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DAM SEEPAGE ASSESSMENT BASED ON COMBINED ELECTRICAL RESISTIVITY TOMOGRAPHY AND ENVIRONMENTAL ISOTOPE TECHNIQUES AT MACHAP RESERVOIR, MALAYSIA

LAKAM MEJUS[1], JAMAL ASFAHANI[2], MOHD MUZAMIL MOHD HASHIM[1], RAHMAN YACCUP[1], MOHAMAD SYAHIRAN MUSTAFFA[1] AND GEOFFERY JAMES GERUSU[3,4]

[1]*Waste and Environmental Technology Division, Malaysian Nuclear Agency, Bangi, 43000 Kajang, Selangor, Malaysia.*
[2]*Syria Atomic Energy Commission of Syria, Kara Souseh P.O. Box 6091, Damascus, Syria.*
[3]*Department of Forestry Science, Faculty of Agricultural Science and Forestry, UPM Bintulu Sarawak Campus, Jalan Nyabau, 97000 Bintulu, Sarawak.*
[4]*Institute Ekosains Borneo, UPM Bintulu Sarawak Campus, Jalan Nyabau, 97000 Bintulu, Sarawak*

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ABSTRACT

Most of the earthen dams around the world unfortunately suffer from common filtration or leakage problems, which may occur either through the bedrock of dam's lake or through the dam body foundations. The dam seepage assessment normally is determined based on a single method to generate seepage pathway. However, the commonly used approach such as geophysical method has yet to be satisfactorily yield reliable results by most of the developing countries including Malaysia. This study aimed to provide reliable and vital data on dam seepage problem based on combination of Electrical Resistivity Tomography (ERT) and environmental isotopes approaches. ERT was applied to characterize the subsurface soil materials within the wetness area and environmental isotope approach was used to determine the water origin. This study was conducted at Machap dam in Peninsular Malaysia. The 2D inversion results based on ERT showed a contrasting resistivity values suggest a one-layer structure model with solid backfill materials on the surface. The most prominent feature in the vertical sections is the clear contrast between the conductive unit (<100 Ωm) and resistive unit (>100 Ωm). The conductive unit is distinctly continuous thick layering with the depth varying from 8 m to 30 m, indicative of potential water saturated zone or recharge pathways. The isotope ratio data revealed that the wetness area or of the natural ground is identical to the groundwater component and far different from that of Machap reservoir water. It is indicated that the wetness area can be associated with groundwater origin and is probably controlled by the natural topography of the groundwater contours and drainage characteristics of the soil media. The study verified that a combination of ERT-environmental isotope approaches able to assess dam seepage effectively and more reliable.

KEY WORDS : Tomographic imagery, Stable isotope, Seepage, Wet areas, Groundwater, Malaysia

INTRODUCTION

Most of the earthen dams around the world unfortunately suffer from common filtration or leakage problems. Water leakage in dam almost occurs either through the bedrock of dam's lake or through the dam body foundations. The geological and tectonic features such as faults, fractures and karstic features are the main factors of the leakage causes in earthen dams (Alsaigh *et al.*, 1994; Johansson and Dahlin, 1996; Panthulu *et al.*, 2001; Wan and Fell, 2004; Rozycki *et al.*, 2006; Oh and Sun, 2008; Asfahani *et al.*, 2010; Boleve *et al.*, 2011; Bedrosian *et al.*, 2012).

The increasing interest in using geophysical methods in dam seepage assessment is because the ability of geophysics to provide spatially distributed models of physical properties in areas that are difficult to sample using conventional sampling methods. Geophysical images often provide information about large-scale geological structures. In addition, strong contrasting subsurface structure can be characterized by different physical properties, which gives the potential for identifying different stratigraphic units (e.g. McClymont *et al.*, 2011). Modern geophysical techniques are actually practiced and considered as an effective tool in dam's water leakage investigations. Recently, Electrical Resistivity Tomography (ERT) technique has becomes one of the main geophysical tools widely employed in earth sciences and hydrogeology applications. ERT has proven its performance in detecting the leakage pathways occurring in earthen dams through numerous works around the world (Seaton and Burbey, 2002; Sjödahl *et al*., 2005; Cho and Yeom, 2007; Zhu *et al*., 2011; Al-Fares 2011; Thompson *et al*., 2012; Ikard *et al*., 2014). Syria has its own experience in this regards, where several dams have been studied and analyzed. The recent case study of Abu Baara dam is an example, oriented towards showing the important role of ERT to solve hydrogeological problems basically related to dam leakages (Al-Fares and Asfahani, 2018). This approach could be easily practiced in other dams suffering from similar leakage's problems.

Results from an individual geophysical method may provide enough information. However, this also may lead to an ambiguous interpretation. In order to minimise the ambiguity and fully utilise the geophysical data, combining method to verify the interpretation or using a priori information within a geophysical investigation may offer greater effectiveness in subsurface characterization. Therefore it would be useful to have methods that are capable of aiding the geophysical investigations.

The origin of seepage water and its inter-relationship with other types of water at and around the dam could be also investigated by using isotope hydrology techniques. There are many case studies involving the use of environmental isotope and tracer techniques reported with regard to better understanding and better addressing the dam seepage and leakage phenomena. For instance, Pakistan Institute of Nuclear Science and Technology (PINSTECH) researchers (Ahmad *et al.*, 2007) used stable isotope techniques in investigating inter-relationship between delay action dams and groundwater in Ziarat Valley of Balochistan, Pakistan. Dam safety and dam sustainability issues like location of seepage entry zones on reservoir side, delineation of seepage paths in dam structures, assessment of efficiency of remedial measures, examination of soundness of bed rocks at dam sites are case studies and have been successfully investigated by using isotope techniques (e.g. Petitta *et al*., 2010; Noble and Ansari, 2017). Additional information provided by this isotopic technique is of course useful for dam owners to help gain a better understanding of their dam safety problems and potential shortcomings. Thus, applying this technique can provide supplementary information and complimentary to conventional geophysical approached techniques in addressing certain dam safety problems.

Literature on dam seepage assessment is still limited especially in Malaysia on reliable method/approach or risk of seepage. Nowadays, dam seepage/leakage is considered as serious risk/threat on downstream safety. In the course of time, dam structure may deteriorate due to ageing and in some cases higher internal pressures and paths of seepage may develop. Usually these processes are slow and not readily discerned by routine examination. In most cases, the origin of undesirable seepage or leakage is unknown and its connection with other water bodies at and around the dam body is not always possible to be predicted using conventional approaches.

The dam seepage assessment normally determined based on single method/approach to generate seepage pathway instead of applying a combined methods/approaches. However, the commonly used approach has yet to be satisfactorily yield reliable results by most of the developing countries including Malaysia. Hence, an attempt have been made to apply a combined method/approach to assess the dam seepage problem is rarely available. In Malaysia, another crucial issue in the assessment of dam seepage are data scarcity, not documented scientifically and difficult to access as most data collected is considered confidential by most of the dam management. The novelty of this research is the determination of dam seepage using a combination of two potential approaches namely ERT and isotope. As the studies on dam seepage assessment are limited, these findings may serve as useful guidelines to initiate a dam risk management practice in Malaysia. Hence, this study aimed to verify the performance of the proposed combination of ERT and environmental isotopes approaches to provide more reliable data on dam seepage problem. The study also evaluating the inter-relationship among the seepage water (wetness area), reservoir water and groundwater flow in vicinity area.

MATERIALS AND METHODS

Geological and Hydrogeological Study Background

Geologically, the Machap dam area is mainly covered by rocks belonging to Lower Mesozoic age (Figure 1). This Lower Mesozoic sedimentary rock are made up of Upper Triassic to Middle Triassic marine sediments composed mainly of alternating sequence of carbonaceous shale, mudstone and rhyolitic tuff with minor of siltstone and sandstone (Khoo, 1983; Leman, 2004). Earlier geological studies have introduced these sedimentary rocks formation name as Gemas Formation (Foo, 1970; Loganathan, 1977; Khoo, 1983). However, following an extensive geological study conducted by Mohamed (1990; 1996), Gemas formation was considered as part of Semantan Formation due to their very similar characters (in term of lithology, paleontology and structural pattern). Semantan Formation mainly distributed at the center of Central Belt of Peninsular Malaysia. Hydrogeologically, the Gemas formation

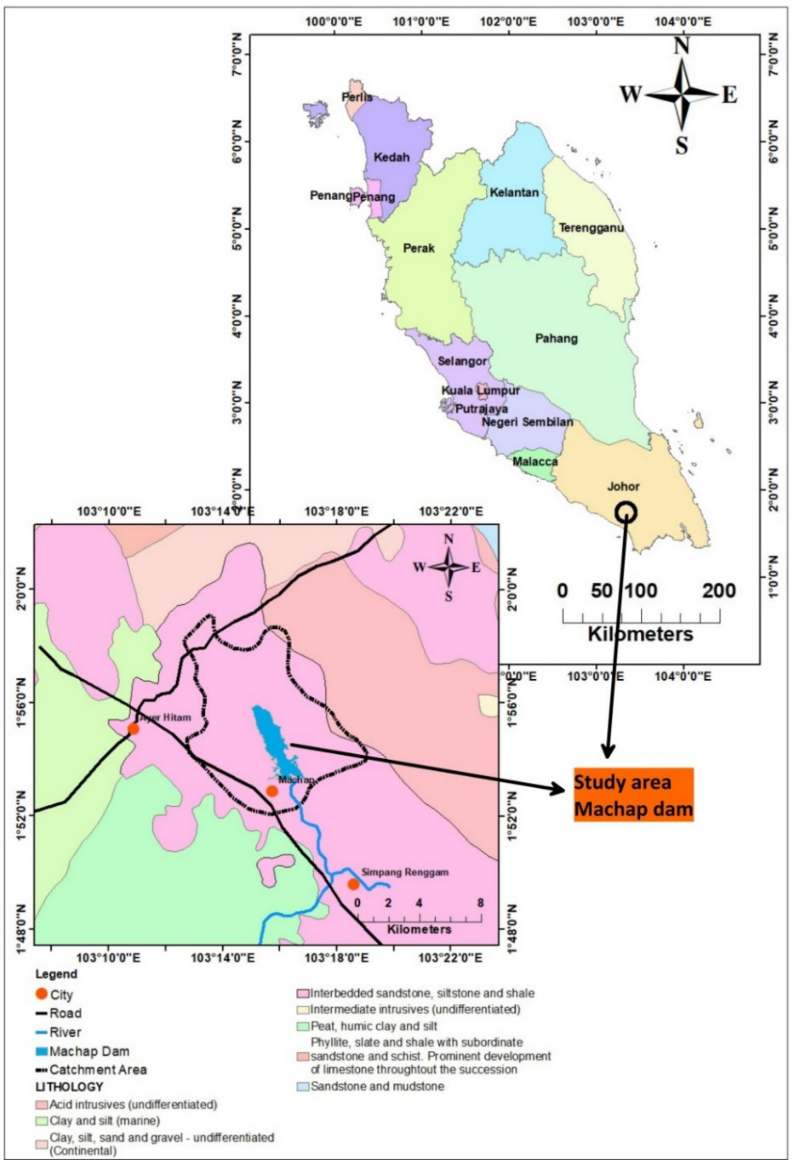

Fig. 1. Location and Geology of the Catchment Area

is considered the main groundwater resource in the area. However, due to the abundance of surface waters in the river systems, groundwater has not been much exploited in the state of Johor Darul Takzim. Most of the water requirements in the state, for domestic, industrial and irrigation water needs, come directly from river sources. Therefore the construction of Machap dam, which completed in 1982, is a part of an extensive drainage infrastructural works carried out under the Western Johor Agricultural Development Project.

Machap Dam Characterizations

Machap dam is situated at the southern part of Peninsular Malaysia, in the state of Johor Darul Takzim. The Machap dam catchment area is 77 km^2 bounded by 1°53.3' N and 103°16.3' E. The dam comprises an earthfill main dam, an earthfill saddle dam and a service spillway structure with radial gates (DID, 2008) (Figure 2). The construction of Machap dam in Malaysia which is completed in 1982 is a part of an extensive drainage infrastructural works carried out under the Western Johor Agricultural Development Project. The primary purpose of Machap dam is for flood mitigation. The dam also serves to store a part of flood discharge of Benut river, thus reducing the intensity of flood downstream. It was designed to retain 25-years flood with a maximum downstream release of 540 cusecs, which is the capacity of downstream channel. The stored water in the reservoir is used to regulate Machap river(one of its major tributaries) flows to Johor Water Company intake located further downstream for domestic water supply.

Electrical Resistivity Tomography

Four electrodes measurements are made in the field environmentto obtain the resistivity distribution of the subsurface. Resistivity or electrical conductivity ($\rho = 1/\sigma$) of a media is obtained by injecting direct current (DC) between two electrodes (C1 and C2) and measuring the voltage difference between two other electrodes (P1 and P2) as shown in Figure 3.

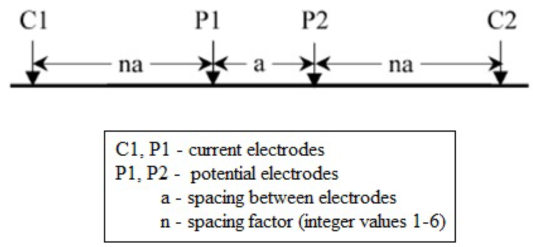

Fig. 3. Schematic showing the Wenner-Schlumberger's electrode configuration used for the electrical resistivity tomography survey in this study (modified from Loke, 1999).

Consequently, resistivity is defined by the product of the ratio of the voltage difference (ΔV) to an induced current (I) and the geometric factor:

$$\rho_a = \frac{1}{\sigma_a} = \frac{G_f \Delta V}{I}, \quad .. (1)$$

where ρ_a is referred to the apparent resistivity, σ_a is referred to the apparent conductivity and G_f is called the geometric factor. The term apparent resistivity is usually used as a convenient measure

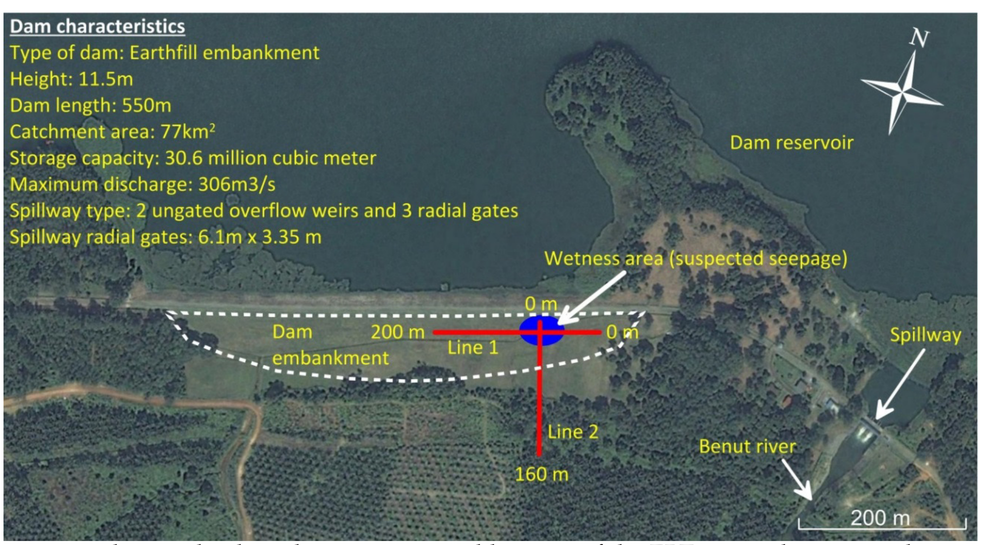

Fig.2. Information regarding to the dam characteristics and location of the ERT survey lines carried out in Machap dam.

to describe the resistivity value for a homogeneous subsurface that is independent of the electrode configuration. In this case, if the flat earth's subsurface is homogeneous, the apparent resistivity (ρ_a) is the true resistivity of the subsurface. However, the earth subsurface is not homogeneous, thus the computation of true resistivity values is necessary accounted for a certain electrode configuration. Electrical resistivity tomography (ERT) refers to the automated collection of a large number of resistance measurements from which an image of the resistivity distribution of the investigated area/ medium is reconstructed. ERT survey has been carried out with an ABEM Terrameter SAS 4000 system and a LUND electrode selector system (ES464) for data acquisition (Figure 3b). The ERT profile was collected by employing Wenner-Schlumberger electrode configuration to provide good lateral resolution. The along-line electrode separation was 2 m, which enable data coverage to a depth of approximately thirty (30) m. Sixty one (61) electrodes were plucked into the ground, where the ES464 system automatically select four active electrodes for each measurement based on the selected array input. The resistance of the subsurface material is determined by injecting a certain amount of electrical current (10-50 mA) into the ground through a pair of electrodes and the resulting voltage (potential) is measured at a different pair of electrodes. The standard deviation of the measured voltage was set at ± 3 % with a maximum 3 stacking cycles to observe a good data quality.

RES2DINV (Geotomo software) inversion package is used for inverting ERT data sets and to generate a two-dimensional (2D) resistivity model as shown in Fig.3-b. The RES2DINV inversion package is a forward/inverse solution for a 2D resistivity distribution based on least-square method involving finite-element and finite-difference methods. This inversion method minimizes the square of the differences between measured and calculated apparent resistivity values, and produces earth resistivity models with gradual transitions across zones of different resistivities (Seaton and Burbey, 2002).

Root mean square error () is used to evaluate the measured data and theoretically calculated data, i.e. the statistical measure of the magnitude of quantity. The error can be calculated as follows:

$$\mathrm{RMS} = \sqrt{\frac{1}{n^2}\sum_{i=1}^{n}\left(\frac{\log(\rho_{\mathrm{meas}_i}) - \log(\rho_{\mathrm{cal}_i})}{\log(\rho_{\mathrm{cal}_i})}\right)^2}, \quad (2)$$

where is the measured apparent resistivity; is the calculated apparent resistivity from a certain resistivity section. The sub index indicates the measuring points and is the number of the measurement points.

Environmental Isotopes

Environmental stable isotopes of water (^{18}O, ^{2}H) are primarily used in isotope hydrology to identify

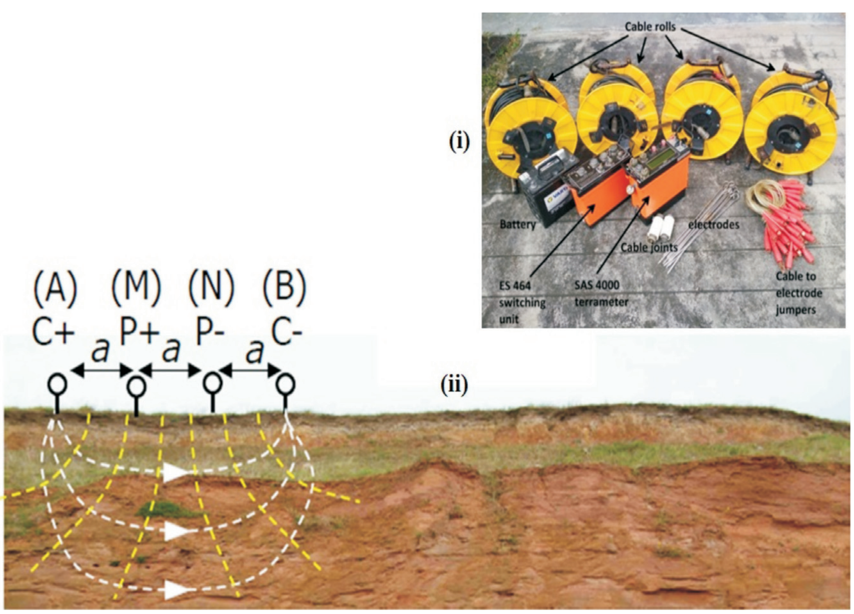

Fig. 4. (i) Instrumentation used for the ERT survey. ii) Illustration of four electrodes measurement in the field and the current paths in a medium.

water bodies of different origins and determine the hydraulic connection, if any, between the surface water (i.e. dam reservoir) and the groundwater system/seepage. A set of water samples (approximately 22 samples, 30 ml each) in the study area were collected from the reservoir (i.e. at several locations), groundwater (i.e. from installed stand pipe type piezometers at different depth), seepage waters (i.e. from the collected surface drain available withinthe wet area in the left abutment of the main dam and outlet pipe)and river waterin the surrounding area of the Machap dam (Figure 5, Table 1). However, some sampling location has no recovery due to dry. All types of water samples were collected during two different monsoon seasons, dry and wet seasons (April 2017 and August 2017 respectively) for the purposed to analysetheir stable isotope composition of oxygen 18 (^{18}O) and deuterium (D or ^{2}H) as well as electro-conductivity (EC). All parameters, which were examined and analyzed from various water bodies at the study site,are to be used for water fingerprinting evaluation. The stables isotopes ^{18}O and ^{2}H were analyzed in the laboratory at Malaysian Nuclear Agency using Isotope Ratio Mass Spectrometer (IRMS) SIRA-2.Water electrical conductivity of each sample was measured in the field using portable conductivity meter to assess the concentration of ions in the water and their inter-relation among water bodies.

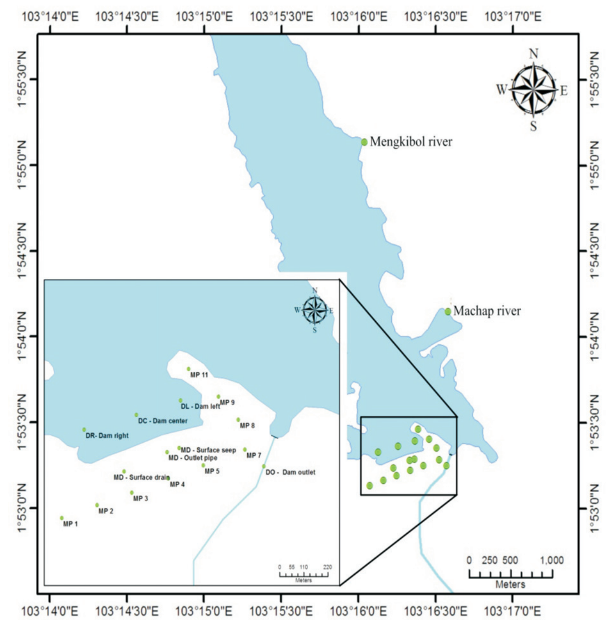

Fig. 5. Water sampling location

RESULTS AND DISCUSSION

2D Electrical Resistivity Tomography

Two dedicated resistivity survey lines (Line 1 and

Table 1. Coordinates and types of water samples collected from the Machap Dam reservoir and surrounding

No.	Coordinates system		Sampling location	Types of water
1	1°53′9.20"N	103°16′2.13"E	MP1	Groundwater
2	1°53′10.92"N	103°16′7.36"E	MP2/2	Groundwater
3	1°53′12.11"N	103°16′12.44"E	MP3/2	Groundwater
4	1°53′14.06"N	103°16′18.48"E	MP4/2	Groundwater
5	1°53′15.78"N	103°16′24.82"E	MP5/1	Groundwater
6	1°53′16.41"N	103°16′30.67"E	MP7/1	Groundwater
7	1°53′16.41"N	103°16′30.67"E	MP7/2	Groundwater
8	1°53′19.52"N	103°16′30.23"E	MP8/2	Groundwater
9	1°53′22.75"N	103°16′28.56"E	MP9/1	Groundwater
10	1°53′22.75"N	103°16′28.56"E	MP9/2	Groundwater
11	1°53′26.92"N	103°16′24.49"E	MP11/1	Groundwater
12	1°53′26.92"N	103°16′24.49"E	MP11/2	Groundwater
13	1°53′17.09"N	103°16′21.77"E	MD - outlet pipe	Seepage water
14	1°53′16.05"N	103°16′17.54"E	MD - surface drain	Seepage water
15	1°53′17.65"N	103°16′21.41"E	MD - surface seep	Seepage water
16	1°53′22.41"N	103°16′23.25"E	DL - Dam Left	Dam water
17	1°53′18.32"N	103°16′5.84"E	DR - Dam Right	Dam water
18	1°53′20.75"N	103°16′13.80"E	DC(S) - Dam center	Dam water
19	1°53′20.75"N	103°16′13.80"E	DC(B) - Dam center	Dam water
20	1°53′16.36"N	103°16′35.20"E	DO - Dam outlet	Dam water
21	1°54′2.52"N	103°16′46.79"E	SM - Machap river	River water
22	1°54′23.02"N	103°16′24.07"E	SMB - Mengkibol river	River water

Line 2), which are considered making a corner and perpendicular to each other are carried out at the concerned left downstream toe abutment. The inversion results of the ERT survey for line 1 and line 2 are shown in Figure 6. The inversion results show that the contrasting resistivity values indicate a one-layer structure model with solid backfill materials on the surface. The black dashed lines were interpreted to represent water saturated zone or clay-rich unit. The most prominent feature in the vertical sections is the clear contrast between the conductive unit (<100 Ωm) and resistive unit (>100 Ωm). The conductive unit is distinctly continuous thick layering with the depth varying from 8 m to 30 m, indicative of potential water saturated zone or recharge pathways to the underlying deeper unit. The high resistive zone (orange contour color) for the upper layer of the surveyed section may be due to impervious material. The contours of resistivity results show in general the existence of in homogeneous strata in the study area. The presence of low resistivity anomalies is probably due to some possibilities. The occurrence of low resistivity anomalies observed at larger depths can be related to the high moisture contents. The pattern of low resistivity anomalies may likely also be related to high porosity (weak zone), preferable zones in which groundwater most likely to flow. Other possible assumption is that the low resistivity anomaly could be related to the presence of material in the bottom liner (i.e., clay layer which is connected to a horizontal drainage blanket provided in the downstream shoulder). It seems there is no indication of seepage water flowing from upstream reservoir channel, and seeped through the soil strata at the left abutment along the main dam. In addition, no possibility of piping is observed within the low resistivity anomalies. Therefore, we assume that this low resistivity zone indicative of potential water saturated zone or recharge pathways.

Stable Isotopes of Water (^{18}O and ^{2}H) and EC

The two sampling campaigns indicate that there is nomuch variation of isotopic compositions for all the analyzed water bodies. However, some groundwater in certain piezometers and all reservoir (dam water) samples exhibit a marked evaporative enrichment especially during the dry season. Table 2 and 3 show the results from the IRMS analysis. Most of the water samples obey the Local Meteoric Water Line (LMWL) of $\delta D=8\delta^{18}O + 13.7$ established from Malaysian's precipitation (rainwater) data. The isotopic data of each sampling campaign is plotted on δ D vs. δ^{18}O diagram as shown in Figure 7 and 8.

The mean isotopic compositions of δ^{18}O of reservoir, groundwater, seepage water and from local rainwater in the first sampling (dry season) are -5.67 %o, -6.83 %o, -6.79 %o, and -6.59 %o respectively. The mean isotopic indices (δ^{18}O) for

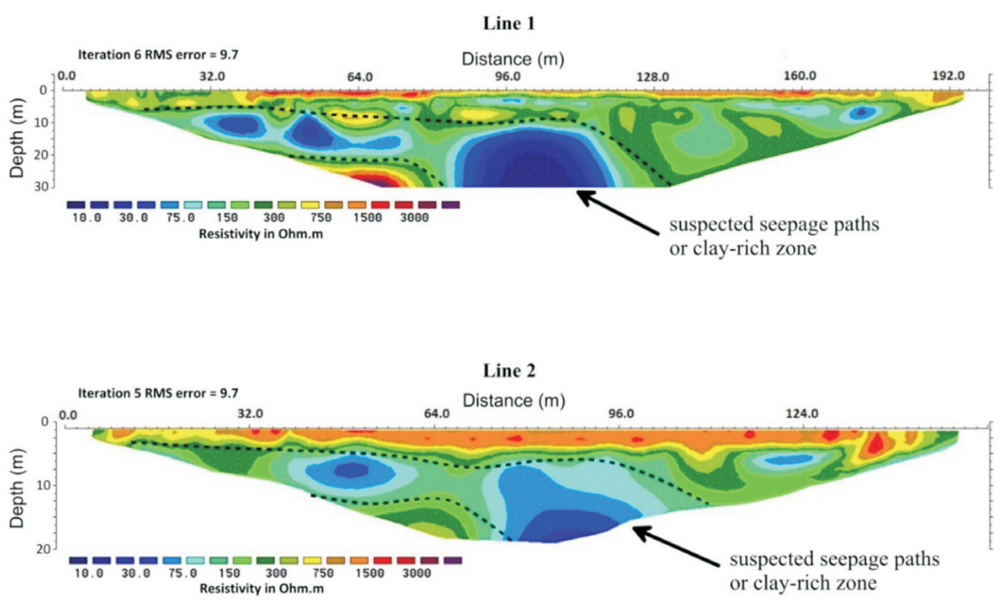

Fig. 6. The inversion results of the ERT surveys. The contrasting resistivity values indicate a one-layer structure model with solid backfill materials on the surface. The blackdashed lines indicate the water saturated (suspected seepage) or clay-rich unit.

reservoir, groundwater, seepage water, river and rainwater in the second sampling (wet season) are -5.22‰, -7.02 %o , -6.92 %o , -6.58 %o and -6.43 %o respectively. This observation indicates that the $\delta^{18}O$ and δD values of groundwater and seepage are relatively depleted during the wet season than the isotopic compositions in the dry season. However, it is shown from the observation of both sampling

Table 2. Isotope resultsfor water samples collected in April 2017 (wet season).

	Sampling location	Types of water	EC (µS/cm)	$\delta^{18}O$ (%o)	δD (%o)
1	MP1	groundwater	22	-6.6	-39.9
2	MP2/2	groundwater	31.4	-7.49	-43.5
3	MP3/2	groundwater	52.1	-7.78	-47.3
4	MP4/2	groundwater	80.1	-7.89	-42.9
5	MP5/1	groundwater	110.5	-7.09	-36.1
6	MP7/1	groundwater	63.5	-7.01	-35.5
7	MP7/2	groundwater	88	-6.96	-35.9
8	MP8/2	groundwater	130.1	-5.92	-34.6
9	MP9/1	groundwater	158	-6.94	-42.9
10	MP9/2	groundwater	234	-7.3	-40.4
11	MP11/1	groundwater	155.4	-6.4	-38.2
12	MP11/2	groundwater	185	-6.0	-39.2
13	MD1 - outfall pipe	seepage water	101.1	-7.22	-40.2
14	MD2 - main drain	seepage water	51.7	-6.79	-37.1
15	MD3 - unexpected seep	seepage water	61.7	-6.75	-38.5
16	DL - Dam Left	reservoir water	36.5	-5.24	-35.6
17	DR - Dam Right	reservoir water	40.8	-5.21	-33.4
18	DC(S) - Dam center	reservoir water	35.8	-5.15	-31.2
19	DC(B) - Dam center	reservoir water	35.8	-5.23	-35.7
20	DO - Dam outlet	reservoir water	40.9	-5.28	-36.2
21	SM - Machap river	river water	31.4	-6.86	-38.8
22	SMB - Menkibol river	river water	45.3	-7.56	-42.2

Table 3. Isotopes result for water samples collected in August 2017 (dry season).

	Sampling location	Types of water	EC (µS/cm)	$\delta^{18}O$ (%o)	δD (%o)
1	MP1	groundwater	30.5	-6.01	-39
2	MP2/2	groundwater	52.5	-6.41	-38.5
3	MP3/2	groundwater	-	-	-
4	MP4/2	groundwater	-	-	-
5	MP5/1	groundwater	248	-6.71	-38.1
6	MP7/1	groundwater	49.1	-7.32	-46.73
7	MP7/2	groundwater	38.4	-6.53	-38.5
8	MP8/2	groundwater	126.1	-6.88	-43.3
9	MP9/1	groundwater	230	-6.96	-42.1
10	MP9/2	groundwater	301	-7.36	-43
11	MP11/1	groundwater	204	-7.5	-41.1
12	MP11/2	groundwater	185	-6.57	-41.5
13	MD1 - outfall pipe	seepage water	45.9	-6.77	-38.9
14	MD2 - main drain	seepage water	42	-6.77	-42.13
15	MD3 - unexpected seep	seepage water	-	-	-
16	DL - Dam Left	reservoir water	61.9	-5.69	-39.3
17	DR - Dam Right	reservoir water	39.5	-5.72	-37.7
18	DC(S) - Dam center	reservoir water	44.6	-5.51	-38.5
19	DC(B) - Dam center	reservoir water	49.1	-5.73	-37.8
20	DO - Dam outlet	reservoir water	66.1	-5.7	-39.2
21	SM - Machap river	river water	-	-	-
22	SMB - Menkibol river	river water	-	-	-

campaigns, that the seepage water of the natural ground is quite identical to the groundwater component and far different from that of Machap reservoir or dam water. Hence, one could say that the seepage water reported to be emanating from below the block drains and found within the wet zone at the left downstream toe seems to have no contribution of Machap reservoir. Additionally, the condition of seepage water during the field investigation was found to be clear and free of sediments.

A buildup of groundwater table due to percolation of rain water through the top pervious stratum during heavy storms is likely to create wetness area and seepage particularly at the left toe abutment. This occurrenceis probably controlled by the natural topography of the groundwater contours and drainage characteristics of the soil media. The general rise in piezometric levels and seepage quantity during and after the heavy storms werealso observed at this studied site. In other word, piezometric levels significantly exceed of the natural ground after rainfall event. It should also be pointed out that the major source of seepage being observed at this place is likely and largely attributable to groundwater table build up in this area (exceed the natural ground). The contribution from reservoir water itself seems to be insignificant.

The EC measurements were reasonably homogeny in all sampling location over the two times sampling period. Slightly lower value of EC measured in the seepage water is anticipated and perhaps may corroborate its occasion with the mixture of shallow groundwater flow pathway in the surrounding area. Nevertheless, the seepage water EC value is slightly higher compared to the reservoir water, especially during the wet season. However, in certain circumstance, the limited EC values observed in all type of water bodies for both campaigns are quite difficult or not straight forward to supportthe findingin term of giving the possibility of hydraulic inter-relation among water bodies at and around the dam.

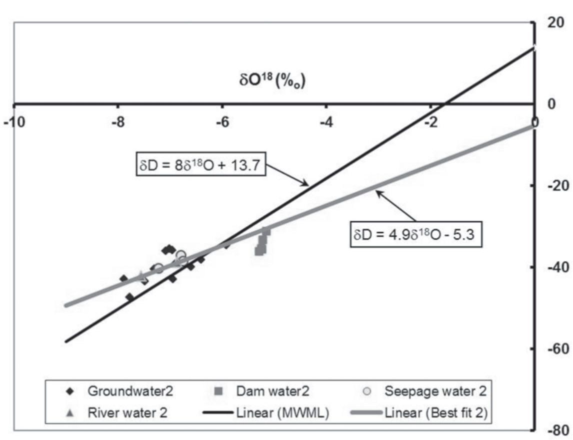

Fig. 7. The plot of δD vs. δ^{18}O of water samples collected in the first campaign (wet period) in April 2017.

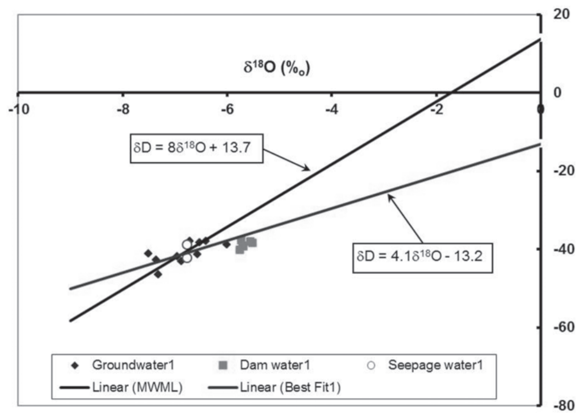

Fig. 8. The plot of δD vs. δ^{18}O of water samples collected in the second campaign (dry period) in August 2017.

CONCLUSION

Reviewing the results and discussions presented, a few conclusions can be made in regard to the site specific observations of the wet area. Information on low resistivity anomaly observed at the downstream toe of the main dam along the left abutment could either be related tothe preferential accumulation of electrically conductive zone due to the earth-fill material(clay-rich material) of the dam embankment foundation system and downstream toe;geologically considered as weak zone in which surface runoff may easily seeped throughor can be related to the present of natural spring. Although the present of this zone is unspecified whether related to the seepage point or wet area, information from isotope data is used to determine the inter-relationship between the water bodies. From isotopic data point of view, the emergence of seepage water and wet areas seem to have insignificant contribution from the reservoir itself. The major source of seepage observed in the left abutment is largely attributable to ground water table build up in this area (exceed the natural ground) mostly during and after the heavy storms. In the light of the results discussed above, there is perhaps a need to keep monitoring the condition of wetting zones (quantity and quality of seepages) when necessary by periodical resistivity and isotopic measurements, especially for few more wet seasons. The hydraulic head measurements are needed in order to assess the hydraulic connectivity between groundwater (from standpipe piezometer) and seepage water from the wetness area.

This study shows the limitation of a stand-alone method which may lead to an ambiguous interpretation. A stand-alone method may provide enough information depending on the specific objective to be achieved, cost related issue andtime required for the measurements and analysis. However, integrated or combined methods can offer more reliable trade-offs between solution uniqueness, data resolution and coverage. This study has verified that combination of ERT and environmental isotope approaches able to provide more reliable and precise assessment of dam seepage occurrence. In addition, more detailed information on the genesis and path behavior of seepage/leakage occurrence (if any) can be achieved.

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