice from rivers is treated extensively in the technical literature. We did not find in the technical literature the approach of the subject of water heating that transits adductions. Possibly, the subject has been examined and the result is insignificant and has not been communicated; or it has not been investigated because it is not interest in the problem.

In this research we used the calculation methods existing in the technical literature. We needed a calculation model for heat transfer, as well as to estimate the rocks mass temperature and water temperature measurements. To develop these topics were consulted various scientific resources.

Water warming in underground hydropower headrace can be approached from two perspectives:

- how much water temperature increase is obtained when transiting a massive underground?
- how much it takes to warm the water so the effect on downstream ice is significant?

This paper tries to answer a question: the water that transits hydroelectric headrace can absorb enough heat to melt the ice from the downstream river? If so, how can this heat transfer be quantified and checked whether the theoretical model is appropriate to the phenomenon?

To answer these questions, it is necessary to first establish the temperature of the mass in which the headrace is built. This issue is treated by Carslaw and Jaeger (1959), Florides and Kalogirou (2007), Mihalakakou et al. (1996) and Ozgener (2011). Rock temperature measurements and temperature estimation in deep excavations are found in the works of Demetrescu et al. (2005), Popiel et al. (2001), Rybach and Pfister (1994).

Regarding thermal transfer, to heating or

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cooling of the bodies in the transient mode, two types of thermal resistances are highlighted: the internal thermal resistances given by the conduction process and the surface thermal resistances due to the convection between the body and the fluid it comes into contact with (Badea, 2004).

The calculation model used in the article for heat transfer between water and headrace is constant surface temperature. This model is described by Popescu (2003); Çengel (2003) and quantifies only turbulent convection between water and headrace. The application of this calculation model for hydropower headrace does not exist in the technical literature.

Warm water released into the rivers suppresses the ice cover by melting it or by preventing initial formation (Ashton, 1982; 2010; Beltaos, 2008; USACE, 2006). Aspects of ice-hydropower interaction have been described without considering the water warming on the headrace tunnels (Gebre et al., 2014). How does the long and deep buried diversion tunnel influence the water temperature in relation to downstream aquatic organisms was described by Ran et al. (2004).

Prediction analysis on water temperature in closed aqueduct (Chen et al., 2012) deals with the problem of water frosting in the cold areas. The ice jam formation on Bistrita River, Romania, is treated by Radoane et al. (2010).

2. Material and methods

We used existing calculation methods in the technical literature, which are described below.

2.1. Heat transfer from soil to water

2.1.1. Ground temperature variation

The undisturbed temperature field $T_{(z,t)}$ at any depth z in the ground and at any time t can be written, using the analytical solution of the one-dimensional, transient, heat conduction Carslaw and Jaeger, 1959; Mihalakakou et al., 1996) Eq. (1).

$$T_{(z,t)} = T_m - A_s exp\left[-z\left(\frac{\pi}{365\alpha}\right)^{1/2}\right] cos\left\{\left(\frac{2\pi}{365}\right)\left[t - t_0 - \frac{z}{2}\left(\frac{365}{\pi\alpha}\right)^{1/2}\right]\right\} \quad (1)$$

where T_m is average annual air temperature and the second term on right-hand side represents the amplitude of the oscillation at point z, and the last term in the cosine function represents the phase delay of oscillation at point z relative to the oscillation at the surface, and α is the soil thermal diffusivity.

The measurements results performed in diferent locations and published in several papers (Florides and Kalogirou, 2007; Ozgener, 2011), show that the ground temperature below a certain depth remains relatively constant throughout the year. As the depth in the measuring point in the ground increases, the high thermal inertia of the soil decreases the temperature fluctuations that occur at the soil surface.

There is also a time lag between surface and ground temperature fluctuations. Thus, at a sufficient depth, the soil temperature can be considered constant throughout the year, its value increasing with depth. From this point of view of temperature distribution, in three areas of the ground are distinguished (Popiel et al., 2001):

- surface area reaching a depth of about 1 m, where soil temperature follows short-term changes in weather conditions.

- surface area extending from a depth of about 1-8 m (for light dry soils) or 20 m (for wet and heavy sandy soils), where the soil temperature is almost constant and close to the average annual air temperature; in this area, the distribution of soil temperature depends mainly on the weather conditions of the seasonal cycle.

- deep zone (below about 8-20 m), where the soil temperature is practically constant (and increases very slowly with depth depending on the geothermal gradient).

Generally, the predicted ground temperature T_p in a point B along the tunnel axis is given by (Eq. 2) (Rybach and Pfister, 1994).

$$T_p = T_m + G \times d + \Delta T_{topo} \quad (2)$$

where, G is local geothermal gradient [°C/m], d is the cover thickness [m], and ΔT_{topo} the influence of the 3D topography in the surroundings of point.

Usually, the in-situ temperature of the rock increases with the depth, i.e. with the thickness of the covering rock. In areas with rugged terrain, such as mountains, it is influenced by the three-dimensional shape of the topography, up to depths of several kilometers, the underground temperature field and thus the course of isotherms.

Other parameters on which underground temperatures depend include soil surface temperature, local geothermal heat flow and a number of geological factors. The prediction of ground temperatures must take into account all these parameters (Florides and Kalogirou, 2007). To use a rock temperature as close as possible to the real situation we used the results of a study in the Eastern Carpathians bend (Demetrescu et al. 2005).

2.1.2. Heat transfer analysis

When heating or cooling the bodies in the transient mode, two types of thermal resistances are highlighted: the internal thermal resistances given by the conduction process and the surface thermal resistances due to the convection between the body and the fluid it comes into contact with (Badea, 2004).

The calculation model used is described by Popescu (2003), Çengel (2003) and quantifies only turbulent convection between water and headrace.

The heat transfer rate, Φ, to or from a fluid flowing through a tube/pipe is according Eq. (3):

$$\Phi = H \times A_s \times \Delta T_{lm} = \dot{m} \times c_p \left(T_{m,out} - T_{m,in}\right) \quad (3)$$

where ΔT_{lm} is the logarithmic mean temperature difference (Eq. 4).

$$\Delta T_{lm} = \frac{\Delta T_{in} - \Delta T_{out}}{ln\left(\frac{\Delta T_{in}}{\Delta T_{out}}\right)} = \frac{\left(T_p - T_{m,in}\right) - \left(T_p - T_{m,out}\right)}{ln\frac{\left(T_p - T_{m,in}\right)}{\left(T_p - T_{m,out}\right)}} \qquad (4)$$

and T_p is the inner pipe surface temperature.

The mean outlet temperature of the fluid is given by Eq. (5):

$$\frac{T_p - T_{m,out}}{T_p - T_{m,in}} = exp\left(-\frac{P \times L}{\dot{m} \times c_p}H\right) \qquad (5)$$

Considering the conduction heat losses through the pipe material, the equation becomes (Eq. 6):

$$\frac{T_s - T_{m,out}}{T_s - T_{m,in}} = exp\left(-\frac{P \times L}{\dot{m} \times c_p}U_{eff}\right) \qquad (6)$$

The effective heat transfer coefficient is (Eq. 7):

$$\frac{1}{U_{eff}} = \frac{1}{U_{cv}} + \frac{1}{U_{cd}} = \frac{1}{H \times A_s} + \frac{1}{2\pi k_p L} ln\left(\frac{D_o}{D_i}\right) \qquad (7)$$

In the above Equations, the variables are H convective heat transfer coefficient, U_{eff} effective heat transfer coefficient, T_s soil temperature in the headrace area, P inner perimeter of headrace, and L headrace length, D_o is external diameter (outside) and D_i is internal diameter of headrace.

In order to determine the convective heat coefficient, H, the water temperature is measured, and water properties are determined from Tables. Then Reynolds (flow characteristics) and Prandtl (fluid characteristics) numbers are calculated, hydrodynamic and thermal entry lengths are determined and the appropriate correlation for Nusselt is selected. Then H is calculated.

2.2. Warm water releasing in rivers

The effect of releasing warm water in rivers is an open water area that may extend many kilometers downstream. In deep reservoirs, water temperature at lake bottom will be closer to 4°C. Generally, water released downstream has a temperature of 1-2°C. In experiences on Missouri River, by releasing warm water from Garrison Dam created an open water with length of minimum 50 km (Ashton, 1982; 2010). For a given air temperature and downstream geometry, the length of the open water is nearly proportional to the product of the release temperature and the discharge (Ashton, 2010). Heat carried per unit time by water of temperature T_w is calculated with Eq. (8): (Beltaos, 2008; USACE, 2006).

$$\Phi_w = \rho \times c_p \times Q(T_w - T_m) \qquad (8)$$

where, Φ_w = heat carried per unit time by water of temperature T_w; T_m = 0°C (32°F) melting–freezing temperature; ρ = water density [kg/m^3]; at 0°C (32°F), water density is ρ = 999.87 kg/m^3; c_p = specific heat of water [4217 J/kg°C at 0°C]; T = temperature in Celsius degrees; Q = river discharge [m^3/s]; T_w = water temperature [°C].

Even small increases in water temperature above the freezing point can stop the ice from thickening. Thus, one of the effects of warm water discharge into a cold river is to limit the ice production that otherwise might occur (Ashton, 2010).

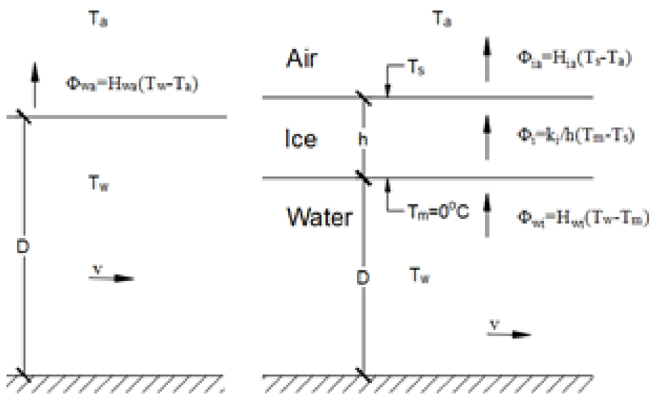

Fig. 1. Sketch for ice thickening analysis (Ashton, 1982; 2010)

The heat loss per unit area of open water surface Φ_{wa} is then given by (Eq. 9):

$$\Phi_{wa} = H_{wa}(T_w - T_a) \qquad (9)$$

where: H_{wa} = heat transfer coefficient; depends on all the variables that determine the energy budget, but is typically between 15.3 and 25.6 W/m^2 °C, with the higher values associated with higher flow speeds (USACE, 1999); T_w = water temperature; T_a = air temperature.

Once an ice cover is on top of the water, it acts as an insulator to the water, with the insulation effect increasing as the ice thickens. Since the water below is at 0°C (32°F), the heat losses are directly transformed into ice production. The heat flow through the ice (and snow) cover, may be analyzed as a quasi-steady state process such that the temperature profile in the ice varies linearly from T_m to T_s over the thickness of the ice. The heat flow by conduction through the ice is then given by Eq. (10).

$$\Phi_i = \frac{k_i}{h}(T_m - T_s) \qquad (10)$$

where: k_i = 2.21-0.011·θ [W/m °C], thermal conductivity of ice (Ashton, 2010); θ = ice temperature [°C]; h = ice thickness.

The heat loss to the atmosphere from the ice Φ_{ia} can be written similar to that from an open-water surface with T_s substituted for T_w in Eq. (9):

$$\Phi_{ia} = H_{ia}(T_s - T_a) \quad (11)$$

The heat flow through the ice equals the heat loss at the surface, so that $\Phi_{ia} = \Phi_i$, which allows T_s to be eliminated between Eq. (10) and Eq. (11) and gives Eq. (12):

$$\Phi_i = \Phi_{ia} = \frac{T_m - T_a}{\frac{h}{k_i} + \frac{1}{H_{ia}}} \quad (12)$$

The melting and thickening of the ice cover is governed by the energy balance at the water/ice interface (Eq. 13) (Ashton, 2010):

$$\Phi_i - \Phi_{wi} = \rho L \frac{\Delta h}{\Delta t} \quad (13)$$

where Φ_{wi} is the heat flux from the water to the ice (Eq. 14):

$$\Phi_{wi} = H_{wi}(T_w - T_m) \quad (14)$$

H_{ia} = heat transfer coefficient between ice and air (19.9 W/m^2 °C); H_{wi} = heat transfer coefficient between water and ice (Ashton, 2010).

$$H_{wi} = C_{wi} \frac{v^{0.8}}{D_w^{0.2}} \quad (15)$$

v = average flow velocity;
D_w = depth of water;
C_{wi} = 1622 [W s$^{0.8}$ m$^{-2.6}$ °C];
L = 3.33 x 105 [J/kg] is latent heat of fusion.

Substitution of Eq. (12) in Eq. (13) result Eq. (16):

$$\frac{T_m - T_a}{\frac{h}{k_i} + \frac{1}{H_{ia}}} - H_{wi}(T_w - T_m) = \rho L \frac{\Delta h}{\Delta t} \quad (16)$$

The potential ice melt rate is calculated with (Eq. 17) (Ashton, 2010):

$$\Delta h = \frac{\Delta t}{\rho L}\left[\frac{T_m - T_a}{\frac{h}{k_i} + \frac{1}{H_{ia}}} - H_{wi}(T_w - T_m)\right] \quad (17)$$

The formulation of Eq. (10) is based on the assumption that the temperature profile is linear in both the ice and the snow. Turbulence, heat exchange, and bed heat flux have been ignored too (USACE, 2006).

3. Results

3.1. Water warming in headrace

From engineering thermodynamics tables, the following water properties (at 0°C) were selected: density ρ = 1000 [kg/m^3], specific heat c_p = 4217 [J/kgK], thermal conductivity k_w = 0.56 [W/mK], and kinematic viscosity ν = 1.79 E-6 [m^2/s].

The dimensionless Reynolds number is:

$$Re_D = \frac{\rho \times u_m \times D}{\mu} = \frac{u_m \times D}{\nu} \quad (18)$$

and dimensionless Prandtl number is:

$$Pr = \frac{\nu}{\alpha} = \frac{\nu \rho c_p}{k_w} \quad (19)$$

Since results for Reynolds show a turbulent flow, the hydrodynamic entry length is:

$$10 \le \left(\frac{x_{fd,h}}{D}\right)_{turbulent} \le 60 \quad (20)$$

and thermal entry:

$$\left(\frac{x_{fd,t}}{D}\right)_{turbulent} = 10 \quad (21)$$

For the internal pipe diameter of D$_i$=5.1 m, the hydrodynamic entry length is 306 m ≪ 8500 m, and thermal entry length is 51 m ≪ 8500 m (Figs. 2 and 3). These results show that the entry lengths are less than 5% of the entire pipe length and thus, the water flow in the whole pipe may be considered as fully developed.

The most used correlation for internal, fully developed flow is the Dittus-Boelter equation (Eq.22):

$$Nu_D = \frac{H \times D}{k_w} = 0.023 Re_D^{4/5} \times Pr^{1/3} \quad (22)$$

from which the convective heat transfer is determined.

The water heat gain depends on pipe characteristics, both geometrical (diameter, length, wall thickness) and physical (material), soil characteristics (type, moisture content), climatic conditions (ground surface temperature variation), pipe burial depth (undisturbed soil temperature), as well as the fluid flow characteristics (mass flow rate, turbulence).

The water temperature at headrace exit ($T_{m,out}$) calculation was made for the headrace tunnels with the following parameters:

- headrace tunnel Piriul Pintei - Galu: L = 8500 m (length of headrace), D = 5.1 m (internal diameter of the tunnel);
- headrace tunnel Topoliceni - Roseni: L = 2000 m, D = 5.1 m;
- for both headraces the inlet water temperature was rated at $T_{m,in}$= 0°C. Flow rate in headrace was rated at 35 m^3/s (operation with a turbine).

Soil temperature around tunnel T_s = 8°C (Earth coverage 30-300 m).

Calculation result of water temperature for Galu outlet is $T_{m,out}$= 5.2°C, and for Roseni outlet is $T_{m,out}$= 1.8°C. The increase in water temperature is significant. Data on the Bistrita River was extracted from previous research (Boariu and Craciun, 2014; Boariu and Bofu, 2016).

3.2. Warm water downstream impact

As a first approximation, the area of open water, and hence the distance to the upstream edge of the ice cover, can be determined for low air temperatures by estimating the heat transfer coefficient and applying it to the average temperature difference between the water and the air (USACE, 2006).

The location for which the parameters of the water heating within the headrace and the downstream thawing effect were calculated is the river Bistrita, upstream the Izvorul Muntelui lake. Here are two hydropower plants, one with a 2 km headrace that has been built and one with an 8.5 km headrace that is under construction. (see Fig. 2 and Fig. 3).

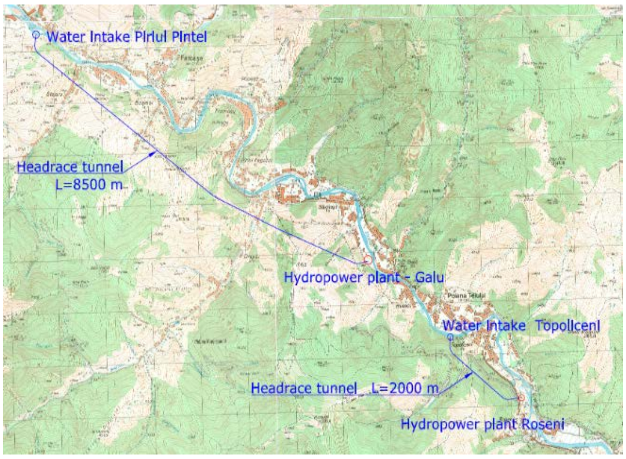

Fig. 2. Situation plan with hydropower plant on Bistrita River

Example 1 (open water)

Consider warm water discharge 35 m^3/s (one turbine function) at T_w = 2°C, T_a = -8°C, T_m = 0°C

Available heat discharge using Eq. (8) is:

$\Phi_w = \rho c_P Q(T_w - T_m)$ = 999.87 x 4217 x 35 x 2 = 295 x 10^6 W.

Open water area is:

$$A = \frac{\Phi_w}{\Phi_{wa}} = \frac{\Phi_w}{H_{wa}(T_w - T_m)} = \frac{295\text{x}10^6}{19.9(2-(-8))} = 1.48 \text{ x } 10^6 \text{ m}^2$$

For river width B = 100 m;

Result length of open water L_{ow} = 14 824 m.

Example 2 (ice cover)

Ice melt rate is calculated with Eq. (17). From the measurements and calculations performed by the authors for the Bistrita River, the parameters obtained are: h = 0.82 m; ice thickness; H_{wi} = 2.27 [W/mK]; heat transfer coefficient between water and ice, Eq. (15); v = 1.09 m/s; average flow velocity; D_w = 0.23 m; depth of water without ice.

For a water heating of 1.3°C in headrace, the ice melt rate obtained is Δh = 0.82 m/day.

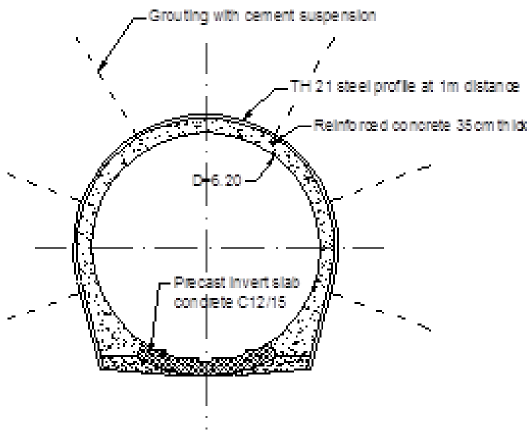

Fig. 3. Headrace tunnel Piraul Pintei - Galu section

3.3. Verification of results

The increase of the water temperature in the above calculation is significant. To check these results, we measured the water temperature at the exit of two headraces in operation.

3.3.1. Bicaz headrace tunnel, on the Bistrita River

This tunnel has the following parameters (Cojocar, 2008), (Figs. 4 and 6): D = 7.00 m, internal diameter, L = 4600 m, length, Earth coverage d = 150-200 m, soil temperature around adduction, T_s = 9°C (Earth coverage 150-200 m). The measurements at Stejaru plant were made at the end of March when the water temperature in the lake at the intake was $T_{m,in}$= 4ºC, (Chiriac et al., 1976). The operating parameters of the Stejaru Hydro Power Plant during the measurements were: Q = 36 m^3/s.

The measurements were made 2 hours after the start of operation to ensure that the water whose temperature was measured had not previously stagnated in the headrace. The measured temperature oscillated between $T_{m,out}$= 5.6-5.7°C. The temperature calculated with the model shown above is $T_{m,out}$= 6.02°C.

3.3.2. Pecineagu - Clabucet headrace, on the Dimbovita River

This headrace has the following parameters, (Cojocar, 2008): D = 3.60 m, internal diameter; L = 9750 m, length; Earth coverage d = 150-300 m; soil temperature around adduction T_s = 10.5°C (Figs. 5 and 6). The execution method for headrace is similar to NATM (New Austrian tunneling method), described by Lee et al. (2019). The measurements at Clabucet plant were made at the beginning of April, when the water temperature in the lake at the intake was $T_{m,in}$= 4ºC, (Chiriac et al., 1976). The operating parameters of the Clabucet Hydro Power Plant during the measurements were: Q = 16 m^3/s.

The measurements were made 2 hours after the start of operation to ensure that the water whose temperature was measured had not previously stagnated in the headrace tunnel. The measured average temperature was $T_{m,out}$= 10.1°C. The temperature calculated with the model shown above is $T_{m,out}$= 10.2°C. This significant heating of the water downstream of the hydropower plant can be an important parameter in establishing the river management solutions (Abdulamit and Ionescu, 2019).

Justifying the temperature of the ground taken into account.

The temperature of the earth around the headrace was evaluated from published research (Demetrescu et al., 2005; Rybach and Pfister, 1994). In Eq. (2), T_m = 7°C, the average annual air temperature for mountain area where headrace is built. In article published by Demetrescu (2005) average temperature measured for 200 m borehole depth is 10°C. Thermal gradient is 53 [mK m^{-1}], or less than 2°C/100m.

Justification of the temperatures considered for the rock massif, which the adduction crosses:

Earth coverage is 30-300 m for headrace Piraul Pintei Galu and Topoliceni - Roseni, so we considered T_s = 8°C; Earth coverage is 150-200 m for headrace Bicaz, so we consider T_s = 9°C; Earth coverage is 150-300m for headrace Pecineagu Clabucet, so we consider T_s = 11°C.

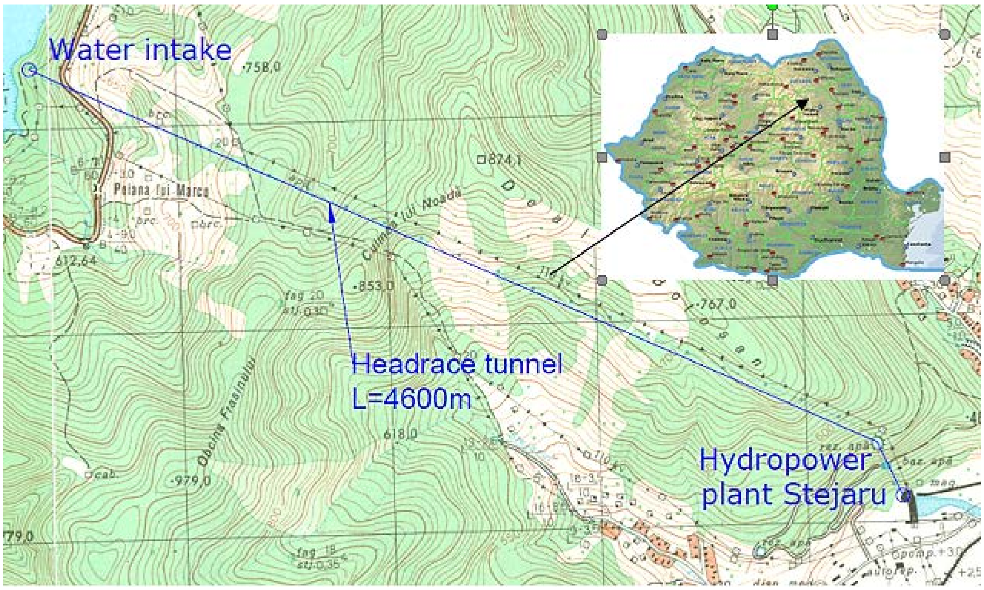

Fig. 4. Situation plan with Bicaz headrace and Stejaru hydropower plant

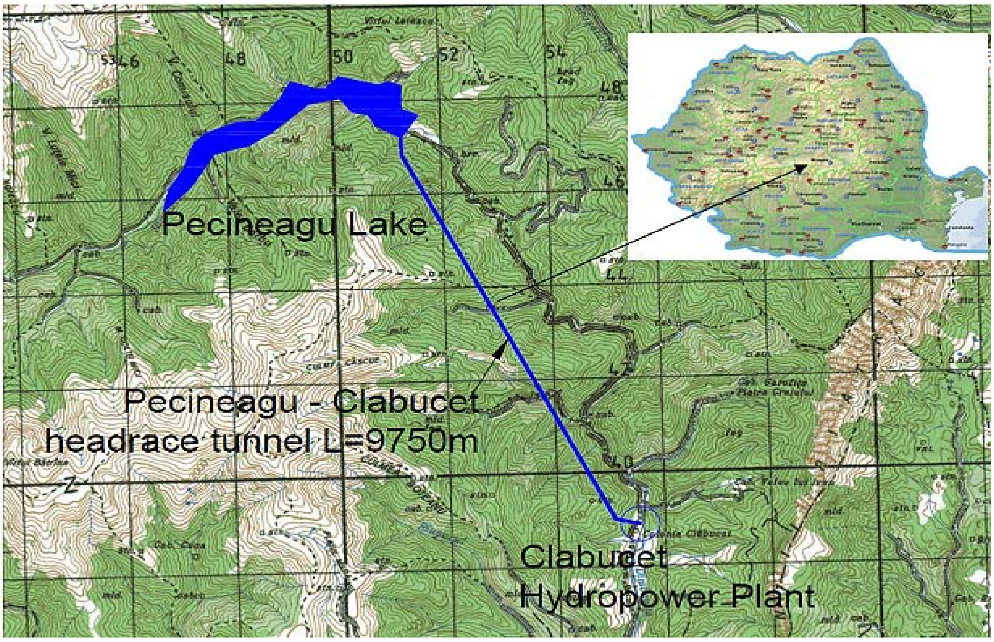

Fig. 5. Situation plan with Pecineagu-Clabucet headrace tunnel and Clabucet Hydropower Plant

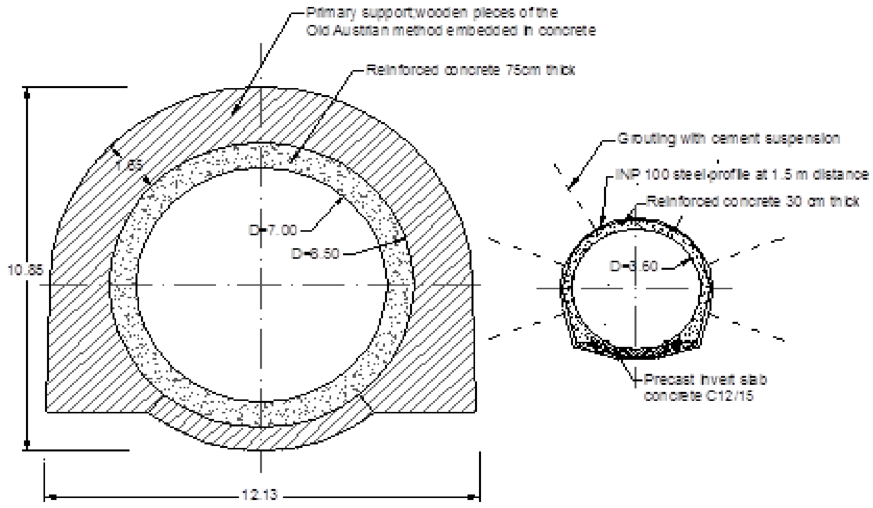

Fig. 6. Sections of Bicaz headrace tunnel (left) and Pecineagu-Clabucet headrace tunnel (right side)

4. Discussion and conclusions

This research started from the need to solve the problems caused on the valley of Bistrita, upstream of Izvorul Muntelui Lake, by the agglomerations of ice. The question was if the water can heat up when it passing through the underground headrace.

In this research the calculation methods and models used are those existing in the technical literature. The novelty is the use of the calculation model regarding the thermal transfer by forced convection. In this sense, for the water flow in an underground adduction, the thermal conditions were approximated for the situation of the constant temperature of the adduction lining and of the surrounding massif. The measurements performed at two hydropower plants in operation validated this calculation model.

The result of the calculations shows that increases of water temperature in the hydroelectric headraces Piriul Pintei-Galu and Topoliceni - Roseni are significant, of 5.2 and 1.8 degrees Celsius, respectively. Downstream spillage of this heated water would stop the formation of ice blockages. The Piriul Pintei - Galu headrace is not completed to make measurements. The Topoliceni - Roseni headrace is in operation only in summer. In winter, the accumulation of ice in the Topoliceni Lake turns off the hydro power plant Roseni. To verify the accuracy of the theoretical model, we measured the water temperature at the output of two hydropower plants with long headrace tunnels, which work during winter because they have deep accumulation lakes.

Water temperature measurements at the exit of the Stejaru hydroelectric power plant give an average of 5.65 degrees Celsius. The calculated value is 6.02°C. The temperature difference between the measurement and the theoretical value can be explained by the composition of the cross section of headrace tunnel. This tunnel was excavated by the old Austrian method, which involves the use of a lot of wood material for temporary support. At concreting a part if not all temporary support remained in the concrete. In this way the thermal properties of the concrete lining, which are otherwise close to the rocks, are changed. The pieces of wood acts as a thermal insulator and thus the transfer of heat between the earth and the water is prevented. Water temperature measurements at the exit of the Clabucet hydroelectric power plant give an average of 10.1 degrees Celsius. The calculated value is 10.2°C.

The small difference between measured and calculated temperatures is explained by tunneling technology. After concreting of the tunnel lining, boreholes were made and the rock around the tunnel was injected with a cement suspension. Therefore, the contact between the concrete and the surrounding rock becomes very good and the heat transfer to the water is better. The calculation relationships used for heat transfer from the tunnel to the water are common (known). The calculation relationships for the effect of heated water on river ice are also known.

The novelty of this research consists in the identification and validation of the calculation model for the thermal transfer between the rock massif and the water that transits the headrace tunnel. Through the measurements made, a correspondence was established between the physical and the theoretical model. We have not found in the technical literature the approach of this subject. The usefulness of this approach has been shown for a real location (Bistrita River upstream Izvorul Muntelui Lake).

Now it is possible to quantify the thermal effect of water circulation through the adductions of hydropower plants that are under construction or in the design phase and for which this result of the calculation can be a parameter to authorize, or not its construction.

The amount of heat absorbed by the water flowing in long adductions can influence also the evolution of the river from the perspective of climate change. In conclusion, the water that flows through the long underground headrace is heated sufficiently so that it melts the ice from the river downstream of the hydroelectric power plant. The water temperature that is discharged downstream can be controlled by changing the flow rate.

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