Energetic Efficiency Improvement of Hydropower Plants with Long Adduction

Nitescu Claudiu Stefan, Constantin Anca and Stanescu Madalina

Abstract—**The** energetic efficiency of a hydroelectric power plant may be increased by a compensating tank (or the large sized upper compartment) attached to the surge tank, which is used as a mean of protection for long adduction hydroelectric power plants. The compensating tank will supply the power duct with an additional flow, reducing the friction losses in the adduction pipe. The stability of the hydro-energetic system will not be influenced by the use of such a compensation tank. The paper present our investigations regarding the dependence of the efficiency on the tank diameter and on the operation time. For a reduced operation time in which a hydroelectric power plant operates (3-6 hours) a large water volume is saved. The spared water volume can be used to produce additional energy, by increasing the amount of time in which the hydropower plant operates or we can consider that for the same water volume more electric energy can be obtained from the turbine-generator system.

Keywords—Hydropower plant, surge tank, compensation tank, adduction tunnel, power duct, storage reservoir, friction losses.

I. INTRODUCTION

IN order to fully and rationally use the hydro-energetic potential of the rivers situated in a certain area, in the engineering design of modern hydropower plants, complex hydraulic schemes were used, comprising many storage reservoirs, adduction tunnels, surge tanks and power plants.

In Romania we can find several examples of operational hydropower plants provided with long adduction tunnels: Someş-Mărişelu – with an adduction tunnel that reaches a length of 8130 m; Lotru – with a 13582 m long adduction tunnel and Râul Mare-Retezat – the length of the adduction tunnel measures 18129 m.

These long adduction tunnels have high friction losses that influence and reduce the amount of energy produced by the hydropower plant. In order to decrease the influence of high longitudinal electrical resistance, the use of a compensating tank is suggested. The compensating tank can be built by improving a nearby valley. The connection can be realized by using a pipe with the same diameter as the surge tank.

C. St. Nitescu is with "Ovidius" University from Constanta, Romania; Faculty of Civil Engineering, Deparament of Civil Engineering, (e-mail: claudiu.nitescu@univ-ovidius.ro).

A. Constantin is with "Ovidius" University from Constanta, Romania; Faculty of Civil Engineering, Deparament of Civil Engineering, (e-mail: aconstantina@univ-ovidius.ro).

M. Stanescu is with "Ovidius" University from Constanta, Romania; Faculty of Civil Engineering, Deparament of Civil Engineering, (e-mail: mada_X_dobre@yahoo.com).

Maximal elevation values and the water level in the compensating tank will equal the ones in the surge tank. The compensating tank will be similar to the differential chamber. The difference is that there will be no discharge from the well to the tank and that the chamber will have a very large diameter. The height of the compensating tank is considered equal to the value of .head loss on the conduit (it can be higher when a exploitation of the tank for a larger range of water levels in the storage reservoir is expected). When operating for few hours, the hydropower plant has a discharge which consists in the compensating tank's flow and the storage reservoir's flow ($Q_T = Q_R + Q_L$). As a result, by using a compensating tank, the head losses in the adduction tunnel will decrease and higher net head values will be obtained. As a result of this situation, the flows are lower when operating at a constant power. The situation is comparable to the previous case. The introduction of this system, upstream the protection means, does not influence the stability of the hydro-technical system, because the surge tank is sized to provide the best conditions for the exploitation of the hydro-energetic system and placed in order to turn the hydraulic shock from the power tunnel into mass oscillation. The diameter of the surge tank should not be modified. This conclusion was also drawn after the section of the surge tank in complex layouts was determined.

When functioning during the time slot corresponding to the maximum energetic consumption of the hydropower plant (for a reduced interval of about 3-6 hours), large volumes of water are spared. If the hydropower plant is used during larger amounts of time, the hydro-energetic system can operate with no problems owed to the utilization of the surge tank, whose efficiency decreases along with the increasing of the time interval in which the plant is being used. After the full consumption of water volume in the compensating tank, the hydro-energetic system will function as it would have normally functioned without the compensating tank. When the hydropower plant is turned off and the water level in the surge tank is stabilized, the compensating tank's filling process begins. The filling time interval varies depending on the interval in which the compensating tank is functional and on its diameter. Therefore, after the compensating tank is filled the running cycle can be restarted. If a utilization of the hydropower plant before the filling of the compensating tank is expected, then the hydro-energetic system can be turned on. The efficiency of the compensating tank will be reduced, but comparing to the normal situation there will be a spared water volume proportional to the filling degree of the compensating tank.

II. PROBLEM FORMULATION

A. General Situation

When functioning during the time slot corresponding to the maximum energetic consumption of the hydropower plant (for a reduced interval of about 3-6 hours), large volumes of water are spared. If the hydropower plant is used during larger amounts of time, the hydro-energetic system can operate with no problems owed to the utilization of the surge tank, whose efficiency decreases along with the increasing of the time interval in which the plant is being used. After the full consumption of water volume in the compensating tank, the hydro-energetic system will function as it would have normally functioned without the compensating tank. When the hydropower plant is turned off and the water level in the surge tank is stabilized, the compensating tank's filling process begins. The filling time interval varies depending on the interval in which the compensating tank is functional and on its diameter. Therefore, after the compensating tank is filled the running cycle can be restarted. If a utilization of the hydropower plant before the filling of the compensating tank is expected, then the hydro-energetic system can be turned on. The efficiency of the compensating tank will be reduced, but comparing to the normal situation there will be a spared water volume proportional to the filling degree of the compensating tank.
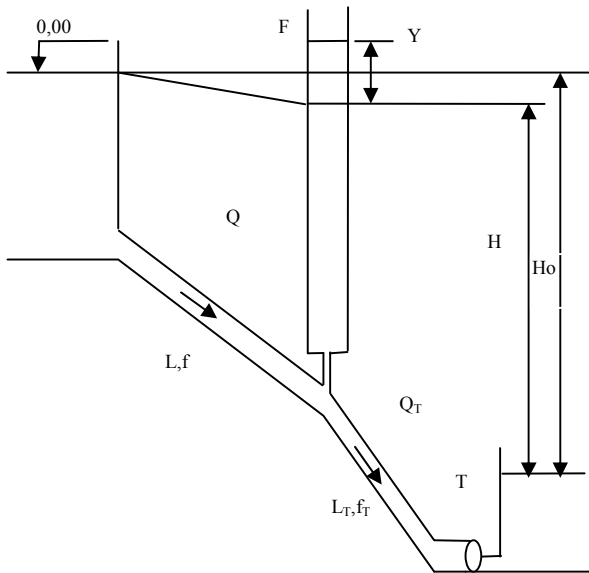

Fig.1 The layout design of a hydropower plant

Where L – length of the adduction tunnel;
W – water speed in the tunnel;
Z – water level in the surge tank;
P' – longitudinal head loss coefficients in the tunnel;
V_s – water speed in the throttling duct of the surge tank;

F – area of the horizontal section of the surge tank;
f – area of the adduction tunnel section;
Q_T – flow rate;
t – time;
g – acceleration due to gravity.

Differential equations of the tunnel-surge tank system oscillations are written in a simplified form for the hydropower plant in Fig.1, [5], [6], [8], [19], [20]:

$$\frac{L}{g}\frac{dW}{dt} + Z + P'W|W| = 0 \tag{1}$$

$$Wf = F\frac{dZ}{dt} + Q_T \tag{2}$$

Where the following notation was used

$$P' = \left(\lambda\frac{L}{d} + \sum\xi\right)\frac{1}{2g} \tag{3}$$

where λ-Darcy's friction coefficient;
ζ-local head loss coefficient.

And the flow is governed by relationship (4) which corresponds to the automatic running of the plant at constant power.

$$N = \eta\gamma Q_T(H + Z) = \eta\gamma Q_0 H_0 = const \tag{4}$$

where η-efficiency;
N-power.

By removing the variables Q and Q_T results

$$\frac{LF}{gf}\frac{d^2Z}{dt^2} + \frac{k}{2g}\left|\frac{dZ}{dt} + \frac{N}{\eta\gamma F(H+Z)}\right|\left(\frac{dZ}{dt} + \frac{N}{\eta\gamma F(H+Z)}\right) -$$
$$- \frac{NL}{\eta\gamma gf(H+Z)^2}\frac{dZ}{dt} + Z = 0 \tag{5}$$

where

$$k = \left(\lambda\frac{L}{d} + \sum\xi\right)\frac{F^2}{f^2} \tag{6}$$

With the sole result given by the initial conditions
$$t = 0 \rightarrow Z = Z_0$$

$$\frac{dZ}{dt}\bigg|_0 = \frac{f}{F}W_0 - \frac{N}{\eta\gamma F(H + Z_0)} \tag{7}$$

We write the differential equation of the volume fluctuation for the compensation reservoir equation derived from the differential equation of fluctuations for the surge tank .

$$\frac{LF}{gf}\frac{d^2Z}{dt^2} - \frac{NL}{\eta\gamma gfH^2}\frac{dZ}{dt} + Z = 0 \tag{8}$$

That represents a second degree differential equation with homogeneous and constant coefficients.

For the initial situation, without compensating tank, total power N is given by the formula:

$$N = \eta \gamma \; Q_T H \tag{9}$$

Where $\quad H = H_0 - h_r = H_0 - z$

$$h_r = \frac{8\lambda \; LQ_T^2}{g\pi^2 d^5} \tag{10}$$

For the situation in which a compensating tank is involved

$$Q_T = Q_L + Q_R \tag{11}$$

Where

$$Q_L = \frac{\pi \; d^2}{4} \sqrt{\frac{2gdi}{\lambda}} \tag{12}$$

$$i = \frac{h_r}{L} = \frac{z}{L} \tag{13}$$

$$Q_T = \frac{N}{\eta \gamma \; H_R} \tag{14}$$

$$H_R = H - h_r = H - z \tag{15}$$

$$Q_R = Q_T - Q_L \tag{16}$$

The spared water volume while using the compensating tank V_*

$$V_* = V - V_R - V_L \tag{17}$$

The additional equivalent time due to a compensation reservoir mounted on the Lotru powerplant (corresponding to the spear water volume V_*).

$$t_\bullet = \frac{V_*}{Q_T} \tag{18}$$

The gained amount of energy is given by the relation:

$$E = N \cdot t_\bullet \quad \text{(MWh)} \tag{19}$$

Efficiency

$$\varepsilon = 100 - \frac{V_L + V_R}{V} \cdot 100 \quad \text{(\%)} \tag{20}$$

The stability of the fluctuations is assured if the section of the surge tank is higher than [2], [3], [4], [10].

$$F_{min} > \frac{L_1 Q^2}{2gf_1 h_r H} \tag{21}$$

B. Case Study

Lotru hydropower plant, situated in the northern part of Oltenia, is the largest hydropower plant built on an inland river in Romania, having an installed c capacity of 510 MW at a head of over 800 m. The main adduction tunnel measures 13.582 km in length and has a diameter D = 5 m; the surge tank D_{CE}=7.60 m with compartments, internal overflow and ground hydraulic resistance; the power tunnel has a length of 1.3 km and a diameter of 4 m; the underground plant is provided with three Pelton turbines with vertical shaft of 170 MW each; the spillway tunnel is 6.5 km long and has a 5.35 m diameter [7], [12], [18].

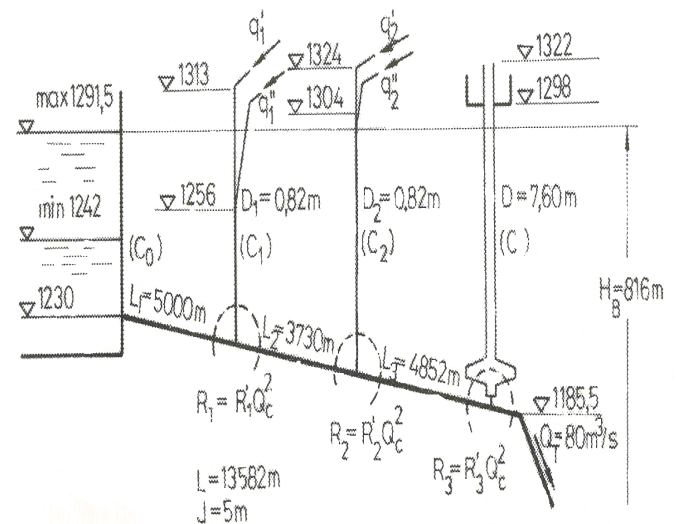Fig.2 LOTRU Power Plant. Underground hydroelectric power plant

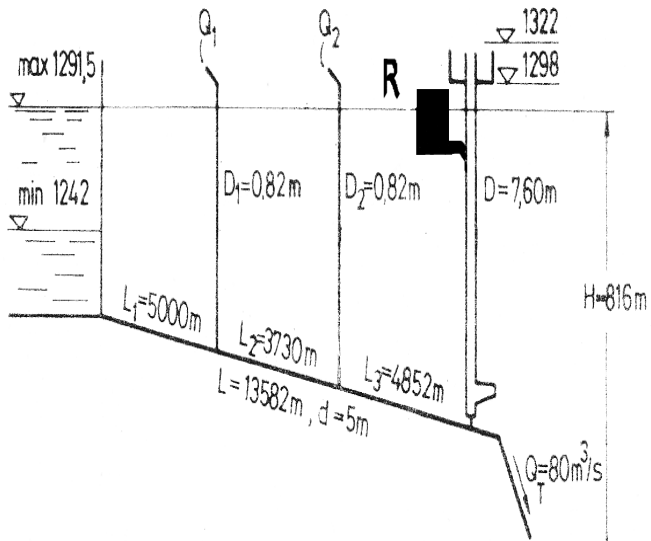Fig.3. Lotru hydropowerplant. Hydraulic layout

Fig.4 Lotru hydropower plant equipped with compensating tank

A compensating tank placed at the upper part of the surge tank is considered, Fig.4. The diameter of the connection piece is 7.60 m (the same as the surge tank's diameter), the connection being placed under the upper chamber at the nominal level. Calculations will be done for a diameter of the compensating tank comprised between 250 m and 1000 m [9], [10].
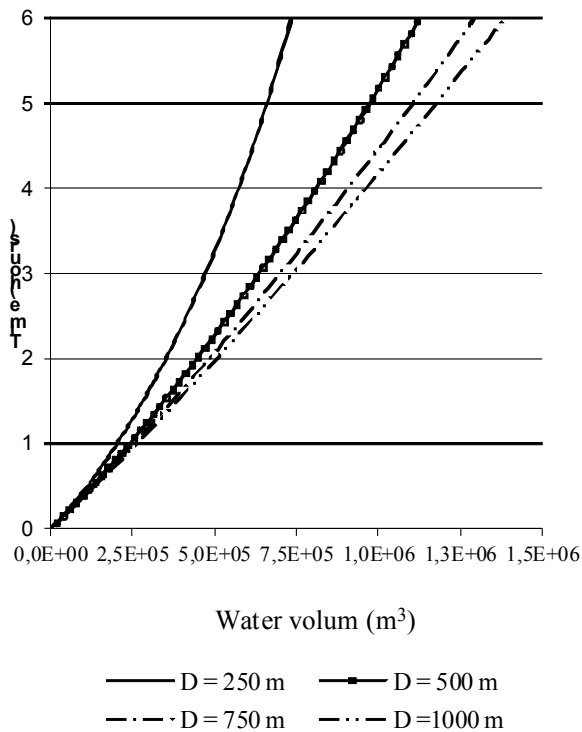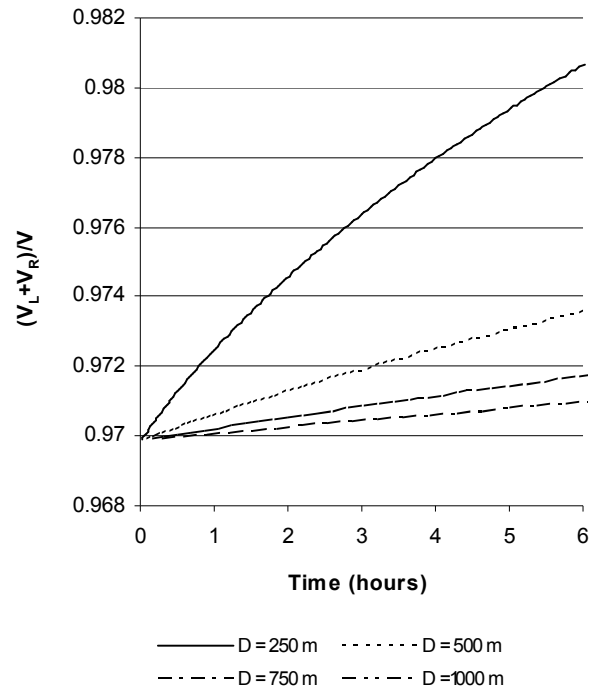

Fig. 6 Ratio of water volumes: with and without compensation, calculated for up to 6 hours operation of Lotru hydroelectric plant

Fig.5 The compensation tank water volume corresponding to 6 hours operation of Lotru hydroelectric plant
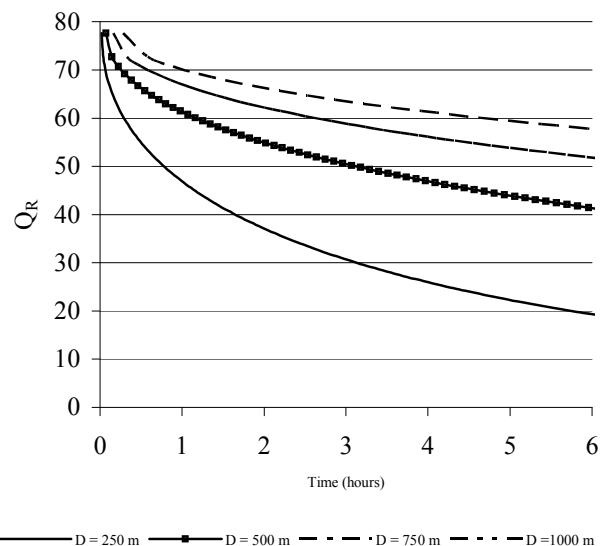

Fig.7 Compensation flow rate during 6 hours operation of Lotru hydroelectric plant

The maximum water level in the storage reservoir is 1291.50 m, and the minimum level is 1242 m. We can consider a 25 m height of the compensating tank, value that equals the head losses in the tunnel. This height can assure the functionality of the hydropower plant for 24 hours up to a reasonable efficiency.

Calculations will be done for a running cycle of maximum 6 hours. Afterwards the plant is going to be turned off for a while.

Building a compensation tank by following the Lotru hydropower plant example yields the advantage of substantial water volumes saving, directly proportional to the increase of tank's diameter. We note a substantial growth in the efficiency of water saving for the range of 250 – 500 m for the tank's diameter, as shown in Fig.8. For the following dimensions, 750 m and 1000 m, although the diameter is longer, the efficiency is considerably reduced. Therefore, the increase of the diameter of the compensating tank while the hydropower plant is running for a reduced number of hours (during the maximum energetic consumption time) does not achieve a substantial proportional increase of efficiency and of water saving.
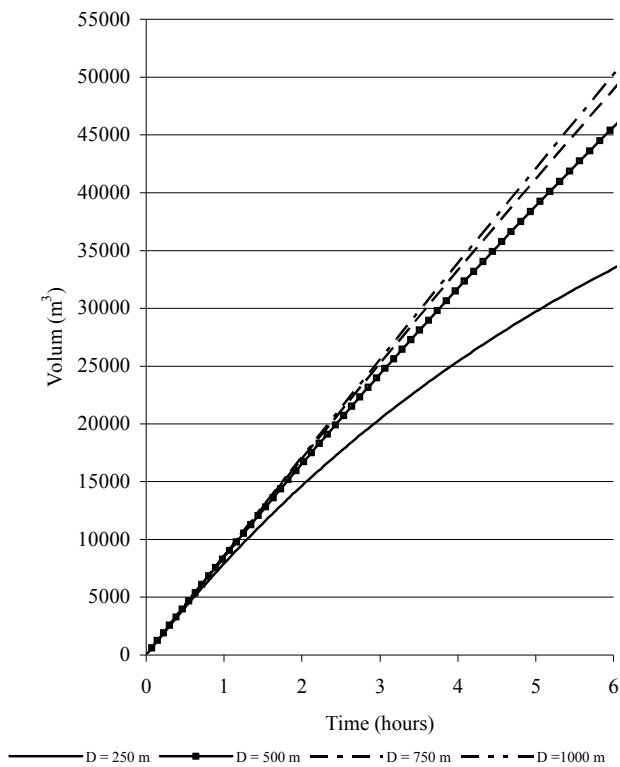

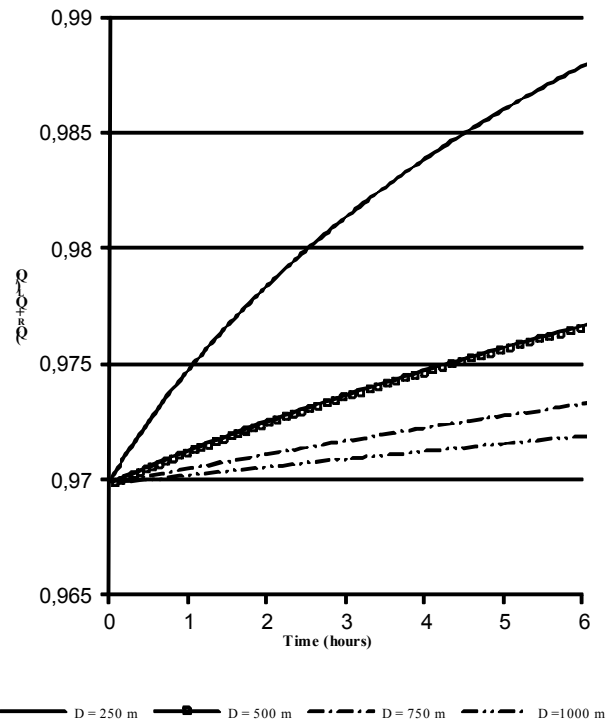Fig.9 Ratio of water flow rates: with and without compensation, calculated for 6 hours operation of Lotru hydroelectric plant

Fig.8 Water volumes gained from using compensation reservoir
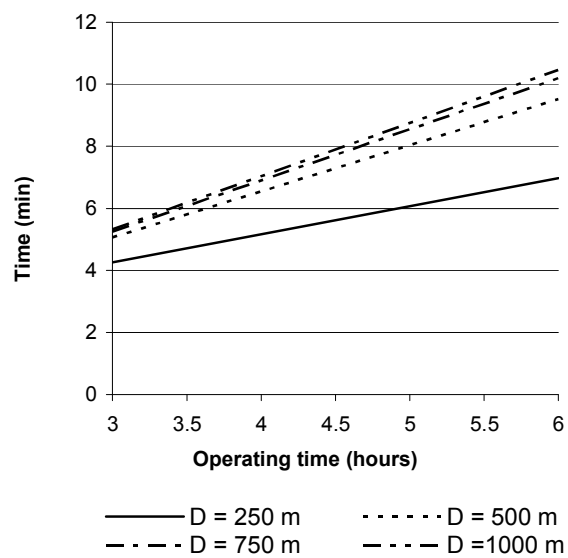

Fig.10 Equivalent time won by compensation during 6 hours of Lotru hydroelectric plant operation
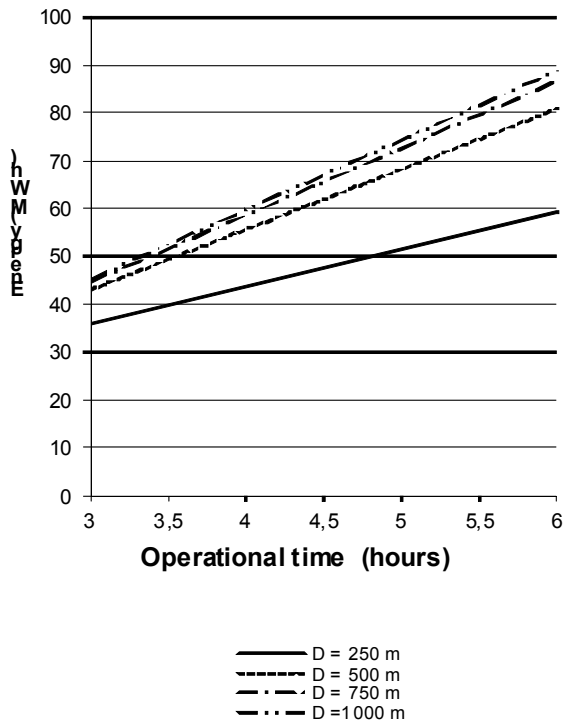
Fig.11 Equivalent energy gained from using compensation reservoir

Speaking of 6 hours operation time, the efficiency increase for each value of tank's diameter is as follows:

D_R=250 m, $\mathcal{E}$=1,935% ;
D_R=500 m, $\mathcal{E}$=2,643% ;
D_R=750 m, $\mathcal{E}$=2,825%;
D_R=1000 m, $\mathcal{E}$=2,905% .

If we consider the efficiency for a 250m diameter tank as a reference value, we find the following efficiency gain due to a greater value of the tank diameter:

$$\frac{D_{500}}{D_{250}} = 2 \longrightarrow \mathcal{E}_{500} - \mathcal{E}_{250} = 0{,}708\%$$

$$\frac{D_{750}}{D_{250}} = 3 \longrightarrow \mathcal{E}_{750} - \mathcal{E}_{250} = 0{,}89\%$$

$$\frac{D_{1000}}{D_{250}} = 4 \longrightarrow \mathcal{E}_{1000} - \mathcal{E}_{250} = 0{,}97\%$$

For a 250 m in diameter compensation tank, the ratio of gained water volume to the initial volume used by the turbines calculated as a function of power plant operation time shows a decreasing slope ($V_{*(6h\text{-}3h)}$=0,428%). For the next diameter values, the slope is also decreasing, but more slowly. This ratio becomes almost constant in the case of a compensation tank of 1000m in diameter ($V_{*(6h\text{-}3h)}$=0,052%), Fig.6.

The water volume gained by the use of the compensation method can be converted in electric energy. Although, the additional operation time is relatively short, consistent values of electric energy are obtained, in accordance with the power plant performance.

Table 1 Extra energy due to compensation tank, for 3 hours operation

D_R	Operational Time 3 hours		
	V_* (m^3)	E (MWh)	%
D_{250}	20418,94	36,15	2,36
D_{500}	24290,43	43,01	2,81
D_{750}	25210,77	44,64	2,91
D_{1000}	25562,00	45,26	2,95

Table 2 Extra energy due to compensation tank, for 6 hours operation

D_R	Operational Time 6 hours		
	V_* (m^3)	E (MWh)	%
D_{250}	33445,48	59,22	1,93
D_{500}	45677,45	80,88	2,64
D_{750}	48932,81	86,65	2,83
D_{1000}	50226,48	88,94	2,90

By functioning for 3 hours, with diameters between 250 m - 1000 m, 36-45 MWh additional energy is acquired, and by running for 6 hours, the hydropower plant achieves 59 – 89 MWh (which represents a 7-8.82 % increase and 11.50-17.45% increase for the second situation).
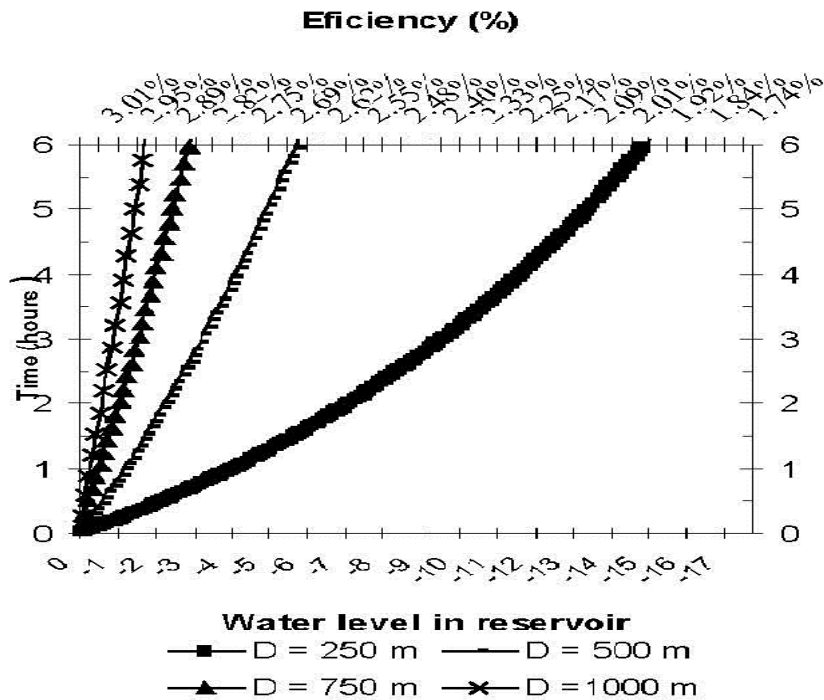
Fig. 12. Synthetic diagram of efficiency improvement as a function of operation time and water level in the tank

The diagram presented in Fig.12 is a synthesis of the above mentioned amounts, showing the interdependence between them. The diagram is dedicated to the engineering design activity, offering a first image to the sizing variants. The dimensions of the compensation reservoir, diameter and height, might be chosen according to this diagram and to the terrain characteristics, in order to obtain an increased efficiency.

III. CONCLUSION

The resulting water volumes can be used to obtain electric energy; even if the additional time in which the hydropower plant will run with this water volume is reduced, substantial quantities of electricity are achieved due to the distinctive features of this type of hydropower plant.

We may notice, an enhanced increasing of water volume saved due to the increase of the tank diameter from250 to 500m. The next range for the diameter, between 750m and 1000m the saving efficiency is considerably lower, even if the diameter value is greater. Thus, we may conclude that the increasing of the compensation reservoir diameter doesn't lead to a proportional increasing of water volume saving efficiency, when we refer to a reduced operation time (during the maximal power consume).

According to the hydraulic features of the power plant, as well as to its emplacement the diameter of the compensation tank may be chosen in such a way the resulting efficiency to be maximal.

Furthermore, the operation timetable of the power plant is of great importance because the maximal efficiency might be obtained only if the compensation tank filling period is achieved.

Calculation were done for an operation time of the power plant up to 6 hours, but the maximal efficiency is obtained for a shorter operation time i.e. 2-3 hours, because the water level in the tank is kept close to its maximal value. This shorter duration covers the period of maximal power consume.

It isn't necessary to build a high compensation reservoir, but its height has to cover the medium operation water levels.

The additional energy achieved this way is similar to the quantity produced by smaller hydropower plants from Romania.

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Claudiu Stefan Nitescu was born in Constanta, Romania, in 1973. He graduated the Faculty of Civil Engineering, "Ovidius" University, Constanta, in 1998, becoming a hydraulic structures engineering. He took his PhD in Civil Engineering at the same university, in 2006. Since 1999 he has been teaching at the Faculty of Civil Engineering, "Ovidius" Constanta, from Constanta.

Chief Assist. Prof. Nitescu published 35 scientific articles. His scientific interest is in fluid mechanics and water supply.