Numerical Modelling of Subsurface Cavities Using 2D Electrical Resistivity Tomography Technique

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Abstract

The formation of subsurface cavities in karstic rocks causes serious engineering problems for shallow and deep foundations. These cavities restrict the urban development and trigger significant geotechnical and geoenvironmental hazards. In this work, 2D Electrical Resistivity Tomography (ERT) technique was adopted to simulate subsurface cavities commonly formed in limestones using Wenner, Wenner-Schlumberger and Dipole- Dipole arrays. Air and water filled cavities were modelled utilizing blocky L1 norm and smooth L2 norm optimization methods. The results showed that subsurface cavities can well be detected particularly at low resistivity noise levels. Their geometry and position are reasonably indicated using L1 norm method due to the sharp resistivity variations especially for air filled cavity model while L2 norm method produces gradual resistivity boundaries for both air and water filled cavities. Dipole- Dipole array and L1 norm method perform better in delineating geometry and position of both air and water filled cavities. It is suggested that ERT technique using Dipole- Dipole array, as non- invasive tool, can be adopted for detecting subsurface cavities in karstic rocks to avoid the catastrophic effects of these features.

Key Words: Numerical Modelling, Cavities, Electrical Resistivity Tomography

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النمذجة الرقمية للفجوات تحت السطحية باستخدام طريقة المقاومة النوعية الكهربائية التصويرية ثنائية البعد

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الخلاصة

ان تكون الفجوات تحت السطحية في الصخور الكارستية تؤدي الى مشاكل هندسية خطيرة في الاسس الضحلة والعميقة. ان هذه الفجوات تحد من تطور المناطق الحضرية وتؤدي الى مخاطر جيوتكنيكية وبيئية كبيرة. في هذه الدراسة، تم استخدام طريقة المقاومة النوعية الكهربائية التصويرية ثنائية البعد في محاكاة الفجوات تحت السطحية الشائعة في الصخور الجيرية بأستخدام ترتيبات فنر، فنر- شلمبرجر وثنائي القطبين. لقد تمت المحاكاة الرقمية لفجوات مملوءة بالهواء والماء باستخدام معياري L1 و L2. لقد بينت النتائج ان الفجوات تحت السطحية قد امكن الكشف عنها وان موقع وشكل هذه الفجوات تم تحديده بشكل جيد خاصة عند مستويات واطئة للتشويش باستخدام طريقة معيار L1 نتيجة للتغيرات الحادة في المقاومة النوعية خاصة بالنسبة للفجوات المملوءة بالهواء بينما انتجت طريقة المعيار L2 تغير تدريجي في المقاومة النوعية لكلا النوعين من الفجوات. ان ترتيب ثنائي القطبين والمعيار L1 اعطى نتائج افضل في الكشف عن شكل وموقع الفجوات مقارنة بترتيبي فنر وفنر- شلمبرجر، ولهذا اقترح اعتماد هذا الترتيب عند استخدام طريقة المقاومة النوعية الكهربائية التصويرية ثنائية البعد في الكشف عن الفجوات لتجنب الاثار الكارثية لها.

الكلمات المفتاحية: النمذجة الرقمية، الفجوات، المقاومة النوعية الكهربائية التصويرية.

Introduction

Natural and man- made cavities in subsurface rocks bring significant geotechnical challenges and problems for environmental and civil engineers. In particular, cavities developed very often due to dissolution of soluble Karstic rocks such as limestone and evaporate cause variable environmental and geotechnical hazards such as roads subsidence, development of fissures in civil buildings and collapsing of soil and engineering structures [1]. The dissolution of karstic rocks might lead to features such as voids, cavities, caves, sinkholes and karst topography. The term cavity is commonly used to denote these karst features [2]. The formation of subsurface cavities lead to restrict the utilization and development of urban areas that are underline by karstic rocks. This problem is worldwide as karst train covers about 7-10% of earth's surface [3]. Costly and time consuming drilling methods have traditionally been used to locate the subsurface cavities as part of geotechnical site investigations. Electrical Resistivity Tomography (ERT) technique offers cost effective and non invasive alternative tool to identify the subsurface features and to determine the appropriate location of test borings needed [4]. Significant advances in this method have taken place with the advent of automated resistivity systems and robust data inversion software that can be used to address wide range of problems [5, 6, 7]. In the literature, ERT technique has routinely been used for environmental and geotechnical investigations [8] to detect, for instance, sinkholes [4], buried fractures [9] and cavities [10]. Numerical modelling of subsurface cavities using ERT technique has been adopted [11, 12, 13]. However, the available studies have focus on delineation of common air filled cavities and sinkholes available due to the acidic effects of natural water. These studies were effective in detection this type of cavities. In the nature, the natural and man-made cavities can be filled with air and water. In addition, a common occurring question in ERT investigations is which of the standard electrode arrays will perform better in delineating the subsurface features. Therefore, this work focuses on application of ERT technique for simulating air and water filled cavities underneath the ground surface using Wenner, Wenner-Schlumberger and Dipole- dipole arrays. Resistivity forward modelling and inversion software have been used to achieve this goal using blocky and smooth optimization methods [14].

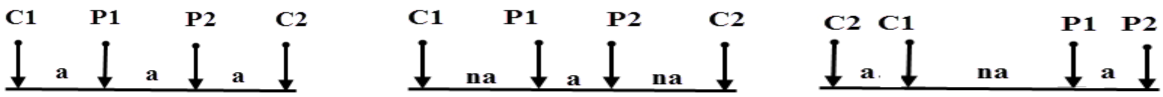
ERT Technique: Data Acquisition and Interpretation

The main principle of the traditional resistivity method is to inject DC or low frequency current into the subsurface medium through two current electrodes and measuring the resulting voltage drop across another two potential electrodes [15]. The measured voltage drop is proportional to the electrical resistivity which can be related to the characteristic properties of the medium, that is:

$$\rho = K \frac{\Delta V}{I}$$

Where, ρ is the soil resistivity (Ohm.m), ΔV is the voltage drop (Volts), I is the current (Amps), and K is the geometric factor (meter) that accounts for the electrode array.

The more recent and effective ERT technique is based on using large number of electrodes and multi electrode and multi channel resistivity systems [7]. In this method, the resistivity measurements are collected along profiles and grids to generate 2D and 3D sections using appropriate interpretation software [16]. The resistivity measurements can be acquired using different electrode arrays of different characteristics. Depending on the relative position of the current and potential electrodes, the characteristic features of the electrode arrays such as signal strength, lateral coverage and sensitivity to vertical and horizontal resistivity changes are different [17, 18]. In this study, Wenner (W), Wenner- Schlumberger (WS) and Dipole-Dipole (DD) arrays have been chosen (figure 1). Wenner array has a high signal strength and sensitivity to the vertical resistivity changes. Wenner- Schlumberger array is a combination of Wenner and Schlumberger arrays. It offers good signal strength and moderate sensitivity to detect both horizontal and vertical structures. Dipole-dipole array is very sensitive to horizontal resistivity changes with higher data coverage but low signal response [6, 18]. 2D resistivity measurements are usually collected using different electrode spacing (a) and (n) separation. The resistivity data obtained are presented in apparent resistivity pseudosections which give a qualitative approximation of subsurface resistivity distribution. To obtained a true subsurface resistivity picture, an inversion procedure is used [16].



(a) (b) (b)

Figure (1): Electrode arrays a) Wenner array b) Wenner- Schlumberger array c) Dipole- Dipole array: C1 and C2 are current electrodes; P1 and P2 are potential electrodes; a and n are electrode spacing and separation factor, respectively

Numerical Modelling Using ERT Technique

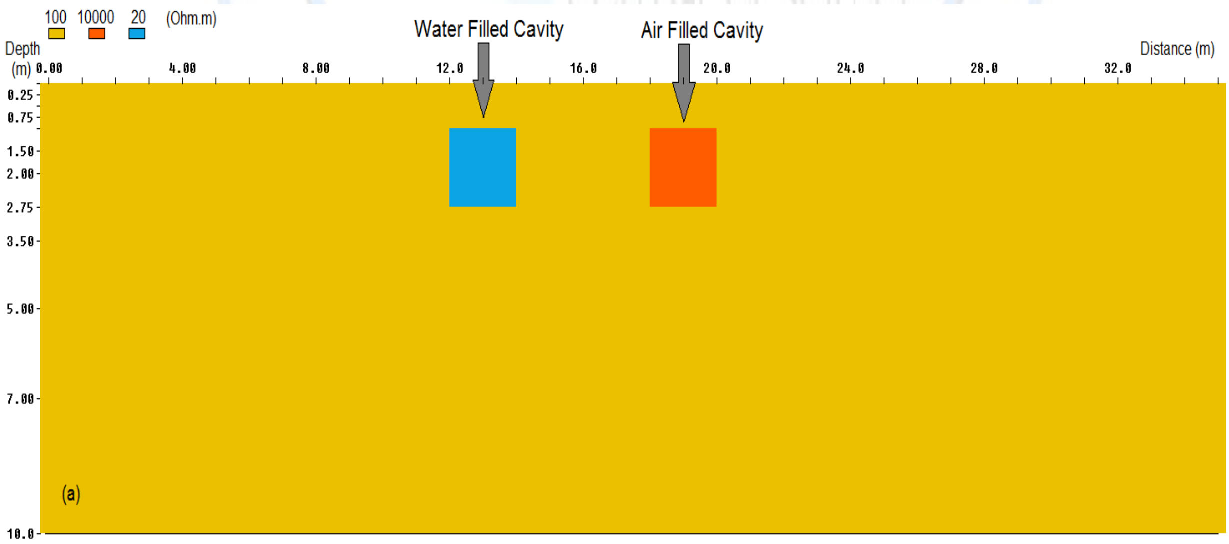
Methodology

The goal of the ERT numerical modelling is to simulate real scenarios and to examine the effectiveness of the method applied before carrying out costly actual laboratory and field investigations [19, 20]. It has increasingly been used to simulate different features such as fractures [17], faults [21], Cavities [13] and soil cracks [22]. Numerical modelling using ERT technique is a procedure of two-step [19]: Firstly, a synthetic resistivity model is created based on the user prior information (i.e. forward modelling); and secondly, the model is inverted to reconstruct the subsurface true resistivity distribution (i.e. inverse modelling).

In the current study, 2D forward modelling RES2DMOD ver. 3.01 [23] and 2D inversion RES2DINV ver. 3.71 [24] software have been used. RES2DMOD is finite difference software that determines the apparent resistivity values for a synthetic survey carried out with a user defined electrode arrangement and resistivity distribution [23, 25]. RES2DINV uses finite difference method based on the regularized least squares optimization procedure [24, 26] to produce true 2D resistivity model from the apparent resistivity data. The software iteratively determines the model resistivity values that will closely produce the measured apparent resistivity data.

The Synthetic Resistivity Model

In the current work, air and water filled cavities in limestone have been modelled. A synthetic model, shown in figure (2a) which consists of limestone host rocks (100 Ohm.m) with air filled cavity (10000 Ohm.m) and water filled of (20 Ohm.m) has been designed using RES2DMOD software. The resistivity values of the model are within the common ranges of the materials reported in literature [11, 13, 27]. Each cavity has (2.0m X 1.75m) dimensions and buried at 1m depth. The model has been discretized and simulated using RES2DMOD software (figure 2b). The total number of the electrodes was 36 with a minimum electrode spacing of 1m.



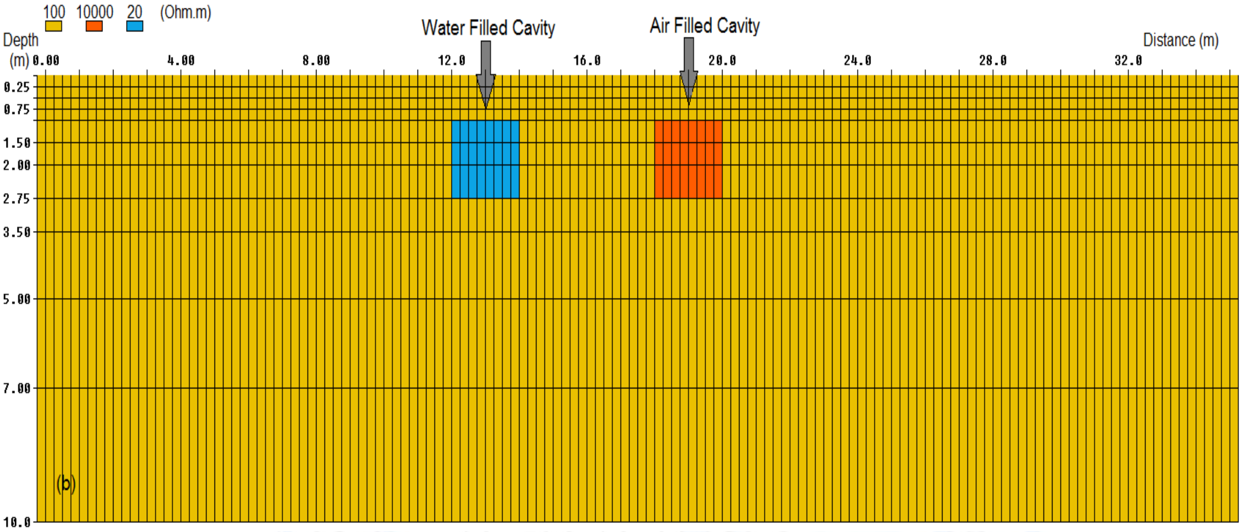


Figure (2) The resistivity synthetic model: a) Air and water filled cavities model b) model discretization

Once the model file is supplied, RES2DMOD is used to calculate the apparent resistivity section of W, WS and DD arrays and the results are saved to be used for input in RES2DINV software to produce the true resistivity sections. The final results are the measured and calculated apparent resistivity sections, and the final inverse resistivity model. To simulate real field conditions, adding scattered Gaussian resistivity noise is a common practice in resistivity modelling [28]. First, the calculations are made for the model with 0% noise then scattered 5%, 10% and 25% noise values are added. Second, the synthetic apparent resistivity data are then inverted utilizing blocky L1 norm and smooth L2 norm optimization methods. The L1 norm attempts to minimize the absolute difference (Abs.) between the measured and the calculated apparent resistivity values while the L2 norm (the conventional least-squares standard method) attempts to minimize the square of difference (RMS) between the measured and calculated apparent resistivity values [14].

Results and Discussion

As mentioned earlier, the outcomes of the ERT modelling are three resistivity sections. As an example, Figure (3) shows the resulted resistivity sections of the model (no noise added) using WS array and L1 norm method: the measured apparent resistivity pseudosection (up), the calculated apparent resistivity pseudosection (middel) and the final true resistivity inverse section (down) after 3 iterations. The low absolute (Abs.) error (0.57%) indicates low absolute difference between the measured and calculated apparent resistivity sections. The inverted resistivity section captures clearly the modelled air and water filled cavities. After that only final inverse resistivity sections of L1 norm and L2 norm methods for the W, WS and DD arrays will be presented and discussed.

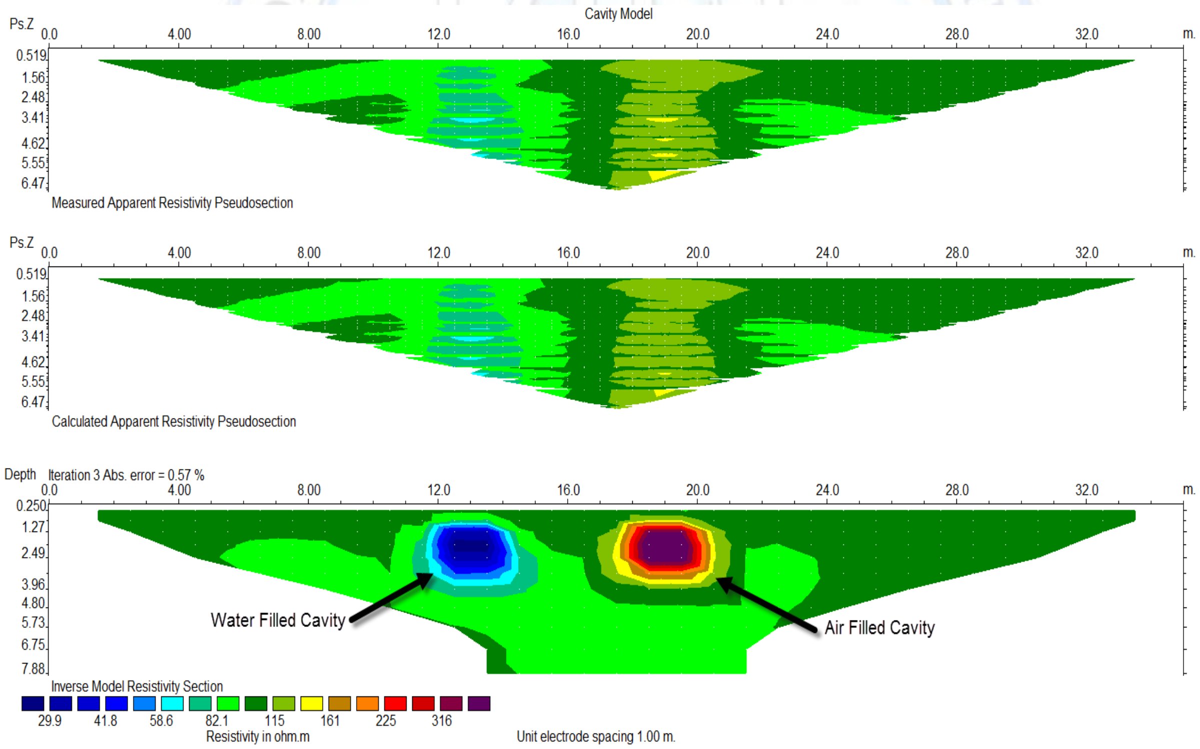


Figure (3):The resistivity sections of the air and water filled model with 0% noise using WS array and L1 norm method

The inverted resistivity sections of 0%, 5%, 10% and 25% noise models using W array and L1 norm method is shown in figure (4). The resistivity sections reflect satisfactory the modelled cavities particularly at no or low noise levels. However, at extraordinary high (25%) noise level (figure 4d), both cavities are not detected. The inverted resistivity sections of 0%, 5%, 10% and 25% noise models using W array and L2 norm method is presented in figure (5). Although the modelled cavities can still be detected, their shape are more exaggerated and smeared comparing to L1 norm sections shown is figure (4), as L2 norm method tends to produce more gradual resistivity variations than L1 method [14]. Therefore, the shape of water filled cavity is relatively more exaggerated. The low resistivity contrast in the water filled cavity case comparing to the air filled cavity is another reason. Similarly, at extraordinary high (25%) noise level both cavities are not captured. As a comparison, L1 norm method performs better in reflecting the shape of the modelled cavities than L2 norm method, particularly for air filled cavity and low noise level. The inverted resistivity sections of 0%, 5%, 10% and 25% noise models using WS array and L1 norm method is shown in figure (6). It can be seen that position and shape of the modelled cavities are well detected. L1 norm method captures the boundaries of the modelled cavities, particularly at no or low noise levels as it tends to produce models with sharp boundaries between different regions with different resistivity values [14]. However, the cavities are smeared and poorly resolved in figure (6d) due to the addition of extraordinary high (25%) noise value. The inverted resistivity sections of 0%, 5%, 10% and 25% noise models using WS array and L2 norm method is presented in figure (7). Although that the modelled cavities are captured in the inverted sections, L2 norm method showed again gradual resistivity variations and boundaries between the host rocks and the cavities. Therefore, the shape of the cavities are relatively exaggerated and their positions are poorly indicated compared to the sections produced using L1 norm method. Again, at 25% noise level, the cavities are smeared and poorly indicated and the water filled cavity is relatively more smeared. However, as a comparison, the resistivity sections produced using WS array and L1 norm method reflected better the modelled cavities than W array using L1 norm method.

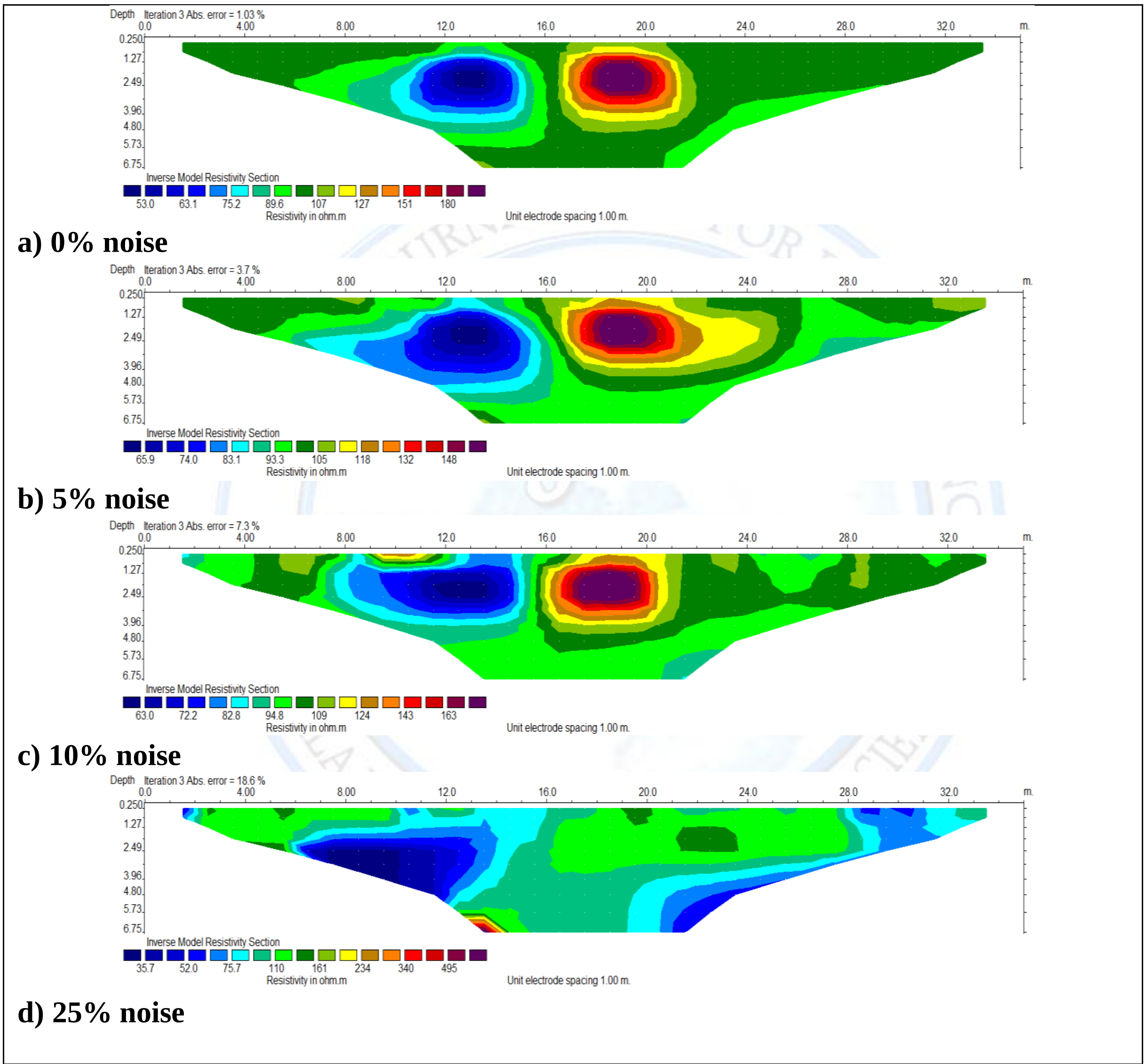


Figure (4) The inverted resistivity sections using W array and L1 norm method with different noise levels

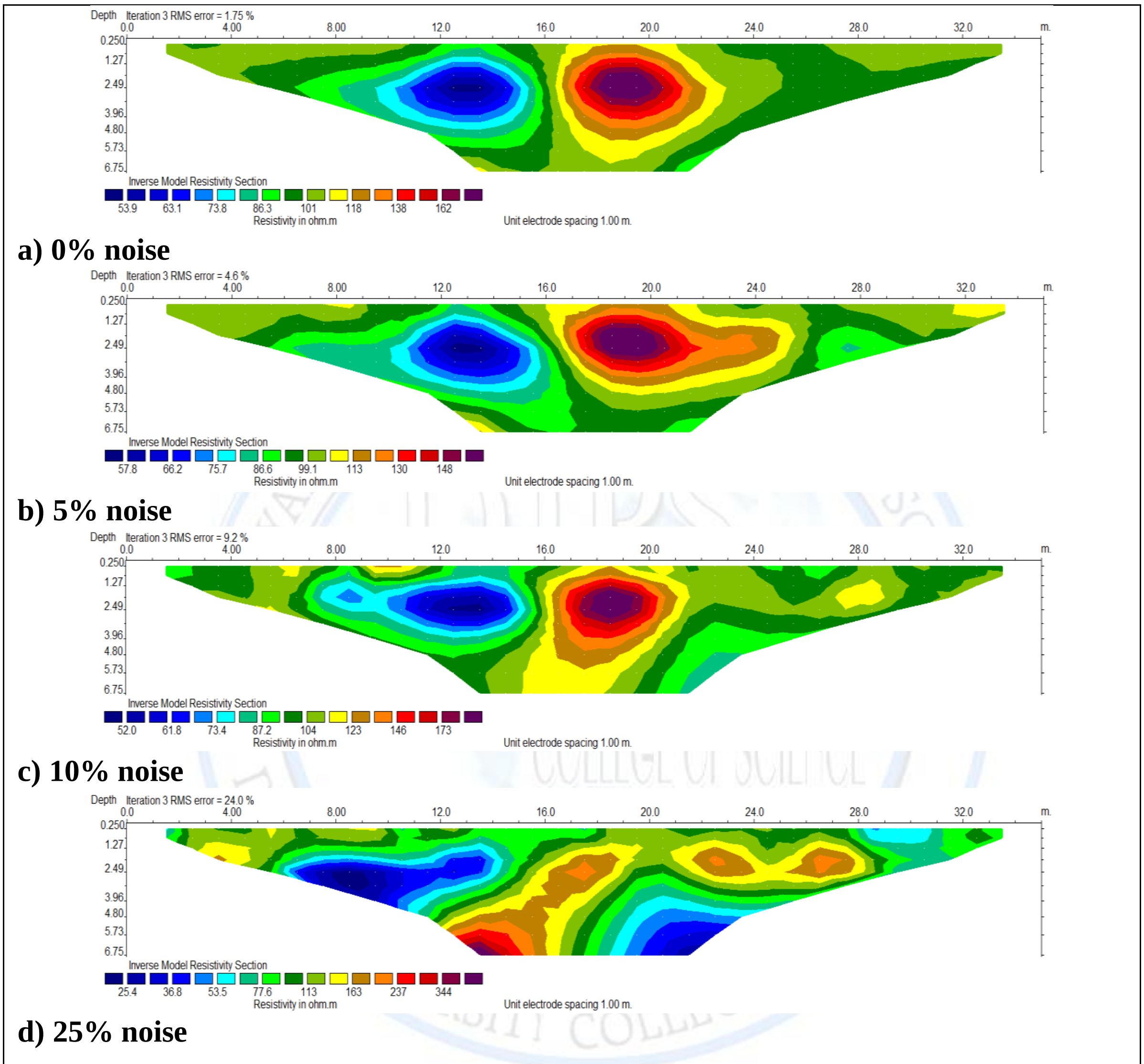


Figure (5) The inverted resistivity sections using W array and L2 norm method with different noise levels

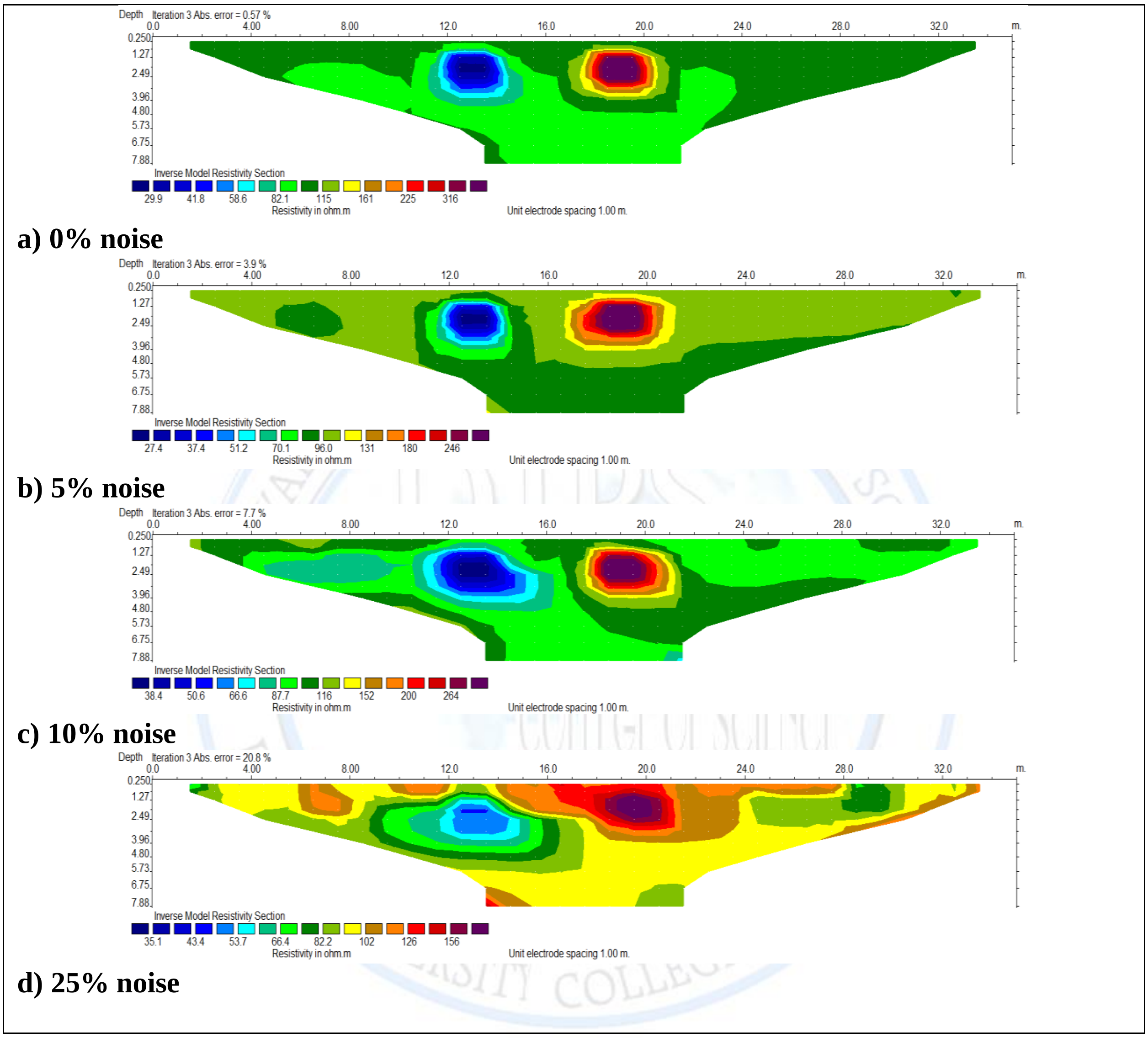


Figure (6) The inverted resistivity sections using WS array and L1 norm method with different noise levels

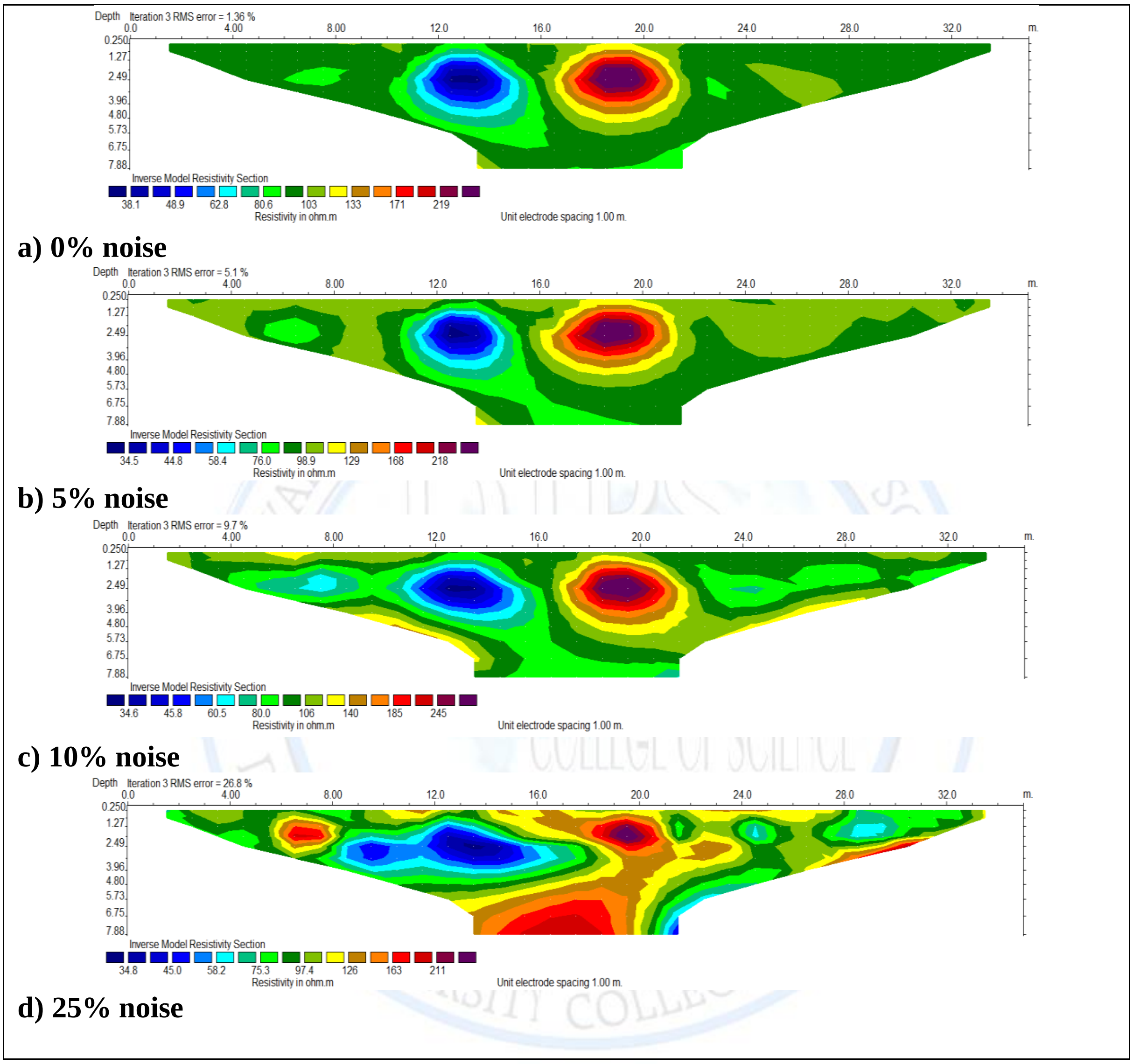


Figure (7) The inverted resistivity sections using WS array and L2 norm method with different noise levels

The inverted resistivity sections of 0%, 5%, 10% and 25% noise models using DD array and L1 norm method is shown in figure (8). Compared to the resistivity sections produced using L1 norm method for W and WS arrays, DD array captured more clearly the modelled cavities.

Their shape and position are obviously more evident even at 25% noise levels, particularly for air filled cavity. This method is more successful in delimiting the resistivity transition between the cavity and the host rocks for both air and filled cavities. This finding aggress with some case histories for air filled cavities reported in the literature [10, 11]. Finally, the inverted resistivity sections of 0%, 5%, 10% and 25% noise models using DD array and L2 norm method is presented in figure (9). Although the modelled cavities are reasonably indicated in the resistivity sections, their shape are relatively smeared and exaggerated comparing to L1 norm sections. Gradual resistivity boundaries between the cavities and the host rocks are noticed, and at high noise (25%) levels the cavities are poorly resolved.

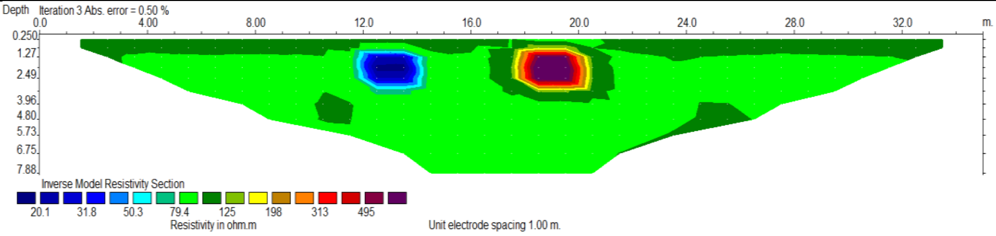
It can be summarized that:

1. Air and water filled cavities can reasonably be detected using ERT numerical modelling particularly at low noise levels.

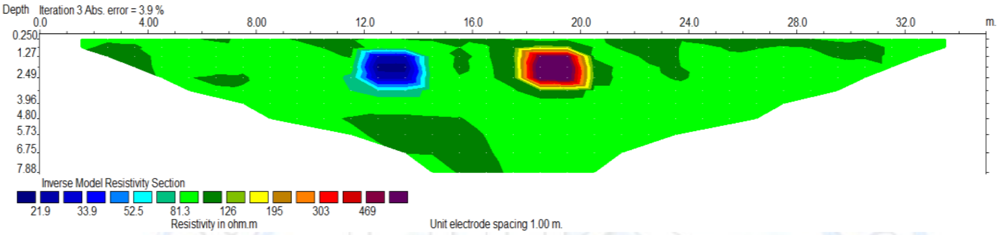
2. The shape and position of the modelled cavities are better indicated using L1 norm method due to sharp resistivity variations especially for air filled cavity model.

3. L2 norm method produces gradual resistivity boundaries for both air and water filled cavities.

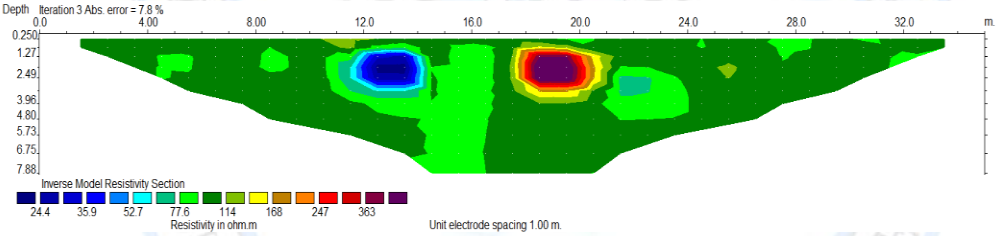
4. Compared to W and WS arrays, DD array using L1 norm performs the best in capturing the modelled cavities even at high noise levels. Therefore, it is recommended to be used for detecting both air and water filled cavities in karst areas.



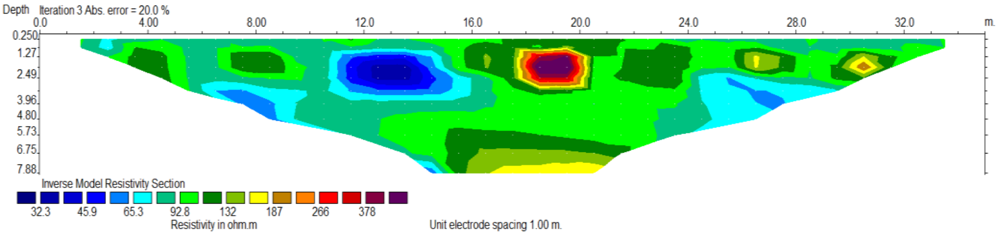
a) 0% noise



b) 5% noise

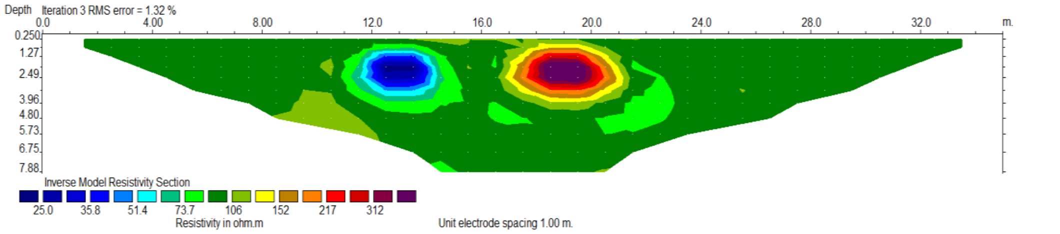


c) 10% noise

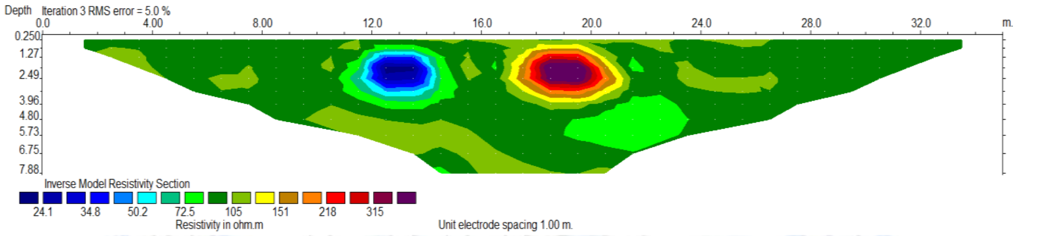


d) 25% noise

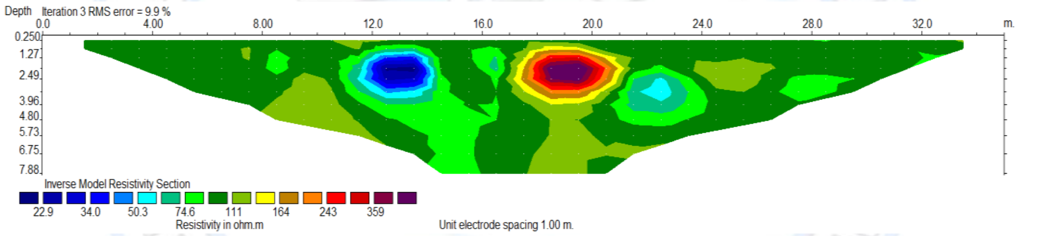
Figure (8) The inverted resistivity sections using array DD and L1 norm method with different noise levels



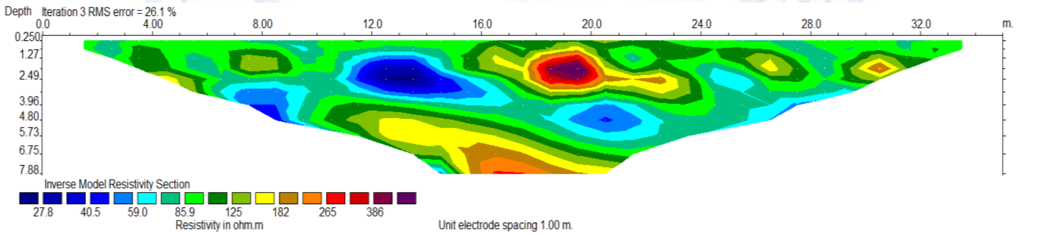
a) 0% noise



b) 5% noise



c) 10% noise



d) 25% noise

Figure (9) The inverted resistivity sections using DD array and L2 norm method with different noise levels

Conclusions

2D Electrical Resistivity Tomography technique was adopted for simulating air and water filled subsurface cavities commonly formed in limestones. Wenner, Werner- Schlumberger and Dipole- Dpole arrays were implemented using blocky L1 norm and smooth L2 norm optimization methods. The results indicated that the modelled cavities can reasonably be detected particularly at low noise levels. The L1 norm exhibits better sensitivity to resistivity variations in the examined models particularly for air filled cavities due to sharp boundaries expected, while L2 norm tends to produce gradual resistivity variations. Dipole- Dpole array using blocky L1 norm method performs better compared to Wenner and Werner- Schlumberger arrays in detecting the modelled cavities even at high noise levels. Therefore, it is recommended to be used for delineating the subsurface cavities in karst areas.

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