Original paper

Integration of electrical resistivity tomography with electromagnetic and soil radon measurements for characterizing the leakage problem in Afamia B dam, Syria

Walid Al-Fares and Mohamed Al-Hilal*

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Resumen

Para comprobar las causas de fuga en la presa Afamia B, y proponer un modelo conceptual, se aplicaron tres técnicas complementarias que incluyen datos tomográficos de resistividad eléctrica (ERT, por sus siglas en inglés), electromagnetismo (EM) y radón gaseoso del suelo. Los datos se acompañan por una investigación geológica y tectónica extensa, las cuales ayudaron a delimitar ciertas vías para una posible filtración de agua desde la cuenca de la presa del lago. Se localizaron zonas significativamente débiles, que incluyen lineamientos tectónicos subsuperficiales, roca fracturada, superficies erosionadas y algunas otras estructuras deformadas. Un análisis adicional de los datos indicó que la estructura geológica subyacente de la cuenca de la presa se compone principalmente de un lecho litológico sucesivo que consiste en capas permeables (arenas y gravas), que se alternan con lechos de margas calcáreas impermeables. La composición heterogénea de tales litofacies puede proporcionar una razón adicional que podría mejorar efectivamente las pérdidas de agua a través de las unidades permeables a lo largo del valle principal. Los resultados generales de las técnicas combinadas han mostrado una correlación positiva entre los métodos aplicados y confirmaron la utilidad de este enfoque para trazar estructuras deformadas ocultas y zonas débiles. Además, la existencia de numerosas ruinas arqueológicas, como tumbas y pozos distribuidos en toda la cuenca de la presa, puede aumentar considerablemente la fuga de agua del lago. En consecuencia, se ha encontrado que el lecho de roca erosionado, la heterogeneidad de los lechos alternados y otras características superficiales detectadas están desempeñando un papel crucial en los procesos de fuga vertical y subhorizontal que ocurren dentro de las formaciones de Neogene y pasan a carbonato cárstico profundo y de rocas de la edad cretácica.

Palabras clave: Técnicas geofísicas, ERT, EM, Levantamiento de radón del suelo, fugas de agua, presa de Afamia, Siria.

Abstract

Three complementary techniques, including Electrical Resistivity Tomography (ERT), Electromagnetic (EM) and soil gas radon measurements were applied in order to propose a conceptual model that may describe the main causes of water leakage in Afamia B dam. The survey was accompanied by extensive geologic and tectonic field investigations which assisted the delineation of certain pathways for possible water leakage from the basin of the lake's dam. Significant weak zones including subsurface tectonic lineaments, fractured bedrock, eroded surfaces, and some other deformed structures were characterized. Further analysis of the resultant data indicates that the underlying geological structure of the dam basin is primarily composed of a successive lithological bedding consisting of permeable layers (sands and gravels) alternating with impermeable calcareous marl beds. The heterogeneous composition of such lithofacies may provide an additional reason which could effectively enhance the water losses through the permeable units along the shoulders of the main valley. The overall results of the combined techniques have shown a positive correlation between the applied methods, and they confirmed the usefulness of such approach for mapping out hidden deformed structures and weak zones. Moreover, the existence of numerous archeological ruins such as graves and wells distributed throughout the dam basin may greatly increase the water leakage from the lake. Consequently, it has been found that the eroded bedrock, the heterogeneity of alternating beddings and other detected subsurface features are all playing a crucial role in the subhorizontal and vertical leakage processes that occurring within the Neogene formations and passing down to deep-seated karstified carbonate rocks of Cretaceous age.

Key words: Geophysical techniques, ERT, EM, Soil radon survey, Water leakage, Afamia dam, Syria.

W. Al-Fares
M. Al-Hilal*
Department of Geology
Atomic Energy Commission of Syria
P.O Box 6091, Damascus, Syria
*Corresponding author: cscientific8@aec.org.sy

Introduction

Afamia dams are located on the eastern margin of the Ghab plain in the northwestern part of Syria, close to Qalet Al-Madiq town (Figure 1). The Ghab plain constitutes a prominent fertile terrain in western Syria that suitable for growing a wide range of agricultural activities. Hence, three adjacent earth-filled dams, (A, B and C), were constructed nearby the great ancient city of Afamia, at about 3 km eastern margin of the Ghab basin. In fact, the Afamia dams were built in this area essentially to divert some water out of the Orontes River (Nahr El-Aasi) to be stored and used afterward for irrigation and other domestic uses during drier months of late summer and autumn. The dam B, which has the maximum storage capacity of 37 millions cubic meters, is subjected to serious problems of leakage through the bedrock of its reservoir. It is worth to mention that the dam body extends along 2870m, with 55m high and it has a constant elevation of 282m above sea level (a.s.l.). In 1999, the dam was set in operation and filled up with water for the first time in order to check its validity for water storage. However, the water level in the lake has shown a clear sign of water loss ranged between 17 and 20 cm per day. Therefore, several geological and geophysical investigations, including vertical electrical soundings (VES) and electrical profiling (EP) surveys, have been carried out in dam by the Syrian General Company of Hydraulic Studies (2001). The objective of their surveys was to characterize the geological and tectonic settings of the dam site. Additionally, some foreign consulting companies performed more hydrogeological and geophysical investigations (Minasian, 2001). The results of these studies revealed various anomalies which indicate some probable scattered zones of infiltration distributed in many parts of the dam lake, but the exact pathways of leakage were not defined precisely. Further assessments of the pervious works were fulfilled by a Swiss company in attempt to identify the problem and to better understand the origin of water leakage (Joos and Bussard, 2004).

Moreover, new contribution was achieved in order to solve the leakage issue in the dam using more adequate geophysical techniques including electrical resistivity tomography (ERT) and electromagnetism (EM), surveys in addition to soil gas radon measurements (Al-Hilal and Al-Ali, 2010; Al-Fares, 2011). The objectives of these approaches were to characterize the subsurface structure of the dam floor and thereby delineate the main geologic and tectonic features that might be responsible for water leakage in the concerned dam.

The electrical resistivity tomography technique is recognized as one of the most important geophysical method which has been rapidly developed and widely used in the last few years (Demanet *et al*., 2001; Van Schoor, 2002; Paula *et al*., 2004; Nguyen *et al*., 2007; Lin *et al*., 2013; Torres-Rondon *et al*., 2013; Khaki *et al*., 2014; Farzamian *et al*., 2015). This technique became quite common method particularly in hydrogeological studies, dam leakage problems and for characterizing subsurface geological structure. This is due to the quality of the acquired data, and the ability of obtaining a continuous underground coverage with more details in 2D and 3D spaces (Panthulu *et al*., 2001; Pham *et al*. 2002; Cho and Yeom, 2007; Sjodahl *et al*., 2010; Al-Fares, 2014; Gutierrez *et al*., 2015). On the other hand, the Slingram electromagnetic technique (EM) can be considered as a practical tool for performing a fast geoelectrical survey in dam's terrains. This technique is proved to be suitable in various geological and hydrogeological conditions, in addition to the detection of different subsurface objects such as buried channels, underground caves and other buried archaeological occurrences (McNeill, 1990; Guerin *et al*., 2004; Perez-Gracia *et al*., 2009; Novo *et al*., 2012; Anchuela *et al*. 2015). Soil gas radon is broadly recognized as a significant natural tracer which can be used for locating a potential fault zone and providing an insight into some hidden structural features that are covered by a thick cover of recent sediments (King *et al*. 1996; Ciotoli *et al*. 1999; Baubron *et al*. 2002; Al-Hilal and Aissa 2015). Moreover, the application of integrated geophysics and soil gas radon surveys was proved as a reliable approach for the delineation of buried fault zones (Zarroca *et al*. 2012; Claudia Schütze *et al*. 2016). Accordingly, the current work represents a joint effort of integrating the results of the electrical resistivity tomography and electromagnetic surveys in combination with soil gas radon measurements, in attempt to identify the accurate locations of the leakage zones close to the Afamia B dam body

Geological and Hydrogeological Settings

The study region is generally situated within a geologic calcareous syncline of Cretaceous age, covered by thick continental formation of Neogene sediments, on which the Afamia dams have been constructed (Figure 1). The area is separated by a number of striking faults that led

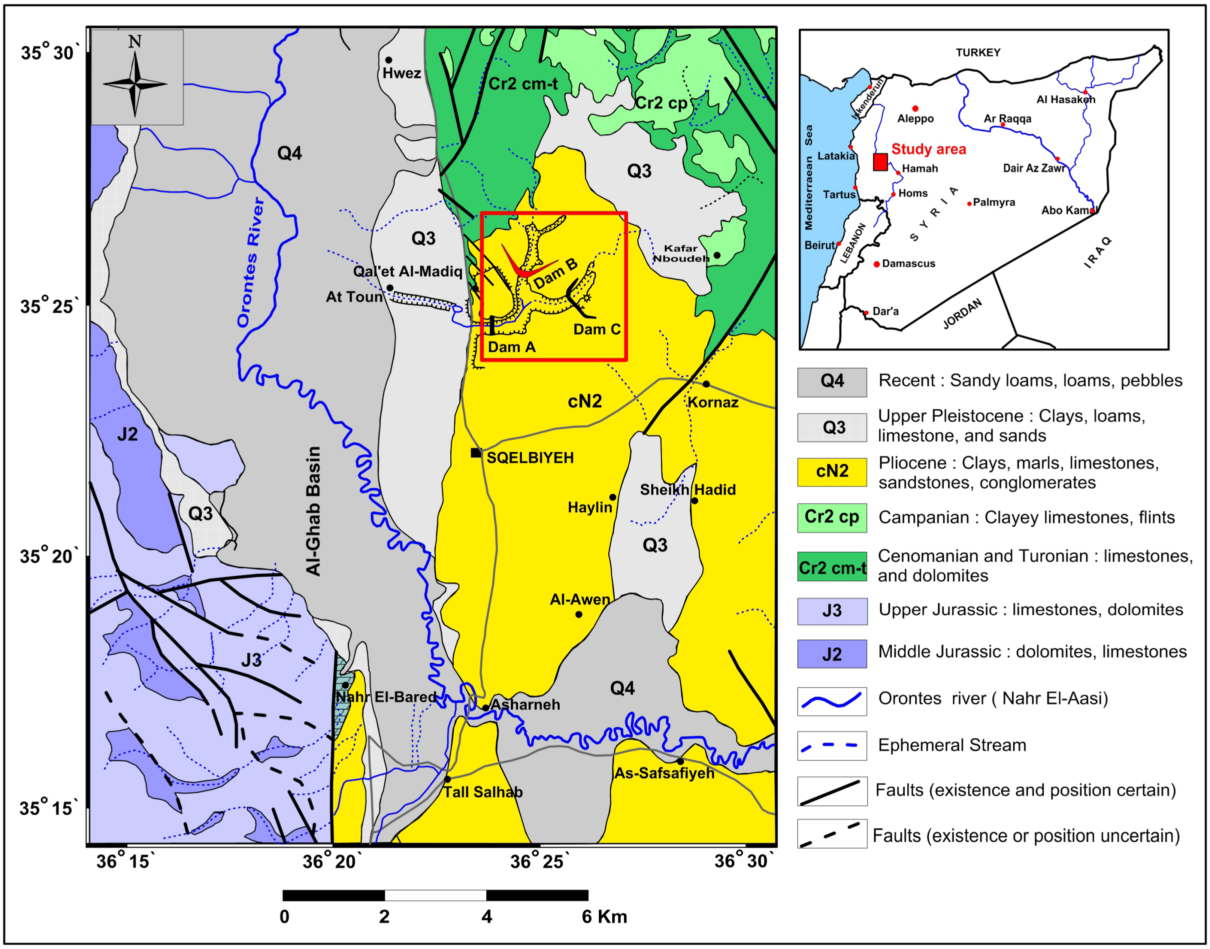

Figure 1. Simplified geological map of the study area showing the locations of Afamia dams (modified after Ponikarov, 1966).

to the formation of several distinct lineaments and tectonic blocks. Locally, the dam's site represents gently rolling hills characterized by thick Pliocene lacustrine sediments that developed in low areas, and covered by a thin sheet of Pleistocene and Recent formations. The prevailing Neogene deposits consist basically of marls and calcareous marls alternating with sands, gravels and conglomerate formations, with a total thickness of more than 100m. The Neogene formations are covered by thin unconsolidated layers of Quaternary deposits which are composed mainly of reddish clays, silts, sandy clays and alluvium sediments. Cretaceous rocks of Cenomanian and Turonian ages consist mostly of fractured and karstified limestone and dolomite rocks. These calcareous formations are partially outcropped on the northwest flank of the dam's area, and they appear to extend underneath the Neogene sediments forming the bottom of the stratigraphic succession in the area (Ponikarov, 1966). From tectonic point of view, the dam's area is located close to the Ghab pull-apart basin that formed initially as a result of the tectonic evolution of the northern left-lateral Dead Sea Fault System (DSFS) in western Syria (Brew *et al*., 2001). In view of that, the study site is struck by many distinctive fault segments some of which are bounding the Ghab basin and some others are branching out from the main extension of the northern DSFS. Additionally, the probable occurrences of karstification especially in the subsurface calcareous rocks may indicate that the underlying structure of the dam's area is highly fractured, and thereby the permeability is feasible for water infiltration through the floor of the reservoir. Since these geologic features and tectonic lineaments are not obviously visible at the surface of the dam basin, so it is very important to trace their pathways and pursue their subsurface extensions towards B dam particularly where the most loss of water is taking place. From hydrogeological point of view, the main groundwater aquifer in the study region belongs to the Cenomanian-Turonian fractured rocks, where a number of natural karstic springs are emerging from the eastern bounding fault of the Ghab basin. The second aquifer is related to the Neogene sediments, which appears on the surface through several springs, scattered in the study area. The absolute water table level of the Neogene aquifer ranges between 215 to 220m (a.s.l.), and the general direction of the ground water flow is trending from east towards west, with slight hydraulic gradient (Ponikarov, 1966).

Methodology

Electrical Resistivity Tomography (ERT)

Electrical resistivity tomography (ERT) is a sufficient and reliable geophysical technique for recognizing shallow subsurface structures. The method provides qualitative information of the electrical characteristics of the penetrated geological formations, and it delineates an expressive image of the subsurface features. An ERT survey is a combination of sounding and profiling configurations, which includes a number of electrodes with a fixed inter-electrode spacing. This technique depends on the measurement of subsurface apparent resistivity ρ_a (Ω.m) of the ground according to Ohm's law:

$$\rho_a = k\,(\Delta v/I)$$

Where k: a geometric constant that depends on the inter-electrodes spacing; Δv: the measured potential difference in mV; and I: the applied electric current in mA.

The measured apparent resistivity is converted into true resistivity using inversion software in order to obtain a 2D geoelectrical cross-section, which can be thereafter interpreted from geoelectrical or geological point of view. In the present work, the Wenner-Schlumberger configuration were applied. The advantages of this configuration are the stability and the ability to identify horizontal and vertical subsurface features. In addition, the Wenner-Schlumberger configuration provides a good signal/noise ratio for the measurements and permits getting full density of data at different levels of depth. (Dahlin and Zhou, 2004; Candansayar, 2008).

In the framework of this study, two main profiles (ERT-P1 and ERT-P2) were chosen in the lake close to the dam body (Figure 2). The first one is extending close to the central part of the dam body and it is perpendicular to the main valley, while the second is stretching along the left bank of the dam basin in parallel line to the course of the main valley. The geoelectrical instrument Syscal Swich-72 multi-core cable was used to carry out the ERT profiles. According to the applied configuration, the ERT profile was consisting of a main sequence of 72 electrodes straightly arranged along the measurement profile. The main sequence is almost followed by many roll-along sequences of 36 electrodes for each one depending on the length of the profile. The two performed ERT profiles have a length of 430 and 320m, with 3m as an electrode spacing step. The raw data were recorded using Schlumberger-Wenner sequence, where the penetration depth could reach, in this case, up to 30m. This sequence includes 759 measurement points distributed on 16 levels of depth. The acquired data were inverted into 2D real resistivity section using the RES2DINV software (Loke and Barker, 1996). The coordinates and the topographical survey of each profile were determined by using the GPS system with Universal Transversal Mercator (UTM) projection.

Electromagnetic survey

The Slingram electromagnetic method was used, in this study, as an additional and supportive tool in order to characterize the shallow subsurface zones or non homogenous geological mediums. This technique has been proven its performance as a practical tool combined with ERT technique in many occasion around the world (Soupios *et al*., 2007; Cygal *et al*., 2016; Osinowo *et al*., 2018).

The measurements carried out by using the CM-031 device, made by the Czech GF-Instrument. This device is practical and fast for performing a geoelectrical survey because it doesn't require any direct connection with the ground. The investigation depth which could be achieved is about six meters and the operating frequency is 9.8 kHz. Two EM profiles (EM-P1 and EM-P2) fulfilled in accordance with the ERT sections (Figure 2), in order to verify some anomalous features obtained by the ERT survey. The length of each EM profile is about 200m, and they both run in parallel lines with the ERT profiles, with 3 to 4m interval distance.

Radon measurement technique

The application of soil gas radon technique for detecting hidden deformed structures is based on the principle that anomalously high radon emission is commonly observed on the surface above fractured zones because of the higher permeability of such structures compared to the surrounding geologic medium.

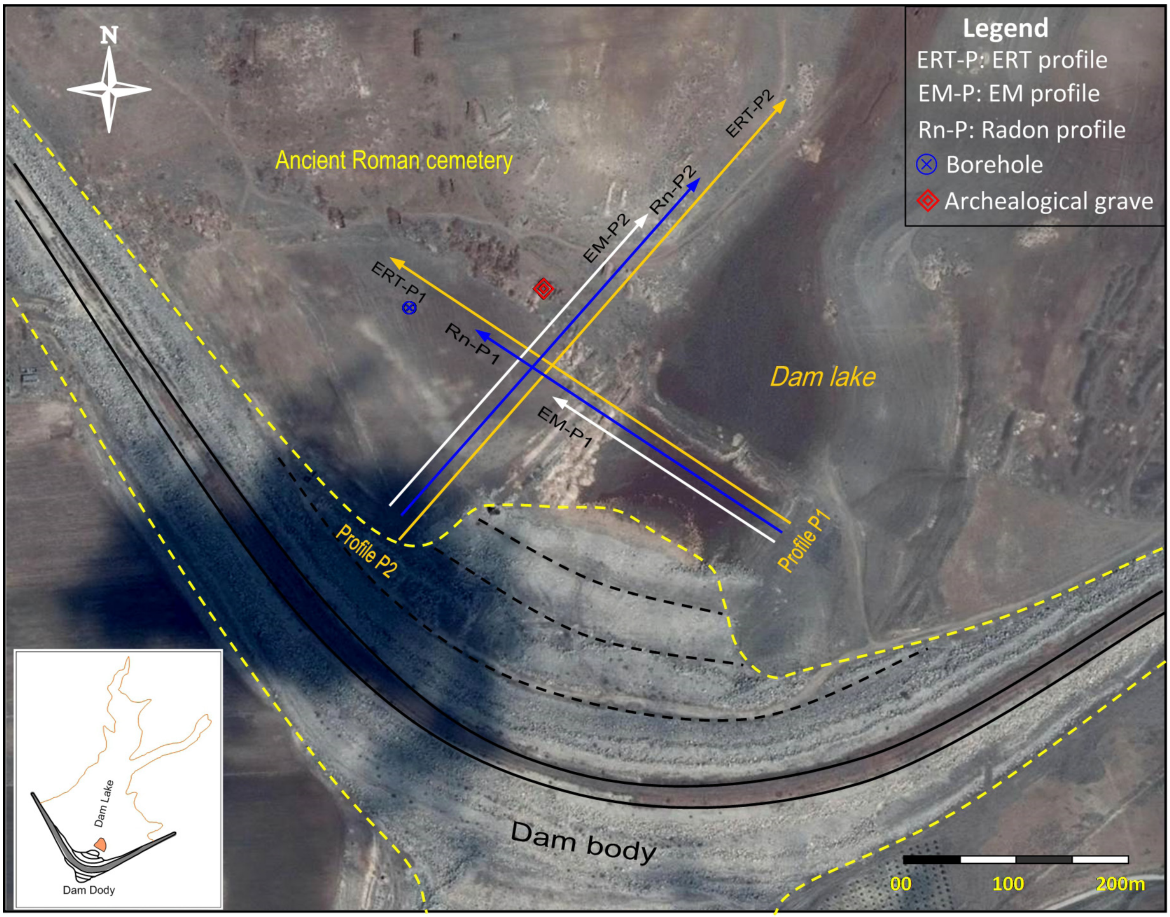

Figure 2. Locations of the ERT, EM and soil radon measurement profiles carried out in the lake of Afamia B dam.

Therefore, the method has been proven as a useful tool for locating the position and trend of buried faults in many tectonic regions throughout the world (Fu *et al*., 2005; Swakon *et al*., 2005; Al-Hilal and Abdul-Wahed 2016).

Direct active method was applied in this survey for determining the concentration of radon in soil gas. The method is based on the use of a portable vacuum soil probe assembly, which allows direct quantitative radon soil gas determinations in the field. The system consists of three attached parts including a portable soil probe assembly model (Pylon-154), a vacuum hand pump and a scintillation Lucas cell model (Pylon-110A). Radon sampling stations were arranged along a measuring profile with a certain interval distance between points. In the field, a hole of 60 cm depth and 5cm diameter is dug in the ground at each sampling station and a special PVC tube is planted inside the hole in order to prevent collapse of the soil. The soil gas is sampled into an evacuated scintillation cell by inserting the vacuum soil probe into the hole and slowly opening the probe valve until the system comes to the atmospheric pressure. After each measurement, the radon sample must be allowed to decay inside the scintillation cell for three hours so that the radon daughters come into equilibrium with the radon. Then, the scintillation cell is placed into the counter (RM 1003-Radon Detector), where the alpha activity is measured in count per minute basis, and then converted to concentration as Bq/m^3. In this study, two radon measurements profiles (Rn-P1 and Rn-P2) were carried out in parallel line with the ERT and EM profiles (Figure 2). Each radon profile consists of 21 sampling points at interval distance of 10-15m.

Results and discussion

The overall obtained results of the integrated techniques of the ERT, EM and Rn measurements revealed a fairly good correlation which may possibly point to some important subsurface deformed structures or buried fractured zones (Figures 3 and 5). The geophysical survey of the included methods carried out along two intersected measuring profiles, denoted as P1 and P2, traversing the main basin of the Afamia dam lake as shown in figure (2). The following sections include detailed discussion and interpretation of the results obtained along both measuring profiles.

Interpretation of the P1 profile

The figure (3) shows the interpretation of the P1 profile, which includes the combination of the ERT-P1, EM-P1 and Rn-P1measuements. The geoelectrical ERT section reveals the presence of thick clay and alluvial deposits layer covering most of the main valley which extends along a distance of 144m. The thickness of these deposits reaches up and more than 10m in some parties. In the middle of the main valley (X= 96m of the ERT section), the alluvial deposits extend downward towards the deeper formations. The extension of the alluvial deposits, in this form, could be resulted by the effect of the leakage of water laden with sediments towards the underline eroded layers (Figure 3).The resistivity values of these deposits seems to be relatively low and vary between 7-20 Ω.m. These deposits lay over eroded and fractured bedrock which is consisted essentially of marls and calcareous marls. The resistivity values of this bedrock are ranging between 50 and 120Ω.m with a thickness could reach more than 20m depending to the applied configuration and the used electrodes spacing step (Wilkinson *et al*., 2006; Szalai *et al*., 2013).

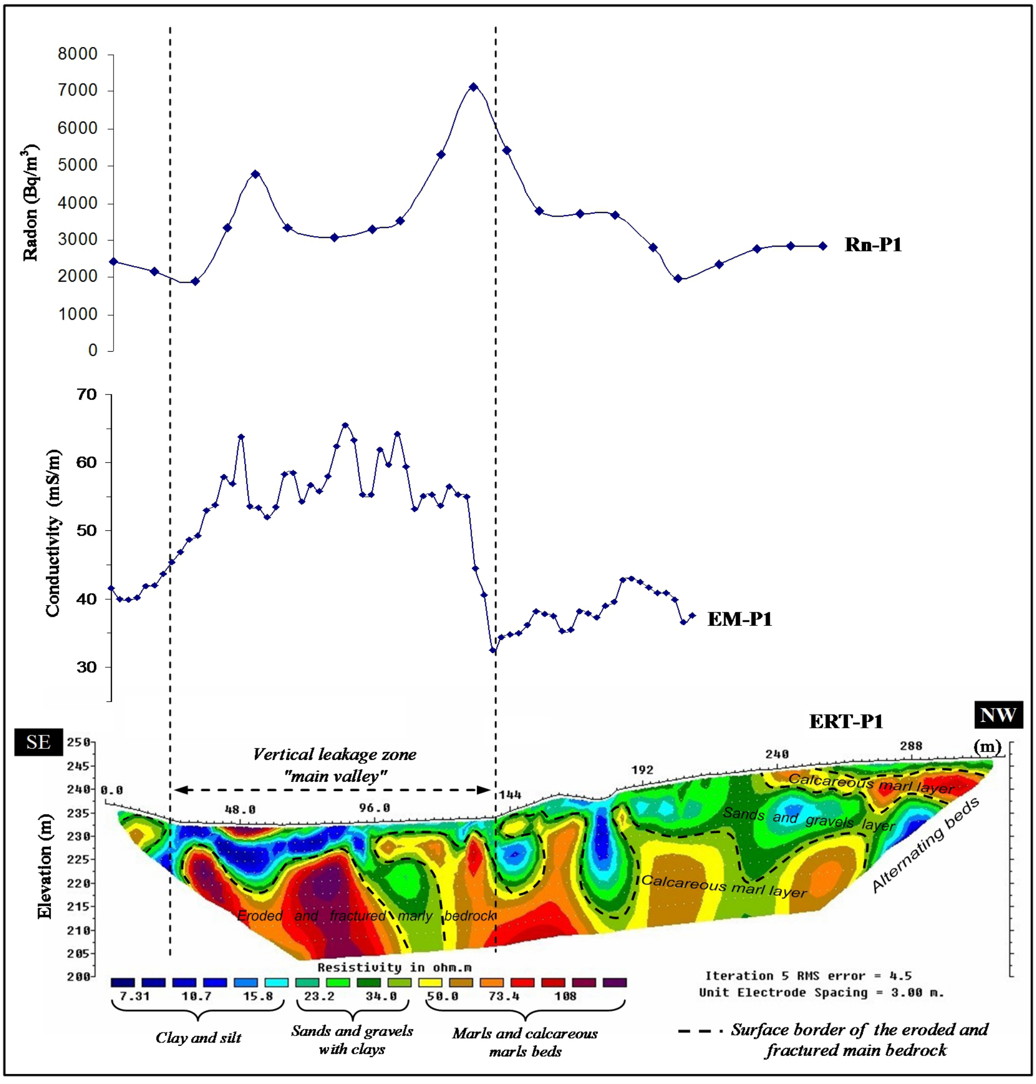

Figure 3. Interpretation of the P1 profile which includes the ERT, EM and soil radon measuements that carried out in Afamia B dam.

In principle, the marly and calcareous marly bed is supposed to be compact and impermeable, but the erosion and tectonic activities deformed its natural feature. It is evident that, the erosion and deformation processes applied on the marly and calcareous bedrock made it permeable and enhance the water to be leached towards the deeper formations. Moreover, the edges of the main valley seem to be associated with local tectonic features, which eventually led to the formation of the present valley in the site. The margins of the valley as well as the irregularity of the marly bedrock surface, which are effectively eroded and deformed, appear to be the principle causative of the vertical leakage in the dam lake. Moreover, the geoelectrical ERT section reveals also a clear alternating lithological succession between sands, gravels and clay layers alternating with marls and calcareous marls beds (Figure 3). The heterogeneity of these beds contributes in certain way by the occurrence of sub-horizontal water leakage through the permeable formations (sandy and gravels sediments) especially when the water storage level begins increasing in the lake. This kind of leakage is almost transformed afterwards to a vertical leakage through the eroded and fractured zones. The alternating bedding, which has been revealed by the ERT section, is confirmed through the comparison with real information of a borehole lithological column drilled close to the dam body (Figure 2 and Figure 4).

With respect to the curve of the EM conductivity (Figure 3), it seems to be well correlated with the inverted ERT-P1 section. The high electrical conductivity values are related with the clay deposits that accumulate within the course of the main valley, where the values reach 70mS/m (≈14Ω.m). However, a sudden decrease of the EM curve appeared to be well corresponded with the margins of the main valley. This decrease could be due to lithological changes between clay deposits from one hand and sands and gravels from other hand, where the conductivity values decrease to reach less than 30 mS/m (≈ 33 Ω.m).

Concerning the radon concentration along the measuring profile (Rn-P1), two notable increases values were noticed at distances of 60m and 145m from the start point of the ERT-P1 section. The first small radon peak was found to be directly correlated with a higher permeability structure due to the presence of subsurface fractured zones close to the left edge of the main valley. The second anomalous soil radon signature was also recorded above the site of a major fracture, which was delineated by the ERT-P1 geoelectrical section at the right margin of the main valley (Figure 3). These relatively high radon signals may reveal the existence of possible spatial relationship with the underlying permeable geologic medium that is associated with the expected fractured zones. Further, this finding may indicate the possibility of using soil gas radon technique as a useful tool for tracing unknown subsurface faults. In view of the geological environment of the studied dam, the

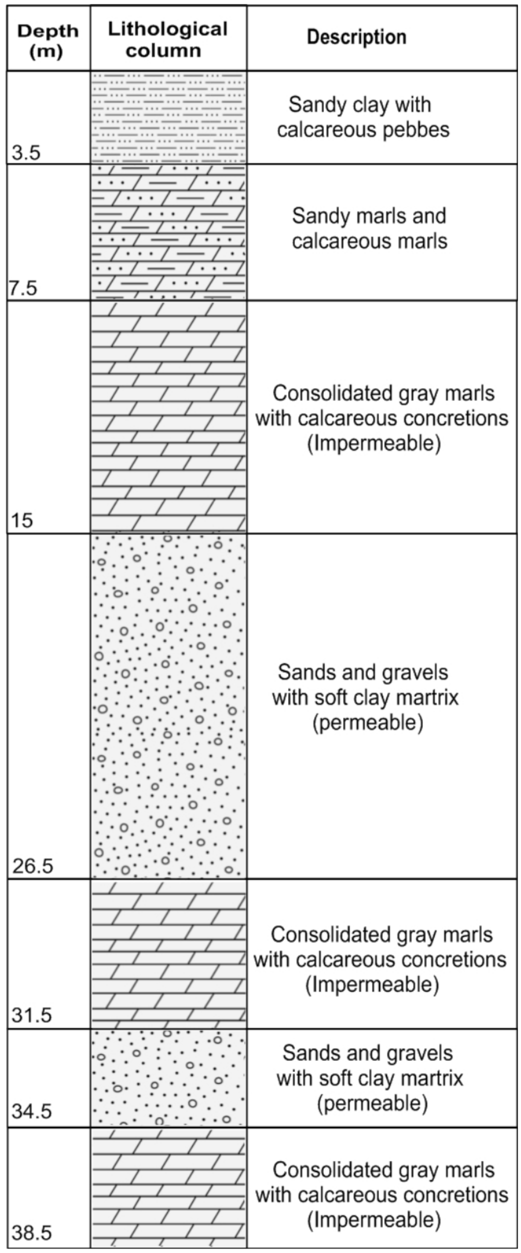

Figure 4. A borehole column illustrates the lithological succession close to the dam body (after the Syrian General Company of Hydraulic Studies, 2001).

clay materials tend to fill cracks and fractures by sliding downward through run off surface water. Based on this observation, the soil gas concentration in such environments may sometimes reflect the presence of clay, which is commonly characterized by higher level of natural radioactivity.

Interpretation of the P2 profile

With regard to the ERT-P2 section (Figure 5), it seems to be structural different from the previous ERT-P1 profile because it does not has the same direction locality with respect to the general bedding trends. The most important thing which characterizes the geoelectrical ERT-P2 section is the existence of an abnormal subsurface feature located at the first third of the section. This anomalous feature has a special geometric shape and located at a depth of 10m from the surface with downward extension. The real nature of this structure did not precisely determined and it could be related to compact massive rocks or archeological remains such as road or tunnel. Thus, more geophysical and archeological investigations are needed to confirm the true nature of this anomaly since the dam's lake is located within the geographic zone of the ancient Roman Afamia city and the site is filled by hundreds of buried Roman graves, wells and others subsurface archaeological monuments. The resistivity of the detected anomalous feature is relativity high and reaches more than 1200Ω.m, whereas it very low and does not exceed 20Ω.m for the clayey deposits that surround the outer edges of the feature. The structural discrepancy between the unknown feature and its surroundings may led to the development of an inhomogeneous

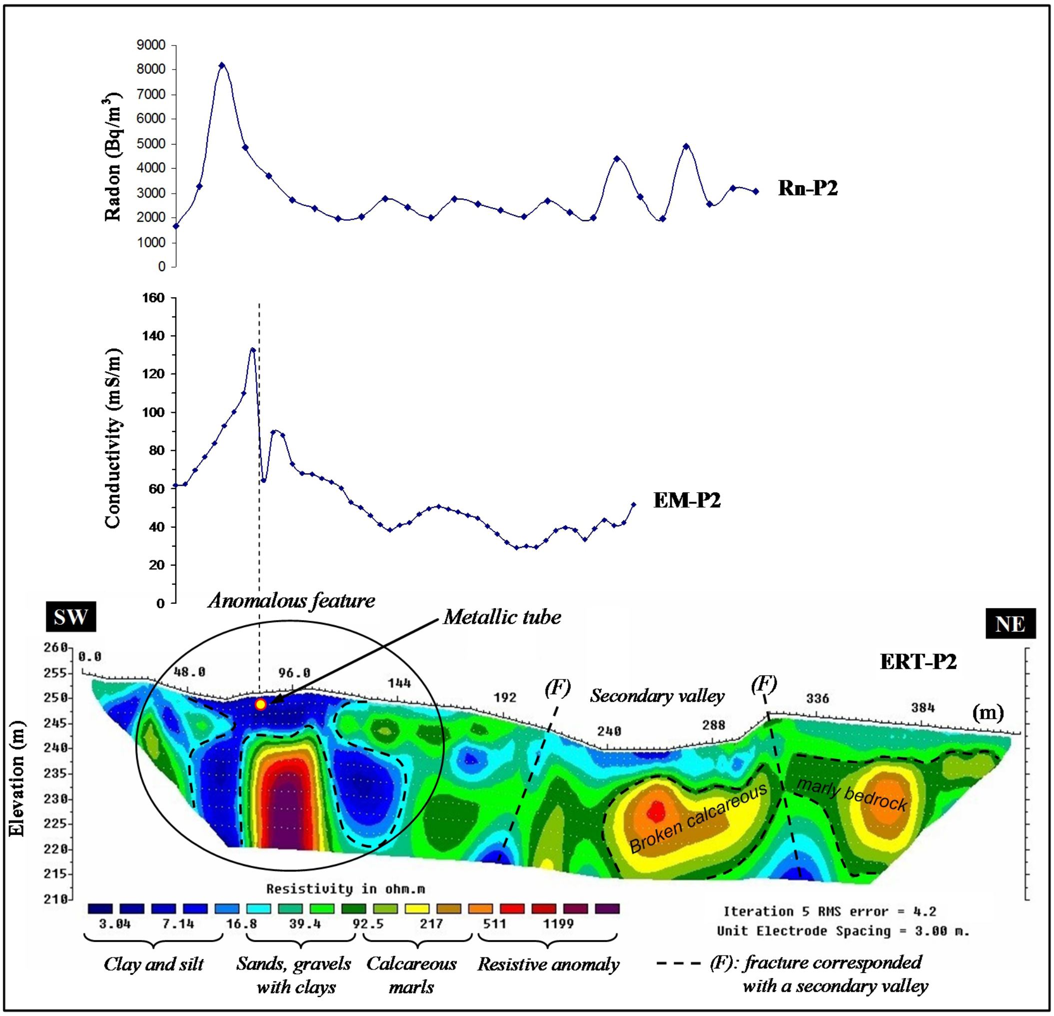

Figure 5. Interpretation of the P2 profile which includes the results of ERT, EM and soil radon measuements carried out in Afamia B dam.

situation and could play a negative role in permitting the water to leak down through the cracks that bounded the anomalous object. As the survey proceeds along the same profile (ERT-P2), another clay deposits were observed between the distances 240 and 300m from the start point of the profile. These deposits are lying through a small depression of branch valley that intersects perpendicularly with the linear course of the main valley in the area. However, the field observations indicate that such upright junction is mostly controlled by local tectonics where small fault segments are probably branching out from the main fault associated with the main valley. Moreover, it is clear that the local tectonic setting has led to the break the impermeable hard marl bed coincided with the secondary valley between the distances 210-310m of the ERT section (Figure 5). This finding may enhance in certain way to the occurrence of vertical leakage processes across the secondary valley.

Concerning the EM-P2 measurements, it has been observed that the electrical conductivity values increased notably above the detected anomalous feature reaching 140mS/m (7Ω.m). The high conductivity values can be attributed to the accumulation of the clay deposits above the aforesaid abnormal feature. The shifting point which is observed on the EM curve at a distance of 80m from starting point of the ERT-P1 section is mostly related to the existence of a buried metallic tube at 2m depth, which is connected to the filling tower for air evacuation uses. As the concerned metallic tube is completely surrounded by clayey deposits, thus it cannot be differentiated clearly by the ERT technique because there is no sufficient contrast in the electrical resistivity, while the EM technique is more sensitive and adequate for detecting buried metallic objects (Bevan, 2013; Dionne *et al*., 2011). On the other hand, a major radon anomaly with a peak value of more than twice higher than the average background level was also recorded at the same locality where the abovementioned subsurface anomalous feature was detected on the ERT-P2 section (Figure5). This anomalous radon observation is probably related to the surrounding environment of the detected object itself, which may provide an additional driving mechanism that could enhance the upward flow of radon gas through the outer boundary openings and fractures. The detected buried feature seemed to be coated by a thin layer of clay which seems to be shifted downwards through bounding fractures and by the flowing water and re-precipitated underneath the surface along the periphery of the object. Such process indicates mostly vertical discontinuity zones which may possibly

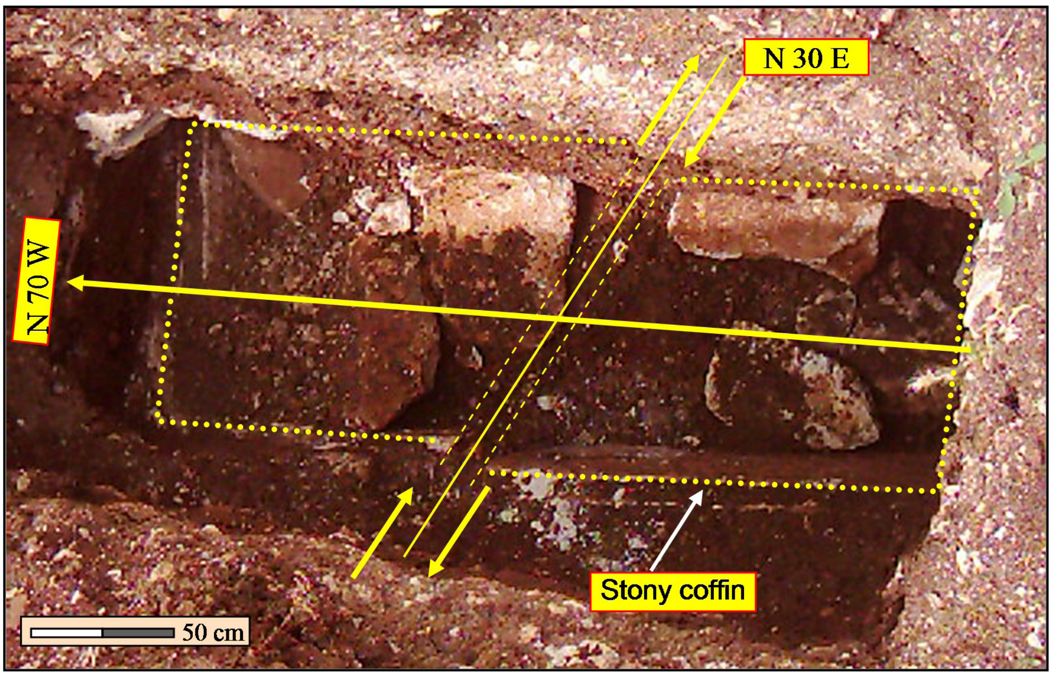

Figure 6. A photo of an archeological grave showing a diagonal fracture in a stony coffin found in the Afamia B dam’s lake.

assist the downward leakage of water from the dam's lake. Another two smaller peaks of radon concentration with EM values were observed along the same measuring profile at a distance of 240m and 280m from the start point of ERT section (Figure 5). These two adjoining radon peaks appear to be consistent with the locality of a deformed structure at the margins of the secondary branch, where it intersects with the course of the main valley. Additionally, as it is mentioned above the Afamia dam's lake forms a distinctive archeological site where a hundreds of ruined graves other old vestiges of human activities are distributed throughout the lake. One of the field observations in this study, revealed the discovery of a tomb containing a stony coffin of 3m length and 1.25m width (Figure 6). This coffin is subjected to diagonal fracture in its middle part (N30E), this could be due to either the influence of the dynamic stress of the surrounding clays, or due to the effect of historic seismic activities which are commonly characterizing the region, where it is believed that one of these seisms is considered the responsible for the destruction of the ancient city of Afamia. The archeological occurrences could also play an additional role in increasing the permeability of the bottom of the reservoir through possible hydraulic connections between the surface and the deeper permeable karstified formations.

Finally, depending on the results of the geophysical surveys interpretations and some lithological column of boreholes drilled in Afamia dam, a conceptual model was proposed to describe the probable mechanism of water leakage in the dam (Figure 7). Accordingly, two types of leakages can be identified; the first one is a subhorizontal leakage which occurs basically through the permeable layers of sands and gravels. The subhorizontal leakage afterward follows vertical paths in certain locations especially when it meets fractured zones within the calcareous marly beds. The second type of water losses is a vertical leakage, which basically takes place through the base of the main valley and its margins. The marly bedrock which constitutes the bottom of dam's lake seems to be severely eroded and deformed, and thereby it strongly enhances the vertical water leakage processes, which represents the major component of the leakage in the dam.

Conclusions

The results presented herein demonstrated the usefulness of using a combination of various techniques including electrical tomography (ERT), electromagnetic (EM) and soil radon survey, for characterizing the main causes of water leakage in Afamia B dam. A positive

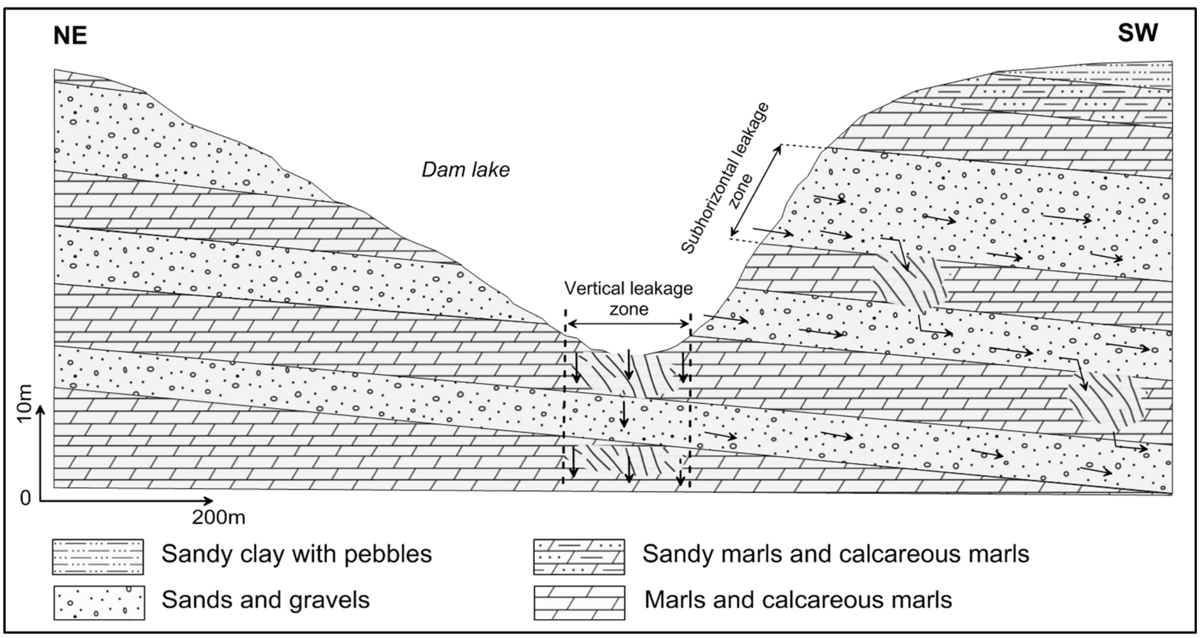

Figure 7. A conceptual model describes the mechanism of the water leakage in Afamia B dam depending on the interpretation of the geophysical and geological data.

correlation has been found between the signals obtained with the application of the three different methods. The interpretation of the ERT-P1 section revealed that the underlying geological structure of the dam basin is mainly consisted of successive lithological beddings of permeable sandy layers alternating with impermeable calcareous marly beds. The difference in permeability properties between the two lithological units is mostly led to a subhorizontal water leakage that occurs through the permeable layers, which form the shoulders of the main valley. This type of leakage is turned out to be a vertical seepage through a pattern of downward trending fractured zones (Figure 7). Moreover, the deformed bedrock and the notable erosion of its surface may play an essential role in developing the processes of vertical leakage through the bottom of the dam lake, especially at the margins of the valley. Such investigated structures could effectively contribute to the water outflow through the concerned dam basin. A notable anomalous subsurface object was detected at the beginning of the ERT- P2 profile, which constitute an additional factor that facilitates water losses close to the dam body. Furthermore, the site of Afamia dam contained numerous archeological ruins such as graves, olds wells and other vestiges human activities, which certainly increase the permeability through the bottom of the reservoir, and thereby enhance the leakage processes from the dam. Finally, the results of this study indicated the successful integrated interpretation of data from geophysical survey (ERT and EM) along with soil gas radon profiles in characterizing buried tectonic structures and delineating various hidden weak zones.

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