

Improper management of dams constructed with local materials, infiltration risk and wasted electric energy

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Abstract. The present paper presents a study case of improper dike rehabilitation and inefficient management of the water volume from two hydropower lakes, with dams built with local materials. In Romania, with its high hydrographic potential, this solution was adopted for construction of more than 600 hydropower plants, many of them now confronted with infiltration and erosion, and appeared into lateral sides of the dikes. The paper covers some theoretical and practical aspects referring to the functioning of hydropower lakes, establishing the cross-sections with problems in exploitation. Reduced water level produces less electric energy than initially estimated. The dam's construction was not correlated with the geomorphologic conditions and climatic parameters, being necessary supplementary measurements and data acquisition to calibrate the numerical model. There are mentioned some considerations referring at the mathematical model, based on new hypotheses of infiltration through sediments with different dimensions and characteristics. The flow through dikes is assumed non-permanent due to massive infiltration. Part of the numerical modeling, the obtained velocities of infiltration, and the streamlines are illustrated. The results of the tested solution prove its efficiency and allow illustrating and some other sections with possible risk in functioning. Some discussions, conclusions, and references are finally presented.

1 Introduction

It must be mentioned that nowadays, nationwide, there are 636 dams constructed realized from local materials, among which the analyzes made in the last four years have revealed a number of shortcomings, as follows:

- 134 dams have concrete damaged tiles;
- 69 dams present infiltration into the dam's body and into the lateral dikes;
- 143 dams have erosion through dams at access roads and pears;
- 186 dams have blocked the bottom of the emptying zone with major defects in the water discharge area, or are not equipped with surge arresters surfaces;
- 21 dams have flaws nowadays not functional;

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- 35 dams have the basin's reservoirs filled with sediments, with 60% clogging rate;
- 63 dams are abandoned, without legal documentation;
- 5 dams are proposed to be listed for abandonment in near future [1].

One of the most serious problems mentioned before is the infiltration through dams and dikes, the erosion through dams, access roads, breaches in dams and the clogging of lakes [1]. From all the mentioned hydropower systems, about 270 have major problems.

These issues have diminished the payload, with immediate effect a decreasing of the produced electricity. A report of the appeared problems for some dams is presented in Table 1.

Table 1. The actual situation of the dams with problems in Romania.

HB	ND	DT	I	ESP	PD	DD	CL	A	D
Someş – Tisa	33	21	5	3	3	0	1	0	0
Crişuri	31	6	4	9	22	0	0	0	0
Mureş	10	6	0	1	1	1	1	0	0
Banat	1	0	0	0	0	0	1	0	0
Jiu - Dunăre	4	0	0	1	1	0	2	0	0
Olt	45	19	6	8	11	0	1	1	0
Argeş – Vedea	119	24	18	43	29	0	0	1	4
Buzau-Ialomita	28	0	0	3	17	0	0	7	1
Siret	76	15	17	2	23	0	9	19	0
Prut - Bârlad	285	43	19	71	79	20	18	35	0
Dobrogea – Seaside	4	0	0	2	0	0	2	0	0
TOTAL	636	134	69	143	186	21	35	63	5

Where: HB- Hydrographic Basins, ND- Number of Dams, DT- Damaged Tiles, I- Infiltration, ESP- Erosion Slopes Pears, PD- Problem Discharging, DD- Damaged Dams, CL- Clogged Lakes, A- Abandoned, D- Decommissioning

The analyzed dams, confronted with infiltration problems in this paper are located on river Crisul Repede on the western slopes of the Apuseni Mountains.

2 Calibration, elaboration of the initial experimental database

The physical and geographical natural unit traversed, the terrain, and the morphological structure of the sediments are conditions of water distribution and the flow regime for the rivers from the basin Cris.

These sediments are the main resource of dams structure. The Apuseni Mountains are distinguished by a greater amount of rainfall compared to other regions with similar altitudes in Romania, due to the west exposure. The average value of precipitation is over 1400 mm/year. In the proximity of the analyzed lakes, it can reach at 30-35 l/s/km², due to the mentioned amount of rainfall, sharp slopes of drain zone, and the petrographic substrate, generally impermeable.

Since the commissioning, the level of the free surface in these two cascade lakes was reduced with 8 m and 9 m respectively, due to permanent infiltration through dikes. As immediate effect was, less electric energy produced. Under these circumstances, the lakes are not able to manage the excess of water appeared during floods as it was in 1999, 2000, 2001, 2002, 2005, 2008, and 2012 (years 2005 and 2008 with massive floods). The maximum flow rate, with 1% insurance can be achieved in Oradea on Crisul Repede, at 970 m³/s and the minimum value, with 80% insurance (period of April-November) at 1.60 m³/s. Some of the registered data are presented in Table 2.

The annual average flow of alluvial deposits in suspension is 3.5 kg/s into the post Salard, 7.5 kg/s in Oradea and 6 kg/s in Zerind post.

Table 2. Water flow rate required to be transported through lakes.

Hydro station	Main Flow rate (m ³ /s)	Minimum Flow rate (m ³ /s)	Maximum Flow rate (m ³ /s)
Vadu Crisului	19,60	0,71/24.11.1972	780/04.2005
Oradea	23,10	0,81/19.12.1953	820/04.1932

The specific annual average leakage of silt in suspension is below 0.5 tons/ha /year in the flat regions and between 0.5- 1.0 tons/ha/year in the hills and mountains with low altitudes. The higher values of leakage in hillside areas can be explained by the presence of the petrographic layer, easier to be eroded. In Table 3 are presented the most important climatic data and in Table 4 the main characteristics of the lakes.

Table 3. The climatic data.

Average annual precipitation	Mountain area - 1600 mm/year
	Hill area - 550-600 mm/year
Average temperature	Mountain area - 4 ⁰ C
	Hill area + 10 ⁰ C

Table 4. The main characteristics of lakes.

Lakes	Volume (mil. m ³)	Used flow (m ³ /s)	Discharged Flow (m ³ /s)	Bottom drain
Lake 1	33768	12,3	0,1	2
Lake 2	44039	10,1	0,14	2

The values mentioned in Table 4 were determined by the National Authority "Apele Romane - Cris", in collaboration with the Environmental Protection Inspectorate Bihor. Consequently, the development of the hydropower system realized along the river Crisul Repede has been finished with the construction of 7 hydropower plants with an installed power of 208 MW, 5 dams, and over 34 km of main and secondary headrace. The dam's realization was accomplished in '80, followed shortly by infiltration through dikes. In Figure 1 are presented the appeared infiltration.



Fig. 1. Infiltration through dikes, a - Lake 1, b - Lake 2.

Due to permanent infiltration, new analysis and rehabilitation are necessary. The purpose of this paper is to establish the actual cross-sections with problems when the lakes are full of water, responsible for infiltration and, if possible to determine also the future risk zones.

3 Mathematical model

Starting from the general equations for underground flow, deduced from the general flow motion for a real fluid [2]:

$$\frac{dv_x}{dt} = X - \frac{1}{\rho} \frac{\partial p}{\partial x} + R_x; \quad \frac{dv_y}{dt} = Y - \frac{1}{\rho} \frac{\partial p}{\partial y} + R_y; \quad \frac{dv_z}{dt} = Z - \frac{1}{\rho} \frac{\partial p}{\partial z} + R_z \quad (1)$$

Where v_x, v_y, v_z are the velocity components, X, Y, Z the components of the unitary mass force, and R_x, R_y, R_z the components of the friction force on the mass unit, we may deduce the velocity for the underground flow.

If the mass forces are only the gravity, $X = 0, Y = 0, Z = -g$, and introducing the hydraulic load $h = z + \frac{P}{\gamma}$ the equations (1) become:

$$\frac{dv_x}{dt} = -\frac{\partial h}{\partial x}; \quad \frac{dv_y}{dt} = -\frac{\partial h}{\partial y}; \quad \frac{dv_z}{dt} = -g \frac{\partial h}{\partial z} \quad (2)$$

For the underground unsteady flow [3], the velocity components are deduced from the Darcy's Law, where k is the permeability:

$$v_x = -k \frac{\partial h}{\partial x}; \quad v_y = -k \frac{\partial h}{\partial y} \quad (3)$$

Based on continuity equation for the considered volume, the Boussinesq equation became:

$$-\frac{\partial}{\partial x} \left(Hk \frac{\partial h}{\partial x} \right) - \frac{\partial}{\partial y} \left(Hk \frac{\partial h}{\partial y} \right) + m \frac{\partial H}{\partial t} - \varepsilon = 0 \quad (4)$$

Where is the flow rate that supplies from the free surface the underground flow [4], H the distance between the impermeable layer and selected area for calculation from the underground water surface, and m the porosity. In Figure 2a are presented the main parameters, and in Figure 2b the main aspect of the underground water flow through the dike.

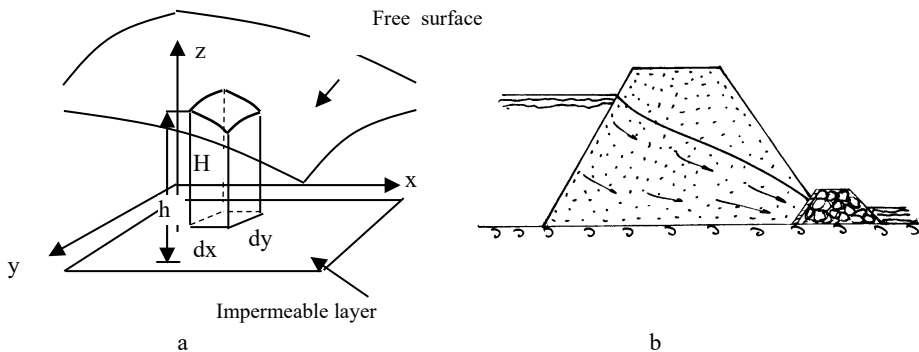


Fig. 2. The scheme of underground water flow.

The double/multiple porosity model is a quite flexible tool to treat cases where a porous matrix and one or more families of continuously distributed fractures are present. It is supposed that the Reynolds number in porous spaces is small enough so that the non-linear terms in the Navier-Stokes equations can be neglected. The model was for the first time described for fractured rocky aquifers with a porous matrix, by assuming two pressure fields locally (one for pores and one for fractures) as well as the validity of Darcy's law in

- the flood flow, $Q = 472 \text{ m}^3/\text{s}$;
- the flow of danger: $Q = 567 \text{ m}^3/\text{s}$.

Table 5. The analyzed sections and their length.

Section type	Length on top	Up stream	Down stream	Applied length [m]	
				Left/Right size	
15m < H < 27m	6,00	0,48	0,08	2627	1827
7.5m < H < 15m	6,00	390	255	2700	3600
2.5m < H < 7.5m	4,00	0,18	0,02	1850	1050
H < 2.5	4,00	13	8	890	546
			Total length	8067	7023

There are analyzed two cases of cross-sections considered significant, discretized in finite elements:

- Case A- with mud lens and screen of protection partially embedded in bedrock;
- Case B - without a screen of protection (as it is nowadays on the right side in Lake 1).

Each color is associated with a specific permeability. The numerical modeling confirms the measurements. The downstream shore is discontinuous, consisting of fine sand, medium rare gravel, sandy clay loam sands-profit, lens mud, and vegetal elements.

The material structure is bedrock with alternative marl, clay marl, and tuff fine sands. The dam is filled with local material, being of two types:

- type I, a material less permeable, made up of ballast and ballast mixed with sterile, proportion 2: 1, used in the core, trapezoidal large-section;
- type II, a material more permeable, made up of clean ballast, used on the periphery of the nucleus from the type I, for upper side, front and foundations.



Fig. 4. The dam discretization in cross-sections, a- Case A and b - Case B.

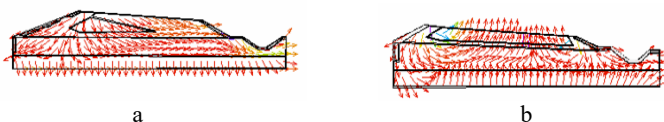


Fig. 5. Distribution of velocity through dikes, a - Case A and b - Case B.



Fig. 6. The stream lines in cross-sections, a - Case A and b - Case B.

First was modeled the effect of the imperfect screen, because it was realized in an area of closure of the natural bed, which do not fit perfectly in bedrock. The underground hydrodynamic flow was modeled with successive steps by increasing the permeability coefficient in the areas where the hydraulic gradients exceed the allowable values. By local measurements was determined in 7 places the occurrence of the muddy lens compacted, with low permeability [8]. Their position was specified by geological correlations and their permeability was chosen correspondingly, $k = 10^{-5} \text{ cm/s}$.

There are zones with streamlines concentration, so the local speeds are quite high, making possible the transport and for others particles, with larger sizes.

It was also considered the effect of the rainfall, with a medium value of 10-20 mm and the drainage factor of 15%. It brings a supplementary contribution to the output gradients, but the depression curve does not change fundamentally. The changes in the hydraulic gradient distribution from the dam structure, and sometimes the local concentration of the streamlines and additional spacing in other areas proved that there are zones inside the dam with infiltration and erosion and areas with sedimentation and clogging. The dam's behavior, a consequence of the improper execution has as result in decrease of the free surface water level, as to maintain and control the infiltration, in both lakes with 8 m and 9 m respectively. The negative effect is summarized in Table 6.

Table 6. The actual situation in analyzed lakes.

Lakes	Situation	Volume (mil. m ³)	Area (ha)	Produced energy (MW)
Lake 1	initial	52,768	605,7	30
	actual	41,810	520,3	18
Lake 2	initial	44,039	510,1	30
	actual	30,420	408	18

5 Conclusions

The non-uniformity of the used material, the screens performed incorrectly, or with major cracks with improper embedding in bedrock, the presence of the irregular lenses of mud in the base material of the dams, and the irregular shore of concrete, has as result apparition of preferential areas of water circulation through dikes and dams.

The obtained numerical results confirm the reality, massive infiltration and supplementary, pointed some new sections with future risk of erosion. The existence of some large fractions of material ensures some stability in the global and local pier. The spectrum obtained presents a hydrodynamic lift, irregular of the depression curve depending on the configuration and spatial distribution of the muddy lens. By analyzing the critical gradients values obtained by numerical modeling, it is obviously evident that nowadays are met the conditions to move fine fractions of sediments, both at entry and exit. An additional screen embedded in bedrock is the only possible solution.

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