The Problem of Water Leakage in Beni Haroun Reservoir (Algeria)

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ABSTRACT

During the last 25 years, Algeria witnessed an intensified drought. Thus, to meet the growing demand for water, especially in peak hours and hot weathers (summer season), more than sixty (60) large water storage dams have been founded to overcome the problem. They help collect a considerable amount of surface water falling in their watersheds. Unfortunately, it has been noticed that these structures are exposed to some hydraulic problems, such as: silting, evaporation, water pollution and water leakage. This latter threatens both the stability of the hydraulic infrastructures and the quality and quantity of the stored water.

This study examines the phenomenon of water leakage at Beni Haroun dam. It is based on the measurements performed on leakage flow, hydraulic head and water level in the lake. The study aims at suggesting ways to protect the dam from the consequences of the threats mentioned earlier. Then, before being too late, it provides the consolidation work needed to be undertaken. In this respect, findings obtained potentially revealed that, over time, the flow of water leakage increases as same as the elevation of water level in the lake of the dam. On the one hand, it is found that the current lines on the right side of the groundwater, located downstream of the dike, headed to the opposite direction of the expected flow (upstream) and then moved downstream. In addition, the same magnitude has been observed on the pressure regardless of the water level. On the other hand, however, those on the left side vary according to the hydrostatic charge created by the lake and are generally directed downstream of the dike. The recorded pressure at this bank is low. This justifies the appearance of resurgences which minimize the under-pressure downstream near the dike.

KEYWORDS: Beni Haroun dam, Underlying structure leakage, Groundwater loss.

INTRODUCTION

Algeria has 70 reservoir dams with a total volume of 7 billion m³. The majority of these dams are used for irrigation and drinking water supply. However, they face three problems of capacity reduction. These are: silting, evaporation and infiltration. Siltation is annually causing a capacity loss of 45 million m³ following the successive deposits of sediments on the foundations of the dams (Remini et al., 2009). Evaporation from dam lakes is a phenomenon that reduces the capacity of dams. It was estimated that the value lost by evaporation amounts to 250 million m³ per year (Remini, 2005). As for the phenomenon of infiltration, the estimated volume lost by leakage through the banks and foundations of dams amounts to 40 million m³ per year (Remini et al., 2009). However, there are 4-5 dams which record extremely high annual leaks. Ouizert dam, with a capacity of 100 million m³, is intended to increase the regularisation of Oued El-Hammam for supplying water to the city of Oran, the Arzew industrial complex and irrigation of the perimeters of El-Habara.
However, seepage through a dam of the banks recorded a leakage rate of 1 m$^3$/s; an extremely high value (Benfetta and Remini, 2008). The dam of Foum El-Gherza with a capacity of 47 million m$^3$ is located in the region of Zibans, the desert door. The dam is for irrigation of 300,000 date palms threatened by the infiltration of water through the two banks. It loses an annual volume of 5 million m$^3$ (Remini et al., 1999).

Beni Haroun dam is considered the largest dam in Algeria, since its capacity is around 1 billion m$^3$ of water. It is intended for the drinking water supply of 7 provinces in the east. Just after it was operated in 2005, the first leakage through the left bank was visible to the naked eye. In this article, we establish a statement of the problem of infiltration across the left bank of the Ouizert dam and a piezometric study. Then, we study the variation of leakage rate according to the rating of the dam.

Study Area and Data Used
Location and Characteristics of the Dam

Previous studies showed that many hydraulic infrastructures of water storage are built in areas which do not respect the required standards. They are generally built in sites that are geologically unfavorable for water storage, either because of lack of suitable sites or because they are exposed to all kinds of pollution. These geological sites cause harmful effects that may endanger the safety of the structures. Therefore, low average annual rainfall, rain with short duration, strong intensity falling on nude soil causing a strong pullout of earthy particles and water leakage are the major consequences. As far as Algeria is concerned, some dams belong to that kind of structures, such as Beni Haroun dam. Despite the remedy work made in areas where water losses exist, the phenomenon of water leakage still appears and persists when the reservoir is filled. Beni Haroun dam is located in the north of Grarem Guga; a town in the wilayat of Mila in the east of Algeria (Figure 1).

![Location of Beni Haroun reservoir](Remini, 2014)

The dam is considered as one of the largest hydraulic projects being accomplished so far. This huge structure was located at the heart of a large hydraulic facility which was built in R.C.C. (Rolled Compacted Concrete); a new technique that was created in 1980 for construction of dams. The dam was approved in 2001 (completion in June 2001) with a completion rate of 100%. Its first impoundment began in August 5, 2003. Technically, it is 118 meters high from the foundation, with a length of 710 meters in peak. Its normal impounding capacity is 960 million m$^3$/year. Its versant basin is estimated at 7725 km$^2$, with an average annual impoundment of about 730 million m$^3$/year with a regulated volume of 435 million m$^3$/year (Figures 2 and 3).
This strategic location is considered a key asset for Constantine and Aures inhabitants. Since the additional infrastructure is planned in a perspective of the coming thirty years to extend its tentacles to the wilayas of Mila, Constantine, Jijel, Oum-El-Bouaghi, Batna and Khemchela, it requires other projects. Beni Haroun dam is a project of water transfer, that was found to overcome the intensified drought in the north-east of Algeria and provide enough water in order to launch economic development sectors, especially agriculture. Despite its importance, Beni Haroun dam is exposed to many hydraulic problems. One of these is water leakage, which occurs through the foundation and the banks. The next sub-section discusses the phenomenon, its causes and consequences.

**Description of the Phenomenon of Water Leakage at Beni Haroun Dam**

Water leakage is a phenomenon that threatens the stability of the dam, given that groundwater flow may create certain phenomena, such as renard. It causes in depth corrosion by increasing physically and/or chemically sections of water circulation. Therefore, the flow of water leakage that comes instinctively from the volume of water will be stored in the lake of the dam. Water leakage could be observed, especially at the left bank of the dike (Figs. 4 and 5).
Thus, this latter is defective and requests special processing. To do so, it should be consolidated at least to minimize the amount of water lost through it and make it acceptable. Moreover, due to infiltration through the foundation of the dam, water leakage remains huge considering only the part captured by drains installed at various galleries. To store water, the hydraulic services are pushed to build urgent hydro-technical facilities in inappropriate locations for two main reasons: first, the lack of geologically favorable sites for the storage of water; second, because of the strategic location in relation to the increasing demand on water and development goals to be achieved at the level of the recipient regions of large contribution in water supply. In addition to what has been mentioned above, there is an important water supply coming from the wadis crossing these sites. These latter require certain features during the construction and exploitation of the asset, especially to consolidate their geological formation using the appropriate scientific materials. These costly operations require companies to provide skilled people, professionals, sophisticated equipment and even consolidation materials that fit tightly to the geological formation of the sites. Beni Haroun dam is one of those places. It is characterized by a defective geology composed of a superposition of limestone and clay showing cracks, joints, shear zones and even hidden and apparent flaws (EDF CIH, 2002). Besides, the existence of defective areas in the site, mainly the lake and banks that have not been studied thoroughly before and during the completion of the dam, is also one of the main causes of this important loss of water. However, the lack of boring wells and their small depth, especially at the left bank, made the geological formation unrecognized. Furthermore, the hydrostatic charge continues to affect the supports and the foundation of the asset.

**Measurement Devices and Data**

In order to make the study come into being, the following equipment have been used.

- **A signal probe:** This device is used for measuring the water level in the piezometers. It has two electrodes connected to a multidecameter. When the electrodes touch the water level in the piezometer, the electrical circuit is established and the device beeps. We read off the multidecameter scale the depth at which the roof of water column is located.
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- **A staff gauge:** It is a device which is installed at the level of the dike of the dam. It is used to read the spot height of the lake.

- **Triangular and rectangular thresholds:** They are used to measure the height of the threshold and therefore the flow.

- **A sump made at gallery number 100 AGL:** It is a place where water seepage accumulates and subsequently is evacuated using four pumps downstream the dam.

- **A canopy.**

- **A ruler:** It is used to measure the height of the threshold.

- **A stopwatch:** Its function is to measure the time necessary for filling the container or the sump.

- **Vibrating wire cells:** They are used to measure the under-pressure deep inside the dike.

- **A sampler:** It serves as a means of sampling water at piezometers, wells and at different places of the lake and boreholes.

- **A pressure gauge:** It helps measure the pressure in the drains.

The recorded data is concerned with the following aspects: rainfall, flow leakage, evaporation, lake dimensions, piezometric dimensions, under-pressure, bathymetry, water releases,… etc. The determination of the corridors of water and underground flow direction is necessary and even mandatory to understand the mechanism of water leakage due to infiltration. To reach these goals, the use of information gathered by the piezometers is very useful. Data recorded by the operation department will be critical to calculate the average speed of infiltration of water into the lake. Measurements of different flows at the galleries, resurgences, sump and temporary derivations allow tracking the fluctuation flow over time depending on the water level in the lake.

### RESULTS AND INTERPRETATION

The results obtained were used to give some shapes which represent geometrically the required estimates. While starting with the monitoring of the change in rate of water leakage due to infiltration over time depending on water level, a spatial representation of groundwater downstream of the dike was introduced. The study began with presenting the principal component of the different parameters, then it highlighted the speed/ permeability (V/K) ratio according to the side of the lake. Finally, it determined water infiltration rate for the different sides of water level which will be the main concern of the present study.

The results obtained are presented in the form of graphs to represent the acquired estimates. They monitor the change in rate of water leakage due to infiltration over time depending on water level.

### Piezometric Study

This study aims at determining the direction of groundwater flow, detecting defective areas of the banks and the foundation of the dike, as well as identifying and locating the possible corridors for the flow of leakage water. To do this, the use of information gathered by the various piezometers along with the operation are very useful. Figure 6 illustrates the arrangement of the various piezometers located downstream of the dike of Beni Haroun dam.
Principal Component Analysis of Piezometers and Lake Information

Principal component analysis of the different varying water levels in piezometers and the lake provided us with the appropriate ways to organize parameters into groups. Consequently, this categorization helps determine which parameters belong to the same group on the one hand and identify the correlations existing between the different parameters on the other hand, through establishing the ratio between permeability coefficient and average infiltration rate depending on water level fluctuation.

This correlation can give a clear and valuable idea on the hydraulic gradient between the lake and the different locations where piezometers are installed. Therefore, it provides more information on the speed of water flow through the layers constituting the support and the foundation of the facility. Piezometers PI-2, POVI-2, PO124, RG-1 and POVII-2 have a poor correlation with water level, confirming that water level in these piezometers depends also on other sources other than the lake of the dam.

Spatial Presentation of Groundwater Downstream of the Dam

The presentation of groundwater downstream of the dam is concerned with following piezometric maps giving the spatial form of the groundwater located downstream near the dike. It highlights the direction of the flow of water leakage through the foundation and the support of the dam. The information collected on the piezometers located downstream of the dike allows to draw some piezometric maps for the different water levels. The selection of information for each representation depends on the following criteria: a) Data from all piezometers should not present gaps. b) The water level in the lake must be stable, which can subsequently give a reasonable interpretation of the various forms of groundwater. Table 1 provides the dates and spot heights for which the piezometric maps are plotted.

<table>
<thead>
<tr>
<th>Date</th>
<th>Spot height (AGL)</th>
</tr>
</thead>
<tbody>
<tr>
<td>11/02/2005</td>
<td>167,25</td>
</tr>
<tr>
<td>11/02/2006</td>
<td>164,79</td>
</tr>
<tr>
<td>25/03/2007</td>
<td>178,91</td>
</tr>
</tbody>
</table>
Spatial representation of groundwater located downstream for different water levels in the lake of the dam over time highlights the healthiest areas where piezometers are to be installed. Figures (7), (8) and (9) show the equipotential lines of the groundwater below the dam in (2005), (2006) and (2007), respectively. The maps also confirm that the hydraulic gradient at the left bank is higher than the one at the right bank. They show the direction of the flow downstream of the dike, which is perpendicular to the plotted equipotential lines. Piezometers on the right bank have piezometric spot heights ranging from 150 to 165 AGL, exceeding the water level in the lake which is less than 165 AGL. This entails that these piezometers are provided with other sources of water, such as rainwater or groundwater. However, on this bank, piezometers located near the lake have higher levels, which explains the flow in the opposite direction. The water level in almost all piezometers on the left bank depends on the lake, which shows the fluctuation of the water column of any piezometer on the left bank of the same magnitude as the fluctuation of the level of water in the dam. Thus, the piezometers on the left bank are closely related to the water level in the lake of the dam.

Figure (7): The form of the groundwater downstream of Beni Haroun dam, Algeria on 11/02/2005 (Harza, 1984; Toumi, 2007)

Figure (8): The form of groundwater downstream of Beni Haroun dam, Algeria on 11/02/2006 (Harza, 1984; Toumi, 2007)
Piezometric Lines Downstream of the Dam

We will draw three pizometric lines in the form of longitudinal profiles from the right bank to the left bank for different values of the level of water in the lake of the dam. Figure 10 shows the geometric shape of the longitudinal profiles obtained. Analysis of this representation gives the idea that at the level of piezometer VIII1, there are two directions for the flow of water with different pressure values. One comes from piezometer IX and the other from piezometer VII1, resulting in a probable damage to the area where piezometer VIII1 operates. The right bank shows constant pressure regardless of the level of water, while pressure recorded at the left bank is variable and depends on the level of water in the lake of the dam.

Figure (10): Piezometric lines for the different levels of water downstream of the dike of BH dam, Algeria
Piezometer–Piezometer Relations and (V/K) Ratio-
Water Level of the Lake

a) Piezometer–Piezometer Relations (Right Bank)

The map representing the arrangement of the different piezometers illustrates the existence of new profiles. Each profile contains two or three piezometers. It shows the relations linking the piezometers of each profile and their response to each other. The representation in the plan of their information seems to be more than compulsory (Figure 11).

![Figure (11): Fluctuation of POIII2 and POIII3 according to P.O.III1](image)

The different regression equations between piezometers of the profiles situated at the level of the right bank of Beni Haroun dam are listed in Table 2.

![Table 2. The different regression equations between piezometers of the profiles situated at the level of the right bank of Beni Haroun dam, Algeria](table)

<table>
<thead>
<tr>
<th>Name of the profile</th>
<th>Regression equation</th>
<th>Determination coefficient</th>
<th>In the form of Darcy law</th>
</tr>
</thead>
<tbody>
<tr>
<td>Profile I</td>
<td>( C_{P_{12}} = 0.2157C_{P_{11}} + 119 )</td>
<td>( R^2 = 0.4581 )</td>
<td>( H_2 = 0.7843H_1 - 119.74 )</td>
</tr>
<tr>
<td>Profile III</td>
<td>( C_{P_{12}} = 1.0392C_{P_{11}} - 4,8595 ) ( C_{P_{13}} = 0.9708C_{P_{11}} + 2,7487 )</td>
<td>( R^2 = 0.9989 ) ( R^2 = 0.9952 )</td>
<td>( H_2 = 0.0393H_1 + 4.8595 ) ( H_2 = 0.0292H_1 - 2.7487 )</td>
</tr>
<tr>
<td>Profile IV</td>
<td>( C_{P_{12}} = 0.4616C_{P_{11}} + 62,402 )</td>
<td>( R^2 = 0.8925 )</td>
<td>( H_2 = 0.5384H_1 - 62,402 )</td>
</tr>
<tr>
<td>Profile 124 RD</td>
<td>( P_{124RD4} = 1.1858P_{124RD3} - 21,074 )</td>
<td>( R^2 = 0.9926 )</td>
<td>( H_2 = -0.1858H_1 + 21,074 )</td>
</tr>
</tbody>
</table>

b) Relation between V / K and Water Level in the Dam (Right Bank)

- Relation between V / K of Profiles and Water Level in the Y Direction

The form of the various ratios \( V / K \) of profiles in the Y direction, which is perpendicular to the dike of the dam and pointing downstream, appears in Figures 12 and 13.
The ratio $V/K$ in the area of POIII2 and POIII1 is very small. In addition, this ratio decreases with the rise of water level.

**POIV2-POIV1 Profile**

Between these piezometers, the ratio $V/K$ is high and its variation depends on the level of water, taking a parabolic shape. The average values of $V/K$ obtained over the specified period of time are listed in Table 3.
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Table 3. The average values for the ratio V / K in the Y direction at Beni Haroun dam, Algeria

<table>
<thead>
<tr>
<th>Name of the function</th>
<th>VL/K (m)</th>
<th>L (m)</th>
<th>V/K</th>
<th>Loss charge</th>
<th>Hydraulic gradient</th>
</tr>
</thead>
<tbody>
<tr>
<td>POI2=f (POI1)</td>
<td>-1,2811</td>
<td>30,1</td>
<td>-0,0426</td>
<td>-1,08</td>
<td>-0,036</td>
</tr>
<tr>
<td></td>
<td>4,945</td>
<td>30,1</td>
<td>0,1643</td>
<td>5,10</td>
<td>0,169</td>
</tr>
<tr>
<td>POIII2=f (POIII1)</td>
<td>0,0655</td>
<td>46,823</td>
<td>0,00140</td>
<td>0,0632</td>
<td>0,00135</td>
</tr>
<tr>
<td>POIII3=f (POIII2)</td>
<td>0,7455</td>
<td>22,895</td>
<td>0,0326</td>
<td>0,7441</td>
<td>0,0325</td>
</tr>
<tr>
<td>POI1=f (POIII1)</td>
<td>0,8133</td>
<td>69,698</td>
<td>0,0117</td>
<td>0,8073</td>
<td>0,0116</td>
</tr>
<tr>
<td>POIV2=f (POIV1)</td>
<td>3,0480</td>
<td>24,34</td>
<td>0,1252</td>
<td>3,0429</td>
<td>1,250</td>
</tr>
<tr>
<td>POI124RD4=f (POI24RD3)</td>
<td>-1,1077</td>
<td>8,005</td>
<td>-0,1384</td>
<td>-1,1124</td>
<td>-0,139</td>
</tr>
</tbody>
</table>

- Relation between V/K of the profiles and Water Level in the X Direction

Since there is a flow in the Y direction at the profiles of the right bank, there is a strong possibility of flow in the X direction (Figure 14). Following are the relationships that can give a view of the flow in that direction.

POIII1-POIV1 Profile

![Graph showing the variation of V/K in the X direction according to water level in the lake](image)

Figure (14): Variation of V / K in the X direction according to water level in the lake

A flow with a very small ratio of V/K is recorded between the two piezometers regardless of the level of water (Table 4).

Table 4. The average values of the ratio V / K in the X direction at Beni Haroun dam, Algeria

<table>
<thead>
<tr>
<th>Name of the function</th>
<th>VL/K (m)</th>
<th>L (m)</th>
<th>V/K</th>
<th>Loss charge</th>
<th>Hydraulic gradient</th>
</tr>
</thead>
<tbody>
<tr>
<td>POIII1=f (POI1)</td>
<td>31,1739</td>
<td>203,085</td>
<td>0,15350</td>
<td>31,19</td>
<td>0,1536</td>
</tr>
<tr>
<td>POIV1=f (POIII1)</td>
<td>0,4250</td>
<td>67,048</td>
<td>0,00634</td>
<td>0,4215</td>
<td>0,00629</td>
</tr>
<tr>
<td>POI124RD3=f (POIV1)</td>
<td>2,17875</td>
<td>29,093</td>
<td>0,07489</td>
<td>2,18</td>
<td>0,07494</td>
</tr>
<tr>
<td>POIII2=f (POI2)</td>
<td>30,84940</td>
<td>192,462</td>
<td>0,16029</td>
<td>30,85</td>
<td>0,16030</td>
</tr>
<tr>
<td>POIV2=f (POIII2)</td>
<td>3,40706</td>
<td>58,712</td>
<td>0,05803</td>
<td>3,40</td>
<td>0,05793</td>
</tr>
<tr>
<td>POI124RD4=f (POIV2)</td>
<td>-1,97861</td>
<td>28,920</td>
<td>-0,06842</td>
<td>-1,98</td>
<td>-0,06833</td>
</tr>
</tbody>
</table>
c) Piezometer - Piezometer Relations (Left Bank)

The relations that link the piezometers of profiles (V), (VI) and (VII) are not linear and the percentages of variance explained are not suitable. However, the piezometers of the profile PORGA adapt well to linear regression with high explained variance and the flow between them follows a linear law, which is also the same for piezometers (PITCH-PORGA1), (bis-POVIII PITCH) (POVIIIbis-POVIIIbis), (POVIIbis-POVIIbis) and (PO124RG1-POV1). The different regression equations between the piezometers of the profiles situated at the left bank of Beni Haroun dam are listed in Table 5.

Table 5. The different regression equations between the piezometers of the profiles situated at the left bank of Beni Haroun dam, Algeria

<table>
<thead>
<tr>
<th>Name of the profile</th>
<th>Regression equation</th>
<th>Determination coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>Profile V</td>
<td>CPOV2 = 246,18(CPOV1)2 - 60984CPOV2 + 4E+06</td>
<td>R² = 0,5997</td>
</tr>
<tr>
<td>Profile VI</td>
<td>POVI2 = 0,5105POVI1 + 67,686</td>
<td>R² = 0,357</td>
</tr>
<tr>
<td>Profile VII</td>
<td>CPOVII2 = -0,1461(CPOVII1)³ + 57,995 (CPOVII1)² – 7668,3(CPOVII1) + 337948</td>
<td>R² = 0,7078</td>
</tr>
<tr>
<td>PO124RG-1POV1</td>
<td>CP124RG1 = 9,43251CPV1 - 1047,7</td>
<td>R² = 0,9374</td>
</tr>
<tr>
<td>POV1-POVI1</td>
<td>CPVI = 0,0592(CPVI1)³ - 22,792(CPVI1)² + 2926,4CPVI1 – 125112</td>
<td>R² = 0,7601</td>
</tr>
<tr>
<td>POVII-POVII1bis</td>
<td>CPVI1 = 0,5286CPVII1 + 58,204</td>
<td>R² = 0,9482</td>
</tr>
<tr>
<td>POVIII1bis –POVIII b</td>
<td>CPVIII1bis = 0,9843CPVIIIb + 3,1235</td>
<td>R² = 0,9499</td>
</tr>
<tr>
<td>POVIII bis-POIX</td>
<td>CPVIII = 0,3356CPIX + 78,431</td>
<td>R² = 0,7116</td>
</tr>
<tr>
<td>POIX-PORGA1</td>
<td>CPIX = 0,9169CPRGA1 + 12,483</td>
<td>R² = 0,9992</td>
</tr>
<tr>
<td>Profile PORGA (bis)</td>
<td>CPORGA2bis= 0,8277CPORGA1bis + 30,76 CPORGA3bis= 0,5659CPORGA2bis + 85,61 CPORGA4bis = 1,0087CPORGA3bis - 3,3099</td>
<td>R² = 0,8975 R² = 0,7261 R² = 0,9566</td>
</tr>
</tbody>
</table>

d) Relation between V/K of the Profiles and Level of Water in Both Directions X and Y (Left Bank)

Five profiles are identified at this side. Figure 15 clearly shows the representation of the ratio V / K in the Y axis (perpendicular to the dike and from upstream to downstream).
The ratio \( \frac{V}{K} \) between these two piezometers indicates the “cotes” of the lake to be below 180.5 AGL. While there is a decrease in the ratio \( \frac{V}{K} \), an increase in \( \frac{V}{K} \) for higher levels is identified. This can be justified by the deterioration in the area between the two piezometers. The average values of the obtained ratio \( \frac{V}{K} \) are listed in Table 6.

Table 6. Mean values for the ratio \( \frac{V}{K} \) and the hydraulic gradient in the Y and X directions at the left bank of Beni Haroun dam, Algeria

<table>
<thead>
<tr>
<th>Name of the function</th>
<th>VL/K (m)</th>
<th>L (m)</th>
<th>V/K</th>
<th>Charge loss</th>
<th>Hydraulic gradient</th>
</tr>
</thead>
<tbody>
<tr>
<td>POVI1=f (POVII1)</td>
<td>5,3650</td>
<td>79,901</td>
<td>0,0671</td>
<td>5,36</td>
<td>0,0671</td>
</tr>
<tr>
<td>POV1=f (POVII2)</td>
<td>0,0655</td>
<td>125,946</td>
<td>0,00140</td>
<td>-30,14</td>
<td>-0,2393</td>
</tr>
<tr>
<td>POVIIIbis=f (POVIII1 bis)</td>
<td>-1,0224</td>
<td>79,192</td>
<td>-0,0129</td>
<td>-1,03</td>
<td>-0,0130</td>
</tr>
<tr>
<td>POVIIIbis=f (PORGA1)</td>
<td>32,6069</td>
<td>105,708</td>
<td>0,3085</td>
<td>32,60</td>
<td>0,3084</td>
</tr>
<tr>
<td>POVIII bis=f (POIX)</td>
<td>31,2449</td>
<td>80</td>
<td>0,3906</td>
<td>31,25</td>
<td>0,3906</td>
</tr>
<tr>
<td>POIX=f (PORGA1)</td>
<td>1,3473</td>
<td>25,708</td>
<td>0,0524</td>
<td>1,35</td>
<td>0,0527</td>
</tr>
<tr>
<td>PORGA2=f (PORGA1)</td>
<td>-1,0127</td>
<td>55,968</td>
<td>-0,0181</td>
<td>-1,01</td>
<td>-0,0180</td>
</tr>
<tr>
<td>PORGA3=f (PORGA2)</td>
<td>-10,2270</td>
<td>125,995</td>
<td>-0,0812</td>
<td>-10,23</td>
<td>-0,0812</td>
</tr>
<tr>
<td>PORGA4=f (PORGA3)</td>
<td>1,7551</td>
<td>198,83</td>
<td>0,0088</td>
<td>1,76</td>
<td>0,0088</td>
</tr>
</tbody>
</table>

From the results mentioned above, a clear idea is obtained in a more or less correct manner on the values of the ratio \( \frac{V}{K} \) which characterize the layers crossed by the various piezometers. Hence, the variation of infiltration rate depending on the level of water plan in the lake is represented in a curve. Thus, a methodology for calculating the average speed of water infiltration at the lake of the dam for a given level of the reservoir is needed in order to link this information with the layers crossed by the piezometers.
Calculating the Rate of Fluctuation of Water Plan at Beni Haroun Dam

The study of fluctuations of the speed of water level change in the lake of this dam aims at determining to which depth the permeability coefficient at the banks and the foundation increases more. For this, tracing the change in water depth over time is a recommended path.

Transformation of the Fluctuation of Water Level in the Lake at Medium Speed

The transformation of water elevation in hydraulic charge and time in days clearly identifies rise and fall peaks of water level and their time. Figure 16 highlights the fluctuations of the lake’s water level over time regardless of the amount of water released, its siltation and evaporation.

The rate of rise or fall is calculated by taking the ratio of the difference in charge between two points and the time between them. In our case, the time is one day. Because water leaks are considered as losses, interest is put on negative speeds. The analysis of these latter allowed distinguishing the representations shown in Figures 17, 18 and 19.

Figure (16): Variation in time of the pair level of the lake with and without taking evaporation, dropped water and siltation into account at Beni Haroun dam, Algeria

Figure (17): Infiltration rate for level of the lake varying from (140 to 154 AGL) at Beni Haroun dam, Algeria
Figure (18): Infiltration speed for level of the lake varying from 154 to 162 AGL at Beni Haroun dam, Algeria

\[ y = 0.0062x^2 - 2.1047x + 177.25 \]
\[ R^2 = 0.794 \]

Figure (19): Infiltration speed for « cotes » of the lake varying from 162 to 172 AGL at Beni Haroun dam, Algeria

\[ y = -0.0359x^2 + 12.246x - 1045.6 \]
\[ R^2 = 0.8102 \]
These latter illustrate the infiltration rate according to the level of water and even deduce its variation with time. It was found that there was an increase in the level of water over time. Besides, the fall speed of water level is remarkable, which demanded to calculate the average permeability coefficient (K) for the dam site. 

\[ V_{\text{Water leaks}} = V_{\text{Fall of water level}} - (V_{\text{evaporation}} + V_{\text{Dropped water level}} + V_{\text{Siltation}}) \]

From level 166 AGL, it was found that there is a decrease in infiltration rate depending on the elevation of water level. This decrease is due to the consolidation work carried out by injection, especially at the left bank. In addition to the amount of water lost through leakage due to infiltration, there is another important amount lost by siltation (silt occupies a volume of the reservoir and is therefore considered as loss) and evaporation. In light of the values obtained from the V/K couples, average speed due to water leaks, V and depending on the level of the lake, these may help calculate the permeability between two piezometers for a given level of water.

**Study of Leakage Rates**

Monitoring of the flow rates of drains that are installed at various galleries allows, first, to know whether these rates increase for the same level of water or not. Second, it determines the galleries producing big amounts of water. The fluctuation of flow rates of the drains depending on the level of water gives the possibility to extend our predictions on the amount likely to be lost through the banks and the foundation of the facility for the highest level of water (HLW). Figure 20 shows the position of the galleries, one over the other, that exist at Beni Haroun dam.

![Diagram](image)

Figure (20): The drainage of groundwater in the various galleries of the dike of BH dam

Fluctuations in the flow lost depending on water level make it necessary to investigate whether they increase further or not when water level exceeds a certain rating. Figure 21, however, represents the fluctuations over time of the rates of leakage due to infiltration at the levels of galleries 100, 120, 134 and 140 and temporary derivation two (TD2).
In order to find the most exposed bank to the phenomenon of water leakage at galery 100, we represent fluctuation according to the level of the lake and the rate of leakage of each bank. Figure 22 shows the change in the rate of leakage at the right bank of galery 100 according to the fluctuation of water plan in the lake of the dam, while Figure 23 provides the fluctuation of leakage flow due to infiltration at the left bank of galery 100.

Figure (21): Variations over time of leakage flow due to infiltration at Beni Haroun dam
(data source: ANBT, 2007)

Figure (22): Variation of discharge according to the level of the lake at the right bank of galery 100 at Beni Haroun dam, Algeria
It can be argued that drains at the left bank lose a significant amount of water compared to those at the right bank (about $Q_g = 5xQ_d$). That is to say that the left bank is more defective than the right one. Drains at the right bank record flows ranging from 39 to 46 l/s, while a fork of 202.5 to 262.5 l/s is common with those at the left bank. At both sides and for levels of water plan in the lake above 178.5 AGL, the flow of leaks is important, especially at the left bank, where huge leaks exceeding 250 l/s were recorded. Figure 24 represents the fluctuation of the total flow of leakage due to seepage at gallery 100.
This representation explains that the rate of leakage due to infiltration at gallery 100 increases with the increase in the rating of water plan of the lake. The hydrostatic charge created by the upstream level increases the flow to percolate through the cracks of the banks and the foundation.

In addition to water loss at gallery 100, we mention losses occurring at gallery 120 (34 drains, of which 17 are descendant drains and 17 are rock ascendant drains), at gallery 134 (5 rock descendant drains) and temporary derivation n° 2. Figures 25, 26 and 27 elucidate, at these locations, the variation in leakage rates according to water plan in the lake.

Figure (25): Variation at drain flow according to the level of the lake at galery 120 at Beni Haroun dam, Algeria

Figure (26): Variation of drain flow according to the level of the lake at galerly 134 at Beni Haroun dam, Algeria
The rates of leakage at gallery 120 and 134 are low. In fact, the whole (leakage) does not exceed 6 l/s for high values of the recorded level of water. At the level of the temporary derivation n°2, the recorded rates of leakage are considerable. Let alone, there has been an increase in these rates for the same value of water level in the lake. In other words, the rates of leakage increase over time for the same bank of water level which is a remarkable risk that must be limited.

To highlight the variation in the total rate of leakage according to fluctuations in water level in the lake of the dam, the diagram in Figure 28 represents this variation.

Figure (27): Variation of drain flow according to the water level in the lake at temporary derivation n° 2 (TD2) at Beni Haroun dam, Algeria

Figure (28): Variation of the rate of leakage according to the level of water at Beni Haroun dam, Algeria
Apart from the flows from the various galleries, there are measured flows at the drains downstream of the dike. Figure 29 shows the fluctuation of the flow of drains for different water levels.

![Figure (29): Fluctuation of the flow of drains downstream of the dike according to the level of water in Beni Haroun dam, Algeria](image)

The average rate of leakage is 673 l/s regardless of the flow rates of the different resurgences and the rest of the deep infiltration water that can reduce this flow beyond measurable values. Although the drainage of infiltration water is required to minimize pressure, it must be also ensured, over time, that there is a constant flow rate for the same side of water plan in the lake. The total flow from the lake will be the sum of the flow coming from the galleries and that of the drains downstream. This helps reduce it by more than 900 L/s for an average depth of the lake regardless of the flow rate of the different resurgences. At the end of this study, a significant quest could be raised: Once the level of water reaches the normal level of retention "NLR" (200AGL) and the flow of leakage due to infiltration, does it continue to rise with the same order of magnitude?

**CONCLUSION**

The results of this study uncovered two main points. First, the geological formation of the left bank of the dam is more defective than that of the right one. The under-pressure recorded at the right bank is almost constant over time regardless of the level of water, while that at the left bank is variable because of the drainage that unfolds at the bottom downstream of the dike. Second, hydraulic continuity between the lake and the area below Beni Haroun dam is one of the consequences of geological permeable foundation and banks that have imperfections. The flow of water leakage was noticed below the dam through the maps giving the equipotential lines representing the underwater. The measurements proved that the volumes lost increase with the elevation of water plan, which threatens the stability of the dike, especially when water reaches the highest water level (H.W.L.).
The fight against the phenomenon of water leakage requires carrying out injection consolidation activities, especially at the left bank and the seat of the dam. Following clear, refined and accurate steps is more than necessary and even mandatory to heal all imperfections appearing in the geological mass when pressure created by water level in the lake reaches a threshold. This allows to have water supply engineering structures that can be filled up to the highest water point (H.W.L.) without any risk, especially regarding assets and population downstream of the dam. Despite the performed work of consolidation, important amounts of water continue to escape from the lake of the dam, mainly through the left flank and the foundation in the form of outbreaks. This requires permanent injection of consolidation materials in places likely to be ideal for leaks until getting a “tight screen”. However, we witnessed a decrease in rate of leakage due to infiltration whenever an action was undertaken. Last but not least, the execution of waterproofing by qualified companies at accurate locations of leaks is vital to minimize the amount of water lost through leaks and ensure stability by using materials that perfectly fit with the nature of the banks and the foundation.

REFERENCES


EDF CIH. (2002). “Campaign for recognition of the slope Sibari, Algeria”.


