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Hydrogeochemical Analysis as a Tool to Verify Seepage Flow Paths in an Earth Dam

Zorany S. Zapata[1], Maria C. Sierra[2], Adriana M. Blanco[3]
[1]Geotechnical Engineer at Integral S.A
Medellín, Colombia
zszapata@integral.com.co mcsierra@integral.com.co
[2]Lead Geotechnical Engineer at Integral S.A
[3] Geological Engineer at Integral S.A
Medellín, Colombia
admblanco@integral.com.co

Abstract **–**In this paper the hydrogeochemical characteristics of the infiltration waters detected in an earth core rockfill dam and its water reservoir are analyzed. The assessment focused on applying different methods of hydrogeological representations and from that, the type of water, its potential origin, and the interaction processes that they have with the rock mass and the reservoir were established. These hydrogeological samplings were carried out later after a geophysical study that suggested preferential flow routes. The hydrogeochemical tests consisted of the determination of in-situ parameters and major ions. The geophysical test was based on the application of an electric current to detect the points with the highest conductivity, and which was related to the presence of water. To complement this, x-ray fluorescence and x-ray diffraction tests were carried out on the solid deposits found in one of the samples. In the end, it was found that both studies suggested that there were no defects in the dam's waterproofing system and that water detected in the downstream embankment flowed first through the abutments.

Keywords**:** Hydrogeochemical, earth dam, seepage, tunnel, geophysical, path, origin.

1. Introduction

This article aims to show the importance of hydrogeochemical analysis to confirm seepage flow paths through an earth dam and its abutments. These paths were previously identified with geophysical surveys. This research was carried out in a hydroelectric project where a reservoir was formed with an Earth Core Rockfill Dam. The dam has modifications in its upper 50 meters and it's important to note that a cement bentonite cut-off was used to reinforce the impervious system in that upper part.

The geophysical study was validated by chemically characterizing the waters that have been detected at the dam site. For that, a testing program was executed to measure major ions data in the water reservoir, leakage in the drainage galleries located in the abutments, water inside boreholes near the cut-off wall as well as in seepage detected and measured in the downstream shoulder of the dam. In addition, water from a stream closed to the dam site was characterized.

Using the results of the hydrogeochemical tests and based on some diagrams such as those of Piper [1], Stiff [2], Mifflin [3], and Chadha [4], it was confirmed that the seepage measured in the downstream slope crossed through the rock abutments as suggested in the geophysical investigation. The seepage collected in the downstream slope is calcium sulphated, similar in ions and cations to the one that leakage in the drainage galleries of the abutments built in the rock mass. Likewise, no flow lines were identified passing through the core or cut-off in bentonite cement because the water in contact with cement-bentonite mix is sodium and potassium carbonated.

2. Project description

As stated before, it is an Earth Core Rockfill Dam (ECRD) 225 m high measured from the riverbed (level 210 meter above sea level-m.a.s.l). The crest is in the elevation 435 m.a.s.l, with 18 m wide and about 550 m in length. The downstream slope is 1,75H:1V average, resulting in a slope of 1,4H:1V with 10 m berms and upstream of 2H:1V (Fig.

1). In the upper part, between levels 380 and 418 m.a.s.l, there is a cement -bentonite cut-off wall (Fig 1). Also, three levels of drainage galleries are in the abutments as shown in Fig. 2.

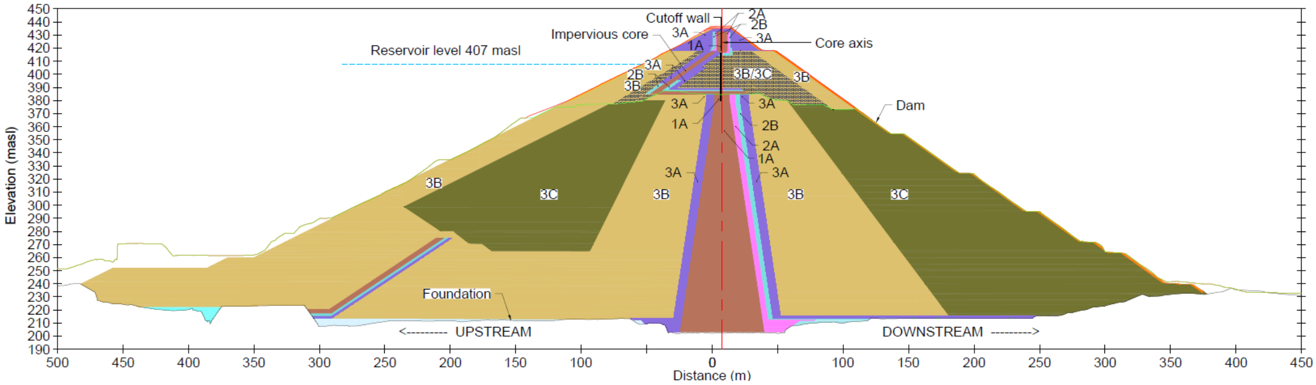

Fig. 1: Detail of the central section of the dam.

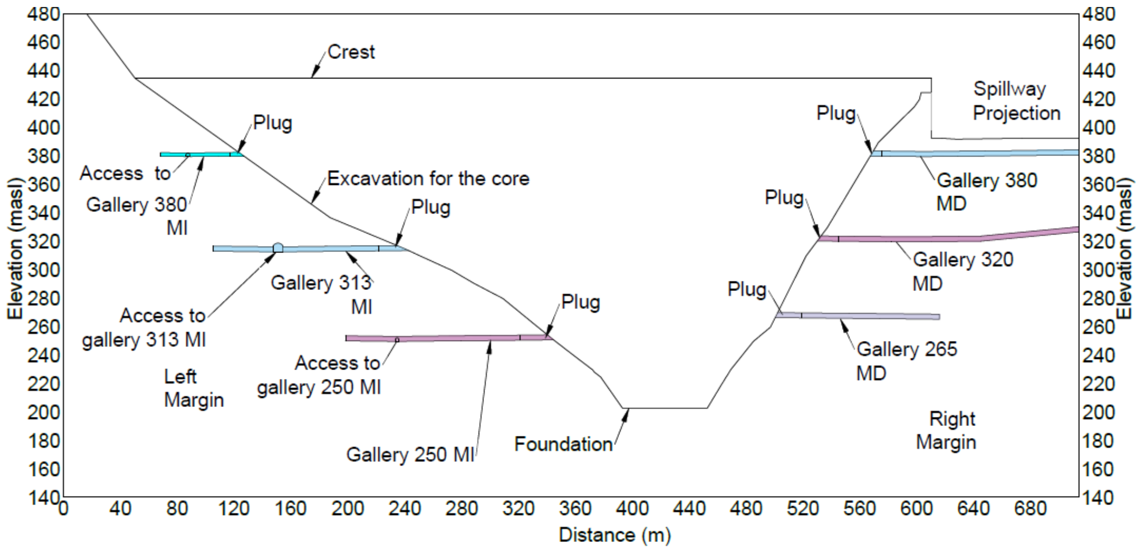

Fig. 1: Detail of the injection and drainage galleries in the abutments.

Since the galleries were mostly dry before the reservoir was raised, the reservoir accounts for most of the recharge. During construction, few flows were identified mainly associated with the most fractured sectors of each tunnel. Therefore, there may be an influence of rainfall, but ultimately, the main input to the system is the reservoir and this was noted with its increase to the current level. From the moment the reservoir rose, infiltrations began to appear in the galleries. The infiltrations in gallery 250 MI at the time of writing this article are of the order of 40 l/sec. In gallery 320 MD these infiltrations are of the order of 13 l/sec. On the other hand, in the shallowest gallery sampled during the study, i.e., gallery 380 MD, approximately 2,5 l/sec are measured.

Also, once the reservoir was filled, leakage appeared in the downstream slope, and it was necessary to study if those infiltrations were crossing through the cutoff wall or the earth core 1A due to a possible defect in it. For this reason, geophysical investigation (with Willowstick technology) and hydrogeological studies were carried out, including hydrogeochemical analyses. The geophysical study stated that there were no flow paths through, beneath, or around the earth core 1A and cement-bentonite cut-off wall.

3.Geophysical studies

A geophysical test to identify the flow paths in the dam was executed in the second half of 2020 (September/October) and the results were published at the beginning of 2021. Hydrametrix-Willowstick [5] developed the study considering the principle that seepage increases the conductivity of earthen materials through which it flows. As an injected signature electric current flows, it concentrates in the more conductive zones where seepage from the reservoir preferentially flows. The main conclusions of this study are listed below (Fig. 3):

• There is no preferential line passing through the dam's waterproofing system (core or cut-off wall).

• An East line (E) was identified that comes from the abutment and bypasses towards the dam through the area of the right abutment, above the 380 MD gallery. Hydrametrix-Willowstick further suggests that this line could be the largest contributor to the seepage seen on the downstream shoulder.

• The other line is located towards the left abutment (West-W), above the western part of the gallery 313 MI. Hydrametrix suggests that this line could be the one that contributes to most infiltrations in the 250 MI gallery, although regarding this last point, the Consultant analyzed other possible causes.

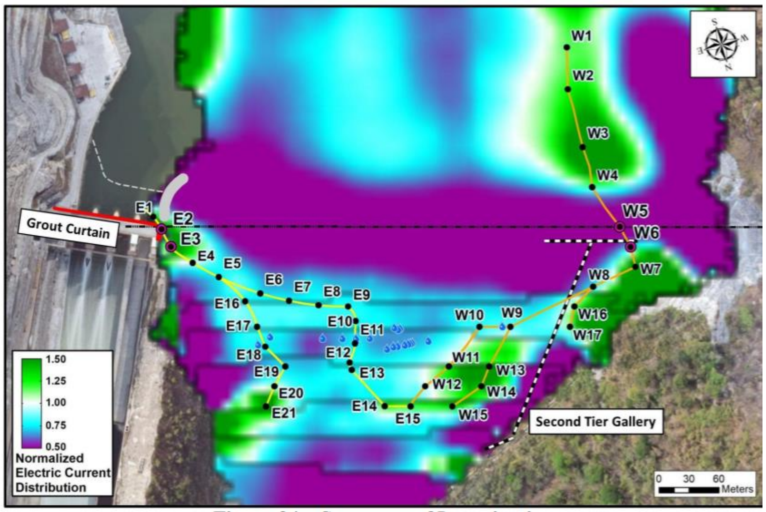

Fig. 3: Plan view of the identified preferential flow lines.

4. Methodology

A sampling program was carried out in the water reservoir, in the infiltration flow captured in the downstream slope, in the seepage of the drainage galleries, water inside boreholes located near the cut-off wall and in the water of a nearby stream. The sites where the samples were taken are indicated in Fig. 4. Since the drainage galleries are underground structures, their surface projection is hardly shown.

In this process, the chemical compounds and constituents of the water were determined by measuring the major ions data in all the liquid samples (water seepage). The major ions are the dominant constituents in the water produced by weathering (calcium Ca^{2+}, magnesium Mg^{2+}, sodium Na^{+}, potassium K^{+}, bicarbonates HCO_3^{-}, carbonates CO_3^{-}, chlorides Cl^{-}, sulphates SO_4^{2-}, fluorides F^{-}). Also, field data such as pH, electric conductivity, temperature, and total dissolved solids, among others, were recorded with a calibrated portable meter. The tests have been carried out from 2019 to August 2022, with an average monthly frequency.

The samples had their respective quality analysis and those that did not comply with the ionic balance were discarded. The chemical data are summarized in diagrams such as Piper [1] and Stiff [2] to understand the chemical process in each sample point. According to [6] in the Stiff´s diagrams the chemical data are plotted to understand the distribution of cations and anions based on their varying patterns. The Piper diagram helps to classify the water in different hydrogeochemical types or origins depending on their dominant cations and anions as stated by [7].

As a complement, the data is also analyzed using diagrams of Mifflin [3] to classify the water according to its evolution (local, intermediate, and regional flows). Additionally, the diagram of Chadha [4] was used to understand the water quality and the hydrogeochemical processes.

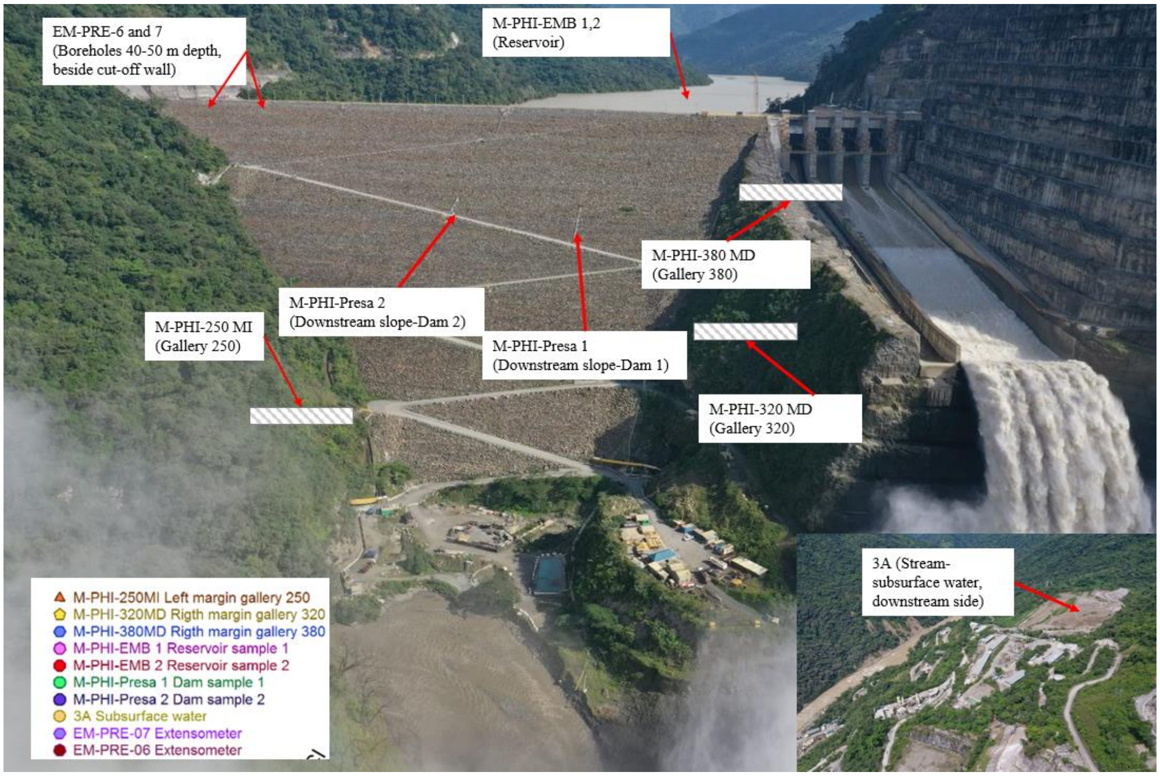

Fig. 4: Location of sampled points (downstream view).

5. Results

With the results of the hydrogeochemical analysis, the type of water was identified and grouped into those that are similar. According to the components, the groundwater is classified as local where a little active flow path is found or where recharge and discharge areas are relatively close to each other and for that they are most affected by temporary variables such as rain. Likewise, the classification includes intermediate zones where the flow is slower compared with the first one and regional, deeper zones where the waters are older, which is identified with the predominant anion that changes from bicarbonate (HCO_3^-) to chlorides (Cl^-) [8]. Also, the regional flow systems are less affected by temporary variables in the recharge. This means that the water with a short path is bicarbonated and as the path increases, sulphates and finally chlorides are added. Fig. 5 gathered the results obtained for the water samples and these are classified using the Piper diagram.

According to Fig. 5, the water in the reservoir corresponds to calcium-bicarbonated waters, and as this water travels through the rock mass, the content of sulphates increases, therefore, the longer the path through the rock mass, the higher the sulphate content. For instance, the higher sulphate contents were detected in the deepest galleries 320 MD and 250 MI. On the other hand, the lowest sulphate content was identified in the most superficial gallery 380 MD. In addition, the water that leakages downstream of the dam is water added with sulphates (calcium sulphate) because the water reservoir flows through the rock mass and leakages trough the abutment. The groundwater collected in the downstream shoulder and the water that emerges in the drainage galleries such 320 MD and 250 MI are in the same area of the Piper diagram.

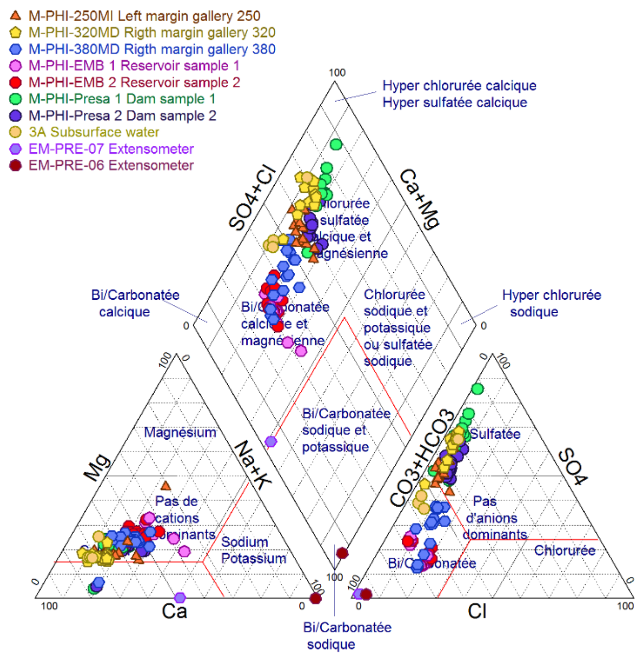

Fig. 5: Piper diagram for the samples.

Testing the water retained inside the borehole near the cement bentonite cut-off wall, it was determined that it has dominant anion of carbonate and cations such as Ca, Na and K, concluding that the facie of these samples is carbonated sodium and potassium. In other words, these waters retained in the extensometers of the cut-off are very different from those of the seepage downstream of the dam, as can be seen in the Piper diagram. This validates that the seepage collected in the downstream slope of the dam does not proceed from seepage through the cut-off wall. As a possible hypothesis, it is proposed that the sodium in the water in contact with the cement-bentonite mix comes from the sodium bentonite that was added to the cement with which it was built. Complementary, the most abundant element in the solid deposits of the water extracted from the boreholes were Calcium CaO with a percentage of 51-57% according to the X-ray Fluorescence (XRF) test results, followed by other elements such as MgO and SiO2. That means the water trapped in the boreholes EM-PRE-6 and 7 was oversaturated with Calcium generating precipitations of this mineral.

The average of all seepage samples is presented in the Stiff diagram, (Fig. 6). An increase in the Ca and SO_4 parameters of the dam samples can be observed with respect to the reservoir samples, in addition, it is observed that these have greater similarity with the gallery's samples (M-PHI-320MD and M- PHI-250MI).

The Siff diagram helps to recognize the seepage in the dam (M-PHI-Presa 1 and M-PHI-Presa 2) as calcium sulphated-type waters, different from those of the reservoir (M-PHI-EMB-1 and M-PHI-EMB- 2) which are bicarbonated type waters. The waters from the dam have a similar affinity to the samples from the deep galleries of the abutments. Groundwater from deep galleries and seepage in the downstream side are associated with intermediate flow systems with longer routes in the rock mass, and once more which suggests that the seepages in the dam were filtered through the abutments and during their course through the rock mass were contaminated by groundwater. This has a direct correlation with the results of the Willowstick test, since infiltration waters that appear in the downstream slope of the dam flowed through the abutments of the dam, and because of that they are influenced with longer paths comparing with waters of the reservoir and shallow galleries.

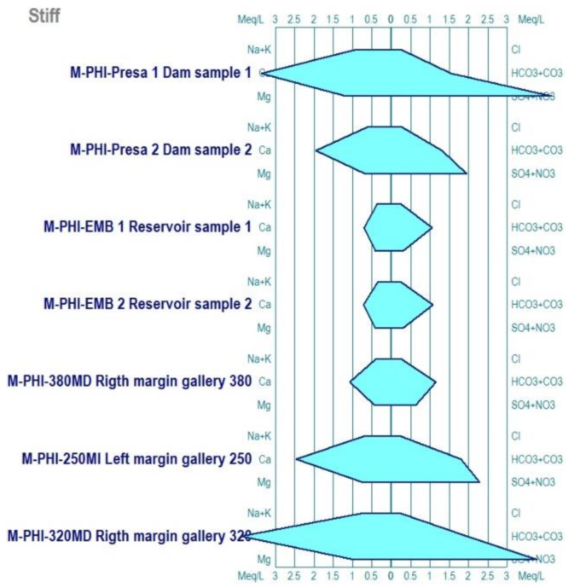

Fig. 6: Stiff diagram for water samples.

The evolution of groundwater proposed by Cheboratev [6] was reinforced by the Mifflin diagram, where the categorization of the three water flows, local, intermediate, and regional, is visible, according to the content of anions and cations to the groundwater. Based on the Mifflin diagram it is concluded that the groundwater belonging to the local flow corresponds to little evolved water (such as that of the reservoir) and of recent infiltration; those belonging to the intermediate flow (dam and galleries) are located with a greater hydrogeochemical evolution given by the time spent in the geological environment and the depth at which they infiltrated. In this study regional flows were not identified that correspond to a zone of deposition of solutes, where the chemical composition of the water tends to increase its mineralization until it becomes saturated with the different ions along the path travelled, characterizing these waters as those with the longest path within the underground medium. Fig. 7 shows the evolution of the seepage waters tested in the Miffin diagram.

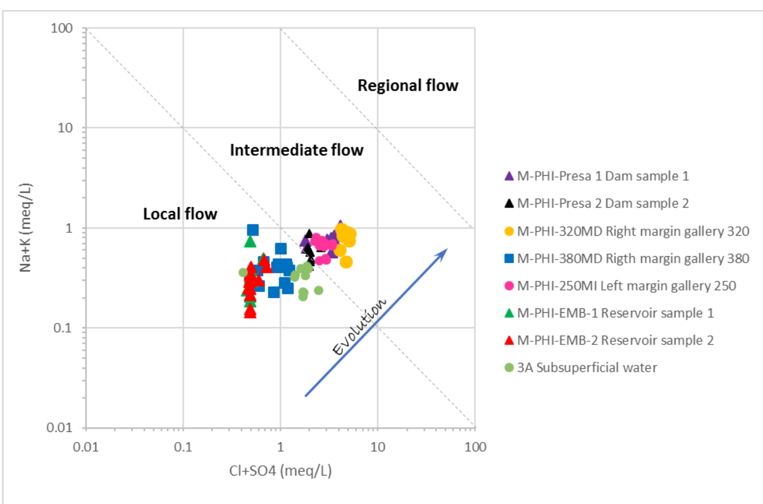

Fig. 7: Mifflin Diagram for water samples.

It is important to note that a similar conclusion regarding the type of flow was suggested in previous studies carried out for the same project. In that previous study, it was stated that according to chemistry and isotopy the infiltration waters of a tunnel of the deviation system named GAD corresponded to a mixture of rainwater and groundwater from intermediate flows in the subsurface environment. Now, comparing with the new study, the physical-physical-chemical physical-structural structure of the waters of the deepest rocky galleries (M-PHI-320MD, M-PHI-250MI) are like the sulphated-calcium water identified in the GAD tunnel according to Fig. 8. That is, the waters of the reservoir that flow through the abutments add sulphates from the groundwater and stated above, the longer the path through the rock mass, the higher the sulphate content.

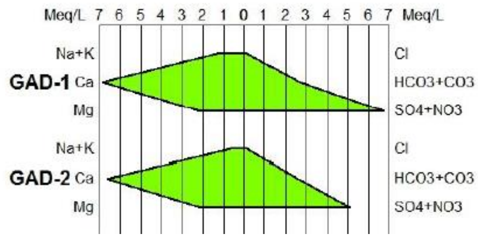

Fig. 8: Stiff diagram for water samples taken in the deviation tunnel GAD.

Finally, the sampling results discussed above are also analyzed following the diagram proposed by Chadha [4] (Fig. 9). That diagram has been used to study various hydrogeochemical processes, such as: exchange of basic cations, contamination by cement, mixing with natural waters, reduction of sulphates, saline waters, and other hydrogeochemical problems. The Fig. 9 clearly shows that the water from the cut off wall is very different from the water collected in the downstream slope.

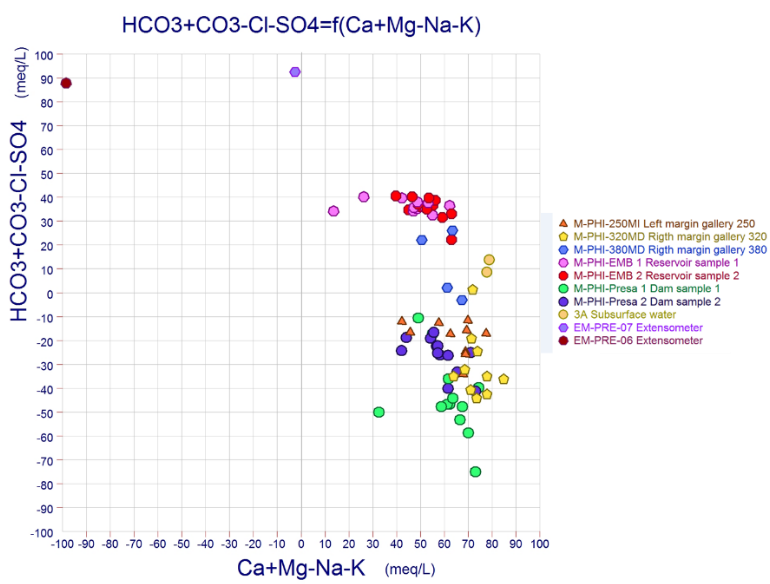

Fig. 9: Diagram Chadha, 1999.

6. Conclusion

The hydrogeological characteristics of the water sampled in a dam (from leakage in galleries, seepage in downstream of the dam, from boreholes, etc.) and its reservoir were identified to validate a geophysical study where preferential seepage flow path was found.

In this research it was concluded that the reservoir waters are of the calcium-bicarbonated type. On the other hand, those waters that depend on the route through the rock mass have more content of sulphates. The sulphate content is dependent on the path length of the groundwater inside the rock. In addition, a sodium-carbonated type water was detected inside the drill holes that are in contact with the bentonite-cement mixture of the cut-off wall.

Through both approaches (geophysical and hydrogeochemical), it was established that the water collected in the downstream embankment of the dam is not due to defects in the waterproofing system of the fills, which is made up of an earth core and a bentonite cement cut-off. In fact, both the geophysical test and the hydrogeochemical study led to the conclusion that the seepage detected in the downstream embankment comes from the right abutment rock mass. The above means that there are no defects in the dam's waterproofing system and that the water that emerges in the downstream shoulder is related to groundwater that previously passed through the rock mass by the abutments.

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