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THE EFFECTIVENESS OF THE ELECTRICAL RESISTIVITY TECHNIQUES FOR EXPLORING GROUND WATER OCCURRENCES IN CAVERNOUS LIMESTONE (LABORATORY CASE STUDY)

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كفاءة تقنيات المقاومة الكهربائية لاستكشاف تواجدات المياه الجوفية فى الحجر الجيري المتكهف (دراسة حالة معملية)

الخلاصـــــة: الهدف من الدراسة هو استكشاف خزان الحجر الجيري المتكهف كدراسة حالة معمليا باستخدام تقنيات المقاومة الكهربائية وتشمل القياسات الكهربائية أحادية الأبعاد (1-D) ، ثنائية الأبعاد (2-D) ، و ثلاثية الأبعاد (3-D). تمت هذه القياســـات على نموذج من الحجر الجيري الصـــلب أبعاده (٢٠٥ سم * ٢٠٥ سم * ٣٠ سم) مع وجود فجوة فى منتصفه أبعادها ٣٠ سم * ٣٠ سم * ١٧ سم.

تم إجراء عدد ٧٧ جسـه كهربائية رأسـية موزعة علي شـكل شـبكة باسـتخدام طريقة فينر لتوزيع الأقطاب حيث تم توزيع أماكن الجسـات الكهربائية على ١٠ قطاعات تمتد من الجنوب إلى الشمال ومن الغرب إلى الشرق على نموذج الحجر الجيري ممثلا في أربع حالات: ثلاثة منها على الفجوة أو الكهف الموجود فى منتصــف النموذج (كهف مملوء نصــفه بالماء، كهف مملوء بالماء، كهف فارغ) والحالة الرابعة خارج الكهف أو الفجوة. تم أيضـــا عمل ٢٨ قطاعاً من المقاومة النوعية الكهربائية التصويرية ثنائية الأبعاد (2-D) باستخدام فينر في اتجاهين (جنوب – شمال) واتجاه (غرب – شرق) حيث تم توزيعهما في أربع حالات أيضـــا، ثلاث حالات تمر عبر الكهف وحالة خارج الكهف علي النموذج وكذلك تم عمل شـــبكة مقاومات (3-D) مكونة من ٤٢ × ٤٢ قطب على مسـتويات مختلفة لتحديد أبعاد الكهف. ومن تفسـير نتائج القياسـات الجيوكهربائية باسـتخدام برامج الكمبيوتر المخصـصـة لذلك تبين ان التتابع الجيوكهربائي الخاص بالنموذج يتكون من أربعة نطاقات جيوكهربائية (A,B,C & D) في حالة كهف نصـــفه مملوء بالماء، ثلاثة نطاقات جيوكهربائية (A,C & D) في حالة كهف ممتلئ بالماء بالكامل وفي حالة الكهف الفارغ والجاف و نطاقين جيوكهربائيين (A & D) في حالة القياس خارج الكهف. وأظهرت النتائج أن السـبب في حدوث تغيرات كبيرة في مقاومة النموذج قد يعزي إلى التباين في المقاومة بين جزء الفراغ عالي المقاومة و الجزء المشـبع الأقل مقاومة. وفقا لهذه الدراسة ، تم تحديد حدود أو أبعاد الكهف في الحجر الجيري أو / تواجدات المياه في الحجر الجيري المتكهف من خلال تقنيات المقاومه الكهربائية المختلفة. وجاءت نتائج المقاومة النوعية الكهربائية التصويرية ثنائية الأبعاد(2-D) والتصوير الكهربائى ثلاثي الأبعاد (3-D) متوافقه تماما مع نتائج الجسات الكهربائية الأحادية 1-D ومطابقة لبيانات الكهف في كل حالة. وقد أكدت هذه النتائج أهمية الطريقة الكهربائية بالتقنيات السـالفة الذكر فى اسـتكشـاف تواجدات المياه فى الحجر الجيرى المتكهف ومن ثم امكانية استخدامها بنجاح فى الصحارى المصرية.

ABSTRACT: *Electrical geophysical techniques, including 1-D vertical electrical sounding (VES); 2-D and 3-D resistivity imaging profiling, have been carried out in the laboratory on a cavernous limestone physical model in order to delineate the effect of the cavities on the measured resistivity values as a preliminary step for a field work in an area covered by cavernous limestone. The dimensions of the used limestone model were 205 cm*205cm*30 cm with a cavity, with dimensions of 30cm*30cm*17 cm, in its center. A number of 77 VES were measured on the limestone model in a grid pattern by using Wenner electrode array starting with a= 5 cm to a= 65 cm. A number of 28 profiles of 2-D resistivity imaging were carried out on the model, covering its middle cavity. 3-D resistivity grid with 42 X 42 electrodes was also carried out on the limestone model. All the above mentioned electrical techniques have been carried out on the limestone model when its middle cavity/cave was completely filled with fresh water, half – filled and empty with few measurements outside the cavity in its four directions. Processing and interpretation of the obtained results, with the above mentioned techniques, showed that the geoelectrical section of the limestone model consists of four layers (A, B, C and D) when the cavity/cave was half filled with fresh water, three layers (A, C and D) when it was completely filled with water and when it was empty, two layers (A and D) only when the measurements were done outside the cavity. These results confirmed the importance of the different geoelectrical techniques in delineating the water conditions of caves and cavities in cavernous limestone and could be applied successfully in the Egyptian deserts, covered by this kind of limestone.*

INTRODUCTION

Water is an essence food and basic component of life. The need for water is strongly ascending and has a diversified function, which is not only important for drinking purposes but it is also vital for any development activities. Nowadays, the use and sustainability of water is getting more complex due to population growth, urbanization and industrialization. Any development is related either directly or indirectly to water utilization.

Due to shortage in water resources, it was necessary to explore more aquifers which can store and transmit significant quantities of water, where groundwater is one of the Nation's most important natural resources. Rocks vary in the way they store water according to their porosity and permeability. The present study is interested in cavernous carbonate aquifers (limestone) because it covers large areas in Egypt and extends in the subsurface. Cavernous limestone aquifer is produced from karistification process. The importance of karst is represented in creation a complex underground water flow network that includes caves large enough for humans to access. Rainwater travels through the network until it reaches the water table. The karstified limestone acts as an aquifer where water can be stored and later extracted by humans. The main objective of this study is to test the effectiveness of electrical geophysical techniques, including 1-D vertical electrical sounding (VES), 2-D and 3-D resistivity imaging profiling, in delineating ground water in the cavities and caves of the cavernous limestone. This study deals with laboratory measurements, with these techniques, on a limestone physical model as a preliminary step for field applications. Electrical resistivity methods are promising techniques to assessment groundwater resources because they are sensitive to physical and chemical variations of the subsurface associated with changing groundwater quality (e.g. Louis et al., 2002; Shaaban 2004; Bowling et al., 2007; Barseem et al., 2016).

Description of the laboratory limestone model and measurements

A massive limestone block with dimensions of 205cm * 205cm * 30 cm was prepared with 30cm * 30cm * 17 cm cavity/cave in its center (Fig. 1) and the face of the model was covered by thin sheet of marly limestone (≈ 3cm). The electrical measurements, with the above mentioned techniques, were carried out on the model in three conditions which are: the cavity/cave is half water–filled, completely filled with fresh water and empty besides some soundings and profiles outside the cavity in all its directions (Fig. 2). The vertical electrical sounding (VES) method was usually applied in order to provide 1-D information about the vertical variation in the resistivity with depth (Ariyo et al. 2003: Enikanselu 2008; Sikandar et al., 2010). Two and three - dimensional (2-D & 3-D) resistivity imaging were subsequently employed to obtain cross-sectional images of the geoelectrical structure related to the lithology and the hydrogeological framework. Electrical Resistivity Imaging (ERI) is particularly well suited to detect groundwater flow pathways, regions of water storage and variations in water saturation (Loke et al. 2015; Eissa et al. 2015).

Several factors affect the resistivity of a rock including interconnected porosity, water saturation and salinity. The VES and electrical resistivity imaging measurements are based on injecting a low frequency current (I) into the ground using two metal electrodes (current electrodes) and measuring the resulting potential difference (ΔV) between another two sensing electrodes (potential electrodes).

DATA ACQUISITION

The electrical resistivity values, with the above mentioned techniques, have been measured on the limestone laboratory model by using ABEM terrameter SAS- 1000 resistivity device. This device has been designed to measure the resistance value (R) which was

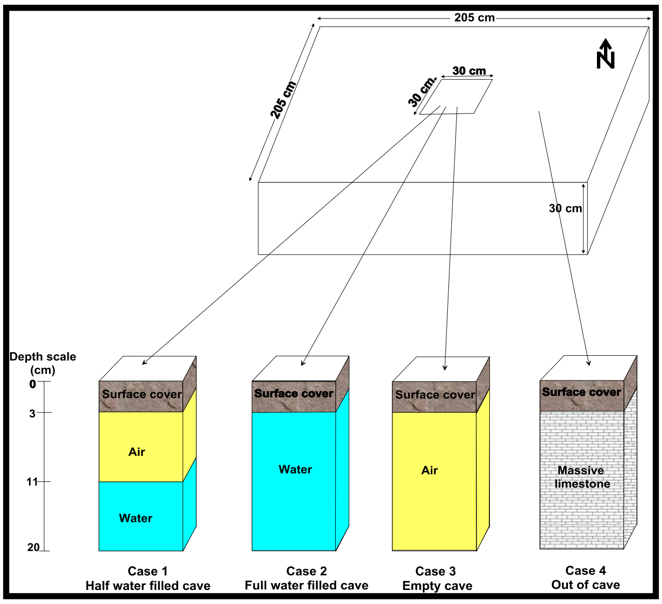

Fig. (1): Limestone laboratory model in its four conditions: cavity/cave filled with fresh water, half - filled, empty and outside the cave/ cavity.

used to estimate the apparent resistivity value in the light of the configuration factor, depending on the used array (Fig. 2). Wenner electrode array was used in this study to collect resistivity values for both sounding and imaging profiling. A detailed description of these measurements will be discussed as the followings:

a- Vertical Electrical Soundings (VES):

A number of 77 vertical electrical soundings (VES) with spacing 5 cm between each two successive stations have been measured on the limestone model by using Wenner electrode array with spacing of a=5 cm to a = 65 cm. These VES stations have been located along 10 profiles, some of them cover the cavity/cave in the middle of the model and others were outside the cavity (Fig. 3). All of the sounding measurements have been carried out when the cavity in its three conditions which are: completely filled with Tape water, half – filled with water and empty.

Fig. (2): Resistivity data acquisition during the laboratory measurements on the top of the limestone model, 10 cm long metal electrodes were used for both sounding and profiling.

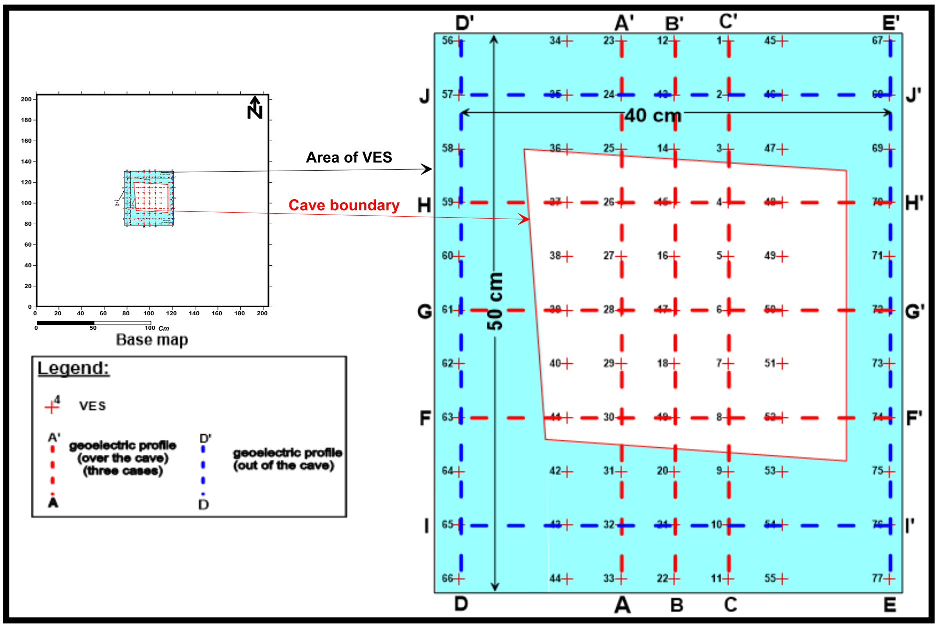

Fig. (3): Locations of the VES stations on the limestone laboratory model, some of them cover the cavity/cave and others are outside.

b- 2-D and 3-D resistivity imaging

A number of 28 two dimensional resistivity imaging profiles have also been measured on the limestone model by Wenner electrode array with 5 cm electrode spacing and a length of 205 cm for the profiles. These profiles were carried out in both directions (N-S and E-W) when the cavity/cave in its three conditions: half water-filled, Full of water and empty, whereas others were also measured outside the cavity (Fig. 4).

From the combination of the measured Wenner 2-D data, parallel and orthogonal the model (Fig.4), we get a Three – Dimensional (3-D) Resistivity grid of 42 × 42 electrodes at different levels. The interpretation of the 3-D electrical data was done by using RES3DINV program which produced six slices at different depths (0–3, 3–5, 5–9, 9–12, 12–17, and 17– 22 cm, respectively).The inversion system used by the RES3DINV program is based on the least squares method (deGroot et al., 1990, Sasaki, 1992 and Lock 2015).

RESULTS AND DISCUSSION

1- Vertical Electrical Soundings (VES) results:

The obtained VES curves on the examined laboratory limestone model with the three conditions of its cavity/cave (i.e. half water- filled, full of fresh water and empty) have been discussed as the followings:

Case 1: Half water filled cave:

In this case the model gave VES curves of KH- type ($\rho1<\rho2>\rho3<\rho4$) above the cavity/cave (sector A, Fig. 5) and A-type ($\rho1 <\rho2 <\rho3$) outside the cavity (sector B, Fig. 5). Automatic interpretation of the KH sounding curves indicated that the geoelectric section consists of four zones which are: the top zone (A) is dry surface cover which is composed of marly limestone, the second high resistivity zone (B) is represented by the air and the third zone (C) is produced by the water in the cavity, while the last zone (D) is the bottom of the cave or / the dry massive limestone. The resistivity values of these zones and their thicknesses are listed in table (1).

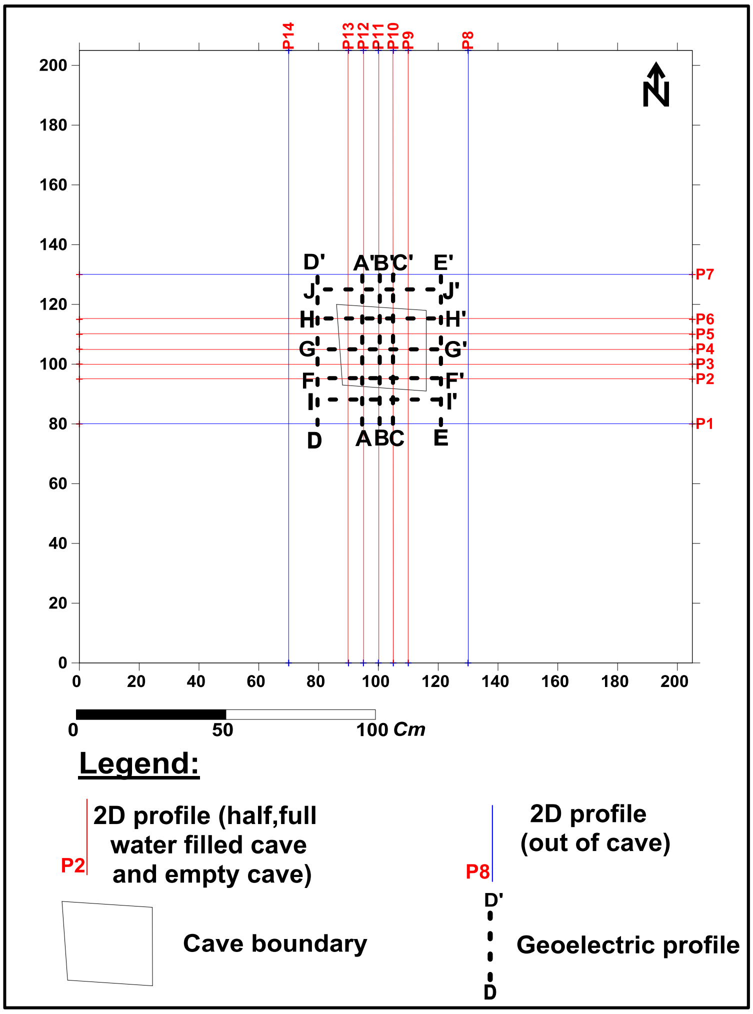

Fig. (4): Locations and directions of 2-D profiles and geoelectrical profiles on the model.

Case 2: Full water filled cave/cavity

The limestone model gave VES curves of H-type (ρ1> ρ2 <ρ3) above the cavity/cave when it was completely filled with fresh water (sector C, Fig. 6) and A-type (ρ1 < ρ2 <ρ3) outside the cavity (sector B). However, the geoelectrical section in this case consists of three geoelectric zones which are: the top zone represents dry marly limestone cover, the second zone is related to the water in the cave which is characterized by a low resistivity value and the third zone is the bottom of the model which is composed of dry massive limestone of very high resistivity. The ranges of resistivity values and thicknesses of these interpreted geoelectrical zones are listed in table (1).

Case 3: Empty cave

In this case the limestone laboratory model gave VES curves of A-type (ρ1< ρ2< ρ3) above the cavity/cave when it was free of water (sector D, Fig. 7) which are similar to the VES curves outside the cave (sectors D & B). However, the geoelectrical model consists of three zones which are: the top zone which is composed of marly limestone cover, the second zone is represented by the air and the third zone which is related to massive limestone of very high resistivity bottom of the model. The resistivity values and thicknesses of these zones are listed in table (1).

Table (1): Resistivities and thicknesses of the interpreted geoelectrical zones for the cavity/cave in its four conditions.

Geoelectrical zones	Case 1 (half water filled cave)		Case 2 (full water filled cave)		Case 3 (empty cave)		Case 4 (out of cave)	
	Resistivity (Ohm.m)	Thickness (cm)	Resistivity (Ohm.m)	Thickness (cm)	Resistivity (Ohm.m)	Thickness (cm)	Resistivity (Ohm.m)	Thickness (cm)
Surface cover zone (A)	408-470	3-3.2	273-389	3-3.2	377-467	3-3.2	291-480	3-3.2
Air zone (B)	1709-1966	8.5-8.8	-	-	1580-1903	16.5-17	-	-
Water zone (C)	118-168	8.5-8.7	148-196	16.5-17	-	-	-	-
Dry massive limestone (D)	6667-9632	-	8125-9580	-	5892-7030	-	5991-7110	-

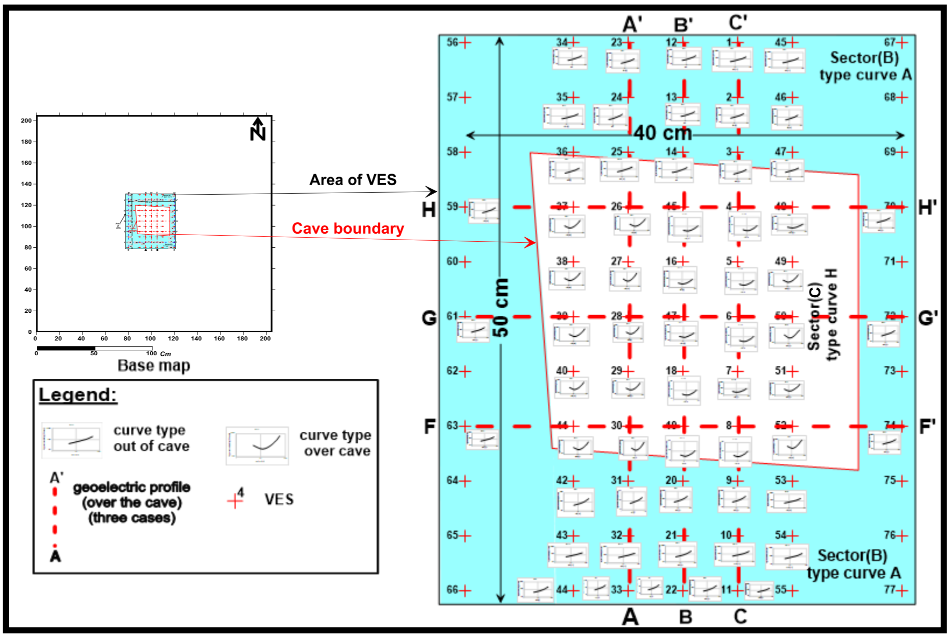

Fig. (6): Aerial distribution of Vertical Electrical sounding curves on the limestone model when the cave is completely filled with fresh water.

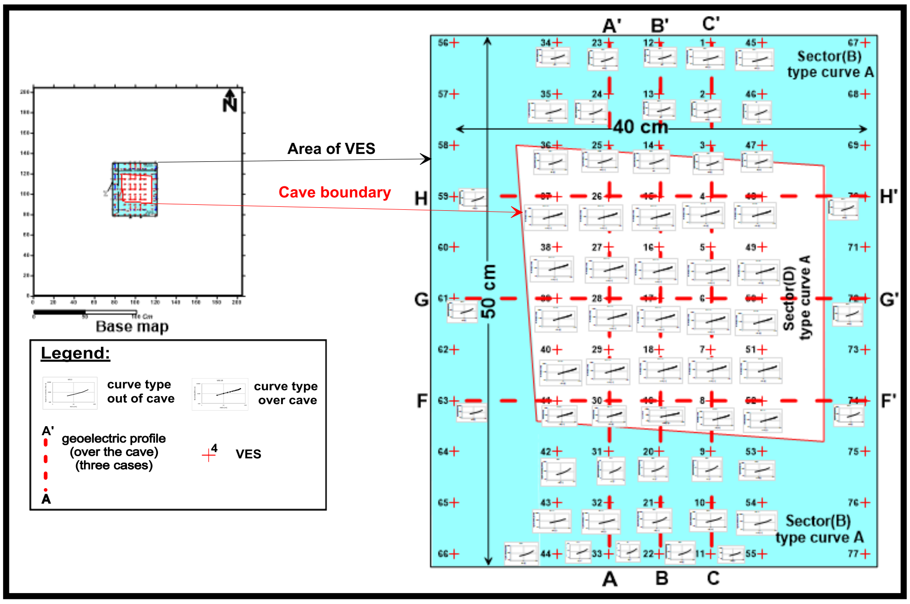

Fig. (7): Aerial distribution of vertical electrical sounding curves on the limestone model when the cavity/cave is free of water (empty).

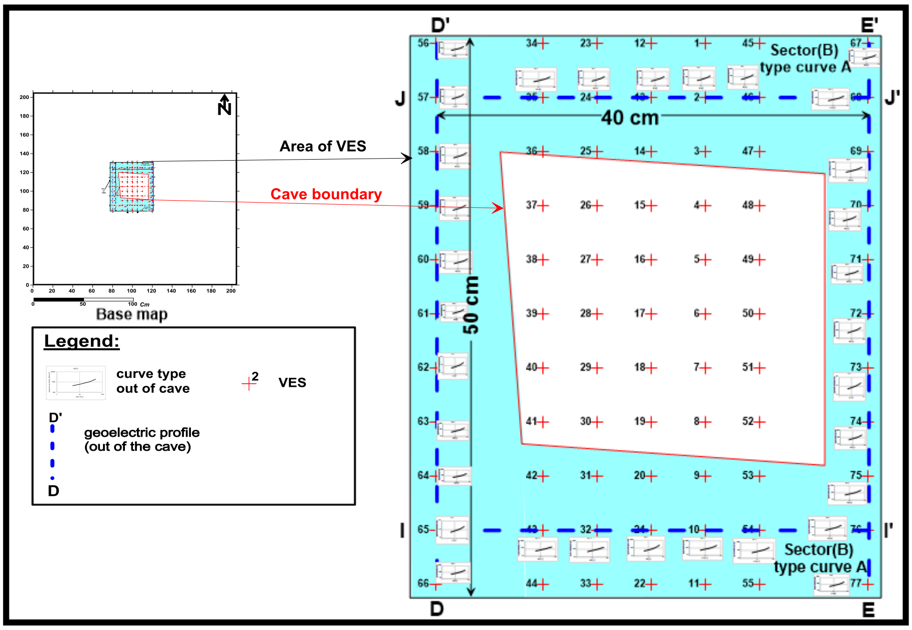

Fig. (8): Aerial distribution of Vertical Electrical Sounding curves on the limestone model when its central cavity/cave is free of water.

Case 4: Out of cave/cavity

In this case some soundings have been measured outside the area of the cavity/cave in all sides. The obtained VES curves are of A-type (p1<p2<p3) in which the apparent resistivity increases downwards from the surface marly limestone to the bottom massive limestone (Fig. 8). These curves are the same as those of sector (B) in the last three figures where the resistivity values and thicknesses of the interpreted geoelectrical zones are listed in table (1).

Geoelectrical cross sections

Geoelectrical cross sections illustrate the geoelectrical sequence, lateral and vertical variations for every zone and the subsurface lithologic changes in its directions. In the current study six geoelectrical sections have been constructed using the results of the interpreted VES curves, three of them in each direction (i.e. N-S and E-W), representing the four cases of the model's cavity/cave (half water- filled, full water filled , empty and out of cave, Fig. 3). The data of the geoelectrical cross sections such as thicknesses, resistivities, and directions are summarized in table (1).

The cross sections (B-B') is an example of S-N profiles and extends a distance of about 50cm. It represents the three cases of the cave/cavity (half – filled, full filled with fresh water and empty, Fig 9a, b, c). Whereas, the cross section (D-D') extends for a distance of about 40cm in the S-N direction and represents the case outside the cave/cavity (Fig. 9d). These cross sections consist of surface marly limestone cover zone with a resistivity value ranging from 273 to 480 Ohm.m, the second zone is the air zone in the cavity which has a resistivity value varies between 1709 and 1996 Ohm.m, the third zone is the water zone in the cavity/cave which has a resistivity value ranging from 118 to 196 Ohm .m and the bottom zone is represented by the dry massive limestone which gave a resistivity value varying between 5991 and 9632 Ohm.m.

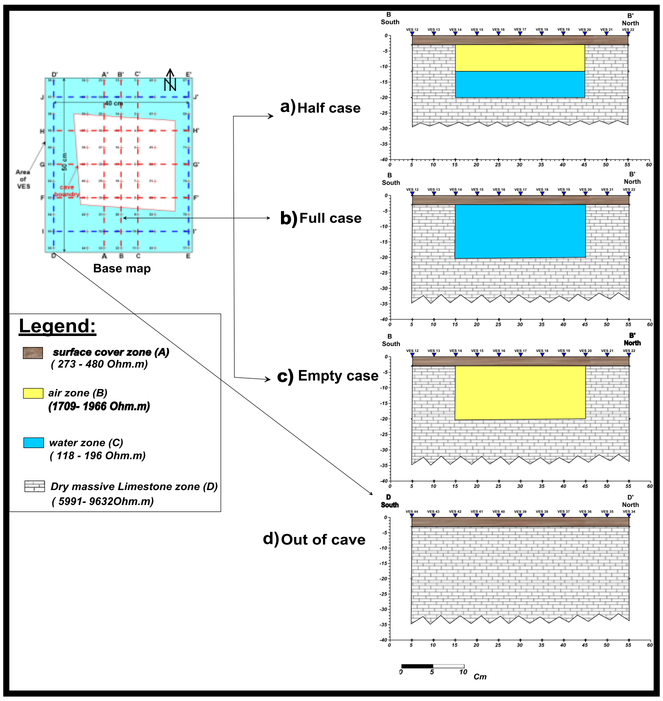

Fig. (9): S-N geoelectrical cross sections in four cavity/cave cases.

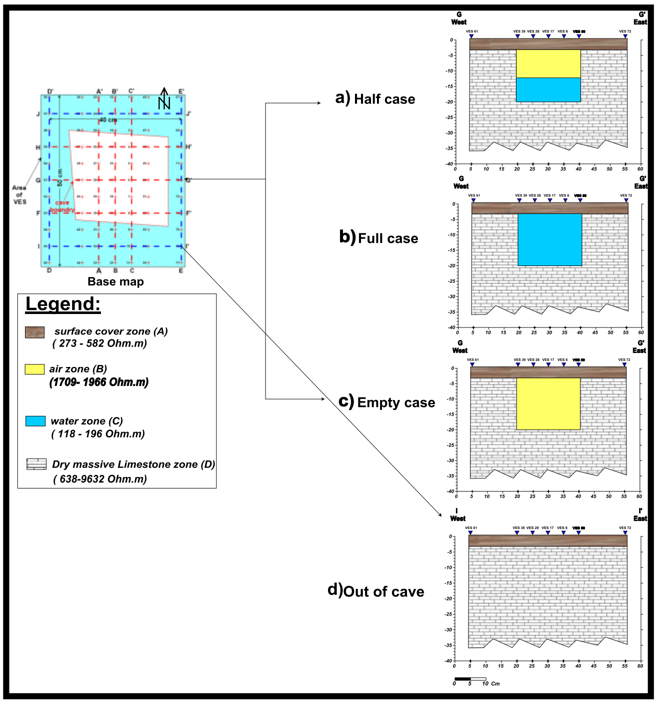

Fig. (10): W-E geoelectrical cross sections in four cavity/cave cases.

The geoelectrical cross section (G – G$^{\backslash}$) is an example of the W-E profiles which extends for about 50 cm and covers the cavity/cave in its three conditions (i.e. half water – filled, completely filled with fresh water, and empty, Fig. 10a, b, c). It has the same geoelectrical zones as those discussed for the previous B-B$^{\backslash}$ section (Fig. 9). Whereas, the cross section (I-I$^{\backslash}$) is an example of the W-E section which extends for a distane of 40 cm, but outside the cavity/cave (Fig. 10d). This section consists of two geoelectrical zones which are: the surface marly limestone cover and the bottom dry limestone zone. They have the same resistivity as those discussed in the previous geoelectrical sections.

2-D resistivity imaging

A number of 14 two dimensional imaging 2D profiles have been measured on the laboratory limestone model depending on the sounding's results in order to delineate the effectiveness of this technique in differentiating between the resistivity in four cases of the cavity/cave (i.e. half water– filled , completely full of fresh water, empty and outside the cave). Seven of these profiles directed S-N and the others in the W-E direction (Fig. 3). Results of the S-N profiles are represented in Fig. 11, where profile number 11 was given as an example. The total length of this profile was 205 cm and crossing the cave/cavity in its three conditions (i.e. half water – filled, full of fresh water and empty). On the other hand, profile number 14, fig. 11 was considered as an example of the 2-D measurements outside the cavity/cave. However, profile number 4 was taken as an example for the W-E profiles, it extends for a distance of 205 cm and also covered the cave/cavity in its three conditions (i.e. full of fresh water, half – filled and empty). Moreover, profile number 7, fig.12 represents the 2-D resistivity measurements outside the cave in the W-E direction. Interpretation of the 2-D profile by RES2DINV (lock 2015) concluded that four geoelectrical zones could be detected when the cave/cavity was half-filled with fresh water, three zones when it was completely filled with water and also when the cave is empty (Figs. 11 & 12). These zones could be described lithologically as follows: zone A (cover zone) which is composed of marly limestone, zone B (air) when the cave was filled of fresh water to its half capacity, zone C (water in the cave) and zone D which is massive dry limestone (bottom of the model).

It is also noticed that zones (B) and (C) are missing for profiles outside the cave/cavity. Resistivity values of these zones and their thicknesses were recorded in figures 11 and 12 which confirmed the effectiveness of the 2-D resistivity imaging in detecting the groundwater in the cavernous limestone and could be applied successfully in the Egyptian deserts.

3-D Resistivity Imaging

Processing and interpretation of the obtained 3-D resistivity imaging data on the laboratory limestone model have been done using the RES3DINV software (deGroot et al., 1990, Sasaki, 1992 and Lock 2015). The inversion program divides the subsurface into a number of small rectangular prisms, and attempts to determine the resistivity values of the prisms so as to minimize the difference between the calculated and observed apparent resistivity values (Sultan et al., 2004). Laboratory measurements were done by applying Wenner array as the 2-D profiles over the cave in two cases: half and full water filled. The 2-D profiles are collected in two different directions (longitudinal and orthogonal to the cave/cavity). By combination of these longitudinal and orthogonal profiles using RES3DINV program we would be able to obtain a 3-D grid. The electrodes for such a survey are arranged in a uniform square grid (42 electrodes in X-direction and 42 electrodes in Y-direction) with a constant spacing 5 cm and 5 cm between the electrodes in both X-direction and Y-direction.

The interpretation of Wenner electrical data using RES3DINV program produced six slices at different depths. Their depths are 0–3, 3–5, 5–9, 9–12, 12–17, and 17– 22 cm, respectively. The obtained 3-D model from the inversion process is presented in horizontal and vertical sections as following:

Case 1: Half water filled cave/cavity

The horizontal sections in this case (Fig.13a) show a high resistivity value of about 1529 Ohm.m corresponding to the air zone (B). This zone starts from slice No.2 and extends to slice no.3 with a thickness of about 8 cm and followed by a relatively low resistivity value of about 117 Ohm.m, corresponding to the water zone (C). This zone starts from slice No.4 and extends to slice No.6 with a thickness of about 9 cm. The vertical sections (Fig.13b) show the same zone (B) of high resistivity value >1529 Ohm.m above zone (C) of a low resistivity value <117 Ohm.m in the middle sections.

Case 2: Full water filled cave/cavity

The horizontal sections in this case (Fig. 14a) show a relatively low resistivity value of about 117 Ohm.m corresponding to the full water filled cave and representing a water zone (C). This zone starts from slice No.2 and extends to slice No.6 with a thickness of about 17 cm. The vertical sections (Fig.14b) show a low resistivity value of about < 117 Ohm.m above the cave/cavity which represents the water zone (C). It is noticed that the thickness of both air zone (B) and water zone (C) is decreasing towards both margins of the measured grid and the high resistivity value of about <423 Ohm.m in the upper slice is due to dry surface zone (A), while the very high resistivity values ranging from 5518 to >19920 Ohm.m in the last slice is corresponding to dry massive limestone zone (D).

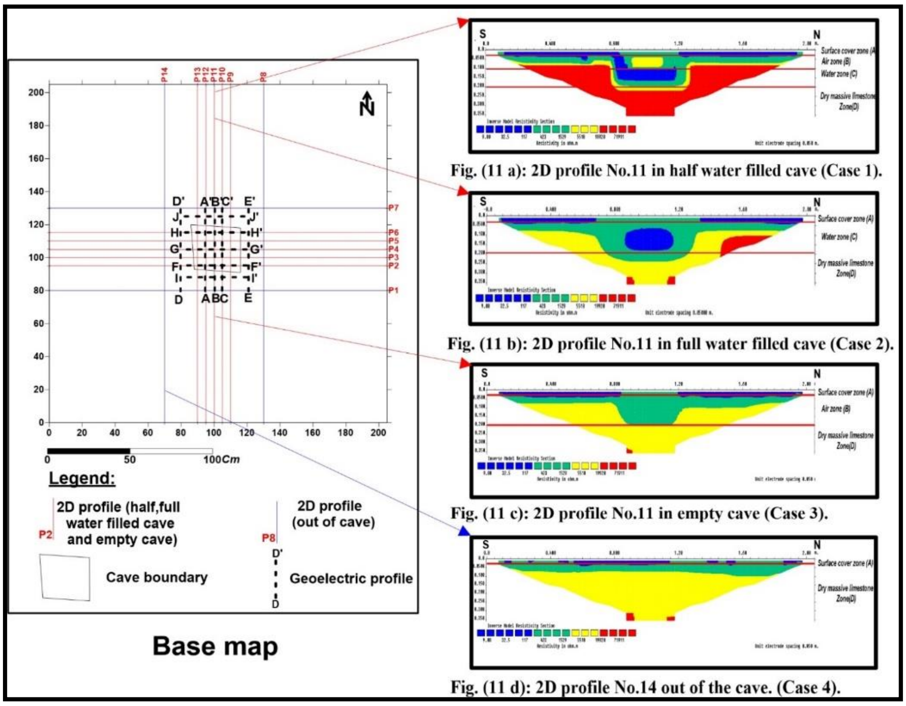

Fig. (11): South-North 2-D imaging profiles.

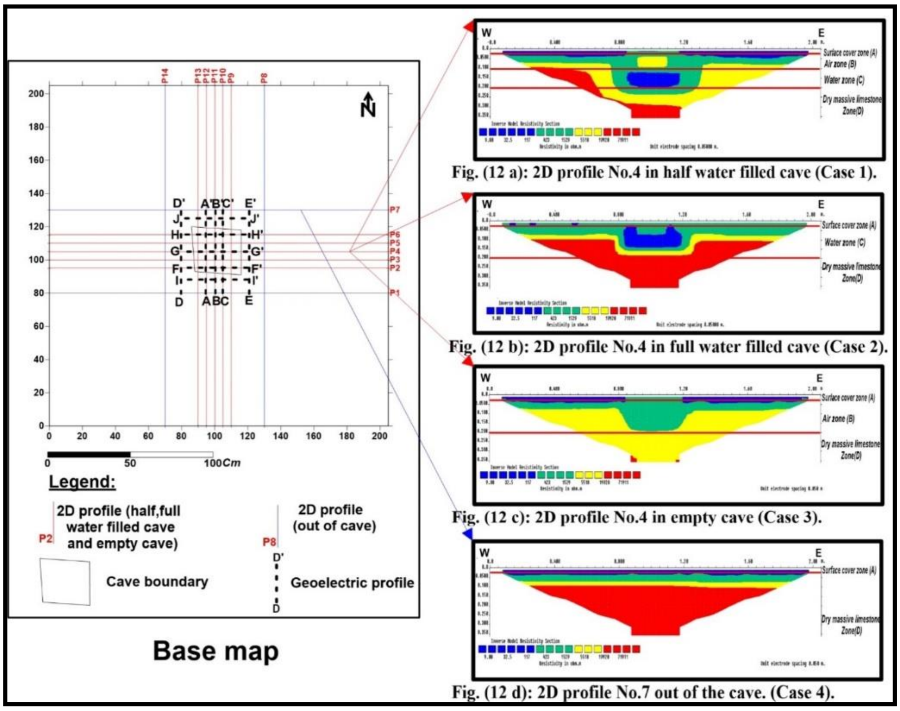

Fig. (12): West- East 2-D imaging profiles.

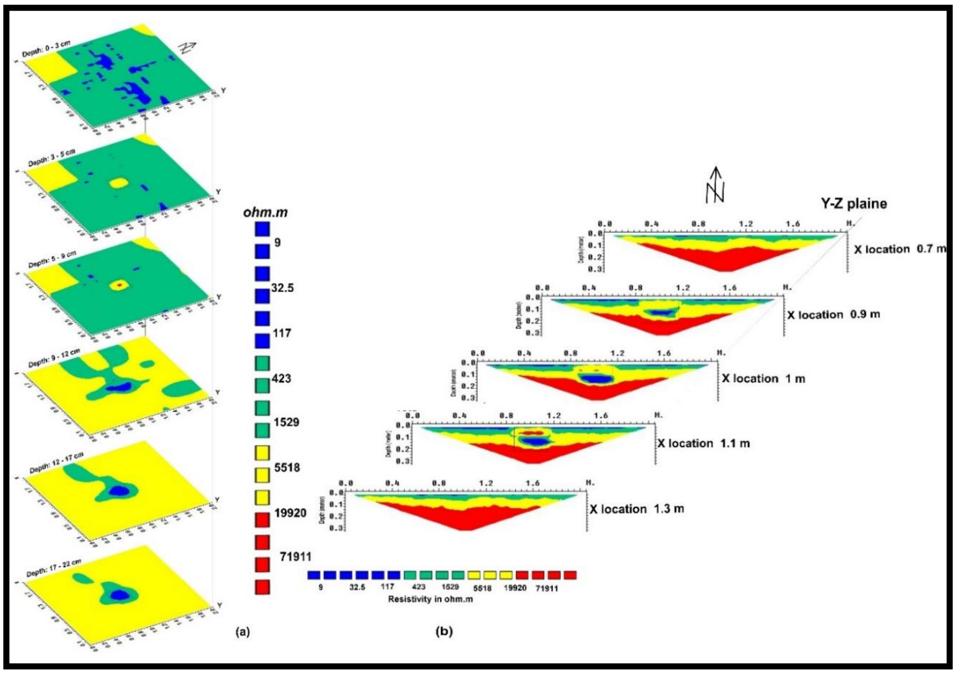

Fig. (13): 3-D model obtained from the inversion results of Wenner measurements on the limestone model.

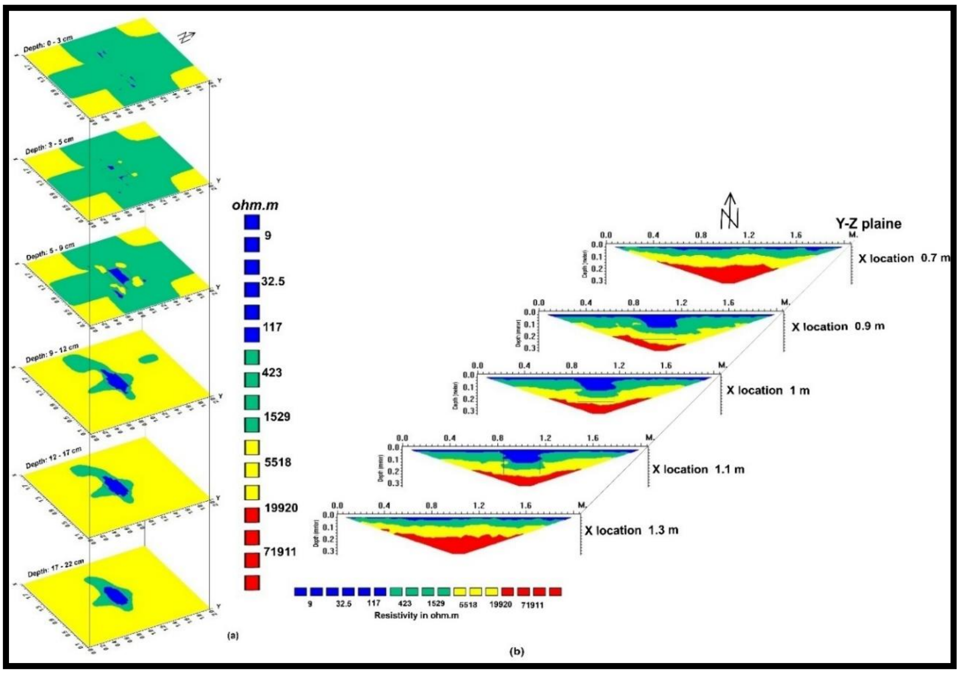

Fig. (14): 3-D model obtained from the inversion results of Wenner survey over the limestone model.

CONCLUSIONS

The electrical resistivity methods, including 1-D; 2-D and 3-D resistivity measurements applying Wenner array, were used to detect the cavernous limestone aquifers in a laboratory scale. These measurements have been recorded on a laboratory physical model consisting of a massive limestone block with a cave/cavity in its center and covered by a thin sheet of marly limestone. Three cases have been considered during the measurements which are: the cave was completely filled with fresh water, half – filled and empty. From the laboratory data the dimensions, extension and depth of the cave/cavity were recognized. The obtained results showed four zones in half water filled case which are: the top zone (A) represents surface cover zone with a thickness of 3 cm and resistivity less than 423 Ohm.m, zone (B) represents the air with a length of 20 cm and a thickness of 8 cm and has a resistivity greater than 1529 Ωm, zone (C) represents the water zone that have a thickness of about 9 cm and resistivity less than 117 Ωm, while the last zone (D) is the bottom of the cave or /dry massive limestone, having very high resistivity values (5518 to more than 19920 Ohm.m). In the full water filled case, the results showed three geoelectrical zones which are: zone (A) represents surface cover zone with a thickness of 3 cm and resistivity less than 423 Ohm.m, zone (C) represents the water zone with thickness of about 17 cm and has resistivity less than 117 Ohm.m and reached to a depth of 20 cm, while the last zone (D) is the bottom of the cave or /dry massive limestone, that has a very high resistivity ranging from5518 to more than 19920 Ωm. In the outside of the cave, the results showed two zones which are: zone (A) is the dry surface cover and has a resistivity less than 423 Ωm, while the bottom of the cave which is represented by dry massive limestone zone (D) and has very high resistivity values ranging from 5518 to more than 19920 Ωm. In the out of the cave, the zones (B) and (C) are absent. Results of this laboratory study supported the efficiency of the electrical geophysical methods including 1-D, 2-D and 3-D techniques in detecting the groundwater in subsurface cavities/caves in limestone bed rock and could be applied successfully for exploring the groundwater in the cavernous limestone in the Egyptian deserts.

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