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Performance of Various Electrical Resistivity Configurations for Detecting Buried Tunnels Using 2D Electrical Resistivity Tomography Modelling

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Abstract

This work aims to evaluate performance of 2D electrical resistivity modelling technique for detecting buried tunnels using various electrode configurations. A synthetic resistivity model was designed to explore the capability of Wenner, Wenner- Schlumberger, Dipole-Dipole, Pole-Dipole and Pole-Pole electrode configurations for detecting buried tunnels at different noise levels. 2D forward modelling (RES2DMOD) and 2D inversion (RES2DINV) software were implemented using blocky L1 norm optimization method. The results showed that the modelled tunnel can clearly be detected at 0% noise level due to the high resistivity contrast between the synthetic tunnel and the surrounding host materials. At 0-30% noise levels, the results indicated that dipole-dipole and Wenner- Schlumberger in the second order perform better than other configurations. This can be attributed to the characteristics features and sensitivity of these configurations for resolving the subsurface resistivity changes. It is suggested that these configurations are more suitable for detecting the buried structures. The results also showed that the inversion artifacts caused by high noise levels may smear the resistivity signature of the burred targets for particular configurations. Thus, obtaining high quality data ensures reliable resistivity interpretations. The study demonstrated the usefulness of the 2D numerical modelling for planning of electrical resistivity surveys.

Keywords: Electrical Resistivity Tomography, Configuration, Tunnel, Noise.
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1.Introduction

Shallow geotechnical site investigation is crucial to characterize the subsurface conditions of the proposed construction site for different engineering projects. Buried tunnels (e.g. Tunnels, pipes, cavities, etc.) in the subsurface soil can cause severe effects on shallow and deep foundations. As a common practice, expensive drilling methods have routinely been used to locate these structures as part of the site investigations. Recently, Electrical Resistivity Tomography ERT technique has increasingly been adopted for geotechnical site investigations [1, 2 & 3]. This technique offers non-invasive and inexpensive data that can be used for detecting buried structures such sinkholes [4], fractures [5] and cavities [6].
However, one of the frequent problems of ERT technique is choosing the most suitable electrode configuration to address a particular problem. Numerical modelling using 2D ERT method is useful for planning of electrical resistivity surveys before carrying out costly field surveys. In the literature, several authors have discussed the suitability of the electrode configurations for resolving the subsurface structures [7, 8, 9, 10 & 11]. For shallow investigations, the presence of noise of different levels is expected. This can produce resistivity artifacts that affect the performance of the different electrode configurations. Therefore, in the current work, five different electrode configurations of different characteristics were used to investigate the suitability of 2D ERT numerical modelling for detecting buried tunnels at different noise levels. A synthetic resistivity model was generated and blocky L1 norm optimization method was implemented. This optimization method was adopted as it is more suitable in areas of sharp resistivity variations [12], such as the buried tunnels modelled in this work.

2.Theoretical Back Ground: 2D ERT Technique

In 2D ERT technique, a number of electrical electrodes are connected to a multi-electrode resistivity system via multi core cable Figure 1. The apparent resistivity measurements of a particular array are acquired using current (C1 and C2) and potential (P1 and P2) electrodes for different electrode spacing (a) and

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acquisition levels (n), and arranged in pseudo resistivity section. To obtain the true subsurface resistivity distribution, cell- based inversion software is used [13]. The software subdivides the subsurface into a number of rectangular blocks and an inversion procedure, such as the regularised least-squares optimization method [14, 15] is used to calculate the resistivity of the subsurface that provides a model response agrees with the measured apparent resistivity data [12].

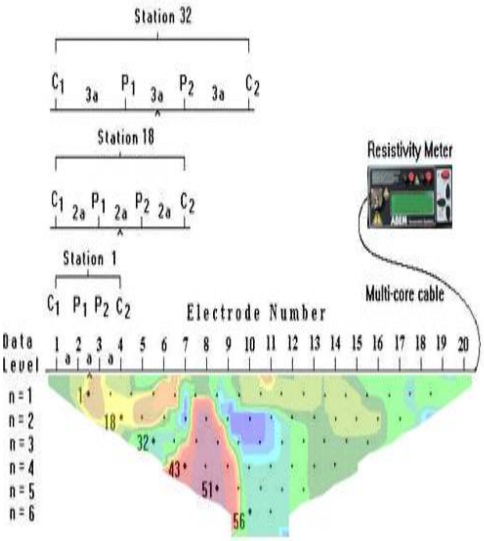

Figure 1: A 2D ERT survey with the sequence of the resistivity measurements (modified after Loke, 2016)

3.Electrical Resistivity Congigurations

The four current and potential electrodes can be placed at different locations on the ground surface. Among others, Wenner, Wennere-Schlumberger, Dipole-Dipole, Pole-Dipole, Pole-Pole configurations have traditionally been used in collecting resistivity data Figure 2. These configurations were examined in the current study. Each of these configurations has particular sensitivity, horizontal coverage, and depth of investigation capabilities. It should be emphasized that using different electrodes configurations over the same structure, the collected apparent resistivity measurements can be very different [16, 17]. Therefore, choosing the suitable configuration for a particular problem is important for successful surveys. Depending on the relative position of the current and potential electrodes, the characteristic features of the resistivity configurations are different Table 1. However, sensitivity of these configurations to a random noise level, expected in the shallow investigations has to be evaluated.

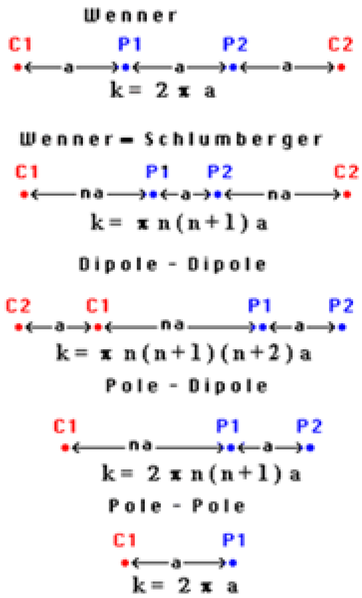

Figure 2: The electrode configurations used in the current study: C1 and C2 are current electrodes; P1 and P2 are potential electrodes; (K) is the geometric factor; (a) is elctrode sapcing and (n) is spacing integer

Table 1 The characteristic features of common electrode configurations [26].

	Wenner	Wenner-Schlumberger	Dipole-Dipole	Pole-Dipole	Pole-Pole
Sensitivity to the vertical resistivity variations	++++	++	+	++	++
Sensitivity to the lateral resistivity variations	+	++	++++	+	++
Depth of investigation	+	++	+++	+++	++++
Horizontal data coverage	+	++	+++	+++	++++
Signal strength	++++	+++	+	++	++++

4.Method: the Synthetic Resistivity Model

Numerical modelling using 2D ERT technique is useful to compare the resolution and efficiency of different electrode configurations before carrying out the field surveys [18]. The procedure involves two steps; a synthetic resistivity model is created based on the user prior information and assumptions, and the model is then inverted to generate the subsurface true resistivity section. The first step is called the forward modelling and the second step is called the inverse modelling [19].
In the current work, a synthetic resistivity model of a buried tunnel (5 m x 2.5m) has been designed using RES2DMOD software ver. 3.01 [20]. RES2DMOD supports finite difference or finite-element method to

calculate the apparent resistivity values for a synthetic survey [20, 21]. The resistivity values of the model components were chosen based on the resistivity ranges of the materials reported in the literature [13]. A model of air filled tunnel of high resistivity (10000 Ohm.m), buried in a clay soil of 20 Ohm.m and covered by thin (0.5m) surface soil layer of 30 Ohm.m was designed. A total of 36 electrodes with smallest electrode spacing of 1m were used. Figures 3 and 4 show the synthetic resistivity model and the model discretization, respectively. RES2DMOD is used to calculate the apparent resistivity sections of Wenner, Wenner- Schlumberger, Dipole-Dipole, Pole-Dipole and Pole-Pole configurations. The calculations are made first for the model with 0% noise then random 10%, 20% and 30% noise values are added to consider the effect of noise level on the performance of the electrode configurations.

Once the apparent resistivity sections are calculated RES2DINV software ver. 3.71 [22] was used to produce the inverse 2D resistivity section of the model from the apparent resistivity data. RES2DINV uses finite difference method based on the least squares optimization methods [14, 22]. The software subdivides the model into rectangular blocks and then iteratively determines the model blocks resistivity that will closely reproduce the measured apparent resistivity data. RES2DINV offers blocky L1 norm and smooth L2 norm optimization methods to produce the inverse resistivity section from the measured apparent resistivity data. The optimization method basically tries to reduce the difference between the calculated and measured apparent resistivity values by adjusting the resistivity of the model blocks. The L1 norm method attempts to minimize the absolute difference (Abs.) between the measured and the calculated apparent resistivity values while the L2 norm attempts to minimize the square of difference (RMS) between the measured and calculated apparent resistivity values [12]. In the current work L1 norm method was adopted to construct the true resistivity section as it is more suitable for problems with sharp resistivity boundaries [12, 23]. By default, RES2DINV sets the width of the model blocks to be the same as the smallest electrode spacing (i.e. 1m). In areas of large resistivity variations, it is recommended to use a model with narrower model blocks [22]. Therefore, a model refinement option (the width of the blocks is half the smallest electrode spacing) was chosen. The final results are given as the measured apparent resistivity section, the calculated apparent resistivity section and the true inverse resistivity model. The inverse resistivity sections of the tested arrays are compared at different noise levels.

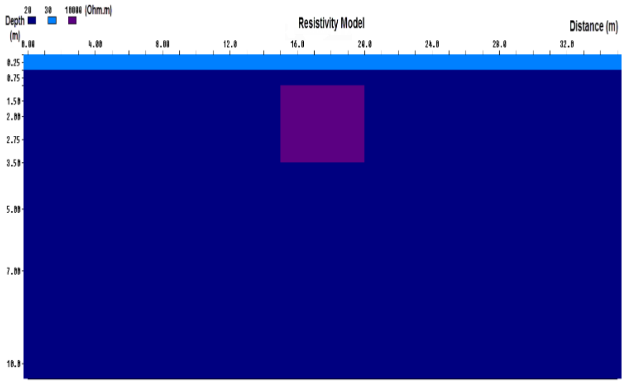

Figure 3: The synthetic resistivity model examined in the current study

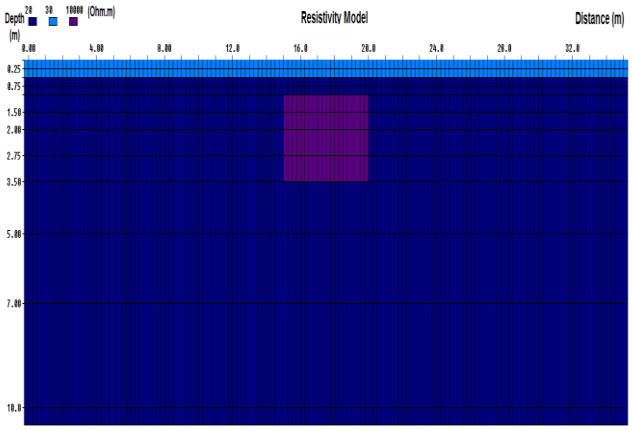

Figure 4: The model discretization

5.Results and Discussion

Figure 5 shows the pseudo apparent resistivity sections of examined resistivity configurations calculated using RES2DMOD software. It is well known that these sections give a qualitative resistivity image of the subsurface resistivity distributions. Consequently, these sections show distorted resistivity models for different resistivity configurations. Therefore, an inversion procedure is required to produce the true inverse sections [13].

Figure 6 shows the true inverse resistivity sections calculated using RES2DINV software with 0% noise level. In all sections of noise free data, a low absolute Abs. error was noticed after five iterations. It can be noticed that the buried tunnel structure is well reflected in the resistivity sections. This can be attributed to the high subsurface resistivity contrast which resulted in the high resistivity anomaly of the tunnel in the inverted resistivity section. However, the resistivity configurations exhibit different resistivity signature of the model. Wenner-Schlumberger, Dipole-Dipole configurations captured reasonably better the

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geometry and position of tested model. In comparison, Wenner, Pole-Dipole and Pole-pole configurations gave relatively exaggerated, smeared or distorted resistivity models. Several studies have reported sensitivity of Wenner-Schlumberger [11] and Dipole-Dipole [8, 19 & 24] configurations for detecting buried structures. Al-Zubedi, (2016) [25] suggested that Dipole- Dipole and Wenner-Schlumberger configurations are optimal for detecting buried structures of shallow and greater depths, respectively.

However, a primary goal of the current work is to evaluate the performance of the examined configurations at different noise levels. The effect of data noise may cause inversion artifacts in the inverted sections and with a very small signal to noise ratio the artifacts may smear the subsurface structures [19]. Therefore, a relatively low (10%), moderate (20%) and high (30%) scattered noise values were added to the model.

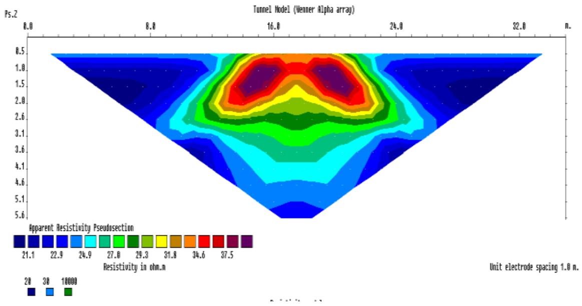
Figure 7 depicts the inverse resistivity sections of the model with 10% noise level. It can be seen that the added scattered noise produces inversion artifacts and affects the inverted resistivity sections of the examined configurations in different ways. Wenner, Pole-Dipole and Pole-pole configurations showed relatively more distorted and smeared models. Dipole-Dipole and Wenner-Schlumberger configurations seem less affected by the noise added.

Figure 8 shows the inverse resistivity sections of the model with 20% noise level. At this noise level, Wenner and Pole-Pole configurations failed in reflecting the geometry and position of the modelled tunnel due to the high resistivity artifacts. Again, Dipole-Dipole and Wenner-Schlumberger configurations can still resolve the modelled tunnel.

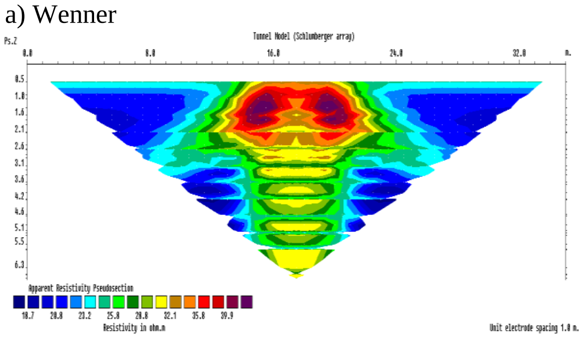
An extraordinary high 30% noise values were added to the model to explore the performance of the different configurations at very noisy situations, as shown in Figure 9. At this level of noise, the geometry and position of the modelled tunnel is reasonably reflected using Dipole-Dipole configuration. In comparison, the signature of the tunnel is relatively smeared in Wenner- Schlumberger resistivity section. All other arrays failed in resolving the buried tunnel. This finding demonstrates the efficiency of Dipole-Dipole and Wenner-Schlumberger in the second order in resolving the buried structures at high noise levels expected in shallow investigations. This finding agrees well with previous studies [8, 11, 19, 24 & 25].

The high performance of Dipole-Dipole and Wenner- Schlumberger configurations can be attributed to their characteristics features. The dipole-dipole array is highly sensitive to horizontal resistivity changes with greater horizontal data coverage and depth of investigation. Wenner- Schlumberger configuration is a combination of the Wenner and Schlumberger configurations. It has good signal strength and moderate features that compromise between the ability to resolve horizontal and vertical structures [13].

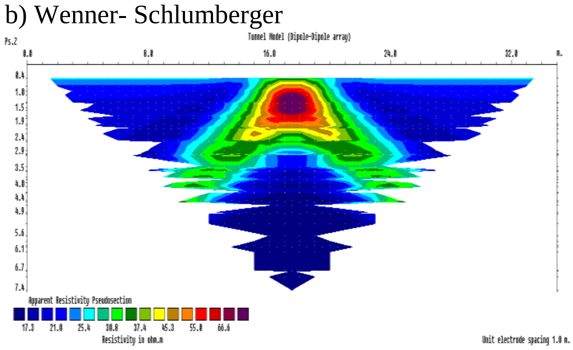
The current work showed the benefits of 2D resistivity modelling for planning of electrical resistivity surveys. However, as subsurface geology varies from area to another, the results should be evaluated and confirmed carefully through actual field studies.



a) Wenner



b) Wenner- Schlumberger



c) Dipole- Dipole

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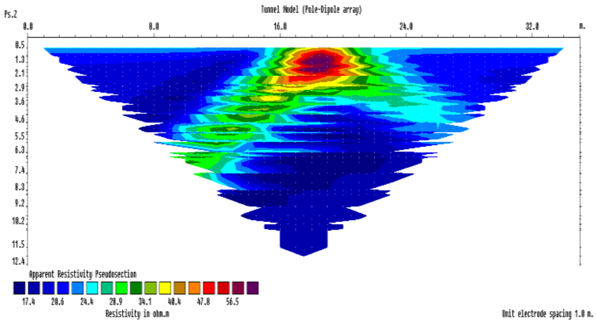
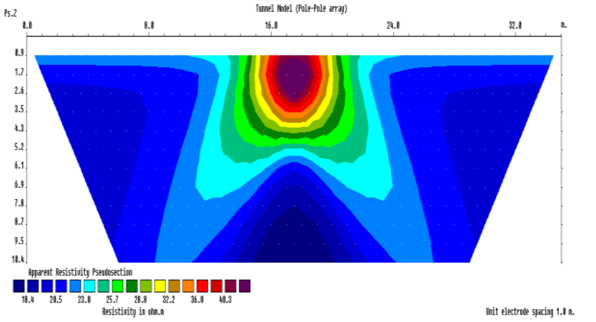
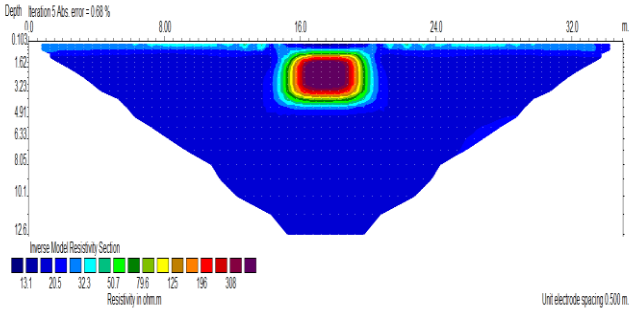


d) Pole-Dipole



e) Pole- Pole

Figure 5: The pseudo apparent resistivity sections for different electrode configurations calculated using RES2DMOD software



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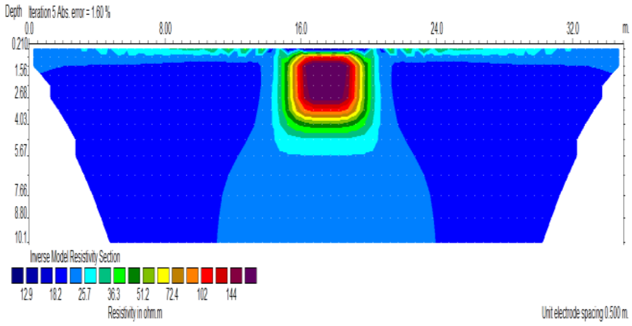
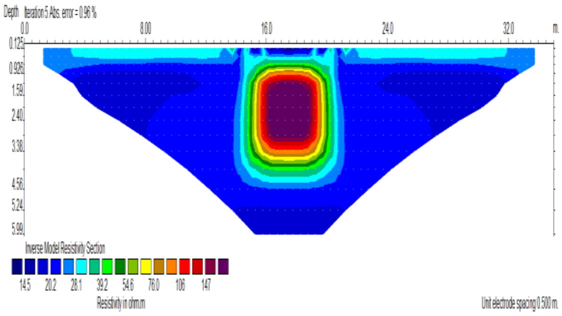
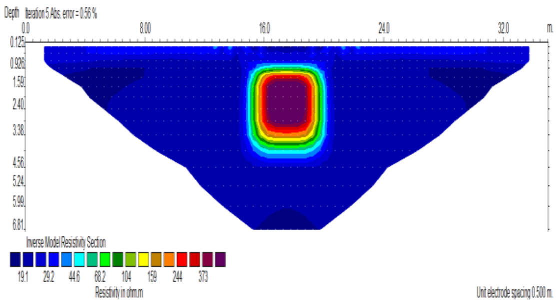


e) Pole- Pole

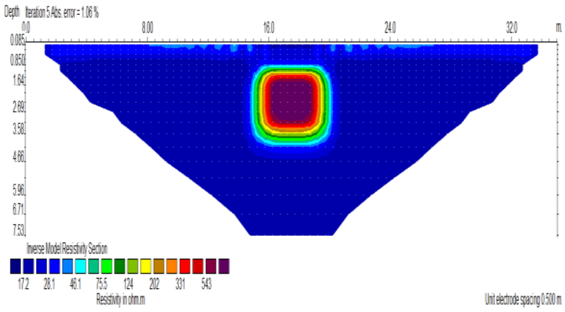
Figure 6: The true inverse resistivity sections of 0% noise model for different electrode configurations calculated using RES2DINV software



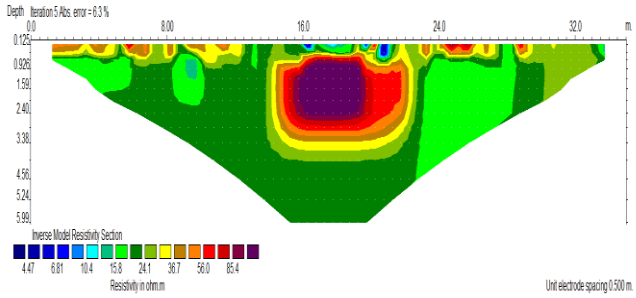
a) Wenner



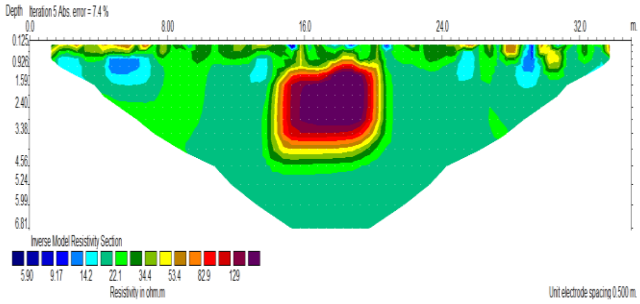
b) Wenner- Schlumberger



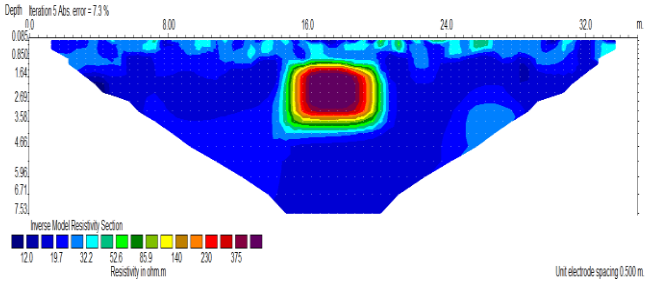
c) Dipole- Dipole



a) Wenner



b) Wenner -Schlumberger



c) Dipole- Dipole

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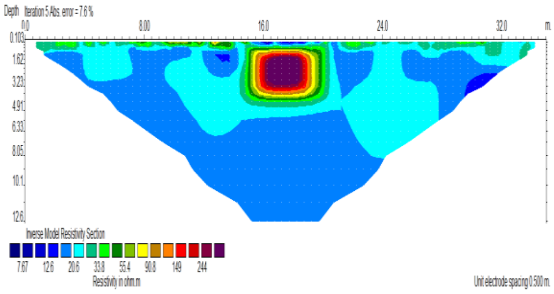
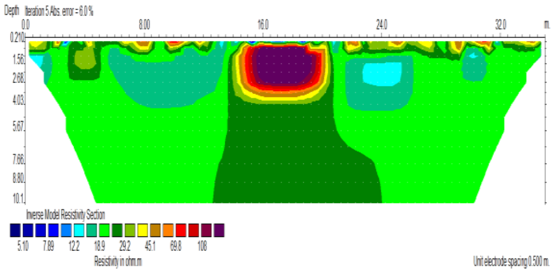
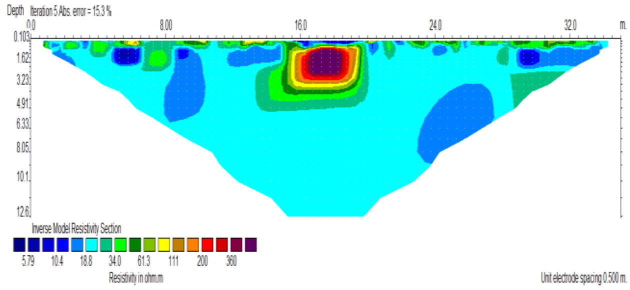


d) Pole-Dipole

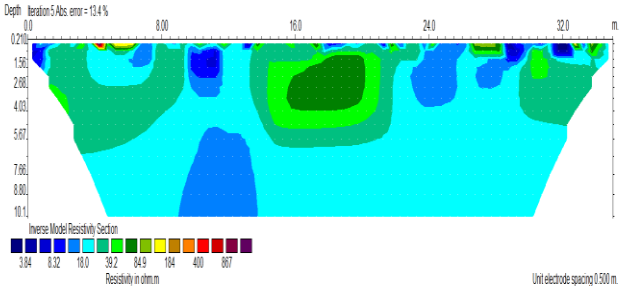


e) Pole- Pole

Figure 7: The true inverse resistivity sections of 10% noise model for different electrode configurations calculated using RES2DINV software

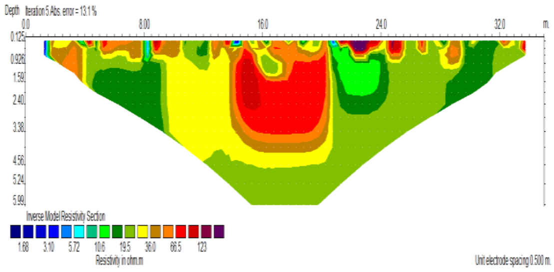


d) Pole-Dipole

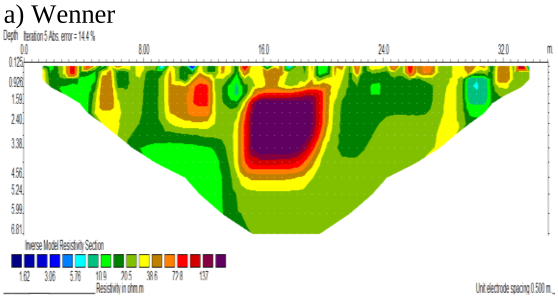


e) Pole- Pole

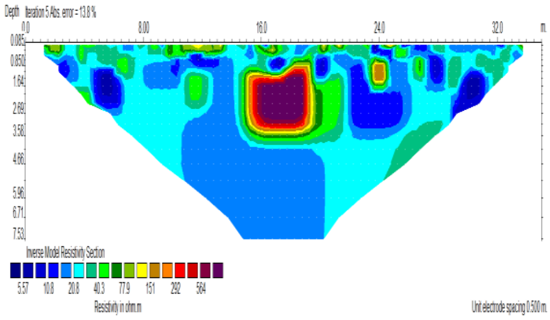
Figure 8: The true inverse resistivity sections of 20% noise model for different electrode configurations calculated using RES2DINV software



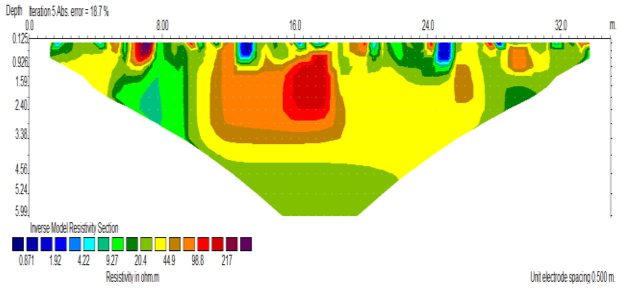
a) Wenner



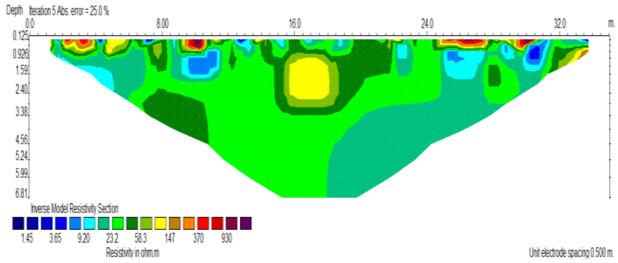
b) Wenner-Schlumberger



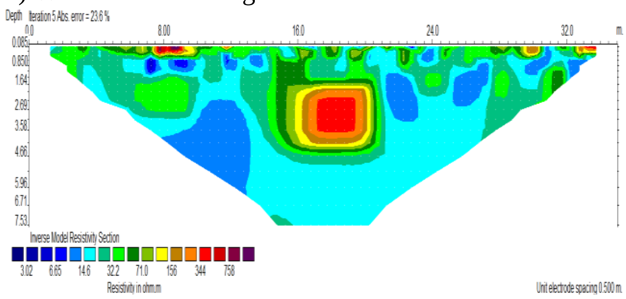
c) Dipole- Dipole



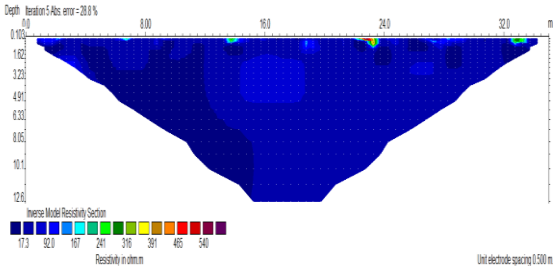
a) Wenner



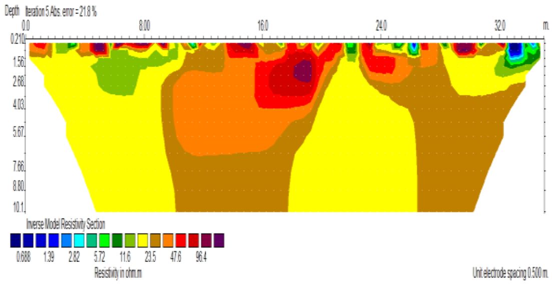
b) Wenner-Schlumberger



c) Dipole- Dipole



d) Pole-Dipole



e) Pole- Pole

Fig. 9: The true inverse resistivity sections of 30% noise model for different electrode configurations calculated using RES2DINV software

6.Conclusions

2D ERT numerical modelling was adopted to explore the performance of five electrical resistivity configurations for detecting buried tunnel structure at different noise levels. Forward modelling and inversion software packages were used. The results indicated that the modelled tunnel can well be resolved at 0% noise level due the high subsurface resistivity contrast. Adding resistivity noise to the model changes the performance of the examined configurations due to the artifacts in the inverted resistivity sections. At different noise levels, the results demonstrated that dipole-dipole and Wenner- Schlumberger configurations perform better than other tested arrays. This can be attributed to the characteristics features and sensitivity of these arrays for detecting subsurface variations. In addition, the high noise level expected in shallow investigations may overwhelm the resistivity signature of the burred targets. Thus, obtaining high quality data in the field surveys can only ensure reliable resistivity sections. The current work demonstrated the potential benefits of 2D resistivity modelling for planning of resistivity surveys. However, as subsurface geology varies from site to site and for different cases, the obtained results should be analyzed and evaluated carefully through actual field surveys.

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